Efficient and Reliable Communications in Industrial Wireless Sensor Networks

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Abstract

Communications infrastructure plays an important role in industrial monitoring, automation and process control. Recently, wireless solutions have emerged to offer communications in industrial processes to establish feedback control. Due to cost efficiency, localized processing, application specific and resource efficient design, flexibility, and self-healing abilities, Industrial Wireless Sensor Networks (IWSNs) emerge as the most promising technology for industrial automation.

Despite the seamless advantages, IWSNs still suffer from the reliability and real-time data delivery issues inherent in the wireless networks. These issues are more prominent in the emergency communications, regulatory feedback control systems and supervisory feedback control systems.

The research focuses on communications and system feedback related problems of IWSNs in applications in automation and process control industry including, emergency systems, regulatory control systems, supervisory control systems open loop control systems, alerting systems and monitoring systems. The research targets communication assurances, reliability improvement, real-time sensory data propagation and energy efficiency in IWSNs. It also targets the traffic scheduling from heterogeneous sensing nodes to improve the overall network efficiency, reliable data scheduling and deterministic schedule formation for coexisting industrial systems.

The notable contributions of the research cover following aspects of IWSNs

- A novel scheme is proposed to ensure instant channel access for emergency communications. The scheme integrates emergency communications within the regular communications channel without compromising the reliability and time sensitivity of the information. Thus, improving network flexibility along with improved reliability

and real-time data delivery. The improvements proposed in the emergency communications are further extended to the regulatory control and supervisory control applications where superframe of variable durations are introduced to offer higher reliability within the communication feedback links.

- Dynamic priority system is proposed which takes in to consideration the critical parameters in industrial processes to offer suitable urgency index to the sensory data based on real-time analysis of parameters. Using the priority system, MAC layer optimizations are proposed to 1) improve the reliability of high priority nodes' communications, 2) ensure pre-specified Packet Reception Rate (PRR) within the network.
- An efficient update mechanism is proposed to offer improved energy efficiency and network reliability in gradient-based routing protocols. Two schemes: periodic setup and multiple setup, are proposed along with secondary update mechanisms to keeps the routing path updated with minimal control overhead. Furthermore, an optimizable gradient cost function is also proposed.
- A low complexity, scheduling algorithm is proposed, which allows multiple classes of industrial systems to coexist and share same wireless resource and to distinctly schedule information from diverse industrial processes with heterogeneous time deadlines.

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Glossary of Abbreviations

AP	Access Point
ATS	Average Time Synchronization
BSS	Basic Service Set
CAP	Contention Access Period
CF-MAC	Critical Feedback MAC
CFP	Contention Free Period
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DSSS	Direct Sequence Spread Spectrum
ECR	Emergency Channel Request
ECS	Emergency Communications Sequence
EE-MAC	Emergency Enabled MAC
ESS	Extended Service Set
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
GAck	Group Acknowledgement
GCF	Gradient Cost Function
GRAB	Gradient Broadcasting
GRACE	Gradient Cost Establishment for an energy aware routing in WSN
HD	Halt Duration
HPNNs	High Priority Non-replaceable Nodes
HPRNs	High Priority Replaceable Nodes
HT	Halt
IBSS	Independent Basic Service Set
ISA	International Society of Automation
ISM	Industrial Scientific and Medical
IWSNs	Industrial Wireless Sensor Networks
KMP	Key Management Protocol
LLDN	Low Latency Deterministic Networks
LPNs	Low Priority Nodes
LQ	Link Quality
MAC	Medium Access Control
MEMS	Micro-Electro Mechanical systems

MTS	Maximum Time Synchronization
NL	Network Load
OD-MAC	On-Demand MAC
O-PEMAC	Optimized Priority Enabled MAC
PE-MAC	Priority Enabled MAC
PLC	Programmable Logic Controllers
PQES	Priority integrated Quality Ensured Scheme
PRR	Packet Reception Rate
PS	Periodic Setup
PS (Back)	PS with Broadcast Acknowledgement Mode
PS (C+A)	PS with Hybrid Mode, ‘Correction + Acknowledgement’
PS (C-intr)	PS with Correction Mode, starting from the intermediate node
PS (U-ack)	PS with Unicast Acknowledgement Mode
PS(C-sink)	PS with Correction Mode, starting from the sink
QES	Quality Ensured Scheme
QoS	Quality of Service
RC	Regular Communications
RMCA	Regret Matching Based Channel Assignment Algorithm
RSSI	Radio Signal Strength Indicator
RT	Reinitiate
RTE	Real Time Ethernet
SCADA	Supervisory Control and Data Acquisitions
SCFR	Source Clock Frequency Recovery
SP	Special Purpose
S-Slots	Shared Slots
SYNC	Synchronization Beacon for RC Channel
SYNP	Synchronization Beacon for SP Channel
TCP/IP	Transmission Control Protocol/Internet Protocol
TDMA	Time Division Multiple Access
TSCH	Time Slotted Channel Hopping
URLLC	Ultra-Reliable Low Latency Communications
UWB	Ultra Wide Band
VCO	Voltage Controlled Oscillator
VLC	Visible Light Communications
WDS	Wireless Distribution System
WPAN	Wireless Personal Area Network

WSNs	Wireless Sensor Networks

Glossary of Symbols

n	Total Time slots in superframe/ Total Nodes
m	Number of emergency nodes/ High priority nodes
$Payload\_bits$	Packet Payload bits
PL_delay	Payload transmission time
T_{LLDN}	Superframe duration (LLDN)
$T_{EE\text{-}MAC}$	Superframe duration (EE-MAC)
R_b	Data Rate
p	Probability of successful communication
λ	Emergency traffic Arrival rate per second
α	Number of emergency requests
t	Time slot duration
d	Access Delay
$d\_success$	Average successful communication delay
$(1-\delta)\times t$	Communication window duration
$\delta \times t$	Acknowledgement window duration
e	EE-MAC average duration of added time-slots
k	Maximum additional slots in CF-MAC
s_i	Nodes communicating in Segment-*i*
q	Communication failure probability
x	No. of emergency requests
y	No. of failed communications per segment
v	count of transmissions until the successful communication
A_f	Average communication failures per segment
$\mathrm{P}(f_{si})$	Probability of Communication failures in segment-*i*
s	Sensor value
Sp	Sensor Setpoint
Th_{High}	Threshold high
Th_{Low}	Threshold low
h	Superframe supervisory control segment time-slots
u	number of supervisory feedback sensor nodes
R_s	percentage channel request queries per unit time
z	Total nodes

φ	Allowable percentage increase in the delay of two consecutive transmissions of a critical node in consecutive superframes
$dl(i)$	Time deadline of node i
Δ	Duration of additional slots added in superframe
f_{stack}	Nodes with failed communications in a superframe
g	Number of additional time slots added in superframe
N	Number of nodes with failed communication in previous superframe
ʒ	Control system stability factor (%age of time for which the process output remains within the threshold)
$n\text{-}m$	Low Priority Nodes (LPNs)
k	High Priority Non-replaceable Nodes (HPNNs)
$m\text{-}k$	High Priority Replaceable Nodes (HPRNs)
P_n	Probability of a node replacement in HPRNs
q	Probability of communication failure
p	Probability of communication success
s_d	Sub-slot duration
Ψ	Guard band
α, β, γ, ʒ and ξ	Weight coefficients
CII_x	Critical information index of node x
W_x	Priority weight of node x
WI_x	Weight index of node x
IFI_x	Information failure index of node x
p_n	Probability of node replacement
δ_p	Time required from communication initiation to delivery
T_{sf}	Superframe duration
ω	Percentage traffic delivered to destination
∂	Delay to deliver ω percent of the entire traffic generated by a high priority node
c	No. of nodes scheduled for communication in a particular frame
D_q	Desired QoS
s_n	No. of shared slots needed to achieve desired QoS
ψ	Percentage of priority nodes
w	Total nodes
$C_u^{s_c}$	Maximum limit on number of channels
s_c	Channels selected for communication
u	Total channels

b	Total contention based slots in SP channel
H	Number of RC channels
C_{grad}	Gradient cost
H_{count}	Hop count
H_{max}	Maximum hops in the network
d_{avg}	Average delay
d_{max}	Maximum delay
ΔE	Estimated power consumption in communication of packet from source to sink
N_t	Times transmitter turns on in unit time
N_r	Times receiver turns on in unit time
P_{VCS}	Power consumed by synchronizer
t_{st}	Start time of transmitter and receiver
t_{tx}	Active time of transmitter
t_{rx}	Active time of receiver
$\mathcal{E}n$	Node's remaining battery
LQ	Link quality
$\mathcal{E}_{frequent-node}$	Energy cost value of most frequently used node
$last\_count$	Packets received since last route maintenance
C, G	Route maintenance cycle adjust coefficients
ε	Network energy
μ_r	Network reliability
e_a	Nodes alive
f_{min}	Lowest sampling frequency
$sfCount$	Total number of subframes
f_bits_i	No. of bits to be transmitted by node i
B_Δ	Information bits communicated in one time slot
Sym_dl	Symmetric time deadline vector
$T_{deadline}$	Time deadline

Dedications

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Declarations

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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1 INTRODUCTION

1.1 Overview

Wireless Sensor Networks (WSNs) are spatially distributed wireless nodes which work collaboratively to cover a large physical area to serve monitoring and control purposes. Each node in the network can be equipped with a processing unit, memory, battery, energy harvesting mechanism, I/O interfaces and one or more sensors. Since these nodes provide a relatively small range for wireless communications, the communication within the networks usually take place in multi-hop fashion. Mostly, the communication among the nodes uses Industrial, Scientific and Medical (ISM) radio band. The use of free spectrum and the developments in Microelectromechanical systems (MEMS) ensures cost efficiency in the WSN based solutions. The wireless nature also makes these nodes more effective sensory feedback links in rotary equipment.

Industrial Wireless Sensor Networks (IWSNs) is a special domain in WSNs which is used for monitoring and control applications within the industrial environments. Some of the applications of IWSNs include area monitoring, air/water quality monitoring, machine health monitoring, structural monitoring, disaster prevention and emergency response systems, sensor and actor networks and automation and feedback control. The low cost of today's senor nodes, the suitability for placement in dynamic environment, the scalability, self-healing abilities, flexibility and ease of deployment are some of the key benefits which encourages the adoption of IWSNs over the traditional wired networks.

IWSNs work quite similar to WSNs. However, due to the critical nature of industrial applications, IWSNs must ensure the required reliability and time deadlines imposed by these applications. For more critical industrial applications (emergency systems, regulatory control systems) the IWSNs must also ensure the predictable behaviour to minimize the anomalies in the underlying control systems.

1.2 Research Motivation

Industries are continuously evolving since the very beginning of the industrial era. This modernization is undoubtedly the outcome of continuous new technology development in this field, which has kept the industries on the verge, looking for new methods for improvement, productivity enhancement and better operational efficiency. More recently the continuous quality improvement has become one of the most essential factors to survive in the industrial race [1]. The past few years have resulted in vast expansion in industries. This expansion equipped the industries with the latest technology at hand, to develop self-sufficient, spontaneous and computerized work environments. With the successful incorporation of advance automation and process control, the productivity and products' quality has greatly improved [2]. Moreover, the incorporation of industry 4.0 introduces intelligent processes, flexible and in time manufacturing, complex task processing and optimized decisions [3]. These improvements though highly impressive yet add high complexity to the industrial processes and in some cases even challenge the sufficiency of existing technologies to cope with these rapid changes.

The incorporation of more and more automated processes and close-loop control systems in the industries, especially in the industry 4.0 where robotic system become a norm, will significantly increase the importance of communication systems [4]. To ensure the effective operation of the industries, these communication networks play a very important role. The communication networks established in industrial environments can be broadly divided in two categories, wired and wireless. However, the strong interference experienced in wireless in industrial environment along with high performance demands make industrial solutions very challenging. It is for the same reason; wired-communication solutions were preferred over wireless in the last decade.

Many wired-communication solutions were proposed to offer high-speed communication, deterministic reliability, and real-time data delivery [5]. Over the years, many wired-communication standards and technologies were introduced to meet the stringent real-time and reliability requirements of the industrial processes. These wired-communication network developments can broadly be classified in the fieldbus systems and Ethernet systems.

Fieldbus systems have played a significant part in the industrial automation for a long time resulting in standardization of numerous technologies such as ones discussed in [6, 7]. Due to a number of desirable characteristics such as deterministic behaviour, lesser sensitivity to electrical noise, simplified connectivity and ability to operate over longer distances, fieldbus networks were widely used in the industrial environment to connect field level equipment including motors, transmitters, control valves, proximity sensors, accelerometers, encoders, monitoring and control devices.

High data rates and larger bandwidth offered by Ethernet qualifies it to serve as a backbone of the industrial networks. Industrial Ethernet received a wide acceptance for communication among Programmable Logic Controllers (PLC) and Supervisory Control and Data Acquisitions (SCADA) with Transmission Control Protocol/Internet Protocol (TCP/IP) enabled interlinking [5]. Furthermore, the switch-based architecture, remote diagnosis, and self-configuring tools of Ethernet offer significant improvement over the fieldbus networks. Therefore, the use of Ethernet at field level appeared to be a promising solution to the interconnectivity problem [8] between high-level (Ethernet) and low-level (Fieldbus) networks [9]. However, an accurate priori delay estimation for effective operation of supervisory control is imperative, therefore, the uncertainty in industrial Ethernet must be addressed. Later, to improve the suitability of Ethernet on field level, Real Time Ethernet (RTE) was introduced [10] which used Time Division Multiple Access (TDMA) based channel access scheme for improved reliability and predictable delays. Use of TDMA resulted in the synchronization issues, which were later addressed in IEEE1588 standard [11].

Although, the wired-communication networks offered modest data rates and reliability but failed in offering scalability, upgrading, cost efficiency and efficient network deployment. All these factors forced the investors and researchers to look into wireless communication solution for industrial automation.

In recent years, IWSNs have emerged as an efficient and cost-effective solution for communication feedback in industrial automation and process control. The advantages offered by IWSNs persuaded many industries in its adoption, especially in low data rate applications [12, 13]. One of the major factors contributing to the popularity of IWSNs is its low installation cost [14]. Compared to the cabling and maintenance costs of wired networks (up to €4337 per meter [15]), the wireless networking technologies offer a very small cost in fraction of a euro for per meter of wireless connectivity. Apart from the cost, the offered flexibility and scalable nature of IWSNs make it an ideal candidate for present as well as future dynamic industrial environments. Furthermore, IWSNs offer many advantages, including flexibility, self-organization, low cost of installation, localized processing, interoperability and easy deployment.

Despite the vast benefits of this technology, it suffers from constrained communication range, small memory, delay, limited bandwidth, reliability issues, limited battery capacity, security threats and interconnectivity issues [16]. The research in the above listed constraints can assist in exploiting the full potential of the technology.

Past few years have been very productive in addressing many challenges presented by IWSNs. The main developments witnessed until 2012 were carefully transformed to the IEEE Wireless Personal Area Network (WPAN) standard 802.15.4e [17], primarily targeting the industrial applications. Most of the amendments listed in this standard further improve the long chain of existing WPAN standards, [18-20], for industrial applications. Many industrial solutions based on these standards also emerged. Some significant contributions include, Zigbee, WirelessHART, ISA100.11a, 6LoWPAN Wia-PA and OCARI [21-26]. The research developments during past three years, also have significant impact in improving the IWSNs credibility for process control and automation. A keen and persistent trend in research developments was witnessed in these years, resulting in significant improvements in Medium Access Control (MAC) protocols, network layer optimizations, energy harvesting techniques and incorporation of new technologies in industrial wireless networks.

These significant research developments in IWSNs have given new heights to this market, resulting in a momentous rise in its projected value, ranging from $944.92 million to $3.795 Billion in coming years [27, 28]. However, it is also expected that the projection would highly depend on the research trends and significance of improvements one witnesses in upcoming years. To cope with the projected market trends, satisfy demands of more sophisticated industrial applications and to meet the crucial deadlines in highly sensitive industrial atmosphere, a dedicated research targeting reliability, real-time data delivery, energy efficiency, incorporation of modular design and interoperability in IWSNs is much needed.

The deployment of wireless technology in wider and more critical industrial applications require deterministic behaviour, reliability and predictable latencies to integrate the industrial processes more effectively. Real-time data communication and information reliability in the wireless channels are some of the major concerns of the control society regarding IWSNs, and hence suitable improvements in IWSNs are required to ensure desired reliability and time-sensitivity in emergency, regulatory and supervisory control systems.

1.3 Problem Statement

In recent years, IWSNs has become one of the main contenders for the communication links in industrial monitoring, automation and process control. The adoption of IWSNs in industries is strongly influenced by its advantages over traditional wired networks. Whilst the IWSNs offer many advantages including flexibility, self-organization, cost efficiency, localized processing, interoperability and easy deployment, they also suffer from constrained communication range, small memory, delay, limited bandwidth, reliability issues, limited battery capacity, security threats and interconnectivity issues [25]. Among all the afore-mentioned factors, where some favor the adoption of IWSNs in many applications, others open new research challenges to be dealt with [16, 29, 30, 31].

In the last few years, a massive shift in WSN research, from asynchronous best effort communication to a periodic sustainable data rate with suitable reliability and sense of urgency has been witnessed. However, the changes proposed are limited by the traditional perception of WSNs. Many IEEE standards and Industrial protocols were presented. However, the existing research and IWSN standards fail to offer desired performance and reliability for critical industrial processes. The existing IEEE standards, IEEE802.15.4 and IEEE802.15.4e fail to ensure time deadlines for critical information. Some variants of these standards were also introduced over the years which offered improved reliability, however, it was achieved at the cost of added delay.

The existing standards like ISA100.11a operate on a time deadline of 100 milliseconds. The relatively relaxed time bounds achieved in ISA100.11a limits its applications in close loop control and process automation where time deadlines of up to 10 milliseconds are expected. Zigbee, one of the most widely used industrial standard with over 70 million devices installed worldwide use Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) based channel access scheme which limits its reliability, especially in a more congested network. Other protocols also suffer similar problems and hence show incapacity to handle critical industrial applications.

The research work presented in the literature also offers a fair amount of contribution to increase suitability of the WSNs for wide variety of applications. However most of the work presented until the recent past mainly target energy efficiency and network lifetime. Recently, more attention has been diverted to IWSNs and time critical applications. However, there is still much room for improvement. In some cases, extensive models have been presented [32, 33] to offer a suitable reliability and time deadlines for time constraint and critical processes but mostly, the achieved improvements cannot be integrated in the existing infrastructure and needs equipment changes or specific features only included with additional hardware and added cost to individual motes.

The existence of different classes in the industrial communication and feedback systems introduce varying requirements needed to be addressed on case-to-case basis. Scheduling of information and maintenance of desired Quality of Service (QoS) from various nodes with dissimilar deadlines, varying priorities and reliability requirements becomes a challenge. Furthermore, the use of same resources for accommodating different traffic types with varying frequency of communications for each node is not addressed and requires effective low complexity scheduling.

In IWSN, the low data rate also serves as a bottleneck and in many cases the performance is degraded due to added delay caused by queued information. It is even severe in cases of large networks or relatively higher number of affiliated nodes to a single coordinator. The use of uniform precedence level in such cases adds to the problems and results in performance degradation, as the existing information in an industrial environment can have different priorities and all cannot be treated equally in order to meet the specified deadlines. However, research in this domain is relatively limited and no extensive investigations can be witnessed on priority based traffic scheduling and transmission. Further to this, almost all of the priority based communication protocols introduced, offer static priority status and hence limit the scope of these protocols to establish efficient schedules on pre-defined priority basis [22, 34]. The protocols using pre-defined priority also perform poorly in the industrial processes where the change in nature of the sensed information significantly matters and hence can greatly change priorities, if the readings from one particular process change from normal ranges to critical ranges. The problem can also be witnessed in existing IWSN standards and industrial protocols as most of the existing standards and protocols in IWSNs either use no or static priority for communication.

While considering the suitability of IWSNs in critical industrial processes, the reliability and real-time data delivery also appears to be the main concern of the control community. Hence, despite the potential, low reliability and delay unpredictability limits the use of IWSNs for time critical processes. The development of real-time reliable and energy efficient schemes for IWSNs can contribute in the wide-scale deployment of WSNs in industrial applications, leading to cost effective, flexible and efficient solution for industrial automation and process control. Therefore, development of schemes to offer improved reliability and real-time data delivery, which can effectively integrate in the existing wireless networks, is much desired.

Ever changing industrial environments and highly complex and dynamic nature of modern industrial networks need IWSNs to evolve to cope with the vibrant changes. The highlighted problems and issues in IWSNs pose significant limitations and hence these need to be addressed.

The research work proposes real-time, reliable and energy efficient communications in IWSNs to offer QoS ensured communications within the automation, process control and feedback systems where the details description of the proposed work is presented in next section.

1.4 Original Contribution

The industrial processes and control systems are usually considered time constrained and highly critical with strict bounds on the communication reliability and response time. The link between the processes and the control unit has always been essential. Therefore, the reliability of the link and the timely communication has always been prioritized above all.

IWSNs carry great potential to meet the needs of the highly critical industrial applications. However, to ensure the smooth running of the processes and to build tolerance against abnormalities, a highly reliable, time sensitive, effective and efficient solution is very desirable. Moreover, the full potential of IWSNs must be exploited to offer a better solution and to meet the deadlines set forth for industrial control, and automation.

The thesis focuses on communication and system feedback related problems of IWSNs in automation and process control applications. These will include the investigation on emergency systems, regulatory control systems, supervisory control systems, open loop control systems, alerting systems, and monitoring systems. The research focuses on the communication assurances, reliability improvement and real-time sensory data propagation in IWSNs. It also targets the traffic scheduling from heterogeneous sensing nodes to improve the overall network efficiency, reliable data scheduling and deterministic schedule formation for coexisting industrial systems along with the network lifetime optimization.

The notable contributions of the research cover following aspects of IWSNs

1. Control channel based MAC protocol is proposed which offers a mechanism for optimizing channel access for emergency communication and introduces a scheme to provide immediate channel access for critical nodes. The mathematical modelling and the

performance analysis of the scheme is presented in Section 3.2.1 and Section 3.3. Further to this, Communication optimization in regulatory, open-loop and supervisory control systems is introduced which provides communication failure compensation for regulatory control systems as well as schedules asynchronous channel access requests for supervisory control systems. The detailed modelling and analysis of this work is presented in Section 3.2.2 and Section 3.3 of Chapter 3.

2. Dynamic priority system is introduced which takes in to consideration the critical parameters in industrial processes to offer suitable urgency index to the sensory data based on real-time analysis of parameters. A priority based communication optimization scheme with sleep scheduling and reliability enhancement mechanism is introduced. The priority system is further extended to offer predictable reliability with adaptive reliability ensured schemes. Further to this, the use of multi-channel and hybrid channel access is proposed for improved reliability and network scalability. A detailed discussion, on probabilistic modelling communication rescheduling, mathematical modelling and the performance analysis of the scheme is presented in Chapter 4 and Chapter 5.

3. An efficient update mechanism in gradient-based network is introduced to offer improved energy efficiency and network reliability. A detailed discussion on mathematical formulation, simulations, physical implementation and performance analysis is presented in Chapter 6.

4. A low complexity, communication traffic scheduling algorithm is proposed, which allows multiple classes of industrial systems to coexist and share same wireless resource to distinctly schedule information from diverse industrial processes with heterogeneous time deadlines using IWSNs. The theoretical development and results of this work are presented in Chapter 7.

The summary of the research issues, existing solutions and original contributions of the thesis in IWSNs is graphically presented in Figure 1.1

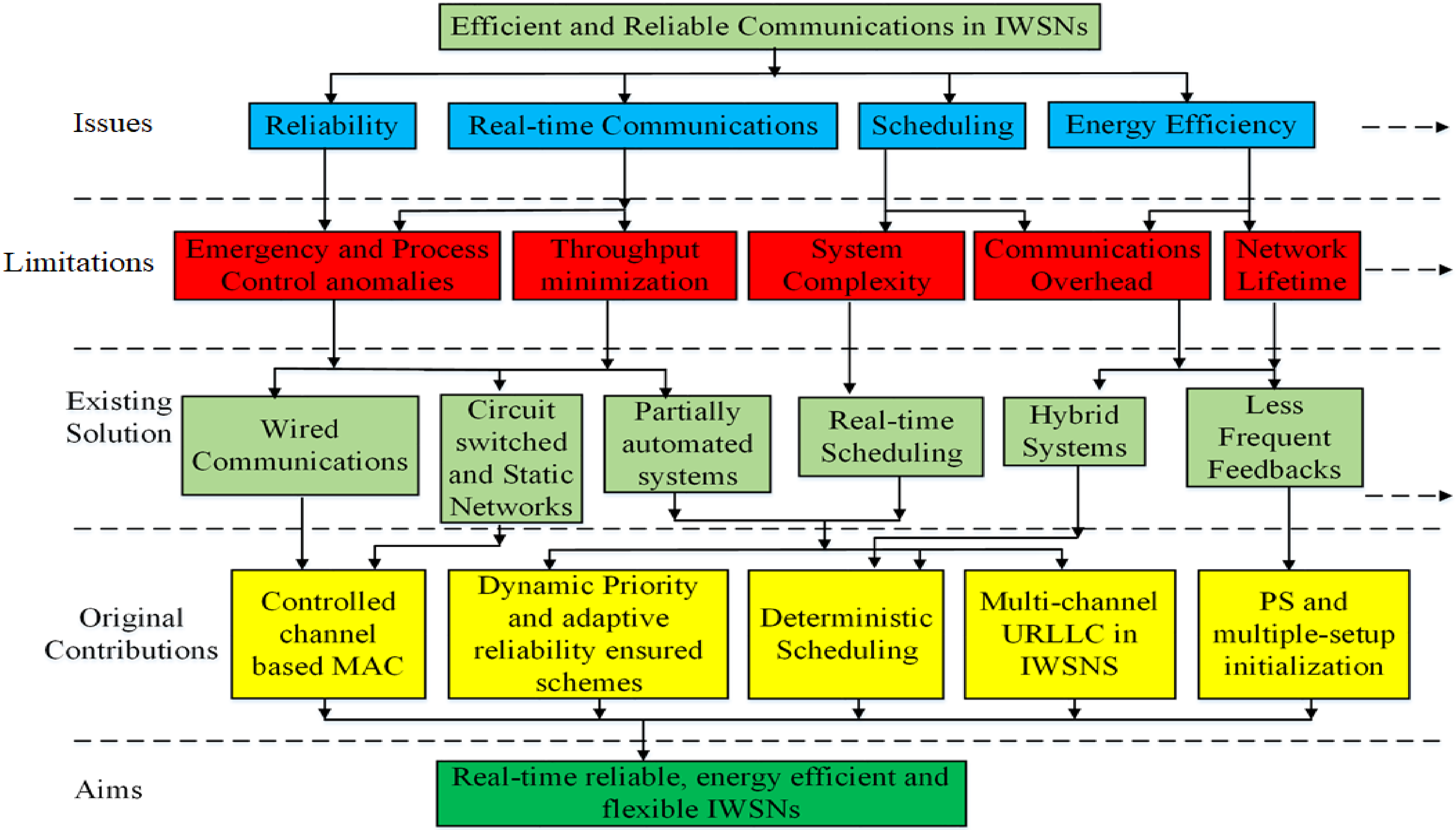

Figure 1.1: The summary of the issues, existing solutions and original contributions for IWSNs

1.5 Publications and Awards

[1] **M. Raza**, N. M. Khan, G. Ahmed, N. Aslam, H. Le-Minh, “Impact of Periodic-Setup Initialization on the Performance of Gradient Routing Protocols for Conventional and Industrial Wireless Sensor Networks”, Springer Mobile Networks and Applications, 2018 (submitted)

[2] **M. Raza**, H. Le-Minh, N. Aslam, S. Hussain, M. Imran, R. Tafazolli and Huan X. Nguyen, “Dynamic Priority based Reliable Real-Time Communications for Infrastructure-less Networks”, IEEE Access 2018 (Submitted)

[3] **M. Raza**, N. Aslam, H. Le-Minh, S. Hussain, “A Novel MAC proposal for Critical and Emergency Communications in Industrial Wireless Sensor Networks”, Elsevier Computers and Electrical Engineering, 2018

[4] **M. Raza**, N. Aslam, H. Le-Minh, S. Hussain, N. M. Khan, Y. Cao, "A Critical Analysis of Research Potential, Challenges and Future Directives in Industrial Wireless Sensor Networks", IEEE Communications Surveys & Tutorials, 2017.

[5] **M. Raza**, S. Hussain, H. Le-Minh, N. Aslam, "Novel MAC layer proposal for Ultra-Reliable and Low-Latency Communication in Industrial Wireless Sensor Networks; A proposed scenario for 5G powered Networks" ZTE Communications 2017.

[6] **M. Raza**, H. Le-Minh, N. Aslam, S. Hussain, "Deterministic Scheduling for Energy Efficient and Reliable Communication in Heterogeneous Sensing Environments in Industrial Wireless Sensor Networks" EAI Endorsed Transactions 2017.

[7] **M. Raza**, L. Rossier-Tillard, S. Vigoureux, H. Le-Minh, P. Coste, ‘‘A Modular Approach for Smart and Efficient Parking Assistance System”, Vietnam Journal of Science, 2017.

[8] P. Dhawankar, **M. Raza**, H. Le-Minh, N. Aslam, “Software-Defined Approach for Communication in Autonomous Transportation Systems”, EAI Endorsed Transactions on Energy Web, 2017. doi={10.4108/eai.14-7-2017.152924}

[9] W. Ellahi, K. Sardar, **M. Raza**, N. Aslam, W. U. Baig, ‘‘Efficient Fingerprint Matching Algorithm for Reduced False Similarity Contribution In Forensics and Partial Finger Prints”, Vietnam Journal of Science, 2017.

1.5.1 Conference Papers:

[10] **M. Raza**, H. Le-Minh, N. Aslam, S. Hussain, "Deterministic Scheduling for Heterogeneous Sensing Deadlines in Industrial Wireless Sensor Networks", 2nd International Workshop on Sustainability and Green Technologies, 2017.

[11] **M. Raza**, H. Le-Minh, N. Aslam, S. Hussain and W. Ellahi, "A control channel based MAC protocol for time critical and emergency communications in Industrial Wireless Sensor Networks," 2017 International Conference on Communication, Computing and Digital Systems (C-CODE), Islamabad, 2017, pp. 122-126.

[12] W. Ellahi, K. Sardar, M. Raza, N. Aslam, W. U. Baig, "Fingerprint Matching by Reducing False Similarity Contribution Using Point Slope Formula”, 2nd International Workshop on Sustainability and Green Technologies, 2017.

[13] **M. Raza**, L. Rossier-Tillard, S. Vigoureux, H. Le-Minh, P. Coste, " Smart Parking Assistance System”, 2nd International Workshop on Sustainability and Green Technologies, Da-Nang 2017.

[14] P. Dhawankar, **M. Raza**, H. Le-Minh, N. Aslam, "Communication Infrastructure and Data Requirements for Autonomous Transportation", 2nd International Workshop on Sustainability and Green Technologies, Da-Nang 2017.

[15] **M. Raza**, M. Hoa Le, N. Aslam, C. Hieu Le, N. Tam Le and T. Ly Le "Telehealth technology: Potentials, challenges and research directions for developing countries." (2017): 233-236.

1.5.2 Awards

1. European commission scholarship, Erasmus Mundus-cLINK (2015-2016)

2. Northumbria University research scholarship (2016-2017)

1.6 Thesis Structure

The thesis is arranged into eight chapters. Following the introduction sessions in Chapter 1, the brief overview of Chapter 2 to Chapter 8 is listed as follows.

Chapter 2 covers the literature review and developments in conventional and industrial WSNs. It discusses the communication standards and industrial protocols in IWSNs. A brief discussion on various IWSN motes, software tools and field trial is provided. Chapter discusses MAC layer developments in detail, offers a classification of various MAC protocols and presents a taxonomy of MAC developments. Network layer developments and classification of routing protocols is also presented in detail.

Chapter 3 presents theoretical development and numerical analysis of control channel based MAC protocols including EE-MAC, CF-MAC and OD-MAC. EE-MAC introduces a mechanism for optimizing channel access for emergency communication where a novel scheme to provide immediate channel access for critical nodes is discussed in detail. CF-MAC deals with the communication optimization in regulatory, open-loop and supervisory control systems. OD-MAC incorporates deadline-based scheduling of the nodes.

Chapter 4 presents a priority enabled MAC protocol to offer real-time and reliable communication of high priority information. A dynamic priority scheme is defined where the priority of the nodes can be predefined or updated with time to prioritize which information needs to be transmitted on urgent basis. A node replacement algorithm is developed to assist the priority establishment process and an optimal sleep scheduling is introduced to enable long network lifetime.

Chapter 5 discusses the multichannel scheme for URLLC in IWSNs. It exploits the use of multiple channels to improve the communication reliability, network throughput and the number of nodes accommodated in the network.

Chapter 6 discusses a network update mechanism for improved energy efficiency and network reliability. Two primary update mechanisms, PS and multiple-setup are presented which are further strengthened with secondary update schemes used to keep the nodes and networks updated for improved energy utilization and network reliability.

Chapter 7 discusses the proposed communication scheduling algorithm for heterogeneous sensing nodes. It presents a novel low-complexity traffic scheduling algorithm, which considers the time-deadlines and frequency of communication to offer static schedule to reduce communication over-head along with improved reliability and energy efficiency of the network.

Finally, **Chapter 8** provides conclusion and discusses possible future aspects for extension of the work.

2 LITERATURE REVIEW

2.1 Critical Nature of Industrial Environments and Traffic Deadlines

2.1.1 Industrial systems

IWSNs offer services to specific range of applications, which are significantly different from the traditional WSNs. Therefore, based on the specific application characteristics, QoS, latency and security requirements, the industrial systems are classified [29]. According to the International Society of Automation (ISA), the industrial systems can be distributed into six classes [35, 36]. This classification is based on the nature of application, standard operating procedure, access schemes, reliability, and latency requirements. These systems are listed as follows.

2.1.1.1 Safety/ Emergency systems

Safety/emergency systems handle issues of greater significance and of critical nature. For such systems, action on the developed situations, are required in matter of milliseconds. Any added delay can contribute to unwanted complications. Fire alarms, leakage of poisonous gases and emission of radiations are some of the examples of emergency systems.

2.1.1.2 Close-loop regulatory control systems

Close loop regulatory systems require a periodic feedback for smooth running of the processes. Such systems include both sensor and actuator elements where a continuous feedback from the sensors is needed to maintain the desired response of the actuation part. Usually the time bounds between sensing values and making the desired corrections using actuators, based on the sensed values, are very low. Some examples of close loop regulatory systems include autonomous cars or piloted drive, motion adaptation for conveyor belt movements and affiliated robotics etc.

2.1.1.3 Close-loop supervisory control systems

Close loop supervisory systems also provide a feedback control like the regulatory systems, except, these systems are asynchronous in nature and a feedback mechanism is established when certain thresholds are violated. Since, these systems are less critical in nature compared to the regulatory control systems, therefore, time and reliability bounds are more relaxed. Examples of close loop supervisory control include slow changing and less critical processes like temperature control of a furnace or boiler etc.

2.1.1.4 Open-loop control systems

The open loop control systems implement human operated process control. These systems, instead of automated analysis, rely on human intervention, where the operator after analysing the sensed data, takes the necessary action.

2.1.1.5 Alerting systems

In industries, alerting systems usually provide feedback of the sequential processes where regular or prompt feedback is established as a surety mechanism. Such systems offer tracking mechanism with regular feedbacks for different stages of the processes. In some cases, event-based alerting is also established.

2.1.1.6 Information gathering systems

Information gathering systems are used to collect sensor reading regarding non- actionable processes. The data gathering is targeted to provide the pattern observations over long period of time, which can serve as a baseline for the future changes and implementing long term plans. These systems and information gathered in similar systems is typically non-critical in nature and therefore, the data accumulation phases can span days. The accumulated data by information gathering systems usually undergoes a computer-based diagnosis to devise the improvement plans on the basis of data analysis.

2.1.2 Traffic types in industrial systems

A number of researches [34, 37-39] have categorized traffic in industrial environments in a number of groups depending on the type and critical nature of the traffic. In this section, the traffic in an industrial setup, in reference to presented industrial systems, is categorized in six groups. These categories are defined on the basis of critical nature of information, reliability, time constraints, medium access control and channel access pattern. These traffic types are listed in most critical to least critical order.

2.1.2.1 Safety/Emergency traffic

The safety or emergency traffic is the traffic of highest priority, if mishandled, may threaten a human life or incur damages to a plant. It is usually asynchronous in nature and rarely triggers due to anomalies and hazards such as risk of explosion or severe electrical surges etc. Due to the sensitive nature of this traffic category, high reliability is expected and fail-safe link is established with multiple contingencies [34]. This type of traffic has highest priority and usually prioritized over the rest of traffic. The time and reliability constraints of such industrial network traffic require careful modelling along with the prioritized access to communication channel [35].

2.1.2.2 Regulatory control traffic

The traffic originated from the systems running close loop regulatory control contribute significantly in density of IWSNs network traffic. There are two primary reasons: the sampling rate of the sensors involved in regulatory control is much higher and the information generated by these systems is periodic. The regulatory control traffic has much higher significance compared to other traffic types [36], except emergency, due to the strict bounds of the close loop systems. Furthermore, such control systems try to minimize the dead-time between two consecutive communications to optimize the performance of the close loop systems. Any negligence or delay in regulatory control traffic at network layer can lead to the safety or emergency trigger, which enhances the importance of this traffic. Since the regulatory control traffic, poses synchronous information load, therefore, it occupies constant bandwidth. Failure in communication may lead to the instability of the process control, therefore high reliability of such traffic is ensured [34, 35] .

2.1.2.3 Supervisory control traffic

The supervisory control traffic is quite similar to regulatory control traffic except, it is asynchronous in nature. In this case, localized processing is incorporated to identify if the specified thresholds are violated in any manner. Based on the initial conditions (if the sensed values are within specified thresholds or not), the priority to traffic is assigned. The behaviour of supervisory control traffic can be related to emergency traffic, however, due to less critical nature of applications at hand supervisory control traffic, depending on the conditions, is either modelled as regulatory control traffic [35] (for value beyond critical thresholds) or asynchronous alerting

Table 2.1: Traffic Categories and affiliated attributes in Industrial Wireless Sensor Networks [20, 40-43]

Sr.	Traffic Category	Case	Priority	Applications	Tolerance		Medium Access Control
					Time constraint	**Reliability**	
1.	Safety/Emergency Traffic [34, 35, 37]	-	Very high	Emergency / Alarms (asynchronous)	Few milliseconds	High reliability requirements	Pilot channels, Dedicated frequency, prioritized slotted access
2.	Regulatory control traffic [34, 35]	-	High	Close loop process control / critical feedback (Periodic)	Tens of milliseconds	High reliability requirements	Slotted access using TDMA or high priority CSMA/CA based channel access with enabled retransmissions
3.	Supervisory control Traffic [34, 35]	Critical	High	Close loop process control / critical feedback (Periodic)	Tens of milliseconds	High reliability requirements	Slotted access using TDMA or high priority CSMA/CA based channel access with enabled retransmissions
		Non-critical	Low	Asynchronous occasional feedbacks	Seconds to hours	Low reliability with occasional packet misses	CSMA/ CA based channel access
4.	Open loop control traffic [40]	-	Medium	Periodic	Seconds-minutes	Medium reliability requirements	Slotted access / CSMA/CA based channel access with high priority overwrite ability
5.	Alerting traffic [34, 35]	Critical	Medium	Periodic	Seconds-minutes	Medium reliability requirements	Slotted access / (CSMA/CA) based channel access with high priority overwrite ability
		Non-critical	Low	Asynchronous occasional feedbacks	Seconds to hours	Low reliability with occasional packet misses	CSMA/ CA based channel access
6.	Monitoring traffic [34, 35, 37]	-	-	Monitoring Application / static feedback	minutes to hours	Low reliability requirements	Best effort service, CSMA/CA based channel access

traffic [34] (for value within the critical thresholds). Since the importance of this type of traffic is dependent on the critical nature of information, therefore, the critical and non-critical categories are dealt separately. In critical case, the information is regularly reported from sensory data to control centre and requires higher level of reliability whereas for the less critical case asynchronous communication is established with less stringent reliability conditions.

2.1.2.4 Open-loop control traffic

It is termed as a low risk control traffic with relatively relaxed time and reliability bounds [44]. Since the failure in one or more communications won't have a significant impact on the implemented process control due to slow changing nature of the target control systems, therefore reliability is not as important as in case of emergency and regulatory systems. IWSNs in such systems mainly report the information of less critical nature to the control unit where an operator analyses the output. One example of such control is the frequency component of legacy hydroelectric generation units. As the frequency changes occur as a function of output load on the system so these changes are relatively slow. Based on the feedback from the sensory elements, sampled frequency values are presented to operator, who decides whether an increase or decrease in water valve opening is needed to regulate the frequency of generated electric power. Since it is a human dependent response system, it can have unaccounted delays which are only affordable because of the less critical nature of this traffic [34]. In such cases, very occasional actions are expected in response to the information received. Nevertheless, the accumulation of readings from the sensors follows a periodic behavior.

2.1.2.5 Alerting traffic

Alerting traffic follows a relatively low duty cycle where the amount of information communicating over the IWSNs is very much limited [35]. The frequency of communication can only be increased if certain anomalies occur. In case the information becomes critical the reliability and priority of this traffic is increased otherwise a relatively lower reliability assurance is needed and occasional failures in packets communications do not cause major problems [36]. This category of industrial communication is more related to emergency traffic in behaviour however, its intrinsic properties are very much different from emergency traffic. In case of anomalies the priority level of this traffic can be considered on the similar levels of that of supervisory control traffic.

2.1.2.6 Monitoring traffic

Monitoring traffic is mostly categorized as single way traffic as it is used to monitor the status of the processes having relatively less significance in the control and automation [35]. In most cases, the information collected in monitoring systems, assist in the formation of future suggestions for system upgrades and improvements. The occasional packet failures are common in such systems and hence demand lower reliability bounds [34].

Traffic types discussed in this subsection along with the priority requirements, time constraints, reliability and medium access schemes, are presented in Table 2.1.

2.1.3 Critical industrial deadlines and failure consequences

The above discussion categorizes the types of the traffic in an industrial environment, to define the priority levels, time deadlines, class of control systems and relative medium access schemes. In critical cases, a delay in conveying sensed information can result in damage to the equipment, may lead to an explosion or threat to a human life. Therefore, it is important to properly identify different traffic types originated in a system to affiliate right level of importance to each traffic type. Although, the specification of needs and categorization of information in different types is step towards the right direction yet there is a lot of work needed in modeling the algorithms and establishing priority as well as reliability constraints acceptable to the control and automation community [45]. Moreover, the full potential of IWSNs must be exploited to offer a better solution than the existing, to meet the deadlines set forth for industrial process control, and automation.

Some of such requirements for different industrial equipment are listed in Table 2.2. As Shown in Table 2.2, even a particular sensing application has a broad range of parameters attached to it. For instance, considering the temperature sensing in close loop control, a wider range of update frequency is affiliated as represented in Table 2.2. The reason is much more dependent on the core process and application area for which the temperature sensing is considered. To justify the variations, consider two application scenarios where in one case the temperature sensing is used in fractional distillation of crude oil and the other involves the operational temperature of pressurized flammable gases. The former is much more variation tolerant than the later as for fractional distillation some significant temperature variations can increase the level of impurities in different oil products, which is undesirable but not hazardous. However, in case of dealing with pressurized flammable gases, the temperature variations are much more sensitive and can even cause fire. Therefore, in dealing with flammable gases, more frequent feedback is desirable. This example also signifies the need for priority of one information type over the other, as a mandatory part of wireless communication link for timely actions on critical processes. The presented information in Table 2.2, gives an overview of possible deadlines in industrial environments, however, an application specific evaluation of different sensors is needed to better classify the significance of a particular sensing process, consequences of failure in its communication and system type to which this sensing operation belongs.

Apart from the time deadlines and frequency of communication of individual nodes, the battery-operated nature of IWSNs also affiliates a suitable value to lifetime of these nodes. Longer

Table 2.2: Typical end-to-end delay and update requirements for industrial processes [46, 30, 47, 48]

Sensor Network Applications	Security Requirements [59], [60]	Update Frequency	Battery Lifetime [17]
Monitoring and Supervision			
Vibration sensor [30, 37]	Low	sec - days	up to 3 years
Pressure sensor [30, 37]	Low	1 sec	up to 3 years
Temperature sensor [30, 37]	Low	5 sec	up to 3 years
Gas detection sensor [30, 37]	Low	1 sec	up to 3 years
Others/Data acquisition	Low	> 100ms	up to 3 years
Maintenance diagnosis	Low	Sec-days	-
Close Loop Control			
Control valve [37, 46]	medium to high	10 - 500 ms	5 years
Pressure sensor [37, 46]	medium to high	10 - 500 ms	5 years
Temperature sensor [37, 46]	medium to high	10 - 500 ms	5 years
Flow sensor [37, 46]	medium to high	10 - 500 ms	5 years
Torque sensor [37, 46]	medium to high	10 - 500 ms	5 years
Variable speed drive [37]	medium to high	10 - 500 ms	5 years
Control Machine Tools [46]	High	1ms to 10 ms	up to 3 year
Interlocking and Control			
Proximity sensor [37, 46]	medium to high	10 - 250 ms	5 years
Motor [37, 46]	medium to high	10 - 250 ms	5 years
Valve [30, 37]	medium to high	10 - 250 ms	5 years
Protection relays [16, 30, 37]	medium to high	10 - 250 ms	5 years
Machinery and tools	medium to high	10ms	up to 3 years
Motion Control	medium to high	1ms	up to 3 years
CAN bus Deadlines			
Periodic Messages [48]	Medium	5 - 20 ms	-

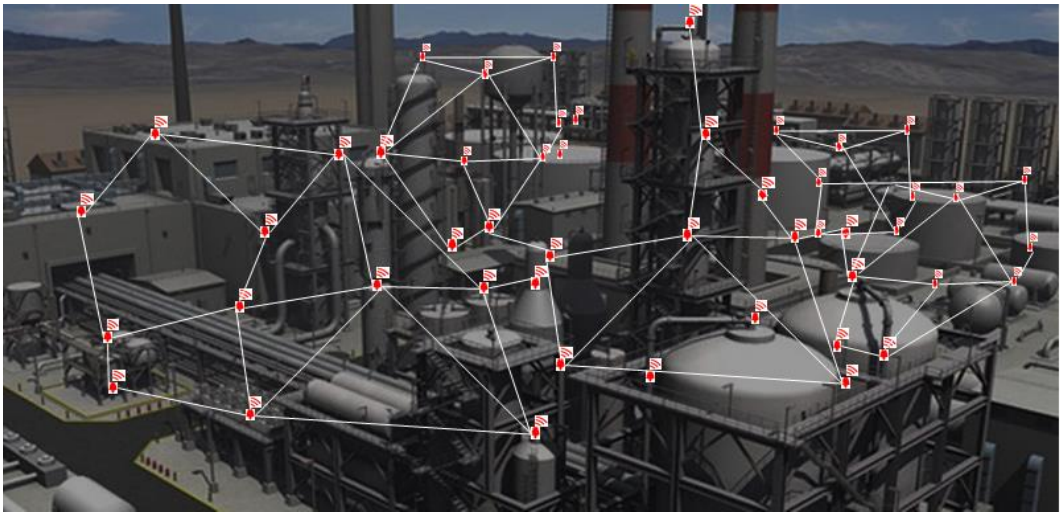

Figure 2.1: Typical IWSN Setup **[36]**

battery life ensures an uninterrupted operation of the processes and reduction in the maintenance cost. Recommendations for the desired battery lifetime of the sensor nodes in different industrial applications are presented in Table 2.2.

2.2 Industrial Wireless Sensor Networks (IWSNs)

2.2.1 WSNs and IWSNs

Wireless Sensor Networks (WSNs) are a type of networks with spatially distributed autonomous devices working collaboratively to offer a variety of monitoring applications [48]. These autonomous devices, referred as nodes, serve as the most appropriate technology to monitor large physical environments [49]. Each node in WSNs has a small range in tens of meters and information from source to destination (Gateway) is transmitted in multi-hop fashion. This collaborative nature of WSNs allows the flexibility of adding new nodes to the network and operate in different network topologies [50, 51].

The transformation of WSNs from non-critical monitoring [52] applications to highly critical process control, automation and real-time decision making [33, 53], pushed this technology to limits. Highly sensitive nature of industrial processes and plants add many constraints which are still a challenge for WSNs. Moreover, since most of the industrial environments have transformed into highly dynamic and vibrant processes, typical WSNs are no longer suitable to serve as a solution.

IWSNs are a special domain of WSNs which particularly targets industrial applications[54, 55]. A typical representation of IWSNs is presented in Figure 2.1. The working principle of IWSNs is quite similar to that of WSNs. However, the need for strict timing deadlines, reliability constraints and critical nature of industrial applications makes IWSNs an entirely different research domain. As the industrial applications may involve close loop control systems and critical processes automation, the primary research focuses in IWSNs are reliability, real-time data delivery and deterministic network designs. In some cases, IWSNs also need a long network lifetime to synchronize the maintenance of wireless networks with the industrial equipment. Though the lifetime requirements highly depend on industrial applications, yet the technological improvements in industrial sector has significantly stretched the maintenance and life cycles of industrial equipment. Therefore, IWSN based communication solutions are also expected to offer an extended network lifetime.

2.2.2 IWSN Architecture

Over the years, a gradual rise in the implementation of IWSNs can be seen. Due to consistent research efforts during recent years, the present architecture can be characterized into several attributes. The performance of IWSNs is mainly influenced by hardware, network topology, channel access schemes, network architecture, data collection and security schemes. Therefore, the suitability of IWSNs in different applications is mainly determined from the selection and choice of these attributes. Each selection of IWSNs scheme, whether it is used for critical or noncritical applications, offer some benefits but also pose certain limitations. Therefore, in application specific design, it is very important to have a careful selection of suitable attributes. Some of the key influencing factors/attributes are discussed as follows.

2.2.2.1 Nodes/Motes

Each network in IWSNs is formed with individual nodes, primarily equipped with a processing unit, radio, memory, sensor board and battery. In certain specific applications, the individual nodes may be equipped with energy harvesters, dual radios or multiple processors to offer off-the-shelf benefits [56-58]. Objective for such variations may include network lifetime extension, diversity, multithreading etc. [59-61].

2.2.2.2 Network Topology

In IWSN architecture, the network topology greatly influences the target application areas. Any IWSN may have a variety of network topologies with each offering a different blend of characteristics. Nodes within a network are generally connected in star, mesh and tree topology. However, some other topologies including ring, bus, grid and circular are sometime considered as well. Furthermore, some variants of the above topologies like tier1 and split-tier1 are also sometime used [62, 63]. The details of various prominent network topologies are described as follows.

1. **Mesh Topology** (as represented in Figure 2.2 (a)) provides better reliability and connectivity in case of larger networks but offers extended delay as a consequence of allowing multiple links to gateway and flexibility to opt most stable route for information communication. In this topology, each node is connected to multiple nodes which allows the networks to offer improved reliability along with self-healing abilities.

2. **Tree topology** (represented in Figure 2.2 (b)) offers dedicated links which allows less information overhead. Each node's communication takes fixed number of hops to reach the destination which adds deterministic behaviour to the communication. Tree topology offers gradient information field which limits the information packets straying from the path. However, this topology is link dependent and failure in key linking nodes can affect large network branches. Furthermore, in time sensitive industrial applications, the use of extended branches is not feasible due to added delay.

3. **Star topology** (represented in Figure 2.2 (c)) offers direct access to the gateway which gives great improvement in the real-time data delivery however, in this topology,

reliability issues arise with the increase in number of connected nodes, especially in contention based channel access schemes.

4. **Bus topology** considers symmetric connection to all the nodes in the network and information is broadcasted onto the network. All nodes in the network can see all the communications but only the intended recipient receives the message. Bus topology is easy to install however, congestion control and security of information are major issues.

5. **Ring topology** forms a circular ring of nodes. Each node in the ring topology is connected to exactly two nodes where each communication in the ring can either be clockwise or anti-clockwise. The ring increases the chances of failure as a disconnection in the ring can result in the failure of entire system. Furthermore, the security and congestion issues are more prominent.

6. **Circular topology** formulates circular sensing area with sink at the centre. The nodes are deployed with uniform density and network can span a large area. The topology can accommodate widespread sensing nodes capable of forming multi-hop network. The communication from the sensor nodes to the sink can be single-hop or multi-hop depending on the sensing node's distance from the sink and transmission range. The circular topology is easy to establish and maintain, however, suitable geographical attributes are hard to find in industrial environment.

7. **Grid topology** partitions the network into non-overlapping square grids of the same size. Each grid accommodates one working node at a time. For grids with multiple nodes, the grid activity is handled by grid-head which collects data from the grid. The routing in this topology is performed in grid by grid manner.

2.2.2.3 Channel access schemes

In IWSNs two channel access schemes, TDMA and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), derived from IEEE 802.15.4 [18] and IEEE 802.15.4e [17] standards are commonly used. In TDMA based channel access, the nodes follow a time slotted access for data communication. The nodes are synchronized using synchronization beacons and each node is scheduled to communicate in a pre-specified time-slot [18]. In this way, a guaranteed channel access is ensured. The TDMA based channel access is well suited for periodic communications needed in regulatory control and open loop control. However, TDMA poses limits to the instant communication ability of a node with the gateway.

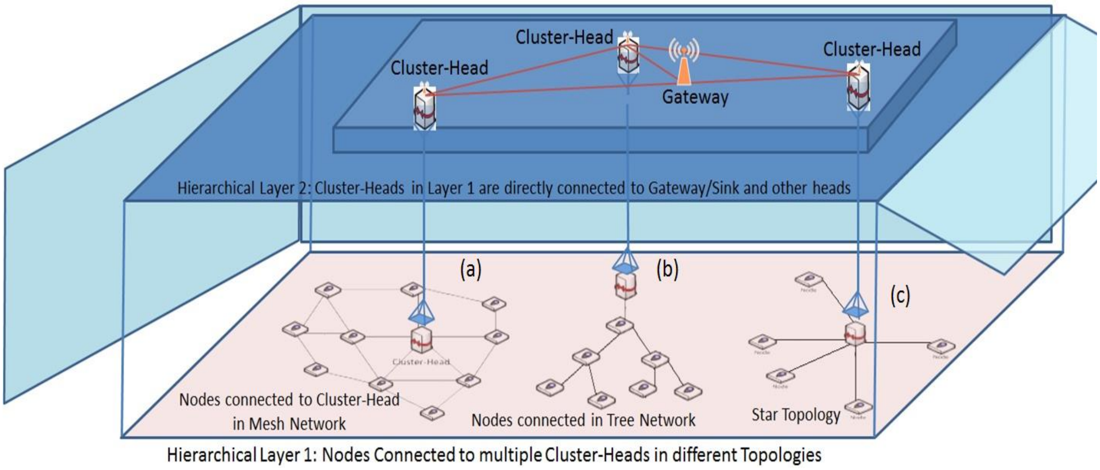

Figure 2.2: Layered view of the Hierarchical architecture in IWSNs. Layer 1: Representation of sensor nodes affiliated with cluster-heads in a clustered network, Layer 2: Virtual representation of Cluster-heads connection with the gateway (a) Mesh Network Representation, (b) Tree Network Representation, (c) Star Topology Representation.

In CSMA/CA based channel access, the opportunistic communication is established where depending on availability of channel, a node attempts to communicate [18]. Since no dedicated bandwidth is specified for a node, a guaranteed channel access cannot be ensured. CSMA/CA based schemes also suffer from reliability issues as the number of connected nodes are increased.

Hybrid channel access schemes are also introduced where the contention based (CSMA/CA) and slotted (TDMA) channel access schemes are adaptively used, to improve overall performance of the network [11, 14, 64]. The details of TDMA based channel access schemes are presented in Section 2.4.2.2 and Section 2.5.1.1, a detailed discussion regarding CSMA/CA based access schemes and standards can be found in Section 2.4.2.1 and Section 2.5.1.3.

2.2.2.4 Network Architecture

Network architecture also serves as a decisive factor in performance of IWSNs. Network architecture may be flat or hierarchical, but the choice is mainly influenced by the requirements of the application. The following discussion summarizes the key features of each architecture type.

1. **Flat architecture** offers traditional benefits of low complexity and is suitable for small networks. However, as the network starts to expand, the delay starts becoming unbearable. Furthermore, to handle the multi-hop communication, the control overhead and data relay path selection information in term of routing tables and path selection mechanisms overstress the network. In addition to this, in flat architecture certain nodes become stress points or bottleneck for the network performance. A representation of flat architecture is shown in Figure 2.3 (a).

2. **Hierarchical architecture**, on the other hand, offer quick access to the critical information and keeps the clusters small enough to avoid traffic overload. On the down

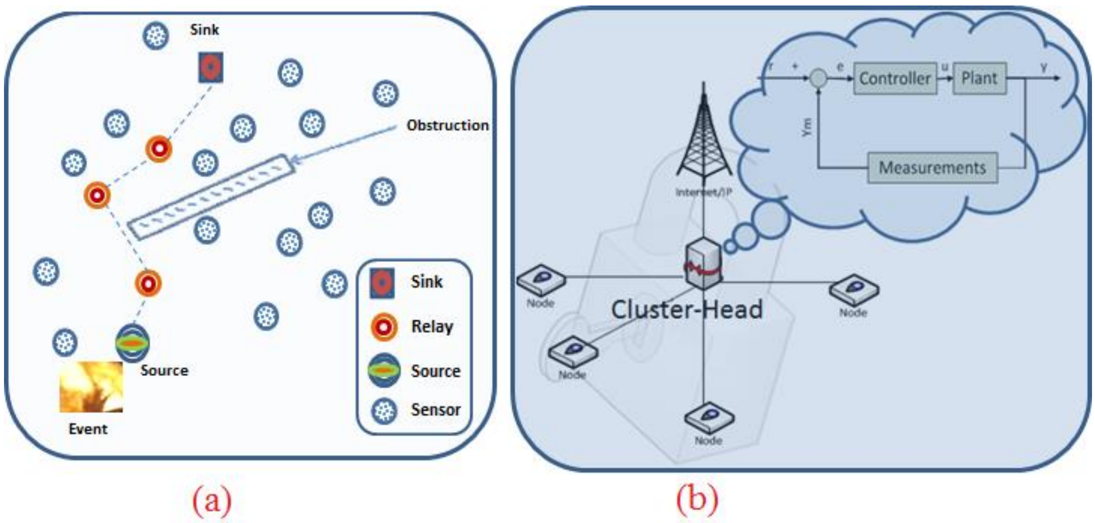

Figure 2.3: Industrial Wireless Sensor Network Architecture. (a) Flat architecture with multi-hop communication to Sink, (b) Distributed control implementation with cluster-head based localized decisions for reduced delay and improved security

side, hierarchical architecture adds extra complexity where each node must be affiliated with suitable cluster head and failure in doing so may induce longer time delays and compromised reliability. A hierarchical architecture is represented in Figure 2.2, where layered view is used to present the connectivity of the nodes. As it can be seen in the figure, at layer 1, the sensor nodes are connected to cluster-head and information from the nodes is collected at cluster-head in timely fashion. Layer 2 represents the upper hierarchy of connections in the hierarchical architecture, where the cluster-heads are connected to the control centre/Gateway. The communication in the represented scenario is a two-step process where in the first step the sensor data is accumulated at the cluster-head whereas in second step the accumulated date is forwarded to gateway/control centre.

2.3 IWSN Design Objectives

In IWSNs, continuous research has provided much wanted improvements in past few years. It is because of the efforts of many individuals and some joint ventures that IWSNs have recently witnessed much wider acceptability in several industrial applications. Due to a broad scope of the potential applications of IWSNs and with rising challenges, certain design objectives need to be considered.

Wireless links in industrial automation, whether it is for emergency communication, process control, feedback systems, altering or monitoring networks, requires certain performance and reliability assurances. To fulfil these requirements, certain design goals and objectives must be set forth. Some of these are listed as follows:

- Managing congestion free communication
- Accurate time synchronization
- Modular design for improved scalability
- Ensuring predictable delay and latencies (Mandatory condition for effective regulatory and supervisory control)
- Real-time assurance
- Heterogeneous information scheduling
- Prioritized communication

Table 2.3: Goals and Objectives: limitations and research developments [15-17, 29, 34, 35, 37, 46, 59, 65-69]

Goals and Objectives	Aspects	Progress and Research Status	Description
Efficient Resource Usage	Battery	Partially addressed	**Limitations** 1) Limited battery capacity 2) Capacity increase at the cost of size, weight, and price 3) Decrease in the battery capacity with time and recharge cycles **Research developments and improvements** 1) Energy efficient utilization of IWSNs – Sleep scheduling – Transmission power control – Deep sleep and passive listening – Data redundancy reduction 2) Use of rechargeable batteries with energy harvesting for extended unsupervised operation
	Processing power	Addressed	1) Wide variety of microcontroller with diverse range of processing capabilities suitable for IWSNs 2) Tremendous reduction in cost factor
	Memory	Partially addressed	**Limitations** 1) Limited memory capacity in the available wireless nodes and microcontrollers 2) Limited code memory, restricting implementation of complex algorithms. **Possible solutions and remedies** 1) Introduction of more powerful nodes with extended memory 2) Optimized memory utilization
	Bandwidth and transmission	Partially addressed	**Limitations** 1) Overlapping spectrum in IWSNs 2) Possible interference due to overlapping channels in Wi-Fi, WPAN and other technologies operating in ISM band **Research developments and improvements** 1) Cognitive channel access for interference avoidance 2) Adaptive channel selection and contention free channel access
Predictable Delay and Latencies	Delay and Deadlines with predictable latency	Partially addressed	**Limitations** 1) Hard deadlines 2) Unpredictable delays in dense networks 3) Unsynchronized deadlines and asynchronous channel access requirements from emergency and supervisory control **Research developments and improvements** 1) Segmented slot access and retransmissions 2) Priority based communication 3) Asynchronous communication scheduling protocols for emergency communication 4) QoS assurance

Table 2.3: Goals and Objectives: limitations and research developments Cont.

Goals and Objectives	Aspects	Progress and Research Status	Description
Congestion free communication	CSMA/CA schemes	Partially addressed	**Limitations** 1) Random channel access 2) Interference 3) Lack of scheduling of communications 4) Back-off based delay in CSMA/CA based access schemes **Research developments and improvements** 1) Channel estimation 2) Kalman based and other congestion control algorithms 3) Use of slotted CSMA/CA schemes
	TDMA schemes	Addressed	1) Use of TDMA for interference free communication 2) Guaranteed channel access
Time Synchronization	Single-hop topology	Addressed	1) Use of beacon enabled communication for nodes' synchronization 2) Synchronization with the master clock. 3) Ensuring recalibration of the faulty (lagging, leading) clocks
	Multi-hop networks	Partially addressed	**Limitations** 1) Large networks with multi-hop communication 2) Non-linear processing and communication delays. 3) Usage of low cost and less accurate clocks **Research developments and improvements** 1) Consensus based time synchronization: Average Time Synchronization (ATS) and Maximum Time Synchronization (MTS) 2) Post facto synchronization and tunable synchronization 3) Source clock frequency recovery (SCFR) based and distributed time synchronization
Real-time assurance	Emergency	Partially addressed	**Limitations** 1) Asynchronous access requirements 2) Effects of TDMA induced access delay on instant channel access requirements **Research developments and improvements** 1) Multichannel solution 2) Priority based channel access execution 3) Maximum delay assurance
	Process control	Partially addressed	**Limitations** 1) Periodic channel access requirements 2) Deadlines in milliseconds 3) Lack of appropriate remedies in case of communication failure **Research developments and improvements** 1) Priority based access 2) Shared slots for retransmission of critical communication 3) On-demand channel access 4) Deadline optimized communications

Table 2.3: Goals and Objectives: limitations and research developments Cont.

Goals and Objectives	Aspects	Progress and Research Status	Description
Security	Security threats, integrity and authenticity	Partially addressed	**Limitations** 1) Information tampering 2) Node control 3) Denial of service 4) flooding 5) radio interference **Research developments and improvements** 1) Hop by hop data integrity 2) Data encryption 3) Cryptographic key establishment 4) Frame protection and device management
Prioritized communica-tion	Static / Dynamic	Partially addressed	**Limitations** 1) Priority Establishment 2) Attributes of priority 3) When and how to be prioritized 4) Static priority systems **Research developments and contributions** 1) Introduction of priority systems 2) Optimization of protocols w.r.t channel access and priority of service 3) Redefinition of usage of shared slots and asynchronous channel access 4) Hybrid channel access schemes for improved flexibility 5) Multichannel schemes for improved performance

The above listed objectives offer best practices for extended network life time, communication reliability, appropriate priori information of delay for efficient regulatory and supervisory control, network stability for modular design, flexibility, improved security features, jitter minimization, surety of real-time communication for sensitive processes, effective scheduling and proper priority affiliation to different traffic types for timely and precedence based communication. The design goals, research developments and limitation in achieving these design objectives are presented in Table 2.3.

2.4 IWSN Potential Technologies and Standards

Wireless networks, have gained much popularity in this decade with many notable improvements in wireless industrial solutions. Significant reduction in individual mote price, improvement in processing and communication capabilities, development of protocols to facilitate communication and overcome interference are some of the improvements one can witness. All these improvements, especially the development of industrial wireless communication standards and protocols, assisted in wide scale implementation of IWSNs in industry. The standardization of wireless technologies in this area of research is mainly carried out by 802.15 (a working group of IEEE which standardizes the wireless technologies that fall in the domain of WPAN). There are ten different groups working in 802.15, where each address certain aspects in standardization of WPAN.

1. IEEE 802.15.1 covers Bluetooth technology which is discussed in detail in Section 2.4.1.1

2. IEEE802.15.2 addresses the coexistence issue in multiple devices operating in ISM band.

3. IEEE802.15.4 addresses the low data rate WPAN and plays a vital role in defining Physical and MAC layer specifications for low rate and low power networks including low-rate WPAN standard for industrial automation and process control. Further details can be found in Section 2.4.2.

4. IEEE802.15.5 addresses the issues of interoperability and scalability of wireless mesh networks in both low and high rate WPAN.

5. IEEE802.15.3 covers high-rate WPAN (suitability issues in industries due to high power requirements and unnecessarily high data rates compared to low data generated by sensors)

6. IEEE802.15.6 covers Body Area Networks (short range, unsuitable for industries)

7. IEEE802.15.7 covers Visible Light Communication (VLC) (Lack of existence of infrastructure and suitability to broader range of applications in industries)

8. IEEEP802.15.8 addresses peer to peer and infrastructure less communication (Fewer application that fall in this category in industrial automation and process control)

9. IEEE P802.15.9 addresses Key Management Protocol (KMP)

10. IEEE P802.15.10 addresses issues in routing in dynamically changing wireless networks (A less likely scenario due to the presence of static environments in industry)

The focuses of 802.15 groups listed in (5)-(10) are out of the scope. However, some details regarding possible developments regarding IWSNs is provided as necessary.

2.4.1 Selected Wireless Technologies and Standards

Many wireless technologies were considered to fulfil the needs of industrial applications. In all the technologies, tested for industrial wireless solutions, the aim was to benefit from the free unlicensed ISM band dedicated for industrial, scientific and medical ISM purposes. Wi-Fi, Ultra-Wide Band (UWB), and Bluetooth are three main technologies other than the IEEE802.15.4 based variants with potential to handle the industrial applications while utilizing the dedicated band. A brief discussion on benefits and shortcomings of these three technologies are presented as follows.

2.4.1.1 Bluetooth

Based on IEEE 802.15.1 standard, Bluetooth offers energy efficiency apart from low cost modules. In Bluetooth, seventy-nine channels are available with each offering a bandwidth of 1MHz to support high data rates [70]. Bluetooth devices use universal short-range radio link with Frequency Hopping Spread Spectrum (FHSS). FHSS ensures the security with the facility to access currently unoccupied channels. The protocol offers two connectivity topologies, piconet and scatternet [71]. Every piconet is formed by a Bluetooth device working as a master. The master-slave connection is established in a piconet where one master device can exist per piconet with one or more slave devices. A slave device can only establish a point to point link with the master, and can be put in the standby mode to improve energy efficiency. In a piconet, a master clock synchronization is also established. Multiple overlapping piconets form a scatternet where one device can be part of multiple piconets. However, a device can work as a master in only one piconet. Bluetooth devices offer a communication range of up to 100m, however, mostly the preferable communication range is up to 10m [71].

Use of Bluetooth offers improved security, cost efficiency and reduced energy consumption, however, the intrinsic properties of Bluetooth limit the maximum number of connected nodes in a network. In earlier versions, only eight nodes could connect to an interface, hence affecting the suitability of Bluetooth in realistic industrial networks. With the introduction of Bluetooth 4.0, some of the constraints are relaxed. However, the master-slave interconnection in Bluetooth lacks flexibility and increases the protocol complexity. Furthermore, Bluetooth does not offer any support for mesh networking and fails to provide suitable mechanism for multi-hop communication, a core aspect of majority of the industrial wireless networks. Apart from these scatternet based multi-hop networks are inefficient and unsuitable for dense industrial networks [71]. The lack of flexibility, support for limited nodes, master-slave link establishment, increased complexity and lack of multi-hop communication support are some of the issues, which affect the suitability of Bluetooth based solutions for fast paced and dynamic industrial networks.

2.4.1.2 Wi-Fi

Based on IEEE 802.11 standard, with possible variations of 802.11 (a/b/e/g/n/p/ac ... ay) [72-76], Wi-Fi offers a high data-rate using the frequency band of 2.401 GHz to 2.473 GHz. Use of Wi-Fi allows large number of nodes, which improves the possibility for scalable networks. The network is formed using a centralized device to offer high data rates over short distances. Several components in IEEE802.11 architecture interact to provide support for station mobility. A primitive cell consisting on mobile or fixed stations, is formed using Wi-Fi technology, referred as Basic Service Set (BSS) based on which IEEE802.11 employs independent basic service set (IBSS) and extended service set (ESS) network configurations [71].

IEEE 802.11 allows formation of ad-hoc networks where the stations can communicate without any Access Point (AP). An extended form of network can also be achieved using multiple BSS where the interconnection is established using Wireless Distribution System (WDS) [71]. However, WDS also has some disadvantages including throughput cut down for each WDS repeating hop, and elimination of rotated encryption key support. Furthermore, Wi-Fi modules are relatively expensive and consume more energy as compared to Zigbee and Bluetooth, which affect the suitability of Wi-Fi in battery operated networks [71]. With high power consumption, the lifetime of the IEEE802.11 networks is severely compromised, increasing maintenance and replacement costs. The short lifetime expectancy of IEEE 802.11 assisted networks also incurs unscheduled off times in the regular operation of industrial processes. Apart from these, high-speed data communication is not always desired, especially when the information is more vulnerable to interception due to high power transmission. Another issue that was noted in Wi-Fi networks was high multipath interference due to reflection of signals from the walls and other obstacles in indoor industrial environments. Furthermore, increasing the number of devices in a single Wi-Fi connection, also affects the signal strength of the individual devices.

2.4.1.3 UWB

In UWB the information is communicated using very short pulses emitted in periodic sequence using radio frequency. Due to the use of impulses, UWB signal can be defined as an instantaneous spectral occupancy signal. UWB has wide band of 500MHz with achievable data rates of 110Mbps [77]. Due to high achievable data rates, the UWB is termed as high-rate WPAN, also referred as IEEE802.15.3. UWB can be used in short-range applications and precise localization. Due to the short-range communication capabilities, UWB is used in indoor applications with high data rate requirements. High data rate in UWB) is suitable to assist multiple video and multimedia streams for indoor applications. Apart from this, UWB can fit in to short range cable replacement such as a wireless alternate for USB 2.0 and IEEE1394 [71].

The standardization and further developments of UWB include IEEE P802.15.3a, IEEE 802.15.3b, IEEE 802.15.3c along with ongoing developments for amendment 3d for IEEE 802.5.3. IEEE P802.15.3a operates in the frequency band of 3.1GHz to 10.6 GHz with fractional bandwidth of 20% with the transmission range of 5m and dynamic power range of 80 dB [78]. The improvements are targeted at imaging and multimedia communications. IEEE802.15.3b improves 2003 standard by adding interoperability to MAC along with some other features like MAC layer management entity, logical link control and added contention periods in frame. IEEE802.15.3c targeted millimetre wave based amendments in the Physical layer operating at a frequency of 57-64GHz with a communication range of 10m [79].

Majority of the improvements introduced in the UWB target high-speed short-range communication, which fail to align with the requirements of industrial applications. More suitable standards like IEEE 802.15.3 and IEEE 802.15.3b can at best serve as a supporting technology for IWSNs. Thus, leaving UWB for industrial applications where the distance is relatively small with a need of extremely high data rate requirements. Furthermore, a relatively higher power requirement and ability to connect to eight motes at most, limit the scope of use of UWB for wide

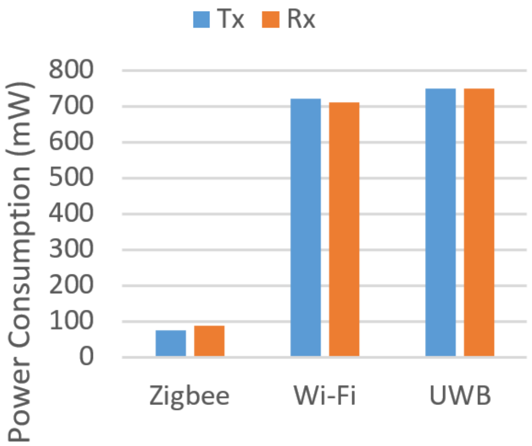

Figure 2.4: Power consumption in various standards

industrial market. High peak energy pulses also make data more vulnerable to security attacks [80].

To give a quantitative comparison of power consumption of UWB and Wi-Fi, in comparison to traditional Zigbee, the power consumption of these three standards is evaluated using similar testing conditions. For the realistic evaluation, the power consumption of CC2430 (Zigbee), CX53111 (Wi-Fi) and XS110 (UWB) are compared. The overall power consumption for the three modules for transmission and reception are presented in Figure 2.4. The power consumption for transmission and reception of each these modules is matched using longer duration of active listening period compared to shorter transmission periods.

2.4.2 IEEE WPAN for WSNs/IWSNs

IEEE WPAN standards offer a baseline for different working groups, covering details of the Physical and MAC layer. Based on the specifications of IEEE 802.15.4 [19] and 802.15.4e [17] ZigBee Alliance, ISA100 wireless compliance institute, HART communication foundation and other groups have defined protocols with upper layer specifications like ZigBee, WirelessHART, ISA100.11a, 6LoWPAN and MiWi [21-23, 81].

2.4.2.1 IEEE802.15.4

1) The standard offers specification of the Physical and MAC layer for low power, low cost, low speed and energy efficient communication within the nearby devices. The technology targets long life self-configurable net- works with the ability of autonomous operation. The standard describes Physical and MAC layer architecture, functional overview, frame formats, management services, security operations, modulation schemes, transmission power, RF requirements and quality metrics.

Physical layer specifications provide frequency requirements, RF details, modulation schemes, spreading parameters, transmission power, channel details and assignment of UWB channels. It also specifies the recommended receiver sensitivity and link quality measure along with the channel state assessment. Details of some of the Physical layer parameters are listed in Table 2.4.

The MAC layer handles the access to the physical channel including generation of beacons, synchronization mechanism to the generated beacons, motes association and disassociation to PAN. It also manages the assurance of contention free medium access by implementing CSMA/CA mechanism, support for device security, handling guaranteed time slot mechanism and reliable link assurance between the MAC entities [18]. In addition, the MAC layer controls the operating conditions of the motes by nominating them either as full-function device or reduced-function device. Full-function device can switch between a coordinator (a node which controls and coordinates a network) and a sensing device (a node which sense data and relay information in the network) whereas the reduced function device only works as a simple sensing device. The MAC layer also defines the layout of the superframe with the details of inter-frame separation, Contention Access Period (CAP) and contention Free Period (CFP).

2.4.2.2 IEEE 802.15.4e

The amendments in the existing WPAN standard IEEE 802.15.4 were focused on enhancing the suitability of existing standard for critical industrial applications of IWSNs. Thus, IEEE

802.15.4e mainly targets the real-time and reliability constraints in IWSNs. Some notable changes were introduced in the existing standard including the use of TDMA based channel access in IEEE 802.15.4e that replaced the CSMA/CA based access technique. This change offers guaranteed access to the channel to improve reliability. The changes introduced in new standard mainly targeted MAC layer with the inclusion of synchronization beacons for synchronization in new TDMA based access scheme. For retransmissions, shared slots are used which follow the CSMA/CA based access scheme with exponential back off (same mechanism is used in IEEE 802.15.4 during regular channel access schemes where the transmitter waits for random slots of time before retransmission, if the channel is busy). The modified standard also includes the structural amendments in the security header and control field.

2.4.1 Selected Industrial Standards

Based on IEEE 802.15.4 and IEEE 802.15.4e many industrial protocols were formed to address the delicate nature and versatility of the industrial applications. Some of these protocols are listed

Table 2.4: PHY Layer Parameters for IEEE 802.15.4 [18]

		Spreading Parameters		**Data Parameters**		
PHY (MHz)	**Frequency Band (MHz)**	**Chip rate (kchip/s)**	**Modulation**	**Bit Rate (Kb/s)**	**Symbol Rate (Ksym/s)**	**Symbols**
780	779–787	1000	O-QPSK	250	62.5	16-ary orthogonal
780	779–787	1000	MPSK	250	62.5	16-ary orthogonal
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
868/915 (optional)	868–868.6	400	ASK	250	12.5	20-bit PSSS
	902–928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868–868.6	400	O-QPSK	100	25	16-ary orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary orthogonal
950	950–956	—	GFSK	100	100	Binary
950	950–956	300	BPSK	20	20	Binary
2450 DSSS	2400–2483.5	2000	O-QPSK	250	62.5	16-ary orthogonal

as under. The listed protocols use Physical and MAC layer specifications of either IEEE 802.15.4 or IEEE 802.15.4e and extend their own upper layers model.

2.4.1.1 WirelessHART

WirelessHART is the technology solution in IWSNs, based on HART communication protocol developed by HART Communication Foundation [82]. With the built-in support for multiple IWSN topologies, WirelessHART offers solutions for monitoring, automation and process control for industrial applications. WirelessHART is widely accepted for industrial automation and

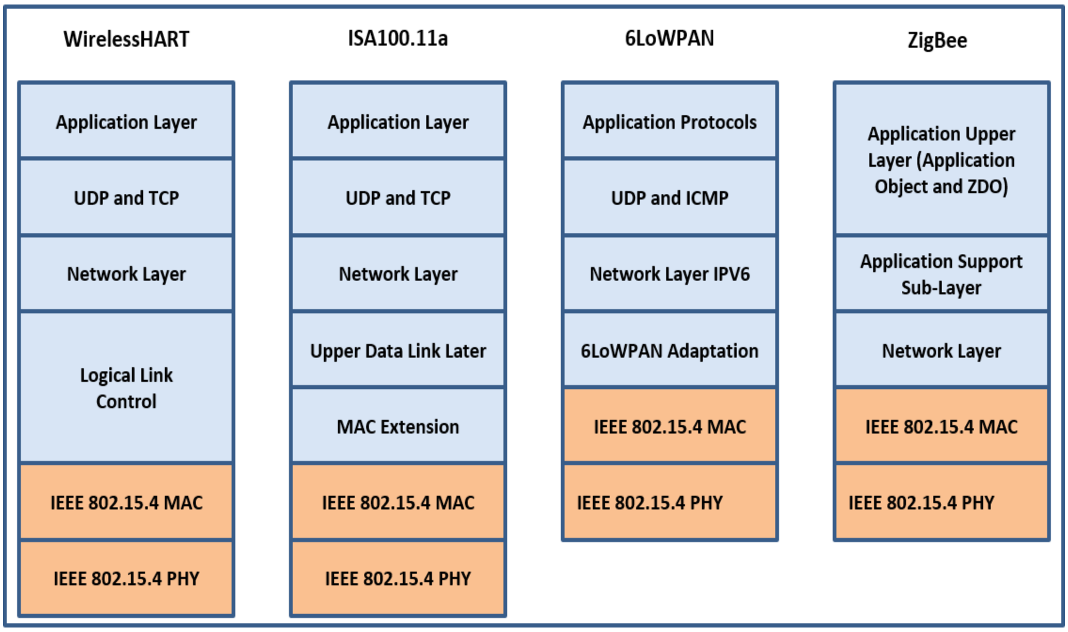

Figure 2.5: Protocol Stack Structure for selected Industrial Standards [82-84]

process control with over 30 million HART devices installed worldwide [26]. The protocol is based on IEEE 802.15.4 standard with Direct Sequence Spread Spectrum (DSSS) and TDMA synchronized channel access mechanism. The protocol offers high reliability by incorporating the suggested modifications in IEEE 802.15.4e [84] along with channel hopping for enhanced security. It also supports the addressing of up to 2^{16} devices.

Link layer addressing is sufficiently large, enabling around 65000 devices within a single network but the network size is limited by the power consumption and latency issues. Nevertheless, the WirelessHART also lacks in interoperability and fails compatibility to IP based devices and internet.

2.4.1.2 Zigbee

ZigBee, a protocol based on the IEEE 802.15.4 and developed by ZigBee Alliance offers a modest data rate of 250kbps [128]. It has sixteen channels each with a bandwidth of 2 MHz and

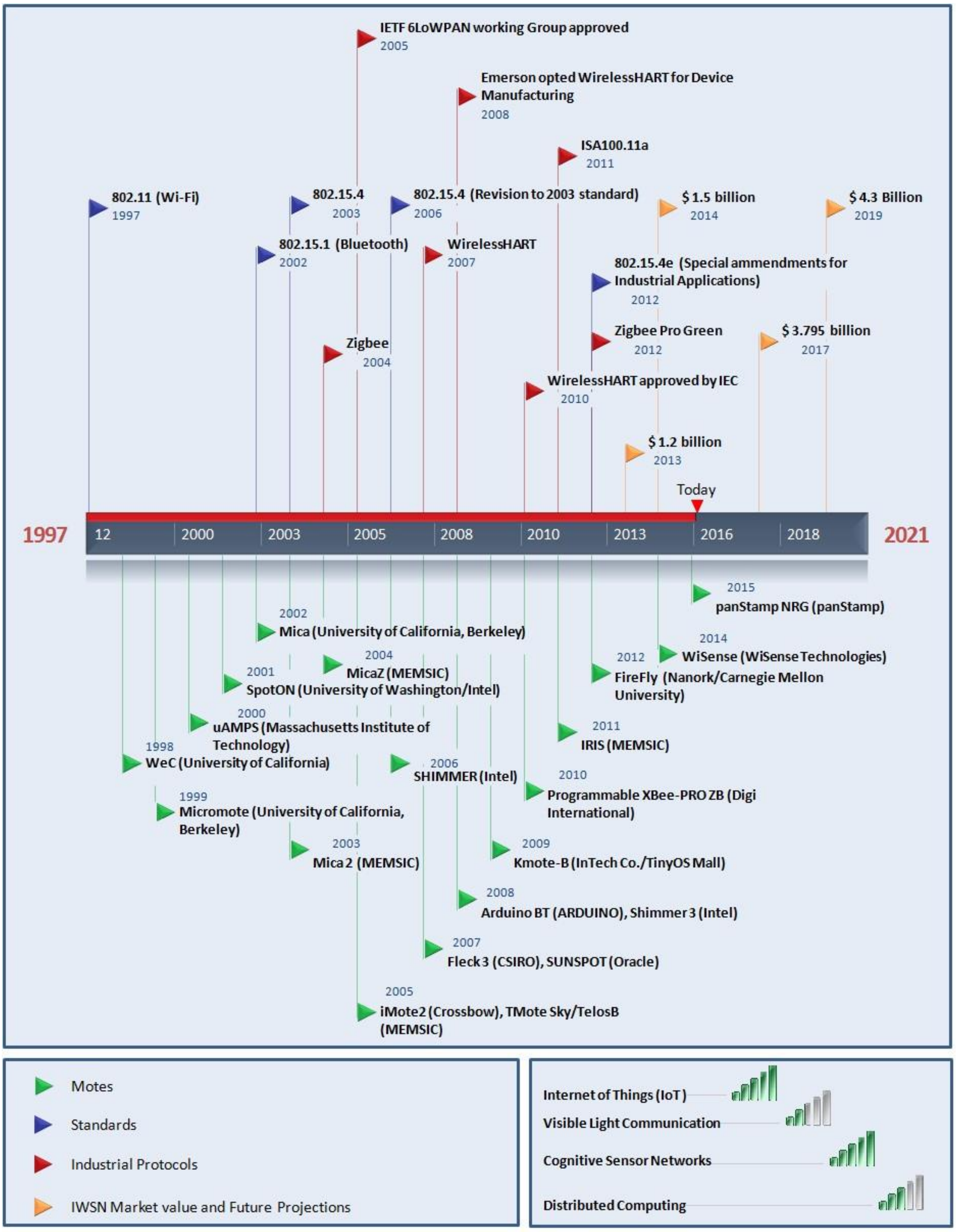

Figure 2.6: Taxonomy of Wireless Motes, Standards, Industrial Protocols, IWSNs Market value & Projections and Future Industrial Technologies [17, 23, 85, 70, 72, 19, 20, 86-89]

an ability to connect 65000 devices at once. These specifications allow the formation of mesh networks with single and multi-hop communication. ZigBee mainly focuses on low cost and low power solution for extended lifetime and improved deployment and maintenance cost.

It is one of the most widely used standards with over 70 million ZigBee devices installed worldwide [23]. Based on the IEEE 802.15.4, ZigBee provides upper layer specifications for a wide variety of applications. Currently, Zigbee Alliance, a non-profit open group offers three solutions referred as ZigBee PRO, ZigBee RF4CE and ZigBee IP. Apart from a relatively wider variety of solutions, ZigBee nodes are capable of connecting in mesh, star and tree topologies which further enhance the scope of its applications in industrial environment. Apart from this, a special feature in ZigBee PRO (ZigBee Green) allows battery less nodes to integrate with the networks, thus providing flexibility of greener technology. ZigBee, on the other hand, uses CSMA/CA scheme for channel access which reduces its scope for time constraint and reliability critical industrial applications. Furthermore, the exponential back-off mechanism triggered in case of channel unavailability unwanted delay, which is not appreciated in time constraint industrial applications. Some of the overlapping channels in ZigBee and Wi-Fi also introduce unwanted interference in the presence of Wi-Fi.

2.4.1.3 ISA100.11a

ISA100.11a is a wireless network solution by ISA100 Wireless Compliance Institute. ISA100.11a targets monitoring, automation and process control applications in industrial setup. A notable architectural resemblance is found in ISA100.11a and WirelessHART. For instance, the use of 2.4GHz operational frequency, implementation of TDMA based synchronized access and channel hopping functions in upper Data Link sub-layer are some of the many similarities in these two protocols. However, Network and Transport layer of ISA100.11a are derived from 6LoWPAN [84], which allows the use of IPv6 addressing in this standard.

The MAC sub-layer uses CSMA/CA mechanism for the channel access. However, retransmissions can benefit from frequency, time and spatial diversity. An optional implementation of IEEE 802.15.4, CSMA/CA based exponential back-off mechanism is also available. It also allows implementation of TDMA based channel access and channel hopping with ARQ interference suppression mechanism.

2.4.1.4 6LoWPAN

6LoWPAN is a IPV6 based low power wireless personal area network [83, 90]. 6LoWPAN offers the benefit of interfacing directly with other IP devices or existing IP networks. It also inherits the security, architecture, network management and transport layer protocols from the existing structure. The use of IPV6 enables the 6LoWPAN devices to readily embed in the existing wired industrial Ethernet setup. To ensure low power operation, the superframe is divided into active and inactive regions where the coord-inator can go into low power or sleep mode to

Table 2.5: Selected Industrial Protocols and Standards [17, 18, 21-23, 81, 85]

Industrial Standard and Protocols	Research group / Institute / Working Alliance	MultiTopologies Support	Estimate of Devices	Access Scheme	Channel Access	Max Network Size	Base Standard	Interoperability (IP& Internet)	Data Rate
Wireless HART [81, 82]	HART Communication Founda-tion	Avail-able	30 Million	Direct Sequence Spread Spectrum (DSSS)	TDMA	2^16	IEEE 802.15.4	No	250 kbps
Zigbee [19, 68]	Zigbee Alliance	Avail-able	70 Million	DSSS	CSMA/CA	2^16	IEEE 802.15.4	Yes (Zigbee IP)	250 kbps
ISA100.11a [17, 82, 84]	ISA100 Wireless Compli-ance Institute	Mesh Rout-ing	—	DSSS & Channel Hopping	TDMA (Transport Layer) , CSMA (MAC)	IPV6 Addressing	IEEE 802.15.4	Yes (IPV6)	250 Kbps
6LoWPAN [21, 37, 83]	Internet Engineer-ing Task Force	Avail-able	—	—	CSMA/CA	IPV6 Addressing	IEEE 802.15.4	Yes (IPV6), 802.15.4 Compliance	20-250 kbps

conserve energy. Low power listening mode is also included to further improve the energy efficiency. To provide security from external attacks, the protocol incorporates 128-bit AES. To extend the scope of 6LoWPAN, the ability to interact with MAC devices is included which enables the 6LoWPAN devices to integrate with other IEEE802.15.4 based devices.

On the other hand, in 6LoWPAN, the channel access and reliability are a bit compromised with the use of CSMA/CA based channel access. To initiate transmission, the devices have to compete for the channel access using CSMA/CA based mechanism which adds uncertainty. Moreover, the protocol support low data rates ranging from 20 to 250 kbps. A brief overview of the selected industrial protocols is presented in Table 2.5 whereas the protocol stack of the above mentioned industrial protocols is presented in Figure 2.5.

The technological developments in the past few years, whether it involves hardware platforms or standardization of access schemes, leaves a significant impact on improving credibility of

IWSNs. A review of the milestones achieved in last two decades is presented in Figure 2.6 It pinpoints the main contributions and milestones achieved in hardware platform design, standards and industrial protocols. The taxonomy presents broader perspective of significant events in the past. The taxonomy also gives a fair insight in the future market value of IWSNs and potential of future technologies in industrial applications.

2.5 MAC Layer optimization and MAC schemes

Over the years many solutions for IWSNs were also proposed by the research community. These proposed schemes involved improvements in reliability, real-time operability, network life enhancement and deterministic network formation. Most of these researches focused on MAC layer optimization, primarily because MAC layer handles two most important tasks, controlling nodes access to the wireless medium and managing the use of radio. Efficient channel access improves both reliability and real-time data delivery and offers better congestion control, whereas efficient use of radio improves network lifetime. In this section, a detailed review of MAC protocols is presented to offer insight of current research trends in MAC optimization for IWSNs.

2.5.1 Classification of MAC Protocols and MAC developments in IWSNs

During the last few years the design objectives of MAC protocols have experienced a significant change [91]. Earlier researches sacrificed throughput and reliability for extended network lifetime [92, 93]. However, for IWSNs, the energy efficiency in MAC protocols has become a secondary objective, where the network can no longer rely on best effort data delivery services [58].

To label the MAC layer developments according to industrial application requirements, an extended taxonomy of MAC protocols is created. The taxonomy labels noteworthy MAC developments according to their suitable application area in industry. The taxonomy of MAC protocols is presented in Figure 2.7, which categorizes MAC based developments with respect to channel access scheme, target application area, latency, reliability bounds and single channel and multichannel attributes. Furthermore, a classification of MAC protocols is also presented in Table 2.6, which classifies notable MAC protocols based on communication priority, latency and area of application.

Over the time a large number of MAC protocols are being presented and one can find an exhaustive list of such protocols in [58, 94-98]. In [98] MAC protocols are classified in four categories. The classification is based on the medium access methods, hence categorizing MAC protocols in to random, periodic, slotted and hybrid access schemes. In [94] the MAC protocols are in four categories namely asynchronous, synchronous, slotted and multi-channel. Each of these categories has their own significance and offer unique benefits. Asynchronous protocols can run on very low duty cycle, a desirable trait for longer lifetime but the efficient communication between the nodes and congestion control are major challenges. Communication challenges present in asynchronous MAC protocols are suit- ably resolved in synchronous protocols but in these protocols channel congestion and collision avoidance remains an issue. Slotted schemes resolve the issue of channel congestion but channel utilization in such cases is relatively low. The multi-channel schemes take benefit of full potential of wireless motes by implementing both TDMA and Frequency Division Multiple Access (FDMA) to improve the channel capacity. Apart from these classifications, there are many protocols that target MAC layer optimization in both TDMA based and CSMA/CA based channel access schemes.

In our classification, the MAC protocols are distributed in: Contention (CSMA/CA) based schemes, TDMA based schemes, multi-channel schemes and priority enabled schemes. Each of these is listed as follows.

2.5.1.1 TDMA based MAC protocols

TDMA based MAC protocols serve more efficiently in ensuring reliability and latency bounds. It is for the same reason, TDMA based MAC protocols are considered more suitable for industrial applications. However, TDMA based schemes do require time synchronization and optimal

TDMA scheduling is a NP-hard problem [99, 100]. In [100], authors have proposed two heuristic algorithms to solve the schedule minimization problem and ensured packet delivery. Authors have also evaluated upper bounds for these schedules as a function of total packets generated in the network. In [101, 102], authors further improved the results in [141] and showed how their work outperforms [100]. In [101], authors considered harsh dynamic environment but failed to offer guaranteed data reliability. In [102], authors improved reliability in harsh control environments and formed hypergraph to increase scheduling flexibility. Moreover, two schemes were also presented in this paper namely dedicated scheduling and shared scheduling and were applied to wireless sensor and control networks for performance evaluation. Another TDMA based scheme, ShedEx is introduced in [99]. This paper extends the concept of reliability improvement by repeating most rewarding slots along with a scheduling algorithm to guarantee certain specified reliability.

With respect to the taxonomy presented in Figure 2.7, the TDMA based schemes are further divided in five subcategories (la- belled E, F, G, M and N) depending on suitability for specific area of application. The TDMA based protocols classified in these subcategories are listed Table 2.6.

2.5.1.2 Multi-channel MAC

Use of multichannel in TDMA based MAC protocols enables improved medium utilization and offer extended features in IWSNs. In last couple of years, a notable trend in multichannel MAC solutions can be seen. In [85], authors present multichannel, TDMA based source aware scheduling scheme for static networks. The algorithm benefits from multiple channels but fails to guarantee reliability. In [104], authors extended the ShedEx scheme to multichannel scenario by introducing scalable integration in existing scheme. Authors also claim to cut latencies around 20% in TDMA schedules from ShedEx. In [105], authors propose a Regret Matching based Channel Assignment algorithm (RMCA), to reduce multichannel overhead. In this paper authors investigated multichannel transmissions and used simulations and hardware implementation to demonstrate performance improvements and complexity reductions respectively. An analytic approach to model and analyze multiple channels is presented in [106]. The affirmation of model accuracy is established from numerical and simulation results. Moreover, multi-level priority for packet transmission sequence is also established.

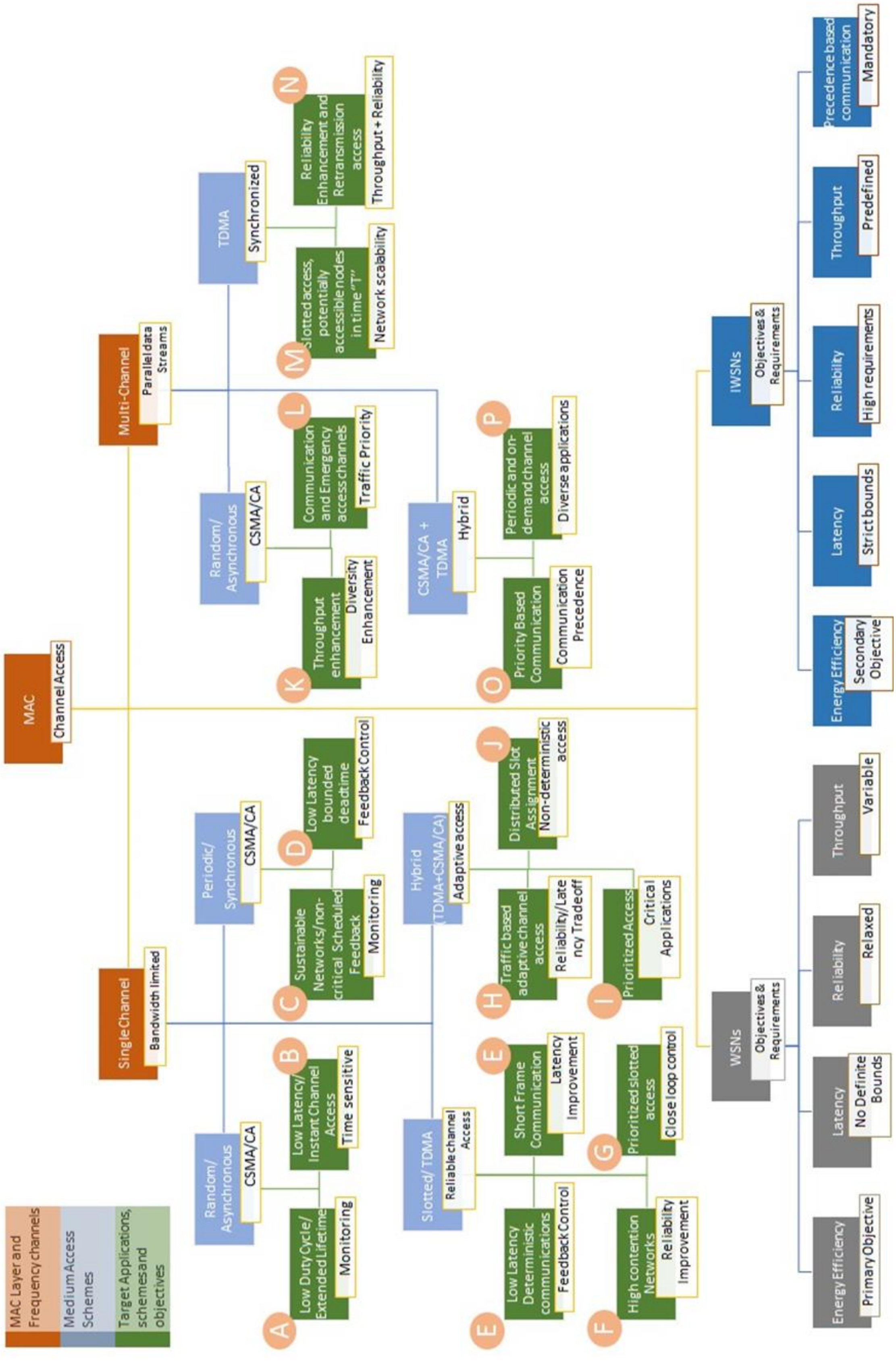

Figure 2.7: Extended Taxonomy for MAC Protocols

Table 2.6: Salient Features of Selected MAC Protocols

Protocols	Channel Access Scheme	Frequency Channels	Application Area as per Error! Reference source not found.	Latency	Priority
STEM [107], PW-MAC [108]	Contention based	Single	A	High	No
STEM-B [107]	Contention based with synchronized paging	Single	A	High	No
SIFT [109, 110], STEM-T [66, 99, 111], D-MAC [112], T-MAC (FRTS) [40], ADCA MAC [41, 67, 68, 113 , Q-MAC [42, 46], D-S Adapt [43, 46]	Contention based	Single	B	Medium to low	No
CCMAC [69]	Scheduled CSMA	Single	C	High	No
B-MAC [34, 37, 114]	Slotted contention access	Single	C	High	No
SyncWUF [15, 34, 37], TrawMAC [116, 117], TICER [17, 117], RICER [117, 118], S-MAC [29, 119, 120], DSMAC[46], Optimized MAC [37, 52]	Contention baSsed	Single	C	High	No
SchedEx [99]	CSMA/CA contention based scheduling	Single	D	Low	No
DW-MAC [121]	contention based	Single	D	Low	No
LLDN [17], TDMA-MAC [122]	TDMA	Single	E	Low	No
LMAC [123], LEACH [124], LEACH-C [124]	TDMA	Single	F	High	No
LAMA [125]	TDMA	Single	G	Low (selected data)	Q
NAMA [125]	TDMA	Single	G	Low (selected data)	R
PAMA [125]	TDMA	Single	G	Low (selected data)	S
EQ-MAC(CMAC) [126]	TDMA	Single	G	Medium to low (selected data)	T
PriorityMAC [34]	TDMA	Single	G	Low (selected nodes)	U
Wise MAC [64]	Hybrid	Single	H	High	No
TRAMA [127]	Hybrid	Single	H	Medium to High	No
FSC [75], SSA [14]	Hybrid	Single	H	Low	No
WirArb [38]	Hybrid	Single	I	Low (selected	V
Z-MAC [128]	Hybrid	Single	J	Medium to low	No
PARMAC [11]	Hybrid	Single	J	Low to medium (Intragrid) High (Intergrid)	No
HMAC [129], EQMAC (CA-MAC) [126]	Hybrid	Single	J	Low	No
GANGS [130]	Hybrid	Single	J	Medium	No
MMSN [131], Y-MAC [132]	CSMA/CA	Multi-channel	K	Medium	No
TMCP [133]	CSMA/CA	Multi-channel	K	High	No
DMC-Allocation [134]	CSMA/CA	Multi-channel	L	Low	No
ALERT [118], T-opt Coverage [103]	TDMA	Multi-channel	M	Medium to low	No

Table 2.6: Salient Features of Selected MAC Protocols Cont.

Protocols	Channel Access Scheme	Frequency Channels	Application Area as per Error! Reference source not found.	Latency	Priority
HyMAC [38], FDP-MAC [136]	TDMA	Multi-channel	M	Low	No
SchedEx (M-C) [104], DMP [59, 137]	TDMA	Multi-channel	N	Medium to low	No
RL-MMAC [138]	Hybrid	Multi-channel	P	Medium to low	No
DSME [17]	Hybrid	Multi-channel	P	Medium (12xhigh data rates)	No
Q: Priority evaluation in two hop neighbourhood, with link activation access provided to priority node					
R: Self and neighbour Priority evaluation by sensor nodes to determine the priority of access to the slot					
S: Prioritized link activation to destination nodes					
T: The scheme classifies the gathered data in to queues based on the importance and the high priority queue gets the privileged access to the channel					
U: Four level Priority is established with high priority node given the access to highjack the timeslot of the low priority node					
V: An arbitration decision period is run and Frequency polling is used where each node is pre-assigned a frequency based on its priority. Based on the frequency polling in arbitration phase node with highest priority gets access to first time slot in arbitration execution period and so on where nodes with lower priorities have to wait till all the higher priority nodes have communicated					

Other multichannel schemes categorized from K to P, in MAC taxonomy as represented in Figure 2.7 , are listed in Table 2.6 along with the salient features of these protocols.

2.5.1.3 Contention based MAC protocols

CSMA/CA based medium access protocols fail to offer deterministic behavior which compromises their effectiveness in critical industrial applications [139]. Hence, industrial applications with less stringent deadlines can only be suitable for CSMA/CA based medium access protocols. In [140], Markov chains are used to model relations of packet transmission, packet delay, and energy consumption. Using this model, a distributed adaptive algorithm is derived to minimize power consumption along with improving packet reception probability and delay constraints. In [108] authors present a predictive wakeup mechanism in asynchronous duty cycling to reserve energy. In [107], authors present a sparse topology and energy management technique which wakes the radio from deep sleep state without the use of low power radio. Some other contention based schemes include [141-145].

Furthermore, to provide an extensive classification of the MAC protocols, in the MAC taxonomy presented in Table 2.6, the contention based schemes are classified in six categories namely: A) low duty cycle with extended lifetime, B) contention based low latency schemes, C) periodic contention based sustainable networks, D) contention based bounded deadtime communication, K) Throughput enhancement using contention based multichannel access and L) delay sensitive multichannel emergency access. The labels A, B, C, D, K and L are same as used in the taxonomy to maintain symmetry. The contention based MAC protocols falling in any of these categories are presented in Table 2.6 along with other attributes of these protocols.

2.5.1.4 Priority enabled MAC protocols

In most of the industrial processes, generated information in some cases is more critical than the rest hence should be prioritized above the rest of the communication. The priority based communication in IWSNs facilitates the communication of high priority traffic by providing adaptive channel access. Some of the proposed work in this domain includes [34, 38, 39, 106, 146]. In [37], authors presented a priority enabled MAC to prioritize messages with high information content. The protocol supports deadline requirements for feedback control systems but assumes full duplex communication which is not true in IWSNs. A priority enhanced MAC protocol for critical industrial applications is presented in [34]. In this protocol, the traffic in an industrial communication network is divided in four groups and the protocols allows the high priority traffic to overtake the low priority traffic bandwidth. The paper presents performance analysis and evaluation of the protocol through experimental implementation. In [38], a priority enabled MAC is defined in which priority is assigned on the basis of arbitration frequency allocated to individual users. The protocol is evaluated using discrete time Markov chain model and guaranteed access of the highest priority user is assured.

A classification of certain other priority enabled MAC protocols is also presented in Table 2.6, where the priority mechanism along with the salient features of these protocols is listed.

2.5.1.5 Summary and insights

In IWSNs, contention based channel access schemes has very limited use in the process control due to the non-deterministic nature. However, the CSMA/CA allows the nodes, freedom to communicate whenever needed and hence serves as a suitable mechanism to offer improved network lifetime in non-critical monitoring and data accumulation applications. Over the years plenty of CSMA/CA based MAC protocols have been introduced. The primary target as observed was to extend the network lifetime by introducing suitable sleep mechanism. Since this communication offered nodes to wake-up only when transmission was necessary so the protocols like STEM, STEM-B [107], PW-MAC [108] offered a suitable solution for monitoring applications.

Another and less frequently used attribute of CSMA/CA based MAC protocols was suitable reduction in the communication delay in the less congested networks. Some MAC Schemes like schemes like SIFT [109], Q-MAC [42], D-MAC [112], T-MAC [40] exploited this attribute to offer low latency in communication delay. Nonetheless, due to the contention based access, the deterministic behaviour can still not be ensured. To incorporate deterministic behaviour, slotted (B- MAC [114]) and scheduled (CC-MAC [69]) CSMA were also proposed.

The implementation of TDMA based communication was introduced to ensure guaranteed channel access, hence eliminating the uncertainty introduced by CSMA/CA based channel access schemes. One such examples is the modification of IEEE802.15.4 for industrial applications in the form of IEEE802.15.4e which introduces TDMA based communication. Since the incorporation of TDMA reduces the uncertainty in WSNs, it can be used for the control application which require periodic feedback. It is worth noticing that IEEE802.15.4e LLDN [17] offers a suitable solution for regulatory and supervisory control applications. TDMA-MAC [122] is another protocol which ensures low latency using TDMA based communication to support feed- back control systems. However, some other protocols using TDMA might not be suitable for control applications due to the introduction of long delay among two communications of an individual node. Therefore, protocols like LMAC [123], LEACH [124] and LEACH-C [124], although using TDMA, are only suitable for monitoring applications. Multi-channel TDMA schemes like ALERT [118] and T-Opt coverage [103] offer suitable reliability and latency assurance to meet the requirements of open loop control applications. Furthermore, these two schemes (ALERT and T-Opt) where work in single channel, can also benefit from the multichannel, which can be exploited to communicate to a larger number of nodes in a given time.

Use of multiple channels in IWSNs offer notable benefits including diversity, throughput enhancement, network scalability, optimized scheduling, on demand channel access and improved network control information. Since, in an industrial process, multiple applications can co-exist, the use of multiple-channels can introduce appropriate control in handling diverse data using parallel data streams. Apart from this, hybrid schemes with both TDMA and CSMA/CA based channel access, to support diverse traffic types, can be facilitated in parallel without introducing conflicts. RL-MMAC [138] and DSME [17] are two hybrid schemes which benefit from multiple channels to facilitate diverse traffic types. Both schemes facilitate both periodic and on-demand communication. DSME particularly focuses on improving the data rates and hence often compromises the delay constraints. RL-MMAC[138] on the other hand offers low latency. MMSN [131], Y-MAC [132], DMC [134] are some of the CSMA/CA based multiple channel schemes which due to the presence of longer delay between the consecutive transmissions limits their scope for low latency process control. Whereas Hy-MAC [135], T-opt [103], ALERT [118] and some others introduce TDMA based channel access for collision free communication for more sensitive traffic.

The diverse nature of industrial applications introduces a wide variety of sensory data to be accumulated at the control centre. Since various industrial processes run simultaneously in an industrial environment and cannot be distributed geographically. Therefore, it is much more obvious that communication link must relay data from regulatory control, supervisory control, open-loop control alerting and monitoring applications through the same wireless link. Under such circumstances, the priority based communication offers a significant improvement in network efficiency by communicating the traffic according to sensitivity levels. However, in IWSNs, the priority based communication is not thoroughly evaluated and very few protocols offer priority based communication. Nonetheless, the significance of the priority based communication cannot be undermined. Priority based communication also increases the diversity of the network by allowing sensory data from different applications to be communicated to the control centre without affecting the critical processes thus improving the efficiency of the entire network.

2.5.2 Extended classification of MAC Protocols

The taxonomy presented in Table 2.6, provides a much wider and in-depth view of possible MAC layer developments, and allows to classify different schemes presented over the years into one of the sixteen possible categories. The taxonomy is developed to assist in the evaluation of the basic requirements of a protocol and its much accurate characterization into one of various application areas in industrial environments. Furthermore, MAC protocols presented in research literature over time are also characterized into the categories specified by the MAC taxonomy. The classification of notable MAC protocols based on the presented taxonomy are listed in Table 2.6. Although, the classification of various protocols is discussed earlier on case to case basis, in general, the presented classification can be broadly distributed in single channel and multi-channel schemes, with further distribution of contention based, slotted and hybrid access schemes. Further subdivision in contention based, slotted and hybrid schemes maps to a particular application domain, dealing with one of the six industrial systems, discussed in Section 2.1. The MAC taxonomy also lists the objectives of WSNs and IWSNs and defines the bounds on key parameters.

The protocols listed in Table 2.6, are classified using the presented MAC taxonomy to evaluate their suitability in IWSNs. For instance, MAC protocols including STEM [107], PW-MAC [108], CC-MAC [69], B-MAC [114], SyncWUF [115], TrawMAC [116], TICER [117], S-MAC [119] and few others can be used in the monitoring applications. However, out of the above listed protocols, STEM, STEM- B and PW-MAC are more suitable for the applications with asynchronous communication requirements whereas almost all of the rest are suitable for periodic monitoring applications. Similarly, LAMA [125], PriorityMAC [34] and EQ-MAC [126] offer prioritized access which make these protocols suitable for the applications where the industrial system is handling more than one type of traffic. Usually these protocols are suitable for the systems dealing with supervisory control and alerting systems, where, depending on the traffic type the priority is assigned. To diversify the monitoring, control, and emergency communication in IWSNs, multi-channel MAC schemes were also presented over the years. The multi-channel schemes like MMSN[131], TMCP [133] and Y-MAC [132] can be used in the asynchronous monitoring applications with relatively larger networks. Whereas schemes like HyMAC [135] and FDP-MAC [136] can be put in use for time sensitive applications. A detailed list of various multi-channel schemes, along with the protocol characteristics and latency details are listed in Table 2.6.

2.6 Network Layer Developments

Network layer plays an important role in real-time and reliable communication of information in IWSNs. A large number of protocols have been proposed to meet routing requirements in diverse applications in conventional and industrial WSNs. Over the years, routing protocols are proposed to improve certain key attributes of a network. Some of the key performance metrics and network attributes optimized by routing include network lifetime, latency, throughput,

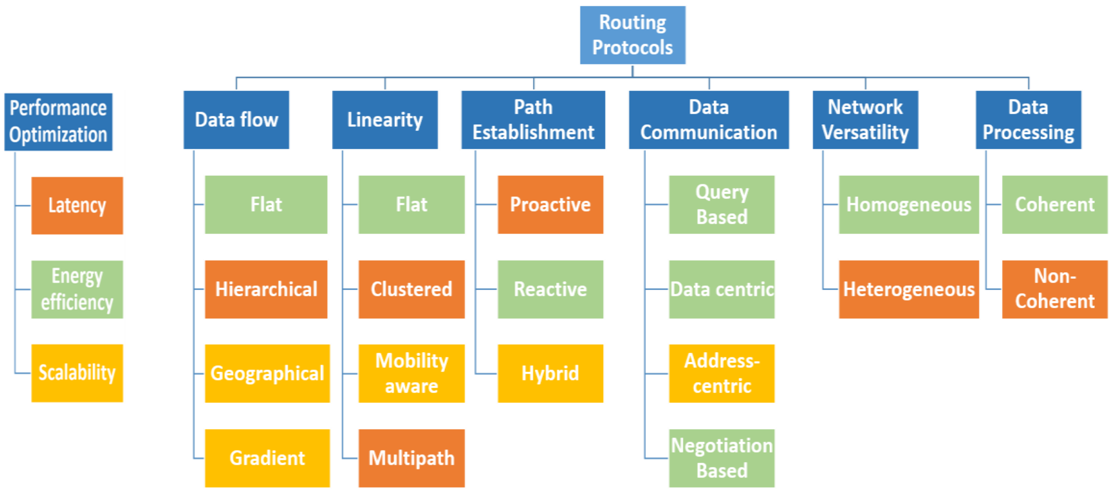

Figure 2.8: Taxonomy of Routing Protocols

reliability, energy efficiency, robustness, Packet Reception Rate (PRR), scalability and algorithm complexity [147]. Extensive list of routing protocols addressing one or more of the listed performance metrics can be found in [147-151].

Routing protocols due to significant variations in the underlay architecture and applications of IWSNs, can be classified in multitude of ways. A few attempts have been made to classify routing protocols based on significant features and some of these classifications can be found in [147, 149-151]. In this section, an extended classification of routing protocols is presented in Figure 2.8. The overall classification of the routing protocols is divided in six sub-categories. The created taxonomy of the routing where distributes the protocols into multiple categories, it also labels each subcategory with respect to performance metrics to highlight the focus of the created category and its suitability for different applications. In Figure 2.8, colour coding is used to label the routing subcategories in accordance with the performance optimization parameters listed in the figure. Three performance optimization parameters are presented, latency, energy efficiency and scalability. Based on these performance metrics and the potential of the routing subcategories is appropriately labelled. Due to the dependence of work presented in Chapter 6, Gradient based routing protocols are discussed in further details.

2.6.1 Gradient based routing

Gradient based routing protocols use gradient cost field establishment to route data from farther ends of the networks to the sink. The concept of gradient cost field establishment is taken from a natural phenomenon where water flows from higher grounds to the valley. Similarly, in gradient based routing protocols data propagates in a direction where it finds minimum cost. Each node maintains a routing table with at least the information of one least cost neighbour. The cost field at each sensor node can be defined in terms of hop count, energy consumption, delay, link quality, node energy etc. Any one or a combination of above described parameters can be used to establish Gradient cost model. In gradient based routing, the cost field can be established as a function of any of the QoS attributes which can optimize the network for desired quality metric. Selection of right quality metric can lead to an application specific and optimized routing solution. Some of the flagship gradient based routing protocols include GRAB [152], GRACE [153], PC-GRACE [154], SGF [155] and RRP [156].

Due to the wide implementation of Gradient based routing protocols, and lesser restrictions on applicability of gradient based routing in various environments, most of the classifications presented in Figure 2.8 can benefit from gradient based routing.

Chapter 2 summarizes the main research developments over the years in IWSNs in context of the research work presented in the following chapters. A detailed and more relevant discussion is also provided in the chapters 3 to 7.

3 CONTROL CHANNEL BASED MAC SCHEME

In emergency and regulatory control communication, strict time deadlines are required. It is therefore necessary that the feedback communication established by IWSNs must meet time and reliability constraints. In this chapter, three MAC protocols for time critical and emergency communications are proposed, namely EE-MAC, CF-MAC and OD-MAC. EE-MAC incorporates emergency communication and allows immediate channel access for emergency traffic. CF-MAC compensates for regulatory and open-loop control traffic and introduces a prioritized access for high priority nodes. It also allows nodes with critical data to reserve communication slots using control channel. Whereas OD-MAC presents a deadline based dynamic scheduler which ensures timely delivery of the time-critical information. The chapter also presents mathematical modelling of the proposed protocols. For evaluation purposes, the performance of the proposed protocols is compared to IEEE 802.15.4e LLDN. The results show that the proposed protocols offer up to 92% reduction in delay of emergency communication at the cost of 5% to 15% increase in delay of non-critical and time-insensitive data. For CF-MAC, a 60% and 85% reduction in the channel access delay was observed for regulatory and open-loop control traffic respectively along with notable improvements in the communication reliability.

3.1 Introduction and Relevant Developments

The recent developments in MEMS technology, have proven substantially influential in forming low cost smart networks. However, the reliance of industrial processes and feedback control systems on communication network imposes an urgent need for higher reliability and real-time data delivery in IWSNs.

Table 3.1: Communication requirements in industrial systems

Traffic Category	Tolerance	
	Reliability	**Time Constraint**
Safety / Emergency Traffic [34, 35, 37]	High reliability requirements	Few milliseconds
Regulatory control traffic [34, 35]	High reliability requirements	Few-tens of milliseconds
Supervisory control Traffic [34, 35]	High reliability requirements	Tens of milliseconds
	Low reliability with occasional packet misses	Seconds to hours
Open loop control traffic [35]	Medium reliability requirements	Seconds-minutes
Alerting traffic [34, 35]	Medium reliability requirements	Seconds-minutes
	Low reliability with occasional packet misses	Seconds to hours
Monitoring traffic [34, 35, 37, 65]	Low reliability requirements	minutes to hours

In the past, many industrial protocols for IWSNs were developed to offer required reliability and real-time communications. Some of the prominent industrial communications protocols include Zigbee [23], WirelessHART [81], ISA100.11a [82] and 6LowPAN [21]. Two IEEE standards, IEEE 802.15.4 [19] and IEEE 802.15.4e [17] were introduced to support these protocols.

As discussed earlier, CSMA/CA based access schemes offer a great potential in optimizing performance in delay sensitive applications. However, in dense networks, the channel access guarantee is usually compromised in CSMA/CA based schemes. This is a direct consequence of need based and unscheduled channel access which results in frequent collisions. Furthermore, the channel access is not guaranteed in any communication in CSMA/CA. Due to these reasons, the suitability of the CSMA/CA based protocols and industrial standards is questionable for critical processes. To address the reliability of channel access scheme and to significantly reduce the collisions, use of TDMA as primary channel access mechanism is preferred where the synchronized beacon enabled communications is established. IEEE 802.15.4e is primarily defined for industrial applications to offer reliable and timely channel access for the critical communications of the nodes. However, the predefined access in TDMA, also induces critical delay to time sensitive and asynchronous applications in industrial environments.

Typically, the IWSN systems offer their services to specific ranges of applications, which are different from traditional WSNs. Therefore, depending on the specific application characteristics, QoS requirements and time constraints are specified [29]. As ISA divides the industrial systems in six different classes [35] based on the nature of applications, standard operating procedure, access schemes, reliability, and latency requirements, therefore, communications traffic in these classes must be accordingly designed. The communications requirements for these systems are listed in Table 3.1.

To address the issues of different application classes in industrial automation, three MAC protocols are presented in this work which target reliability improvement and time-constrained communications. Each protocol targets specific application domain and can work individually to address certain communication issues. These protocols are briefly introduced as follows, where a detailed discussion is provided later in the chapter.

(i) Emergency Enabled MAC (EE-MAC) introduces a mechanism for optimizing channel access for emergency communications and introduces a scheme to provide immediate channel access for critical nodes.

(ii) Critical Feedback MAC (CF-MAC) deals with the communications optimization in regulatory, open-loop and supervisory control systems. It provides communications failure compensation for regulatory control systems as well as schedules asynchronous channel access requests for supervisory control systems.

(iii) On-Demand (OD-MAC) incorporates deadline based scheduling of the nodes in the network where the scheduler is run on the coordinator. The protocol allows the coordinator to adaptively adjust the urgently required information which allows improved performance in meeting the critical time deadlines.

3.2 System Model

In the proposed system, TDMA based channel access scheme is used as a baseline to ensure reliability and collision free communications. The memoryless communications channel is considered due to a notable delay in two consecutive communications from a single communications source (Sensor node). Presence of multiple interference sources is assumed which can cause certain degradation in PRR. A hierarchical architecture is assumed to ensure a maximum two-hop delay from a sensor node to a control centre and star topology is considered for communications between the sensor nodes and the relevant coordinator node. The communications between the coordinator nodes and the control centre uses multi-channel access scheme to establish parallel streams to meet the higher data rates and reduced delay.

In order to ensure real time and reliable communications of critical and emergency information, the proposed MAC protocols are described as follows.

3.2.1 EE-MAC

EE-MAC allows the nodes with critical/emergency information to request the channel access. Since the occurrence of the emergency communications is asynchronous and is relatively rare so a hybrid scheme is introduced where the regular communications continues in a TDMA based superframe.

In case of emergency, a slotted request mechanism using control channel is introduced, which allows the coordinator to halt the regular TDMA based transmission and initiate emergency communications by inserting appropriate number of time slots in the TDMA frame. In case of multiple emergency requests triggered in a particular time, a queuing function is used to allocate the resources sequentially. For such cases the communications of regular TDMA can be stopped for multiple timeslots. To ensure the collision free transition, a halt (*HT*) and reinitiate (*RT*) sequence are defined which informs the nodes to stop and resume communications as necessary. The coordinator initiates *HT* and *RT* sequences to stop regular time frame communications and resume these communications respectively. A minimum halt duration is also included in *HT* sequence to improve energy efficiency of the network.

To improve the reliability of control channel, non-overlapping communications band is dedicated for control channel. The communications over control channel use higher transmission power to improve communications reliability. As evaluated from the experimental results, the transmission power for control channel communications use 10 dBm margin compared to the normal communications. By doing so, the overall communications reliability of the control communications is notably improved. Since the control channel is assigned non-overlapping communications band, and TDMA is incorporated for time isolation, therefore increase in transmission power will not cause interference.

A pair of CC2420 radios (used in Sun SPOT wireless sensor motes) was used to evaluate PRR for different received signal strengths to evaluate suitable transmission power for the regular

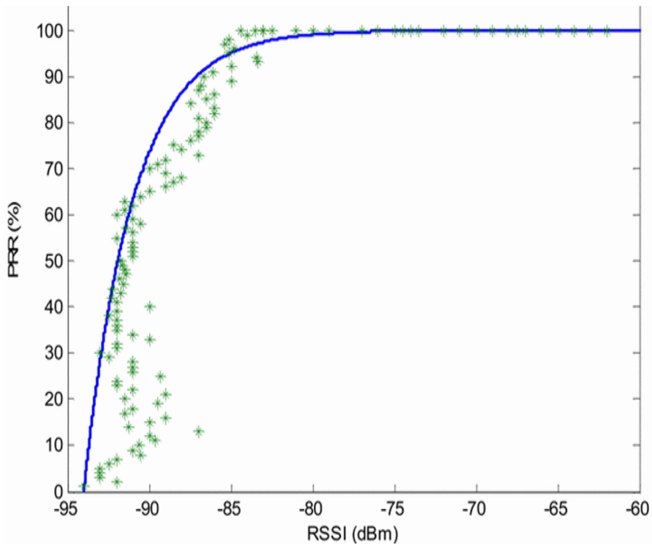

Figure 3.1: Packet Reception Rate (PRR) as a function of RSSI using CC2420 [40]

communications and control channel. For evaluation purpose realistic channel conditions were ensured with non-line of sight multipath channel characteristics. In the experiment, receiver sensitivity was identified as -85 dBm as represented in Figure 3.1. Since the packet reception is relatively poor below -85dBm (see Figure 3.1), at least 10dB margin is suggested for normal communications. Whereas a further 10dB margin is added for the control channel. Therefore, normal channel communications were targeted to maintain RSSI between -70 to -75dBm whereas, for the control channel this range was suggested to be -60 to -65 dBm. The suggested range ensure near 100% packet reception rate in control channel with up to 10 dB path loss fluctuations, as represented in Figure 3.1.

In Figure 3.2, superframe structure of EE-MAC and other related details are presented. As represented in figure, each superframe is divided into n timeslots, each of duration t. Each timeslot is further divided in communications and acknowledgement window of duration $(1-\delta) \times t$ and $\delta \times t$ respectively.

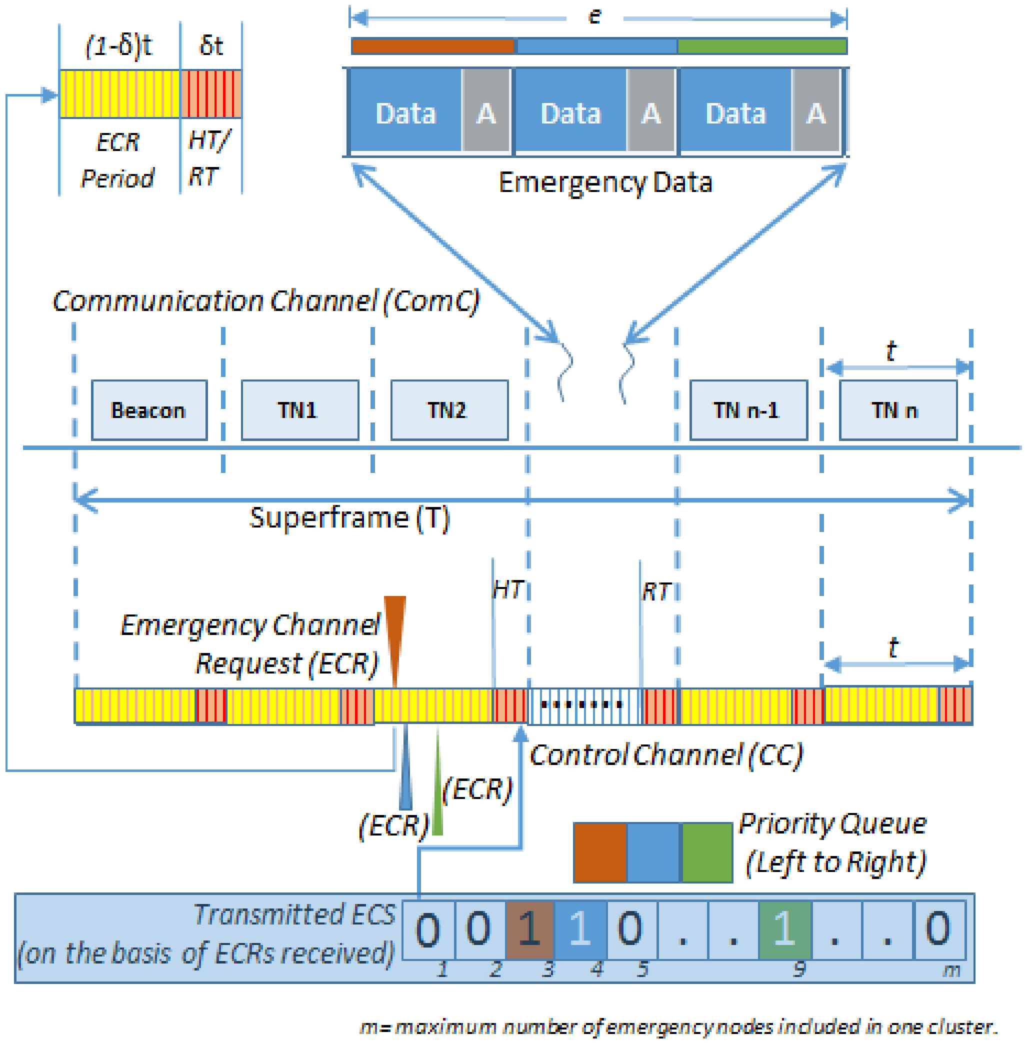

Figure 3.2: EE-MAC Operation

Table 3.2: Description of variables and selected values

Parameters	Variable(s)	Value(s)
Total Time slots in IEEE802.15.4e LLDN superframe	n	20
Number of emergency nodes included in a cluster	m	1,2,…10
Packet Payload bits	*Payload_bits*	960 bits
Payload transmission time	*MAC_payload (PL_delay)*	3.84ms
Superframe duration (LLDN)	T_{LLDN}	10ms
Superframe duration (EE-MAC)	$T_{EE\text{-}MAC}$	10ms±Δ
Data Rate	R_b	250kbps
Probability of successful communication	p	0.7-0.999
Emergency traffic Arrival rate per second	λ	1-500
Number of emergency requests	α	-
Time slot duration	t	≅300μs
Access Delay	d	-
Average successful communication delay	*d_success*	-
Communication window duration	$(1-\delta)\times t$	-
Acknowledgement window duration	$\delta \times t$	-
EE-MAC average duration of added time-slots	e	-
Maximum additional slots in CF-MAC	k	5
Nodes communicating in Segment-*i*	s_i	-
Communication failure probability	q	-
No. of emergency requests	x	
No. of failed communications per segment	y	-
count of transmissions until the successful communication	v	
Average communication failures per segment	A_f	-
Probability of Communication failures in segment-*i*	$\mathrm{P}(f_{si})$	-
Sensor value	s	-
Sensor Setpoint, Threshold high and Threshold low	Sp, Th_{High}, Th_{Low}	-
Superframe supervisory control segment time-slots	H	-
number of supervisory feedback sensor nodes	u	-
percentage channel request queries per unit time	R_s	-
Total nodes	Z	-
Allowable percentage increase in the delay of two consecutive transmissions of a critical node in consecutive superframes	φ	
Time deadline of node *i*	*dl(i)*	-
Duration of additional slots added in superframe	Δ	
Nodes with failed communications in a superframe	f_{stack}	
Number of additional time slots added in superframe	g	
Number of nodes with failed communication in previous superframe	N	
Control system stability factor (%age of time for which the process output remains within the threshold)	ʒ	99.7%

The control channel is synchronized with communications channel. In control channel each time slot of duration t is divided in the Emergency Channel Request *(ECR)* period and halt/Reinitiate (*HT/RT*) communication Period. In the ECR period, a slotted access is used where the ECR period is divided into m slots where m is the number of total emergency nodes. Each emergency node is provided one of these m slots to initiate ECR (The division of these slots among the emergency nodes can be overlapping to accommodate larger number of emergency nodes with more frequent channel request opportunity). At the completion of the ECR period if one or more channel requests are received, the coordinator initiates *HT* during *HT/RT* period to halt the ongoing regular communication. By default, the regular communication is stopped for single time slot but if more than one emergency communication requests were received during *ECR* period, the halt duration is extended accordingly and this duration is communicated during *HT* sequence transmission along with the Emergency Communication Sequence (ECS) (See Figure 3.2 for the ECS based on the ECRs received in the ECR period). This allows the regular communication nodes to go to sleep mode for the halt duration (*HD*) to conserve energy. Furthermore, the regular communication nodes in the network only need to stay active during the timeslots when these nodes are communicating, whereas the nodes will be in passive listening mode during the beacon and *HT/RT* period (passive listening can be adjusted to alternative slots as any one of *HT* or *RT* sequence transmission if received will be enough to adjust the listening node’s transmission slot, except the timeslot just before the node’s own transmission) and sleep mode for the rest of the time. It must be noted that the beacons are used to synchronize the communications from various sensor nodes and since, in each superframe further time slots can be added therefore the superframe duration can vary, hence beacons may not be separated by equal intervals. Each node is assumed to have a local clock to keep it synchronized. Furthermore, HT/RT sequences are used whenever new slots are added, which serve as secondary marker for time synchronization. For evaluation purposes Table 3.2, presents variables/parameters used in the discussion. Selected values of different parameters are also presented.

The performance of the EE-MAC protocol is compared with the IEEE 802.15.4e, LLDNs framework, specifically defined for the critical industrial applications. Mathematical model for the proposed EE-MAC protocol is also presented.

The superframe duration of LLDN is represented as T_{LLDN}, whereas in case of the EE-MAC the superframe duration of $T_{EE\text{-}MAC}$ is given by

$$T_{EE-MAC} = T_{LLDN} + e \tag{3.1}$$

here *e* is the duration of the average additional timeslots, each of duration *t*, added to the superframe to compensate emergency communication. It also considers the deviation (Δ) from the mean duration. Since the emergency communication in industrial environments is asynchronous and event-driven, i.e. at a particular time, during the experiment, one or more of the emergency nodes in IWSNs may request emergency communications channel. A certain probability value can be assigned to the occurrence of emergency conditions. If the large number of emergency nodes are reduced to a single node, the probability that this node will develop emergency condition can be determined by Poisson distribution. Thus, the occurrence of emergency channel request by emergency nodes is modelled as a Poisson distribution. It is assumed that the probability distribution of occurrence of emergency condition of one emergency node is same as the other emergency nodes and all are mutually independent.

The duration of timeslot (*t)* is presented in Eq. 3.2 whereas the PMF of the Emergency occurrences (x) in ECR period ((1-δ)*t*) is presented in Eq. 3.3.

$$t = \frac{T_{LLDN} - MAC\_Payload}{n} \tag{3.2}$$

$$P_X(x) = \begin{cases} \dfrac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} & where\ x = 0,1,2,\ldots,m \\ 0 & otherwise \end{cases} \tag{3.3}$$

here *m* refers to the number of emergency nodes included in a cluster and α=λ*t*. The time duration of the emergency slots within a superframe (*e = duration of average no. of emergency slots* ± Δ) is given by

$$e = t \times \left\{ \left(\sum_{x=0}^{m} \left(x \times \frac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} \right) \right) \pm \left(\sum_{x=0}^{m} \left(x - \sum_{x=0}^{m} \left(x \times \frac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} \right) \right)^2 \right) \times \frac{\frac{\alpha^x e^{-\alpha}}{x!}}{\sum_{y=0}^{m} \frac{\alpha^y e^{-\alpha}}{y!}} \right\} \tag{3.4}$$

In Eq. 3.4, $\alpha = \lambda T_{LLDN}$. The occurrence of emergency communication is considered random and in reference to a particular superframe, it can occur anywhere during the frame with equal probability as the emergency cases can occur at any time within an industrial environment. Therefore, occurrence time of the emergency communication is modelled as uniform distribution. The access delay between the time when, need for emergency transmission is developed to the time when the transmission is started, has great significance in emergency communications. For LLDNs, it is ensured that the maximum channel access delay is kept fixed to T_{LLDN}, however, for evaluation purposes the average access delay (d) is used for both EE-MAC and LLDNs.

Average access delay of LLDNs (d_{LLDN}) and Average access delay of EE-MAC ($d_{EE\text{-}MAC}$) for emergency data is presented in Eq. 3.5 and Eq. 3.6 respectively.

$$d_{LLDN} = \frac{1}{2} T_{LLDN} \tag{3.5}$$

$$d_{EE-MAC} = \sum_{x=1}^{m} \left[\left(\delta t + \frac{1}{2} t + (x-1) \times t + \left(\frac{x}{n} \times PL\_delay \right) \right) \left(\frac{\alpha^x e^{-\alpha} / x!}{\sum_{y=1}^{m} \alpha^y e^{-\alpha} / y!} \right) \right] \tag{3.6}$$

In emergency communications, average delay time (time from emergency transmission need is developed to the average time when the transmission is successfully completed) for LLDN and EE-MAC ($d\_success_{LLDN}$, $d\_success_{EE-MAC}$) is presented in Eq. 3.7 and Eq. 3.8 respectively.

$$d\_success_{LLDN} = d_{LLDN} \times \sum_{v=1}^{\infty} v \times p(1-p)^{v-1} \tag{3.7}$$

$$d\_success_{EE-MAC} = d_{EE-MAC} \times \sum_{v=1}^{\infty} v \times p(1-p)^{v-1} \quad (3.8)$$

Here p is the probability of successful transmission and v is the count of transmissions until the successful communication takes place.

The performance of this protocol is evaluated for emergency systems in terms of channel access delay and average successful communication delay, details of which are presented in Section 3.3.

3.2.2 CF-MAC

CF-MAC takes in consideration the critical feedback information in close-loop regulatory control systems, open-loop control systems and close-loop supervisory systems. Due to the relatively different requirements of the above-mentioned application areas, the operation of this protocol is divided in two cases depending on the targeted objectives.

3.2.2.1 Failure compensation (CF-MAC)

For feedback control systems, the proposed protocol allows the retransmission of the failed communication to improve the system reliability as well as time bounded delivery of the critical information. Since regulatory control systems require synchronous feedback for controlled operation of the process, therefore, the number of retransmission slots that can be inserted in a superframe are limited to restrict the maximum delay between two consecutive transmissions of sensory nodes. To ensure minimal delay, the time duration of a superframe is also limited to 10 ms, which can only be extended by a duration no more than $\varphi \times \mathrm{T}_{LLDN}$, (where φ defines the allowable percentage increase in the delay of two consecutive transmissions of a critical node in consecutive superframes). For simplicity, the extension in the duration of superframe will be referred as g from now onwards where $g = f(\varphi, T_{LLDN})$, the number of additional time-slots that can be added in the superframe.

The addition of time-slots in the superframe is initiated by the cluster-head and a time slot request using control channel is not required from the sensor nodes. Rather, on unsuccessful communication between the sensor node and the cluster-head, the cluster-head adds an additional slot at the end of a transmission sequence/segment as represented in Figure 3.3. *HT* and *RT* sequences are used to halt and reinitiate regular transmission. Since the delay between the consecutive transmissions in regulatory control is bounded by the process control, therefore, the communication in a superframe is divided in four priority levels, where the maximum allowable additional slots are filled with the retransmission of the highest priority nodes first. Once the retransmission of the failed communication of high priority nodes is scheduled, if further slots can still be added to the superframe, then the lower priority nodes can be scheduled as well. This ensures higher reliability for more critical sensor nodes. The superframe for transmission of sensory feedback in process control with priority wise segmentation of the superframe is represented in Figure 3.3. As represented in the figure, the communication in the superframe supports four industrial applications, regulatory control, open-loop control, supervisory control and monitoring systems. If the transmission of one or more nodes in a particular segment fails, the additional slots for retransmission are added after the segment ends. Since a limit on total number of slots is added therefore, high priority nodes are scheduled first.

Mathematical modelling of the key performance attributes is presented as follows whereas the performance of CF-MAC in comparison to IEEE802.15.4e LLDN is presented in Section 3.3.

Since the communications in segment 1 (regulatory control communications), consist of s_1 transmissions, therefore, the number of successful communications are dependent on the probability of success, *p*, of an individual communication. It is to be noted that communications of each of the nodes in segment 1 is not influenced by the communications made by any other node, hence, the communication of each node is independent and identically distributed (i.i.d). Due to the similarity of the problem with binomial distribution, the probability of failures in communication of nodes in any particular segment with s_i transmissions is modelled as a binomial distribution. The probability mass function is presented in Eq. 3.9 whereas the average communication failures per segment is presented in Eq. 3.10.

$$P(y) = \binom{s_i}{y} q^y (1-q)^{s_i - y} \tag{3.9}$$

Here s_i is the number of nodes communicating in *segment-i*, y is the total number of failed communications and q is the communication failure probability of single node.

$$A_f(i) = \sum_{y=0}^{s_i} \left(y \times \left(\binom{s_i}{y} q^y (1-q)^{s_i - y} \right) \right) \tag{3.10}$$

The CF-MAC allocates additional slots for retransmission, of failed communication, which improves the reliability of the system as a whole. The probability of failure for *segment-1* (Figure 3.3: High priority section), in CF-MAC is presented in Eq. 3.12 in contrast to IEEE802.15.4e LLDN, presented in Eq. 3.11.

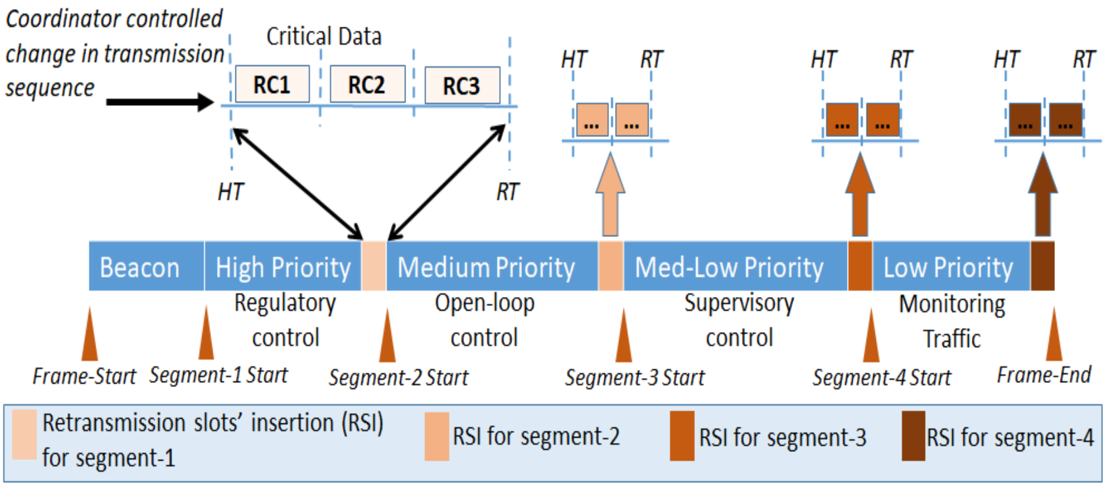

Figure 3.3: CF-MAC Superframe

$$P(f_{s1})_{LLDN} = \sum_{y=1}^{s_1} \left(\binom{s_1}{y} q^y (1-q)^{s_1 - y} \right) \tag{3.11}$$

$$\begin{aligned} P(f_{s1})_{CF-MAC} = {} & \sum_{y=1}^{k} \left[\left(\binom{s_1}{y} q^y (1-q)^{s_1-y} \right) \times \left(\sum_{x=1}^{y} \binom{y}{x} q^x (1-q)^{y-x} \right) \right] \\ & + \left[\sum_{y=k+1}^{s_1} \binom{s_1}{y} q^y (1-q)^{s_1-y} \right] \end{aligned} \tag{3.12}$$

Since communications in *segment-2* in the superframe (Figure 3.3) are also termed as important, therefore, a relationship for probability of failure of *segment-2* is represented in Eq. 3.13.

$$P(f_{s2})_{CF-MAC} = \sum_{y=1}^{k}\left[\left(\binom{s_2}{y} q^y (1-q)^{s_2-y}\right)\right.$$

$$\left.\times\left(\left(\sum_{x=1}^{y}\binom{y}{x} q^x (1-q)^{y-x}\right) + \left(\sum_{z=k-y+1}^{k}\binom{s_1}{z} q^z (1-q)^{s_1-z}\right)\right)\right] \quad (3.13)$$

$$+\left[\sum_{y=k+1}^{s_1}\binom{s_1}{y} q^y (1-q)^{s_1-y}\right]$$

Using Eq. 3.11 to 3.13, the probability of successful communications is defined as $P(S_{si}) = 1 - P(f_{si})$, where $P(S_{si})$ is the probability of successful communications in segment-i.

The probability of failure in segment-3 and segment-4 ($P(f_{s3})_{CF-MAC}$ and $P(f_{s4})_{CF-MAC}$) can also be derived, however, segment-3, dedicated for supervisory control traffic is discussed in detail in Section 3.2.2.2 and due to the lesser significance of communication in segment-4, and marginal improvements introduced by CF-MAC in this segment, the effect is not thoroughly investigated.

To further investigate the impact of insertion of additional time-slots in the superframe, the average channel access delay of *segment-1* nodes after communication failure is modelled for both IEEE802.15.4e LLDN and CF-MAC and is presented in Eq. 3.14 and 3.15 respectively.

$$d_{LLDN\_s1} = T_{LLDN} \quad (3.14)$$

$$d_{CF-MAC} = \left[(s_1 \times t) \times \left(\sum_{y=1}^{k}\binom{s_1}{x} q^x (1-q)^{s_1-x}\right)\right]$$

$$+\left[T_{LLDN} \times \sum_{k+1}^{s_1}\left(\left(\sum_{x=k+1}^{s_1}\binom{s_1}{x} q^x (1-q)^{s_1-x}\right)\right)\right] \quad (3.15)$$

3.2.2.2 Asynchronous communication (CF-MAC)

For supervisory control applications, the protocol allows the asynchronous feedback, needed for such type of systems. The nodes with critical control information can request a transmission slot using the control channel. The request can be initiated if a notable change in the sensor reading occurs and need to be reported. As an example, Figure 3.4 represents the sensor readings, where feedback control is established to maintain the readings between the specified range of sensor value, marked by green strip. In the figure, a steep drop can be seen for value of x-axis (Time) near 1000. Under such circumstances when value violates critical threshold, sensor node requests coordinator for channel access, which is being dealt in a similar manner as in case of EE-MAC using control channel request. However, while handling supervisory control information in CF-MAC, two main differences from EE-MAC can be observed. Firstly, after observing a change in sensor value, the initiated request from the senor node for time slot is not instantly addressed, rather, the coordinator/cluster-head will schedule the communication in segment-3 (see Figure 3.3). Since the Segment-3 is dedicated for supervisory control so communication in this segment is on-demand based and communication in Segment-3 only takes place if criticality of one or more implemented processes violate the threshold. Secondly, maximum number of additional slots added for CF-MAC are limited and unlike EE-MAC, due to lower priority of application at hand, communication requests from some nodes might be postponed to next superframe for communication. Hence, the coordinator in CF-MAC also implements queuing function, where requests are addressed sequentially based on the traffic priorities. The proposed system uses two level of priorities depending on the requests from supervisory control systems and alerting systems, where supervisory systems are prioritized over alerting systems. However, the priority queuing can be optimized based on the application at hand.

A careful modelling is needed for scheduling asynchronous transmission. Therefore, a probabilistic model is presented to specify the number of sensor nodes that can be served by a specific number of timeslots in the superframe. Further, to this, since no sensor node in segment-3 receives a dedicated time-slot, a thorough evaluation of slot to sensor ratio is established to provide desired QoS.

Figure 3.4 (left y-axis) represents the sensor thresholds (Th_{Low}, Th_{High}), defined with respect to the setpoint (Sp). An approximate density function of control processes is represented and labelled in Figure 3.4 (right y-axis). By ensuring the careful modelling, frequent threshold

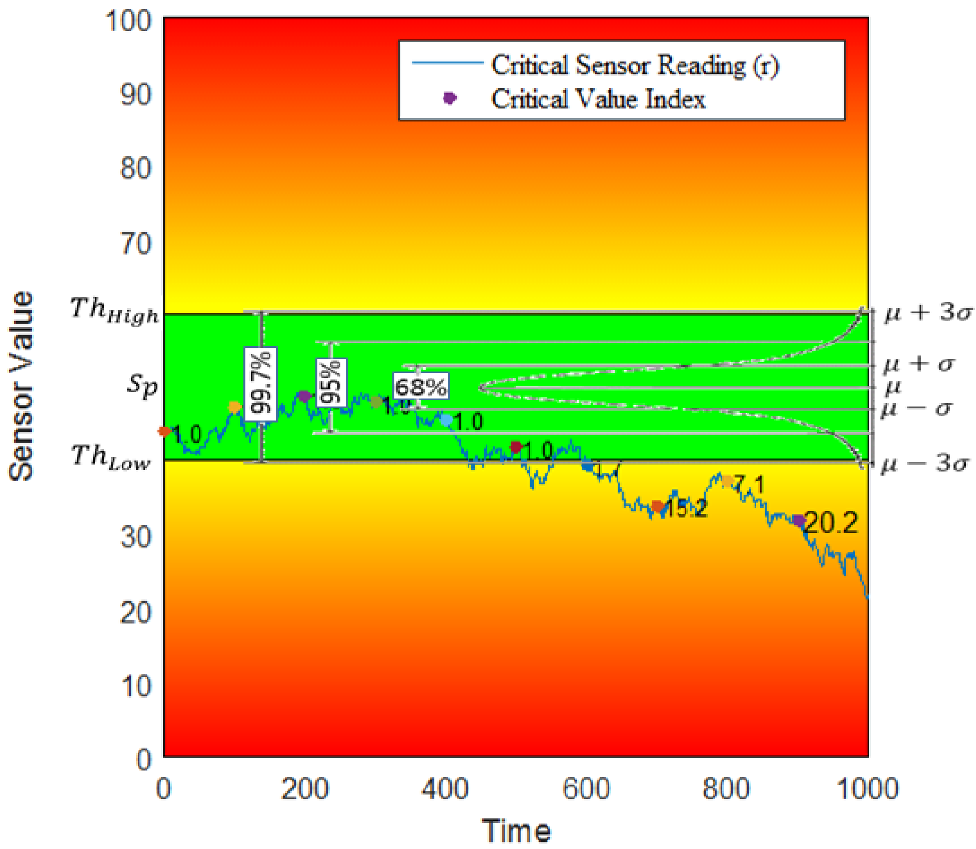

Figure 3.4: Sensor Readings

violations can be avoided. The probability density function of system output for sensor reading is modelled as

$$f(s) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{3.16}$$

Here, s is the sensor value where process control is modelled so that $Sp = \mu$ and $Sp \pm Th_{High/Low} \cong \mu \pm 3\sigma$. The specified condition ensures a relatively lower probability for control processes to violate the threshold. To limit the variations in controlled processes, an upper limit $\mathfrak{z}$ is specified to limit the violations of threshold such that

$$P[Sp - Th_{Low} < s < Sp + Th_{High}] > \mathfrak{z} \tag{3.17}$$

Further to this, number of nodes accommodated in h time-slots (dedicated for supervisory nodes) in superframe are represented by u in Eq. 3.18.

$$\sum_{i=h+1}^{u} \binom{u}{i} r^i (1-r)^{u-i} \leq R_s \tag{3.18}$$

here u is number of supervisory feedback sensor nodes, $r = 1 - P[Sp - Th_{Low} < s < Sp +$

$Th_{High}]$ and R_s is the percentage channel request queries per unit time exceeding the number of slots provided.

The performance of CF-MAC is evaluated in terms of reliability improvement and access delay for regulatory control. Whereas the network scalability under prespecified QoS conditions is evaluated for supervisory control systems. A detailed discussion can be found in Section 3.3.

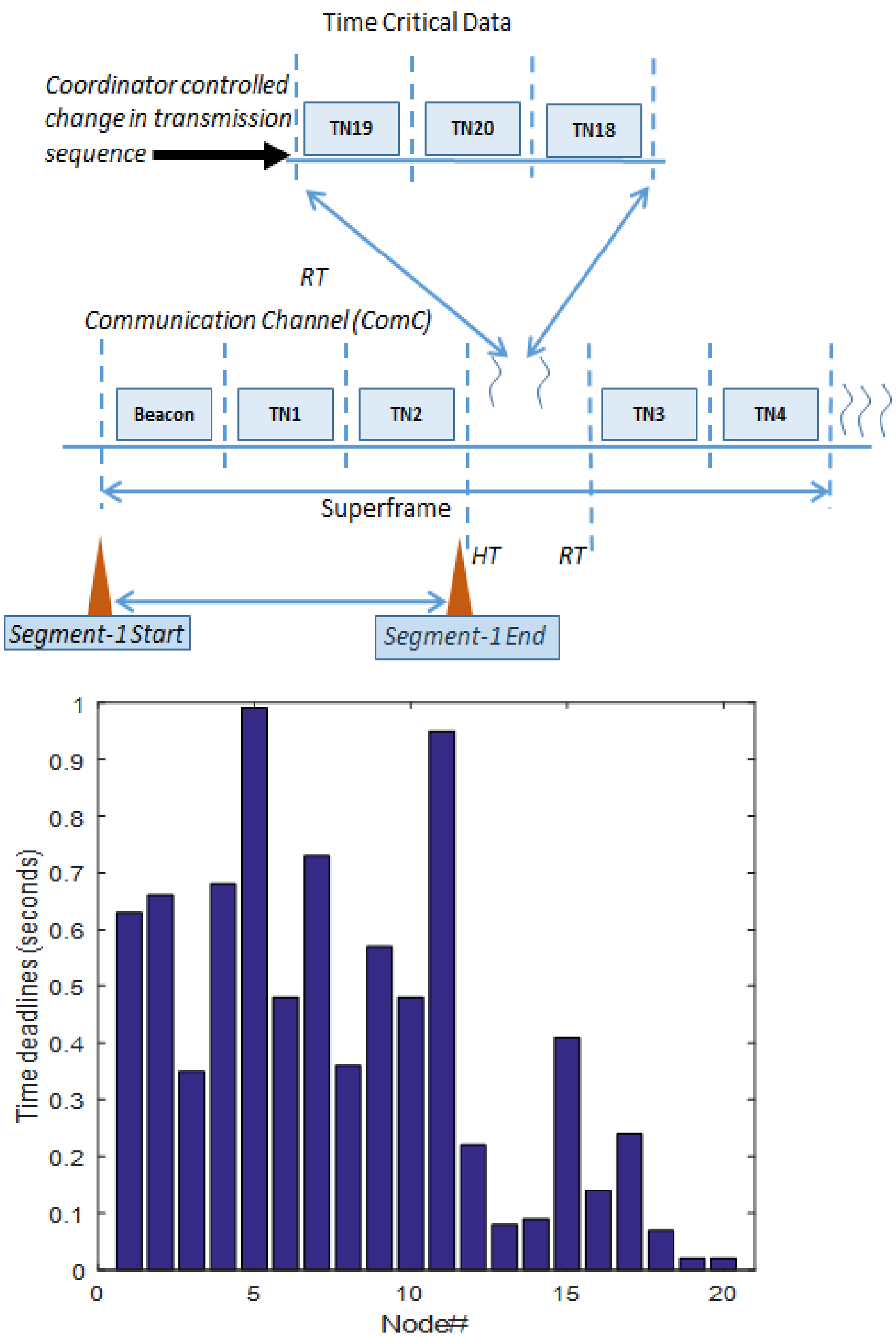

Figure 3.5: OD-MAC Operation

3.2.3 OD-MAC

OD-MAC targets two critical aspects of the industrial automation, deadline based scheduling and on-demand communication. The control channel is used for the information request from the nodes in the cluster. Since the communication is controlled by the coordinator, on demand communication can be initiated by the coordinator at any time. However, to keep the schedule as predictable as possible, on demand communication is only initiated at the mid and end of the superframe, if needed. The communication in OD-MAC allows the coordinator to schedule the on-demand communications as well as deadline based communication. OD-MAC also introduces a deadline based scheduler, running at the coordinator, which manages the schedule of communication of the nodes and, where needed, alters the transmission sequence by inserting a special on demand transmission block. An example scenario is presented in Figure 3.5. It can be seen that a regular sequence of transmission is followed up to certain extent, however, due to the relatively short deadline of nodes 19, 20 and 18 (TN19, TN20 & TN18, as represented in deadline bar graph in Figure 3.5), are specially accommodated. Since TDMA based channel access is used, regular beacons at the start of every superframe is introduced to synchronize the sensor nodes. Time deadline based scheduling improves on-time data delivery as well as efficient scheduling of heterogeneous time deadlines.

The deadline based scheduler allows application versatility and schedules load more effectively. The algorithm for deadline based scheduling for heterogeneous sensing deadlines is presented as follows where the control channel based communication is used for communicating updated schedule at the start of the superframe.

The proposed scheduling algorithm formulates a schedule for each superframe based on the sensor deadlines and failures in the previous communications, as represented in Algorithm-3.1 (*lines 2-5*). While, the coordinator receives information from the nodes, based on the broadcasted schedule, if communication fails it is rescheduled either at mid or end of the superframe (*achieved* *by lines 6-12*).

Algorithm 3.1: Deadline based and on-demand communication Schedule

Input:$(\boldsymbol{dl}(1), \boldsymbol{dl}(2), .. \boldsymbol{dl}(\boldsymbol{z}), \boldsymbol{f}_{stack}, \boldsymbol{N}, \boldsymbol{z})$

Output: $(\boldsymbol{N}, \boldsymbol{f}_{stack})$ /*Transmission Schedule + failed communications */

1. Timer0.start(); w=1; /*starting timer to track superframe duration, T_{OD-MAC}*/
2. $for(i = 1 \rightarrow z)\ \{sd(i) = sortAscending(dl(i));\}$/* sorting nodes w.r.t deadlines*/
3. $Sch(1 \rightarrow N) = f_{stack}$; /*Scheduling failed communications in earlier superframe, a total of N nodes scheduled */
4. $for(i = (N+1) \rightarrow (n+N))\{Sch(i) = sd(i-N)\}$
5. $T_{OD-MAC} = T_{LLDN} + \Delta$; // Δ=$N$ ×t; //current duration of OD-MAC frame
6. $Broadcast(sch/beacon)$/*broadcasting schedule during the beacon transmission*/
7. $for(i = 1 \rightarrow n + N)$ {
8. $pkt.rcv(ch, i)$; /* receiving packet from *scheduled node i on channel (ch)*/*
9. $if(crc = true)\{ack; reset(deadline)\}$; /* ack sent+ resetting node's deadline for next transmission*)*/*
10. $else\{f_{stack}(w) = n_{id}; w++;\}$
11. $if\left(\left\{i = ceil\left(\frac{n+N}{2}\right) or\ i = n + N\right\} \&w > 1\right)$/* mid/end of frame reached */
12. $\{initiate(HT);\ transmit(f_{stack});\ initiate(RT), \}$;/Retransmitting failed communication by halting scheduled communication. }
13. $for(i = 1 \rightarrow z)\{dl(i) - \text{Timer0}\}$; //updating deadline
14. Timer0.reset()
15. Return to 1;

$transmit(f_{stack})\{$

$for(i = 1 \rightarrow w)\{pkt.rcv(ch, i); temp = 1;$

$if(crc = true)\{ack\}; else\{f_{temp}(temp) = n_{id}; temp++;\}\}$

$f_{stack} = f_{temp};\ w = temp;\}$

3.2.4 Applicability of proposed protocols in industries

In industrial environments various applications run simultaneously. These applications can belong to different classes of industrial systems and can have diverse requirements. An example scenario is presented to elaborate the working of the proposed protocols and how these protocols can assist in facilitating uninterrupted operation in the industries.

As an example, a typical industry is considered which consists of three main classes of industrial systems: 1) critical and highly sensitive systems which are activated in case a major anomaly is occurred, 2) process control systems which introduce automation and process optimization and 3) monitoring systems to accumulate sensory data, to investigate plant efficiency and to analyse potential future improvement possibilities. The effective communication of traffic generated by these systems play an important role in uninterrupted operation of the sensor nodes.

Emergency systems are usually triggered to minimize safety threats and lessen the severe consequences of uncontrolled changes in the automated systems to avoid operational and safety hazards. Emergency communications are one of the integral parts of emergency systems. These communications ensure timely delivery of critical information. Mostly such communications are isolated from the main communications and are provided dedicated channels which allow uninterrupted delivery of such messages to the control centre. Although the discussed solutions work, however, it requires dedicated communication bandwidth. Automation and process control systems require communication between sensory elements and the control centre. Traffic generated by such systems can either be synchronous, initiated after regular intervals (e.g. regulatory and open loop control systems) or asynchronous, generated whenever some thresholds are exceeded (e.g. supervisory control systems). Monitoring traffic is generated by time insensitive and less critical processes and information accumulated has no direct effect on the operations of industry, rather gives statistical values to evaluate bottlenecks in system and potentials for future improvements.

For the presented case scenario, consider Figure 3.6 where cluster-1 has nodes from all three

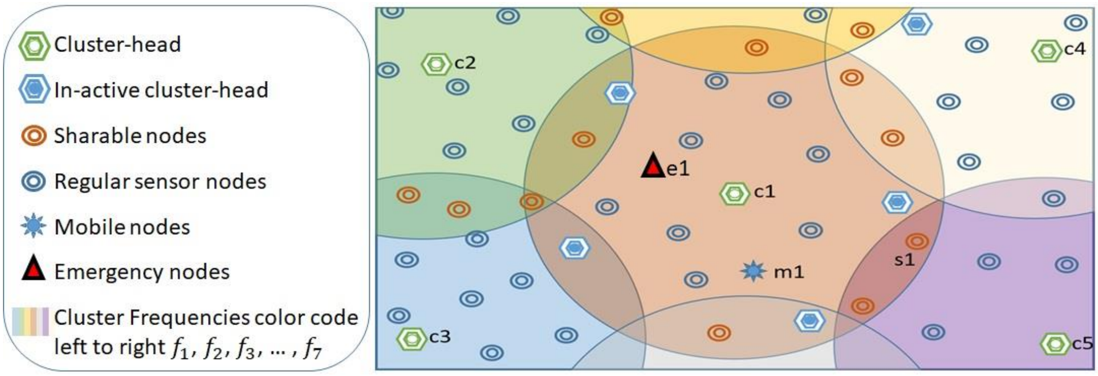

Figure 3.6: Geographical representation of cluster based IWSNs

systems present in the same vicinity. In such cases isolating emergency communication degrades systems performance. Apart from this, less careful communication scheduling may also cause unnecessary delays in regulatory and supervisory control communication. Communication failure can also have significant effect on reliability and real-time data delivery. To address these issues the proposed protocols can play an important role. EE-MAC allows embedding emergency traffic within the regular traffic and optimizes the bandwidth efficiency and coexistence of diverse processes. It also ensures that the channel is instantly allocated for emergency communication requests. CF-MAC optimizes priority based communication. It takes in to consideration priority of different traffic types and reschedules communication accordingly. The scheme facilitates regulatory and open-loop control traffic communication within the specified time deadlines. It also ensures a suitable reliability in supervisory control traffic. In cases where traffic from multiple systems co-exist, the scheduling of such information is also a challenge. To schedule the communication from different communication systems while ensuring the time deadlines are met is the objective achieved by OD-MAC. All the three protocols collectively offer optimized channel access, priority based communication rescheduling and deadline based information scheduling.

3.3 Results and Discussion

The performance of the EE-MAC is judged in comparison to the IEEE802.15.4e LLDN standard, where the performance of EE-MAC is represented in terms of access delay, average timeframe extension and average delay till emergency communication to be successfully completed.

In Figure 3.7, the access delay for MAC LLDN and EE-MAC is presented as a function of number of emergency nodes. Since the LLDN offers a TDMA based access so the emergency nodes are provided with uniform access delay represented in the figure. On the other hand, since EE-MAC provides on demand channel access, therefore the access delay for the EE-MAC is relatively lower to that of the LLDN. The figure shows that the EE-MAC even under extreme conditions (m=10, λ=500 emergency communication requests per second (on average)) manages to offer a 50% reduction in the access delay in comparison to IEEE 802.15.4e LLDN standard. The average access delay for less extreme cases is evaluated to be under 0.6 milliseconds. The overall reduction in the access delay by EE-MAC can range from 50% to 60% for relatively extreme conditions and 88% to 92% for less extreme conditions.

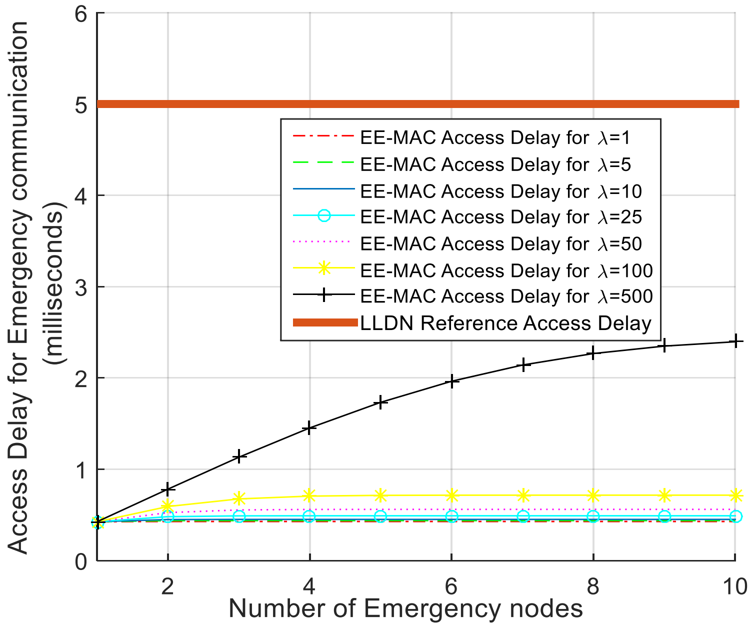

Figure 3.7: Channel Access Delay as a function of number of emergency nodes (m)

To further investigate the delay in emergency communication, the average delay till successful communication for the different values of λ (the number of emergency communication requests per second) and *m* (number of emergency nodes) is presented in Figure 3.8. The figure shows that the EE-MAC under poor channel conditions (p = 0.7) and high number of emergency requests (500 requests per second, on average) still manages to reduce the average delay to 4.89 milliseconds. The average delay for less extreme cases is estimated to be less than 1.2 milliseconds. The presented analysis show that EE-MAC manages to reduce the average delay till the successful communication, of emergency information, takes place by 31% in extreme circumstances. However, in less extreme circumstances ($p > 0.9$ & $\lambda<100$) delay reduces by 84% to 91.5% in comparison to IEEE 802.15.4e LLDN. Under normal conditions an overall 80% reduction is delay is expected in the proposed schemes. It can be seen that the access delay (d) and average successful communication delay (*d_success*) are not the same as the scheduling failures are also considered in the evaluation. For evaluation purposes, the channel is considered to be symmetric.

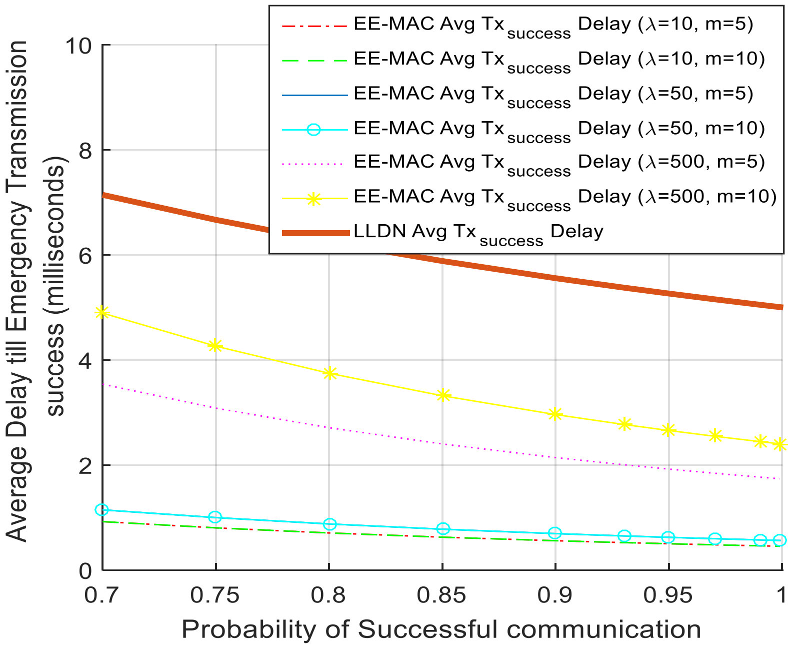

Figure 3.8: Average delay till successful communication for different channel conditions (*p*)

The improvements in the average delay of emergency communications was achieved with the insertion of additional slots to the MAC superframe, which extends the superframe duration and the average access delay of non-emergency communication. In Figure 3.9, the average superframe duration for both IEEE802.15.4e LLDN and EE-MAC for different number of emergency nodes is presented. It can be seen that the average access delay in EE-MAC is increased by 1.5

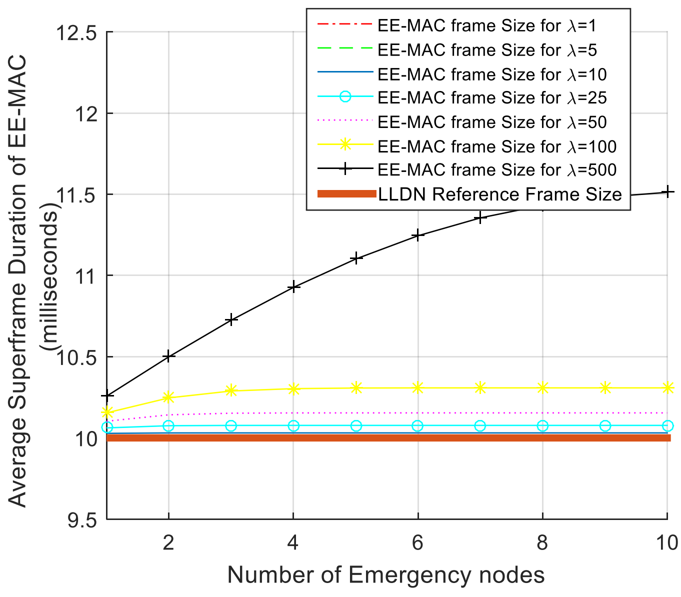

Figure 3.9: Average Duration of superframe as a function of number of emergency nodes (m)

milliseconds for extreme conditions (m=10, λ=500). Since the delay is added to the communication nodes with less stringent time constraints and an overall increase in average delay is below 7% for most of the cases which is considered non-critical. Apart from this a reduction of up to 92% in the emergency transmission delay is achieved.

The evaluation of the EE-MAC suggests that the use of control channel, to request a time-slot and extension of superframe duration effectively handles the emergency communication. It reduces the channel access delay and improves communication reliability for emergency traffic. Due to the added delay (~7%) in the regular communication, it is recommended that emergency traffic is isolated using selective frequency channels where the monitoring traffic can be transmitted on the same channel. Overlapping emergency traffic with monitoring traffic allows up to 92% delay reduction in emergency traffic without having any notable impact on the monitoring traffic due to its immunity towards delay. The effects of added delay for communication optimization of emergency traffic can be easily mitigated with logical blocks like smith predictors in cases where all the traffic (Emergency control and monitoring) uses same

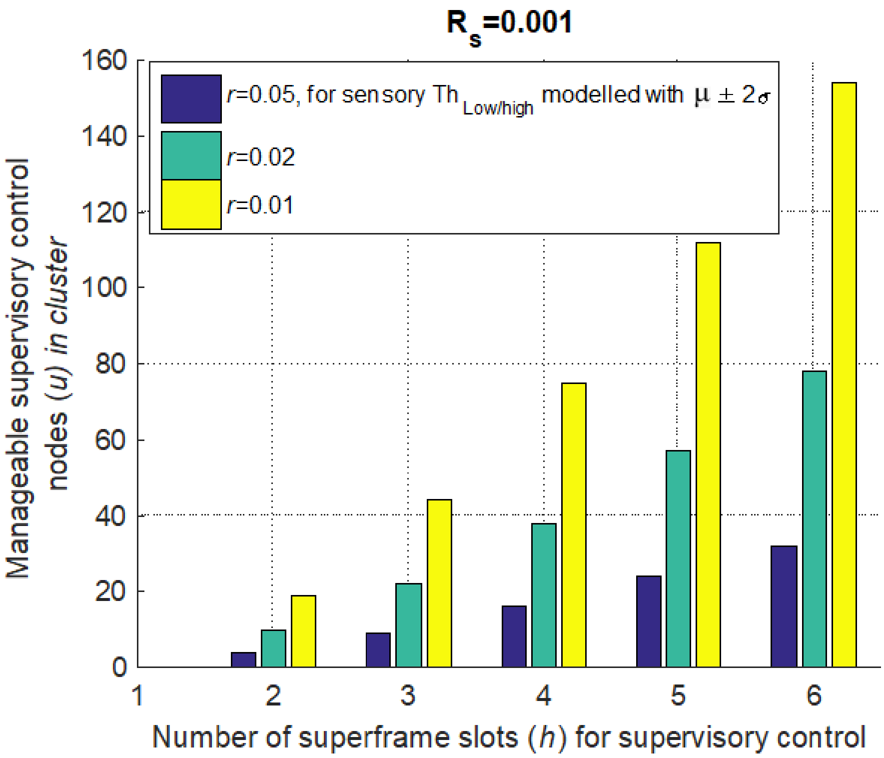

Figure 3.10: Supervisory control traffic time-slots (*h*) to supervisory nodes (*u*) ratio

channel.

CF-MAC targets regulatory control traffic, open-loop control traffic, supervisory control, alerting, and monitoring traffic. The performance in regulatory and open-loop control is evaluated based on the reliability improvement and channel access delay in comparison to IEEE802.15.4e LLDN. Since IEEE802.15.4e LLDN uses no segmentation, a natural segmentation is established for comparison purposes. Furthermore, for evaluation purposes the maximum extension to the superframe duration in CF-MAC is defined by k, where k is fixed to 5.

Since the regulatory control, open-loop and monitoring traffic are periodic so dedicated slots are scheduled in the superframe for each of these traffic types as represented in Figure 3.3. Supervisory control and alerting traffic are asynchronous in nature, therefore, a careful modelling for these type of nodes is presented in detail in Section 3.2.2.2, and a ratio is established between the number of time-slots (h) in segment-3 (Figure 3.3) and total supervisory/alerting traffic nodes (u) affiliated to a cluster. In Figure 3.10, a ratio between h and u is represented where the time-slots represented on x-axis can accommodate supervisory control nodes represented by bar graphs, while ensuring that 99.9% of the times the channel access requests from supervisory nodes will not exceed the designated time-slots in the superframe. This allows asynchronous communication to be incorporated in regular frames without affecting the specified QoS.

To evaluate the performance of regulatory control and supervisory control traffic, reliability and channel access delay are considered. The successful communication in a superframe segments (details in Section 3.2.2 and Figure 3.3) for both IEEE802.15.4e LLDN and CF-MAC is presented in Figure 3.11. In this figure, with the increase in communications failure probability (represented along *x-axis*), the communications using IEEE802.15.4e LLDN suffers significantly. Since there is no specific mechanism defined by IEEE802.15.4e LLDN for nodes in different segments so performance of segment-1 and segment-2 are exactly same. However, due to the adaptive rescheduling introduced in CF-MAC, the performance decline is much steadier. In Figure 3.11, At communication failure probability, q=10^{-2} (99% PRR ensured from individual sources), the success ratio of entire segment drops to 95% for segment size (s_1) of 5 and 90% for s_1 equal to 10 in case of LLDN. Whereas for the same communication failure probability (q=10^{-2}), the success ratio for the segment-1 and segment-2 remains almost 100% in CF-MAC (for both s_1=5, 10; s_2 =5, 10). CF-MAC noticeably improves the communication reliability. However, due to the lower

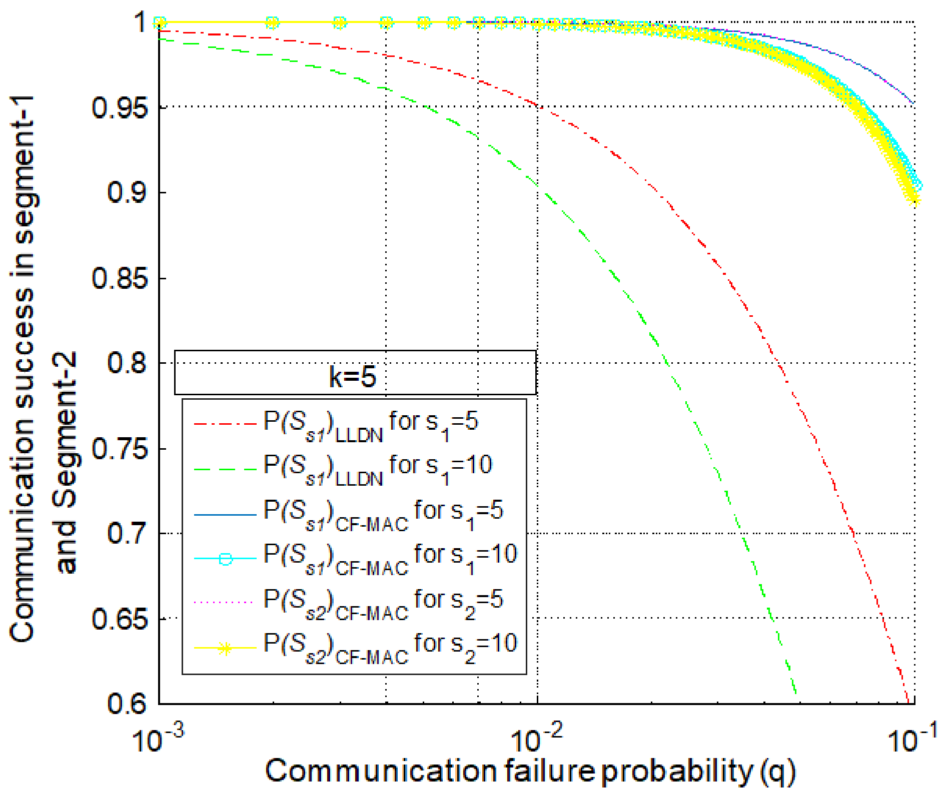

Figure 3.11: Segment-wise communication success ratio, CF-MAC vs LLDN

priority of segment-2 nodes, reliability of segment-2 is slightly lower than segment-1. Therefore, it can be seen that the plots for probability of success in communication of segment 1 for CF-MAC ($P(S_{s1})_{CF\text{-}MAC}$) for $s_1=5$ and probability of success in communication of segment 2 for CF-MAC ($P(S_{s2})_{CF\text{-}MAC}$) for $s_2=5$ are almost overlapping. Same is observed in plots of $P(S_{s1})_{CF\text{-}MAC}$ for $s_1=10$ and $P(S_{s2})_{CF\text{-}MAC}$ for $s_2=10$.

In CF-MAC the channel access delay after communication failure is also improved in

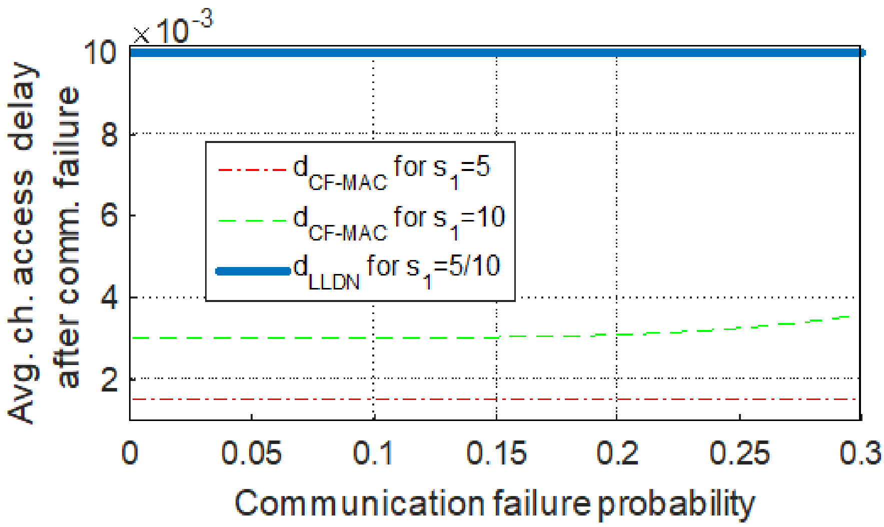

Figure 3.12: Channel access delay: CF-MAC vs LLDN

comparison to LLDN. As represented in Figure 3.12, average access delay in CF-MAC, for regulatory and open-loop control traffic is reduced to 1.5ms and (3ms to 4ms) respectively depending on the channel conditions. CF-MAC enables 85% reduction in channel access delay in regulatory control traffic (segment-1, Figure 3.3) whereas a 60% reduction in channel access delay in supervisory control traffic (segment-2, Figure 3.3) is observed.

3.4 Summary

The proposed MAC protocols discussed in this chapter offer real-time and reliable communication in wide variety of applications in industrial automation and process control. The performance of the protocols was verified using mathematical modelling along with the simulation based performance analysis of these protocols in comparison to IEEE802.15.4e LLDN.

Results showed that the proposed protocols offered notable improvements in comparison to IEEE 802.15.4e LLDN. For emergency systems, EE-MAC offered a 31% decrease in average delay till successful transmission (*d_success*) of emergency communications in harsh conditions whereas, in favorable channel conditions, *d_success* is decreased up to 84% to 91% compared to the IEEE 802.15.4e LLDN. The access delay (d) for emergency communication was also reduced from 50% to 92% at the cost of under 7% increase (for majority of the cases) in delay of non-critical communication taking place in the network. For regulatory and open-loop control traffic, CF-MAC offered a notable improvement in reliability, whereas a 60% and 85% improvement in channel access delay over LLDN was observed in regulatory control and open-loop control traffic.

4 PRIORITY BASED COMMUNICATIONS IN IWSNS

4.1 Introduction and Relevant Developments

Communication infrastructure plays a crucial role in industrial monitoring automation and process control. Due to a number of factors such as cost efficiency, localized processing, application specific and resource efficient design, flexibility, and self-healing abilities, the IWSNs emerge as one of the most promising communications technology for industrial automation.

Presently, IEEE 802.15.4 and IEEE802.15.4e standards influence widely used industrial communication protocols. In particular, IEEE802.15.4e targets real-time and reliable communication in industrial applications. However, the data traffic in industrial networks can typically be characterised into multiple categories depending on the critical nature of the information and heterogeneous time deadlines. Therefore, along with IEEE802.15.4e, priority traffic characterization can be used to further improve the performance of IWSNs. Priority based communication not only increases timely delivery of critical information but also can be used for selective optimization.

In IWSNs, the priority-based communication is yet being fully explored and fewer schemes can be found that prioritize communication based on the source of information. Some of the priority enabled MAC schemes can be found in [16, 76, 107, 145, 153]. In [153], priority is established based on the information content in the messages. In this scheme, full duplex communication is used to meet the deadline requirements of the feedback control system. However, almost all of the commercially available nodes use half duplex communication [99, 157] which limits the scope of this scheme. In [34], authors present another priority enabled MAC scheme. The protocol divides the traffic of an industrial setup into four categories and high priority traffic is allowed to take over the low priority traffic bandwidth. However, it is a static scheme in which priorities once defined are not changed during the network lifetime. WirArb is defined in [38] which uses arbitration phase where each node uses preassigned arbitration frequency to find number of time slots it has to wait until its communication takes place. The protocol is evaluated using discrete time Markov chains and assures channel access for high priority user. However, this scheme also offers static priority as the arbitration frequency is preassigned, based on the priority of the node. Moreover, the scheme needs a special coordinator to receive all the arbitration frequencies and respond accordingly at once. The scheme also overlooks the need for number of orthogonal arbitration frequencies in case of large number of nodes. Further to this, the existing schemes are static in nature and are unsuitable for time constraint and critical applications.

This chapter will present a dynamic priority scheme, which establishes distinct priority levels using the priority system to allow real-time characterization of the criticality of the nodes. A priority enabled traffic trade-off mechanism to offer real-time and reliable communication of high priority information is introduced. A node replacement algorithm is defined to assist the priority establishment process and an optimal sleep scheduling is introduced to enable long network lifetime. Furthermore, A trade-off between the number of transmissions per superframe and Quality of Service (QoS) is established which is exploited to improve the QoS for entire cluster. Dynamic priority system is also integrated with QoS optimization for application specific and selective optimization.

4.2 System Model

Most industrial applications have a centralized control system where all functional blocks in the plant are connected to the control centre by IWSNs. The present IWSNs use both TDMA and CSMA/CA based channel access schemes depending on the requirements and nature of the application at hand. A suitable energy conservation mechanism is also utilised to offer extended lifetime of the network. Furthermore, in automation and process control, some control loops in the plant always have precedence over the rest, and the information from these blocks should be prioritized, whenever, a shared wireless communication resource is used.

The proposed medium access protocol uses TDMA instead of the conventional CSMA/CA scheme to offer more reliability and guaranteed channel access. Apart from this, the proposed scheme offers sleep scheduling for extended lifetime and priority system to optimize information delivery to the control centre in acquaintance with the precedence system in place. A detailed description of the network topology, priority cost function, sleep scheduling and mathematical modelling is presented in the next sections.

4.2.1 Network Topology, Superframe Structure and Distribution of Nodes

In the proposed scheme a star topology is considered with a support of data reception of twenty nodes' in a 10 millisecond duration (specified feature of IEEE 802.15.4e, Low Latency deterministic networks [17]). The network scalability is ensured with the hierarchical architecture to connect as many nodes as possible. Since TDMA based channel access scheme is used, nodes in the network are synchronized using a beacon signal at the start of each communication frame. The superframe duration is assigned for a period of 10 milliseconds, which is suitable for time critical industrial applications, ensuring very low system latency [17]. In addition, many applications in process control and feedback systems have a maximum sampling rate of 100 Hz (10 milliseconds) [46, 30, 47]. It is therefore suitable for selecting the same duration for the superframe.

The proposed superframe is presented in Figure 4.1 whereas the frequent system variables are listed in Table 4.1. The superframe is started with a beacon followed by the communication of the individual nodes. A maximum of *n* nodes can communicate in a single superframe (*n* time slots per superframe). The initial k time-slots are reserved for High Priority Non-Replaceable Nodes (HPNNs). The next *m-k* time slots are reserved for High Priority Replaceable Nodes (HPRNs). All the Rest of the time slots (*n-m*) are for Low Priority Nodes (LPNs). The proposed

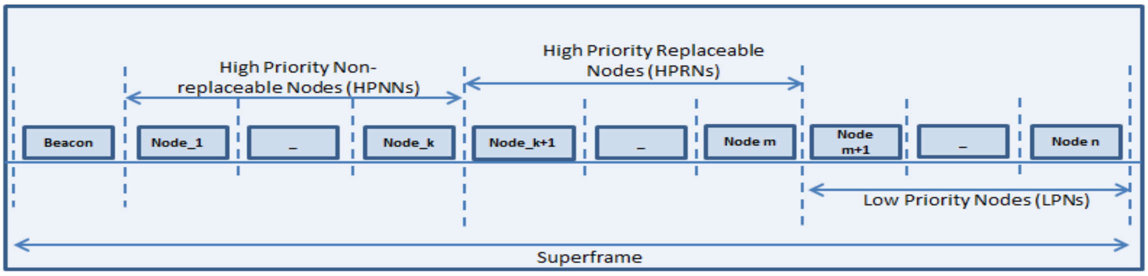

Figure 4.1: Superframe structure with *n*-Nodes

scheme offers flexibility to alter the priority of HPRNs and LPNs in real-time to better suit the application requirements. In Figure 4.1, *n* (total nodes in a cluster) is assumed to be twenty, i.e. the maximum number of nodes compensated in one superframe. In Figure 4.2 (a), *n* is assumed to be less than twenty, so the remaining time-slots are referred as the shared slots (S-slots) used for retransmission of the previous erroneous data. Figure 4.2 (b) represents an individual time slot which is divided in 's_d' sub-slots. Here each slot is divided in transmission section (Tx) and an acknowledgement section (Rx). Both of the communications (during Tx and Rx) take place on

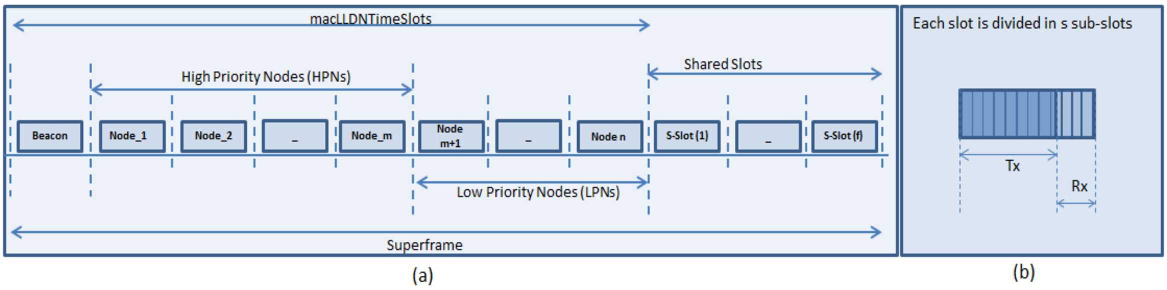

Figure 4.2: Superframe (n<20)

different frequency channels in order to process the close time vicinity of the Tx and Rx and to overcome time delays in switching from reception to transmission mode.

To incorporate the limitations of currently available wireless sensor motes, a half-duplex communication system is considered and due to relatively higher delays in switching from transmission to reception mode, two frequency channels are used for communication where, the

Table 4.1: List of Variables

Parameters	Variables	Value(s)
Total Nodes per cluster	n	$20, 100, 200$
High Priority Nodes (HPNs= HPNNs + HPRNs)	m	$1, 2, \ldots 10$
Low Priority Nodes (LPNs)	n-m	-
High Priority Non-replaceable Nodes (HPNNs) ∀ (PE-MAC & O-PEMAC) cases Scheduled slots ∀ (QES & PQES) cases	k	-
High Priority Replaceable Nodes (HPRNs) ∀ PE-MAC & O-PEMAC cases	m-k	-
Superframe Duration	T_{sf}	$10\ ms$
Time slot duration	t	~300 μs
payload	$Payload$	$3.84\ ms$
Probability of a node replacement in HPRNs	p_n	0-0.1
Probability of communication failure	q	0-0.15
Probability of communication success	p	0.85-1
Sub-slot duration	s_d	~26 μs
Guard band	Ψ	5 MHz
Weight coefficients	Α,β,γ, δ_1, δ_2	-
Critical information index of node x	CII_x	-
Priority weight of node x	W_x	-
Weight index of node x	WI_x	-
Information failure index of node x	IFI_x	-
Time required from communication initiation to delivery	δ_p	60 μs
Percentage traffic delivered to destination	ω	99.99%
Delay to deliver ω percent of the entire traffic generated by a high priority node	∂	-
Beacon Duration	B_D	350 μs
Ack duration	d_{ack}	~50 μs
Average Active listening period of LPNs (norm.)	L_A	-
No. of nodes scheduled for communication in a particular frame	c	-
Degradation in packet transmission rate	D_{PTR}	
Desired QoS	D_q	0.999-0.99999
No. of shared slots needed to achieve desired QoS	s_n	
Percentage of priority nodes	ψ	10%

transmission and reception takes place on two different frequency channels, separated by guard band of Ψ Hz.

4.2.2 Priority Weight Function

Most of the existing priority enabled MAC protocols use static priority system [34, 38] where a predefined precedence system, based on the source of information, is established. Each node in the network is treated according to predefined priority levels no matter how critical the nature of its information is. To compensate for the above discussed issues, a priority weight function is defined. The function takes in account: (1) communication in earlier time slots, (2) critical nature of the sampled data/information, (3) the natural precedence of the source of information and (4) consequence of failure in delivery. The priority weight function also allows the weighted contribution of all of the above stated factors. The priority weight function is defined in equation 1. For better understanding of the input parameters in this equation and their role in the evaluation of priority of nodes at the cluster-head/coordinator, each of these parameters is defined as follows.

$$W_x(t) = \alpha \times CII_x(t-1) + \beta \times WI_x + \gamma \times IFI_x(t) \tag{4.1}$$

Here $W_x(t)$ is the Priority Weight of the node 'x' at a particular time 't'. Based on this function the precedence of nodes is defined in the network. In the proposed system a higher value of $W_x(t)$ will lead to a higher priority.

$CII_x(t-1)$ is Critical Information Index, defined on the basis of sensed values. If the received sensor values are within a stable range, $CII_x(t-1)$ will have a small magnitude but if the sensed values received at the cluster-head at time $t-1$ deviate from the stable range, i.e. violate the critical threshold, the magnitude of $CII_x(t-1)$ increases.

WI_x is a time independent parameter based on value and importance of the equipment to which a particular node x is attached.

$IFI_x(t)$ is defined on the basis of predicted consequences of not delivering/delaying information to central unit from source 'x' at time 't'. Its value also depends of channel conditions and number of failed attempts in earlier superframes. $IFI_x(t)$ is defined as

$$IFI_x(t) = \left[\left(\frac{1}{T_{deadline} - t}\right) \times \delta_1\right] + \left[\left(\frac{1}{q}\right) \times \delta_2\right] \tag{4.2}$$

Here $T_{deadline}$ is the specified time deadline for an information to be delivered from source node to the cluster head. The packet delivery failure ratio, $\left(\frac{1}{q}\right)$, is used to ensure sufficient time for retransmission of packet. δ_1 and δ_2 specify contribution of both time deadline and channel conditions. Note that all of these parameters are dealt as the attributes of the node object, which are uniquely identifiable at every node.

The parameters $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and γ are introduced as the weight contributions. In other words, they incorporate flexibility and ensure weighted ensemble in priority weight function. Selection of the range of **α**, **β**, and γ are dependent on applications. Some selected cases with certain conditions on **α**, **β**, and γ are presented as under.

- To ensure the weighted sum of all the parameters, $CII_x(t-1)$, WI_x and $IFI_x(t)$, **α**, **β**, and γ must have comparable magnitudes.
- To ensure static priority hierarchy, primarily based on the value and importance of the equipment, **β>>(α&γ)**
- To ensure less frequent shift in the priority of nodes and to guarantee that the priority of nodes only change in critical cases, ranges of **α**, **β**, and γ should be adjusted so that **(β>α)** & **(β>γ)**. For such cases, change in $CII_x(t-1)$ and $IFI_x(t)$ will not have significant effect on the priority weight of the nodes, except where the critical thresholds are violated, hence very occasionally the priority of HPNs is reduced to give precedence to other critical nodes.
- To ensure uniform contribution from each parameter in the priority weight function, $\boldsymbol{\alpha} \cong \boldsymbol{\beta} \cong \gamma$
- To ensure the timely delivery of the critical data to the cluster head **α**, **β**, and γ should be adjusted so that **(α>β)** & **($\boldsymbol{\alpha} > \gamma$)**.
- To suppress the subsequent failures in the transmission of individual nodes **α**, **β**, and γ should be adjusted such that **(γ>β)** & **($\gamma > \boldsymbol{\alpha}$).** The stated configuration allows the node's priority to rise instantly with the failure in its communication.

4.2.3 Nodes' Timeslot Replacement

In order to enable communication of high priority nodes in a superframe duration, the HPNs are arranged at the start of the timeframe. This arrangement ensures retransmission within the specified deadline. As represented in Figure 4.1, the first k time slots are reserved for high priority nodes and are non-replaceable. However, one or more HPRNs can be demoted to LPNs if their priority level decreases due to the stable information feedbacks in previous time slots from these nodes or as a consequence of increase in the priority of LPNs, exceeding the priority level of HPRNs by a specified margin (υ). In such cases the associated time slots of the nodes must also be switched. The replacement of node's transmission slot can be achieved with a rescheduling instruction from the coordinator. However, to ensure an error free transition the slot swapping takes place after certain predefined wait states. The process of swapping HPRNs with LPNs is depicted in the flow chart presented in Figure 4.3.

After the completion of each superframe, the coordinator evaluates the priority index of all the HPRNs and LPNs and compares priority index of LPNs to that of HPRNs. If the priority index of each of the LPNs is less than the priority index of every HPRN, no change takes place and previously allocated slot sequences are used. However, if the priority index of one or more of the LPNs is greater than the HPRNs and fulfills the minimum specified margin requirements, υ, which is used to avoid frequent changes, the change sequence is initiated. To filter out misread spikes in the priority index of the nodes in order to assure validity of the change, a certain waiting time (wait_state) is introduced to postpone the change by pre-specified time units. It also ensures the error free shifting of nodes from one slot to another. If the initiated replacement remains valid for the time duration equal to wait_state, the swapping finally takes place.

It is noted that the replacement of the nodes during the network lifetime is dependent on the number of HPRNs (m-k) and number of LPNs (n-m). Hence, in the worst scenario, the total nodes replaced in a unit time can reach up to the number of LPNs (n-m) or number of HPRNs (m-k), depending on whichever is smaller.

A generalized relation for the probability of number of replacements in a single time unit in either cases n-m>m-k or m-k>n-m, i.e. HPRNs>LPNs or LPNs>HPRNs, is represented in Eq. 4.3.

$$P_R(r) = \binom{x}{r} {p_n}^r (1 - p_n)^{x-r} \qquad r = 0, 1, 2, 3, \dots, \min[(m-k), (n-m)] \tag{4.3}$$

Here p_n is the probability of replacement of a single node and can be expressed as a function of

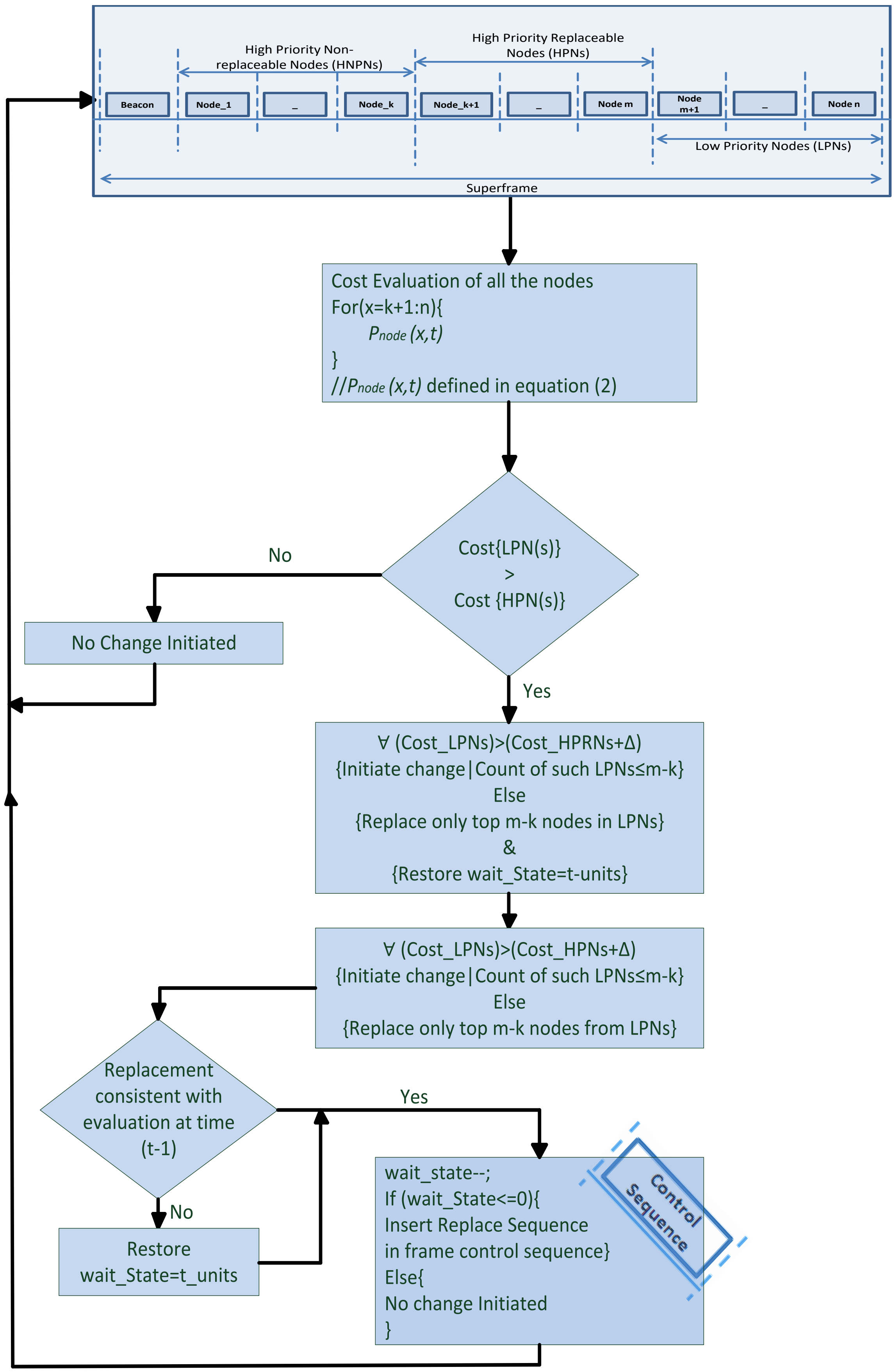

Figure 4.3: Flowchart for Priority based Node Replacement mechanism

probability weight function ($W_x(t)$), probability of communication failure, mean and variance of the sensed values, specified critical thresholds of the sampled information and stable data range boundaries.

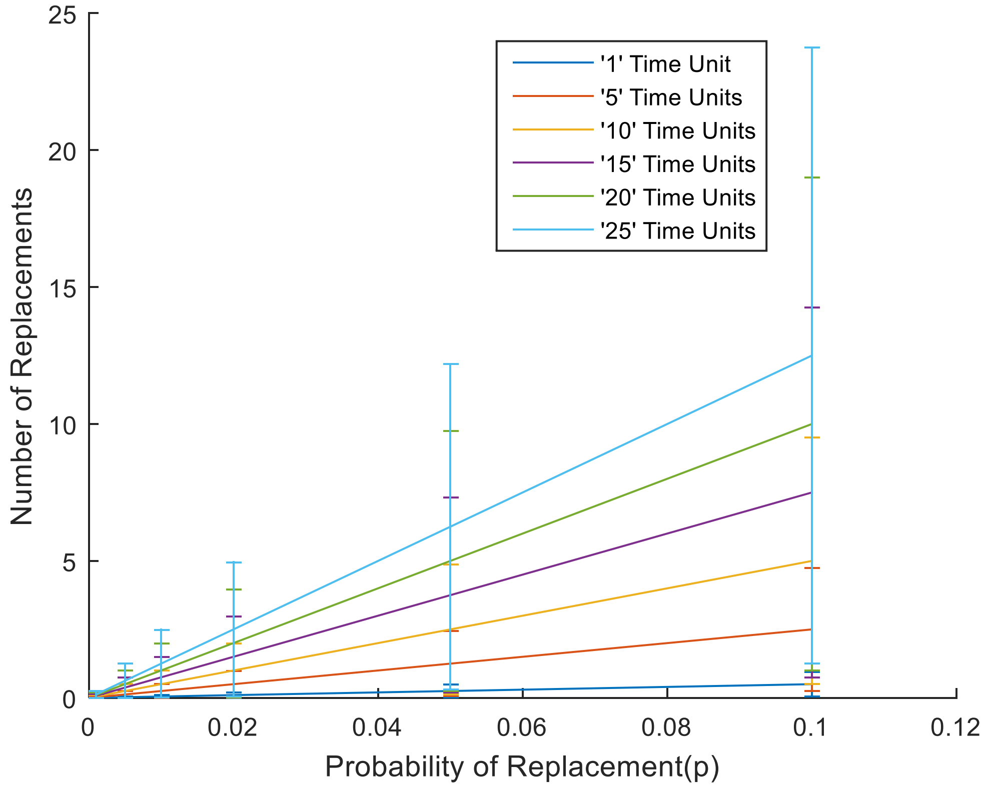

Figure 4.4: Average replacements and the expected deviation over time

As represented in Figure 4.1, the HPRNs occupy dedicated slots in the superframe, and out of the *n*-*k* nodes (all replaceable nodes in the network) only most critical nodes can be allocated these slots. Since the dynamic priority system is used, a LPN can become a HPN based on parameters defined in Eq. 4.1. With the change in the priority of nodes, the allocated time slots in the superframe are also changed. In order to ensure error free execution of the protocol these replacements must be kept to a minimum. Timeslot replacement can be set to a minimum with an efficient priority cost function. For experimentation purposes, HPRNs are limited to a maximum of five, however, the scheme can easily be extended to higher number of HPRNs. In order to give a better understanding of the replacement patterns, average replacements with possible deviation from mean are represented in Figure 4.4. From the figure, it can be seen that the replacement requests increase significantly as the status of the nodes start changing more quickly. Therefore, in order to maintain a steady network, it is suggested to limit the probability of replacement of timeslots to 0.05 or less.

4.2.4 Sleep Scheduling and Priority based Channel Assignment

In the time critical industrial applications, the energy conservation is not always a major concern, however, an extended network lifetime is always desirable. To achieve a prolonged network lifetime in the proposed scheme, a sleep schedule is defined. An effort has been made to efficiently trigger nodes among active and sleep states to conserve as much power as possible without undermining the network performance. In Figure 4.5, sleep scheduling algorithm is presented. In the figure, it can be seen that the HPNs (Node 1 to Node m) are only active when the actual communication is taking place. However, LPNs (Node m+1 to Node n) are active, either when they are communicating or when the high priority node, they are affiliated to, is communicating with the cluster head. For instance, during the transmission slot of Node 1 (S_{node_1}), LPN, node m+1, is also active so in case the communication from Node 1 fails, its slot can be reserved for the retransmission of Node 1 data. In such cases LPNs need to be active only during the period represented by yellow stripe (see ① in Figure 4.5) in order to receive the broadcast from the coordinator (cluster head) regarding status of the communication by relevant HPN. However, due to the short duration of this period, currently available radio modules [165-

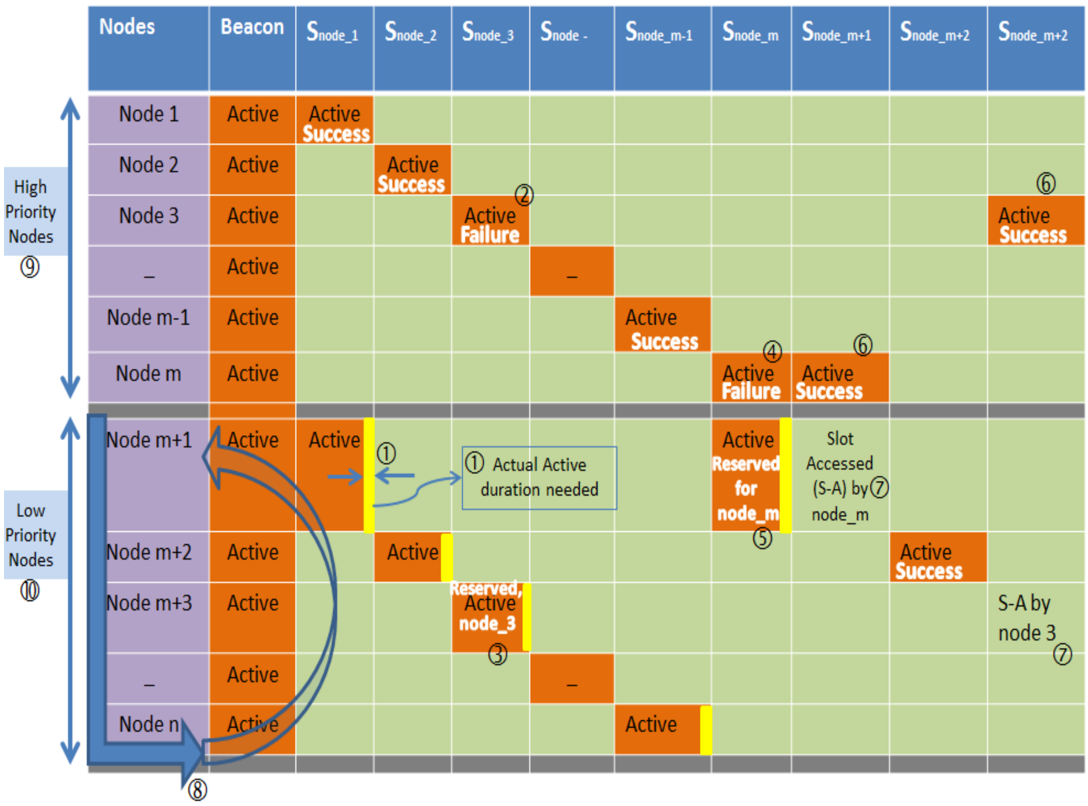

Figure 4.5: Sleep Scheduling and priority based channel allocation

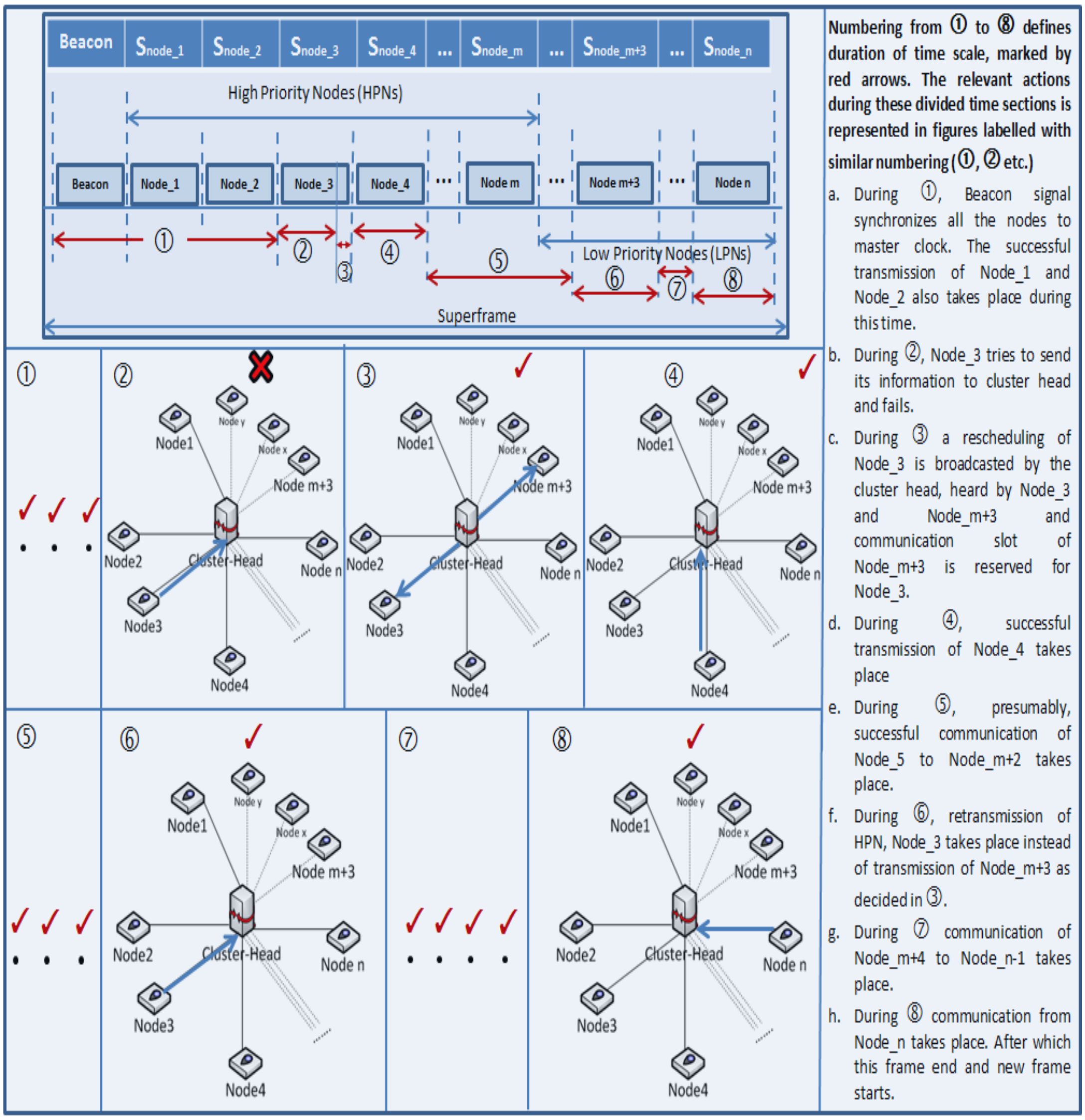

Figure 4.6: Demonstration of the superframe execution and the priority based channel allocation

168] are incapable of switching between active and sleep states so suddenly, hence, the active duration is taken equal to one complete time slot.

To facilitate the retransmission of HPNs, the LPN slot is reserved when communication fails. The scenario is presented in Figure 4.5. When the communication from Node 3 is failed and as a response the time slot of the LPN, Node m+3, is reserved (see ② and ③). Similar case can be seen in ④ and ⑤ in Figure 4.5. So during the slots S_{node_m+3} and S_{node_m+1} (dedicated slots of LPNs, reserved for retransmission of data of HPNs) the retransmission from HPNs, Node 3 and Node m, takes place (see ⑥ Figure 4.5), whereas the LPNs, Node m+1 and Node m+3 remain in the sleep state (see ⑦ Figure 4.5). A graphical demonstration of a superframe execution and priority based channel allocation is represented in Figure 4.6.

In the depicted schedule in Figure 4.5, a special case is considered where HPNs are more than the low priority nodes, so a second iteration is run in which the time slots of LPNs not yet reserved are affiliated to remaining HPNs in cyclic manner as represented by arrows (see ⑧ Figure 4.5).

4.2.5 Mathematical formulation

The proposed work is divided in four algorithms, where the information from LPNs is halted in order to transmit information from HPNs. These Two schemes are referred as Priority Enabled MAC (PE-MAC), Optimized Priority Enabled MAC (O-PEMAC), Quality Ensured Scheme (QES) and Priority integrated Quality Ensured Scheme (PQES) in the following discussion.

PEMAC allows single retransmission of the failed communication originated from the HPNs, given LPN slot is available. In O-PEMAC multiple retransmissions can be allowed to ensure the information delivery from HPNs to coordinator within the specified time deadline.

To offer deterministic performance for the HPNs a special case referred as QES is defined where the ratio of transmission slots to shared slots is established to achieve desired PRR. Whereas PQES offers a hybrid scheme which takes into consideration both priority weight function and QES to offer selective improvements in the communication of the nodes in IWSN.

In order to evaluate the performance of the proposed scheme, a mathematical formulation of the possible scenarios for typical IWSN as well as priority enhanced MAC is presented as follows.

4.2.5.1 Percentage Error/Failure percentage in Communication of HPNs in IWSNs using IEEE 802.15.4e framework

In any single hop network the percentage error of communication failure primarily depends on the channel conditions and can be influenced by multiple factors including multipath fading, dispersion, reflection, refraction, interference, distance, congestion, transmission power restrictions and receiver sensitivity. In this case, since the percentage error in communication of HPNs is evaluated over an entire frame, number of HPNs added in the cluster also affects it. With the increase in the number of HPNs the possibility of at least one failed transmission from these

HPNs increases significantly. In order to model the failure in communication, binomial distribution is considered where the total number of HPNs is represented by m. The probability of failure (q) in a single communication between source and coordinator is assumed to be symmetrical and independent of the earlier transmissions.

Since the superframe communication failure is evaluated, therefore, one or more high priority nodes' communicate during each superframe. For a superframe to be successfully transmitted, all of the communications from individual nodes must be successful. As each of the nodes are randomly deployed, the communications success of an individual node is independent of any other communications taking place within the same superframe. If a total of *m* nodes communicate during a superframe, than a sequence of *m* independent but identical experiments will run to transmit information from each node to the base station. This communications experiment can be modelled as binomial (*m*, p), where *m* is the number of high priority nodes communicating (i.e. number of independent trials in binomial distribution) and *p* is the probability of successful communication (i.e. probability of success in each trial of binomial distribution). Since, the i.i.d nature of the experiment is already discussed, therefore, it can be accurately modelled as binomial distribution.

A generalized relationship for at least one failure in HPNs communication for IEEE802.15.4e is represented by Eq. 4.4.

$$P(Failure\ in\ HPNs\ Communication\ of\ IEEE\ WPAN) = \frac{m!}{1!(m-1)!}q(1-q)^{m-1} + \frac{m!}{2!(m-2)!}q^2(1-q)^{m-2} + \ldots + \frac{m!}{(m-1)!(m-(m-1))!}q^{m-1}(1-q)^{m-(m-1)} + \frac{m!}{(m)!(m-(m))!}q^m(1-q)^{m-m} \tag{4.4}$$

this equation can also be expressed as

$$P(Failure\ in\ HPNs\ Communication\ of\ IEEE\ WPAN) = \sum_{x=1}^{m}\binom{m}{x}q^x(1-q)^{m-x} \tag{4.5}$$

4.2.5.2 Percentage Error/Failure in HPNs' Communication in PE-MAC and O-PEMAC

In order to enhance the performance of proposed scheme, the LPNs should be greater than or at least equal to the HPNs, affiliated to a single coordinator. The above stated condition limits the number of HPNs in low latency networks to a maximum of ten. One must consider this as a soft bound to reap full potential of the proposed scheme. Nevertheless, in order to evaluate performance for both the cases, a system of equations is developed. Each of these cases is listed as follows.

1) **Case 1: (n-m>m, i.e. LPNs > HPNs)**

In the proposed scheme PE-MAC, for low latency deterministic networks; given that the LPNs are greater than HPNs, the Percentage error in communication of HPNs can be expressed as.

$$P(Failure\ in\ HPNs\ Communication\ in\ PEMAC|\mathrm{n}-\mathrm{m}>\mathrm{m}) = \tag{4.6}$$

$$\frac{m!}{1!(m-1)!}q(1-q)^{m-1}(q)+\frac{m!}{2!(m-2)!}q^2(1-q)^{m-2}\left[\sum_{x=1}^{2}\binom{2}{x}q^x(1-q)^{2-x}\right]+\ldots+\frac{m!}{(m-1)!(m-(m-1))!}q^{m-1}(1-q)^{m-(m-1)}\left[\sum_{x=1}^{m-1}\binom{m-1}{x}q^x(1-q)^{m-1-x}\right]+\frac{m!}{(m)!(m-(m))!}q^m(1-q)^{m-m}\left[\sum_{x=1}^{m}\binom{m}{x}q^x(1-q)^{m-x}\right]$$

In this case a single retransmission of failed communication from HPNs is allowed. Since the retransmission takes the dedicated slots of LPNs

In O-PEMAC, the retransmission of one or more failed HPN's communication is carefully scheduled with ability to retransmit multiple times given the network conditions are fulfilled. The failure in communication of HPNs in O-PEMAC is expressed in Eq. 4.7.

$$P(Failure\ in\ HPNs\ Communication\ in\ OPEMAC\ \mathrm{n}-\mathrm{m}>\mathrm{m}) = \tag{4.7}$$

$$\frac{m!}{1!(m-1)!}q(1-q)^{m-1}q^{n-m}+\frac{m!}{2!(m-2)!}q^2(1-q)^{m-2}\left[\sum_{x=n-m-1}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right]+\ldots+\frac{m!}{(m-1)!(m-(m-1))!}q^{m-1}(1-q)^{m-(m-1)}\left[\sum_{x=n-m-(m-2)}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right]+\frac{m!}{(m)!(m-(m))!}q^m(1-q)^{m-m}\left[\sum_{x=n-m-(m-1)}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right]$$

In this case, the performance of communication in HPNs is improved by allowing multiple retransmissions. However, it will obviously affect the communication efficiency of the LPNs. Therefore, heterogeneous sensing is introduced in order to optimize the communication efficiency by affiliating variable time deadlines. These time deadlines along with the information of $IFI_x(t)$ (failure in earlier communication slots of node x) is used to define whether the LPN 'x' should be reserved for communication of HPNs or not. In some critical cases, the critical LPN is only occupied by HPNs if all other LPNs are reserved.

Eq. 4.6 and Eq. 4.7 representing communication failure in PE-MAC and O-PEMAC respectively can be collectively expressed as

$$(Failure\ in\ HPNs\ Communication\ in\ PEMAC/OPEMAC \mid \mathrm{n-m>m}) \tag{4.8}$$

$$= \sum_{y=1}^{m}\left[\left(\binom{m}{y} q^{y}(1-q)^{m-y}\right)\left(\sum_{x=s}^{z}\binom{z}{x} q^{x}(1-q)^{z-x}\right)\right]$$

$$given \begin{cases} s = 1, z = y & PE-MAC \\ s = n-m-(y-1)\,, z = n-m & O-PEMAC \end{cases}$$

2) Case 2 (m>n-m i.e. HPNs > LPNs)

For cases where HPNs are greater than the LPNs, the possibility of failure in HPNs communication greatly increases. Failure in delivery of HPNs information to coordinator, hence, depends on the ratio of LPNs to HPNs. The percentage error in communication of HPNs in PE-MAC is presented in Eq. 4.9.

$$P(Failure\ in\ HPNs\ Communication\ in\ PEMAC \mid \mathrm{m>n-m}) = \tag{4.9}$$

$$\frac{m!}{1!(m-1)!}q(1-q)^{m-1}(q) + \frac{m!}{2!(m-2)!}q^2(1-q)^{m-2}\left[\sum_{x=1}^{2}\binom{2}{x}q^x(1-q)^{2-x}\right] + \cdots +$$

$$\frac{m\,!}{n-m\,!(m-(n-m))\,!}q^{n-m}(1-q)^{m-(n-m)}\left[\sum_{x=1}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right] +$$

$$\frac{m\,!}{n-m+1!(m-(n-m+1))\,!}q^{n-m+1}(1-q)^{m-(n-m+1)} + \cdots +$$

$$\frac{m!}{(m-1)!(m-(m-1))!}q^{m-1}(1-q)^{m-(m-1)} + \frac{m!}{(m)!(m-(m))!}q^{m}(1-q)^{m-m}$$

The failure in communication of HPNs where HPNs are greater than LPNs in case of O-PEMAC is presented in Eq. 4.10.

$$P(Failure\ in\ HPNs\ Communication\ in\ OPEMAC \mid \mathrm{m} > \mathrm{n-m}) = \tag{4.10}$$

$$\frac{m!}{1!(m-1)!}q(1-q)^{m-1}q^{n-m} + \frac{m!}{2!(m-2)!}q^2(1-q)^{m-2}\left[\sum_{x=n-m-1}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right] +\ldots+ \frac{m\,!}{n-m\,!(m-(n-m))\,!}q^{n-m}(1-q)^{m-(n-m)}\left[\sum_{x=n-m}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right] + \frac{m\,!}{n-m+1!(m-(n-m+1))\,!}q^{n-m+1}(1-q)^{m-(n-m+1)} + \cdots + \frac{m!}{(m-1)!(m-(m-1))!}q^{m-1}(1-q)^{m-(m-1)} + \frac{m!}{(m)!(m-(m))!}q^m(1-q)^{m-m}$$

Eq. 4.9 and Eq. 4.10, the probability of failure in communication of PE-MAC and O-PEMAC respectively can be expressed as a unified notation presented in Eq. 4.11.

$$P(Failure\ in\ HPNs\ Communication\ in\ PEMAC/OPEMAC \mid \mathrm{m} > \mathrm{n-m}) \tag{4.11}$$

$$= \sum_{y=1}^{m}\left[\frac{\left(\binom{m}{y}q^y(1-q)^{m-y}\right)\left(\sum_{x=s}^{z}\binom{z}{x}q^x(1-q)^{z-x}\right)}{\left(\sum_{x=s}^{z}\binom{z}{x}q^x(1-q)^{z-x}\right)\left(u\big(y-(n-m)\big)\right)}\right]$$

$$given\ \begin{cases} s = 1, z = y & PEMAC \\ s = n-m-(y-1)\,, z = n-m & OPEMAC \end{cases}$$

A detailed evaluation of the performance of the proposed schemes in comparison to the IEEE 802.15.4e is presented in section 4.3. For the evaluation purposes the number of HPNs do not exceed LPNs.

4.2.5.3 Delay analysis for communication in HPNs for PE-MAC and O-PEMAC

For priority optimized MAC protocols, delay serves as a decisive metric to evaluate the impact of the scheme on the time constrained delivery of the information to the coordinator. In case of PE-MAC, the retransmission allows improvement in average delay in communication from HPNs to the coordinator. The Delay in a communication from HPN to the coordinator is expressed in Eq. 4.12. In this equation, δ_p is the time taken from transmission initiation to the information delivery to the destination and is taken to be 600 µsec. T_{sf} is the duration of the superframe after which the next transmission takes place and ∂ is the delay to deliver ω percent of the entire traffic generated by a HPN. Eq. 4.13 represents the geometric series since geometric distribution is used to evaluate the delay of the communication originated from HPNs whereas Eq. 4.14 states the condition for evaluating P (for typical 802.15.4e network).

$$\partial = (P \times T_{sf} + \delta_p) \tag{4.12}$$

$$S_x = \sum_{x=0}^{i} a_x = \sum_{x=0}^{i} q^x = \frac{1 - q^{i+1}}{1 - q} \tag{4.13}$$

$$\forall\ (1 - q) \times S_x > \omega, P = i \tag{4.14}$$

In this case the maximum delay, ∂_{max} is evaluated, within which ω percent of the traffic originated from the HPN is delivered to the destination. Here ω is set to 99.99% to meet the industrial standards and solving $(1 - q) \times S_x > \omega$ for i i.e. $1 - q^{i+1} > \omega$ will give $i > \frac{|l\,n(1-\omega)|}{|ln(1-q)|}$.

In order to define symmetric equation and to reduce the complexity, the number of HPNs in PE-MAC and O-PEMAC are limited to a maximum of 10 nodes. For O-PEMAC an approximate relation for maximum delay, ∂_{max} is used. The values of parameters P, for PE-MAC and O-PEMAC are defined by $i/2$ and $i/3$ respectively.

4.2.5.4 Performance analysis of LPNs

In this section, the performance degradation observed in the LPNs in terms of packet transmission rate and energy efficiency are evaluated. The selection of packet transmission rate and energy efficiency are primarily motivated due to the notable impact on these two performance metrics in LPNs.

Since the proposed scheme allows HPNs to highjack the communication of the low priority nodes, performance degradation in LPN's reliability is expected. The extra bandwidth provided to HPNs to overcome latency and reliability issues results in drops in packet transmission rate of LPNs. The overall degradation in the performance of LPNs is evaluated in terms of degradation in PRR of LPNs. The mathematical notation for the degradation in packet transmission rate

(D_{PTR}) of LPNs for PE-MAC/O-PEMAC is given by

$$D_{PTR} = \left[\sum_{y=10-(n-m)+1}^{m} \binom{m}{y} q^{y} (1-q)^{m-y} \right]^{C} \tag{4.15}$$

where *m* is the number of HPNs and *n-m* is the number of LPNs and C is the factor defining heterogeneous deadline. A detailed discussion of the percent degradation in the performance of LPNs is discussed in detail in Section 4.3.1.5.

Energy is another important attribute for the low power sensor devices. Although, in the proposed scheme the energy consumption of the HPNs is not affected, yet the LPNs are kept in active listening period for longer duration as compared to IEEE 802.15.4e. The sleep schedule for the nodes is presented in Figure 4.5. As shown in the figure, HPNs remain active only during their data communication and the superframe beacon transmission. Whereas, the LPNs have to stay in active listening mode for the duration of communications of the HPNs to which they are affiliated. During the communication of HPN, if the communication fails, instead of Ack, new slot is allocated (a slot previously allocated to LPN). In order to avoid collision, the LPN (affiliated to HPN) also stays in active listening mode to ensure whether it transmits or not during its slot. For Further details on sleep scheduling refer to Section 4.2.4.

The average active listening period of IEEE802.15.4e for LPNs is given by

$$L_A(\text{IEEE WPAN}) = \frac{(B_d + d_{ack})}{T_{sf}} \tag{4.16}$$

The normalized average active listening period of PE-MAC/O-PEMAC for LPNs is given by

$$L_A\ (\text{PE-MAC/O-PEMAC}) = \frac{\left\{B_d + d_{ack} + \left(q \times \left(\frac{m}{n-m} \times t\right)\right)\right\}}{T_{sf}} \tag{4.17}$$

Further discussion on the analysis LPNs and impact of optimizing HPNs communication is provided in Section 4.3.1.5.

4.2.5.5 Quality Ensured Scheme (QES)

A deterministic approach is introduced in QES to ensure the desired QoS for nodes communicating in a superframe. The proposed scheme offers a scheduled to shared slot ratio to offer 99.9% to 99.999% successful communication in a superframe depending on the requirements. The channel conditions for the previous transmission are used to specify the desired scheduled to total slot ratio. Each superframe is divided in '*n*' time slots for communication of information. A maximum of '*c*' number of distinct nodes can communicate in a single superframe while '*n-c*' shared slots are added. Here '*c*' is the number of nodes scheduled for communication in a particular frame.

Instead of contention based channel access in shared slots, as presented in IEEE standards [17, 18], the presented model allows the coordinator (cluster head) to allocate the shared slots, in case a node communication fails. To save the communication overhead and to allocate shared slots, group acknowledgement (GAck) is sent for an individual time frame. The bit sequence of GAck allows sensor nodes to identify which shared slot should they use to communicate if their communication was unsuccessful The superframe structure and GAck bit sequence used in QES and PQES is presented in Figure 4.7. This allows sequential allotment (highest priority first) of shared slots to nodes with unsuccessful communication. In case, a communication from a node remains unsuccessful after the retransmission or fails to get hold of a shared slot due to non-availability, the communication is rescheduled in next superframe.

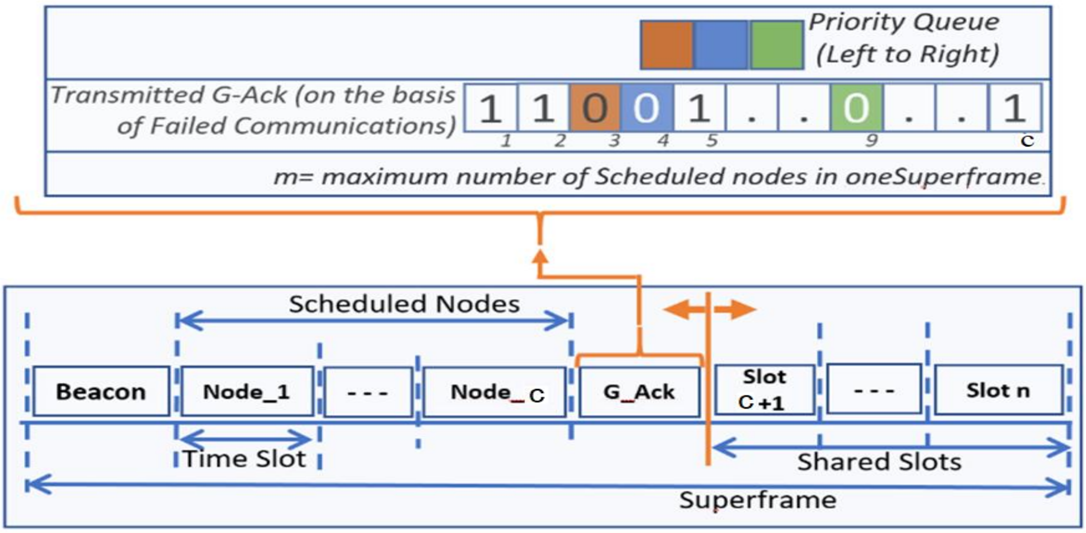

Figure 4.7: Superframe structure with c-Nodes

Total time slots (n) in a superframe are sum of the scheduled (c) and shared slots (n-c). The scheduled to shared slots ratio is adjusted with each superframe using PRR from the previous communications which is modelled as a recursive function. A mathematical equation for the probability of failure in superframe is represented as follows.

$$P(Failure\ in\ Superframe\ Communication \mid c > (n-c)) = \sum_{y=1}^{n-c}\left[\left(\binom{c}{y} q^{y}(1-q)^{c-y}\right)\left(\sum_{x=(n-c)-(y-1)}^{n-c}\binom{n-c}{x} q^{x}(1-q)^{(n-c)-x}\right)\right] + \left[\sum_{y=n-c+1}^{c}\binom{c}{y} q^{y}(1-q)^{c-y}\right] \quad (4.18)$$

Note that q is the packet error rate and it represents the probability of failure in single packet communication. The QES ensures desired QoS by empirical estimation of the optimum ratio for the scheduled and total slots in a superframe as presented in Figure 4.8, where

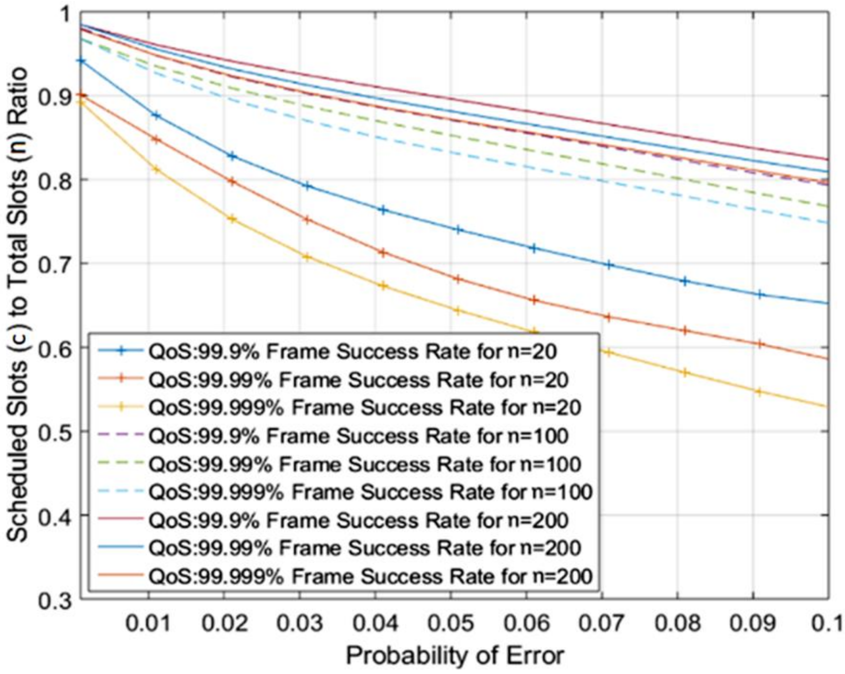

Figure 4.8: Number of scheduled slots in a superframe (Normalized) for desired QoS

$P(Failure\ in\ Superframe\ Communication) < 1 - D_Q$ is achieved for a given q. *Here* D_Q is the desired QoS bound for successful packet transmission rate.

4.2.5.6 Priority integrated Quality Ensured Scheme (PQES)

PQES offers a hybrid scheme which takes into consideration both priority weight function and QES to offer selective improvements in the communication of the nodes in an IWSN. PQES uses the dynamic priority system to identify the most critical nodes and ensures a pre-selected QoS for these nodes. Since PQES only focuses on improving the QoS for the critical nodes instead of optimizing the entire network communication, therefore the scheme allows a much better network load management and significantly optimizes the network efficiency. The mathematical model for PQES is also presented where the desired QoS in the high priority nodes is modelled as a negative binomial distribution and additional shared slots in a superframe are added accordingly to achieve the specified QoS. The mathematical formulation of PQES for added shared slots for desired success ratio of high priority nodes is modelled as follows

$$s_n = w - (\psi \times n) \mid \left\{ \sum_{x=\psi\times n}^{w} \binom{w-1}{x-1} q^x (1-q)^{m-x} > D_Q \right\} \tag{4.19}$$

where $\psi \times n \leq w \leq n - \psi \times n$. Here s_n is the number of shared slots needed to achieve the desired QoS for $\psi \times n$ transmissions, where ψ is the percentage of total transmission slots with critical information which need to be prioritized.

4.3 Results and Discussion

In this section the performance analysis of typical IEEE 802.15.4e along with the proposed schemes PE-MAC and O-PEMAC will be presented. The performance analysis of these protocols takes in account both reliability of communication and the overall delay. Moreover, the performance evaluation of the proposed schemes is limited to the more obvious cases where the LPNs are greater than or at least equal to HPNs. In other words, the number of HPNs in a single cluster does not exceed a maximum of ten nodes.

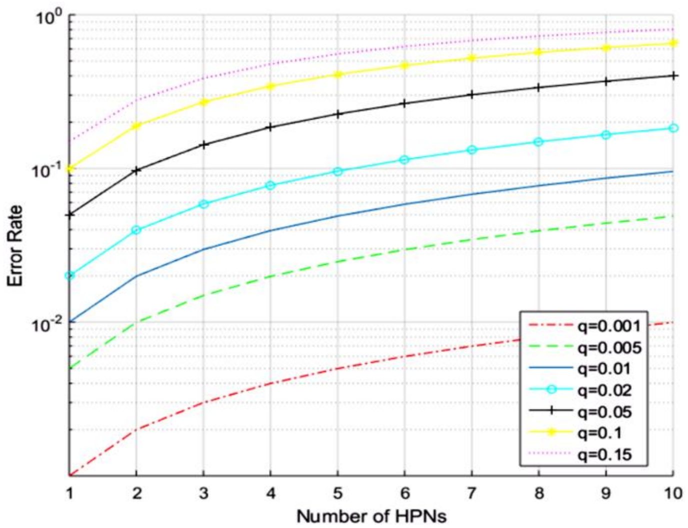

Figure 4.9: Error Rate in communication of Typical IEEE 802.15.4e based Wireless Networks

4.3.1.1 Reliability analysis in HPNs' communication in IEEE 802.15.4e

The IEEE 802.15.4e LLDN standard is capable of incorporating up to 20 nodes within a single cluster and allows the coordinator to listen to the transmission within a duration of 10 milliseconds, which is specified for superframe in LLDN, particularly introduced for time critical industrial networks. Out of these 20 nodes, some may have precedence over the rest and due to critical nature of their information, need higher data delivery ratio compared to other nodes in the networks. IEEE 802.15.4e itself do not include any precedence system and for that reason all the nodes are treated equally. For the performance evaluation in IEEE 802.15.4e, number of HPNs in a cluster is plotted against the percentage error in communication. The plots are presented in Figure 4.9 where the normalized error rate is plotted against the number of high priority nodes taking part in communication. Here, two parameters are defined: (1) the error rate in HPNs' communication (defined on the basis of possible failures in communication of one or more HPNs) and (2) q (probability of failure in communication of any node in the network, independent of any other communication).

4.3.1.2 Reliability in communication of HPNs' in PE-MAC

The PE-MAC facilitates a retransmission of failed communications of HPNs by reserving the time slots from the low priority traffic. It is for the same reason the overall frame error rate in PE-MAC is notably less compared to IEEE 802.15.4e LLDN. The overall frame error rate for the PE-MAC is represented in Figure 4.10. Due to the adaptive change in the priority of the sensor nodes,

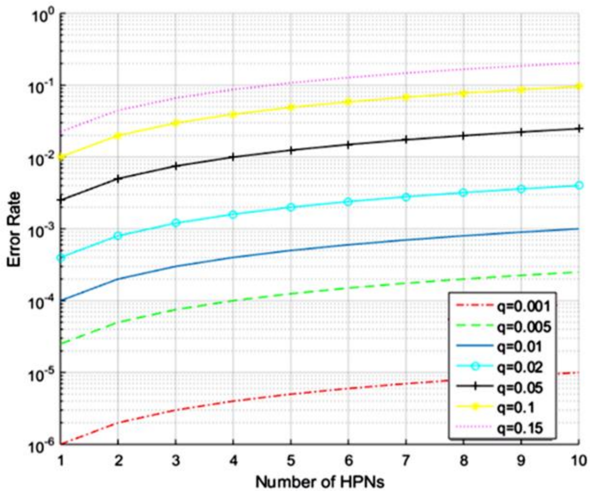

Figure 4.10: Error rate in superframe communication of PE-MAC

effective information communication from the sensor nodes is also maintained which ensures timely delivery of data from important nodes without depriving specific nodes. PE-MAC in comparison to IEEE 802.15.4e LLDN offers 75% reduction in error in extreme cases.

4.3.1.3 Reliability in communication of HPNs' in O-PEMAC

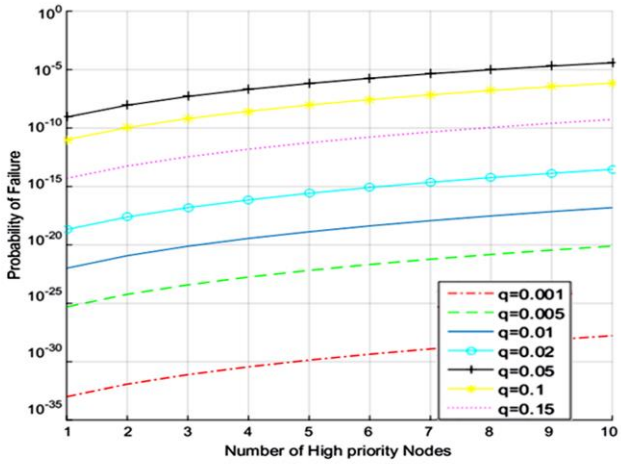

Figure 4.11: Superframe Error Rate in O-PEMAC

The O-PEMAC aims to improve the communication reliability to facilitate critical and emergency communications in IWSNs. The allocation of additional bandwidth from low priority nodes and ability to transmit data from critical nodes within the specified time window allows O-PEMAC to offer very high communication reliability. The frame error rate for O-PEMAC is represented in Figure 4.11. O-PEMAC offers 99.999% successful frame rate for extreme channel conditions whereas, the reliability is further increased in less critical cases. The simulations show that even in case of 10 HPNs scheduled per superframe and PRR as low as 85%, the scheme works reasonably well and reduces the chances of communication failure significantly. This ensures suitability of O-PEMAC for emergency, regulatory and supervisory control applications in industries.

4.3.1.4 Delay Analysis for HPNs in PE-MAC and O-PEMAC

To evaluate the suitability of PE-MAC and O-PEMAC in real-time industrial applications, the maximum delay is investigated which ensures 99.99% packet success ratio of an individual node. The maximum delay for the above stated case is presented in Figure 4.12 for IEEE802.15.4e LLDN, PE-MAC and O-PEMAC. The overall delay between two consecutive communications of a HPN are within tolerable bounds of process control for both PE-MAC and O-PEMAC. Even

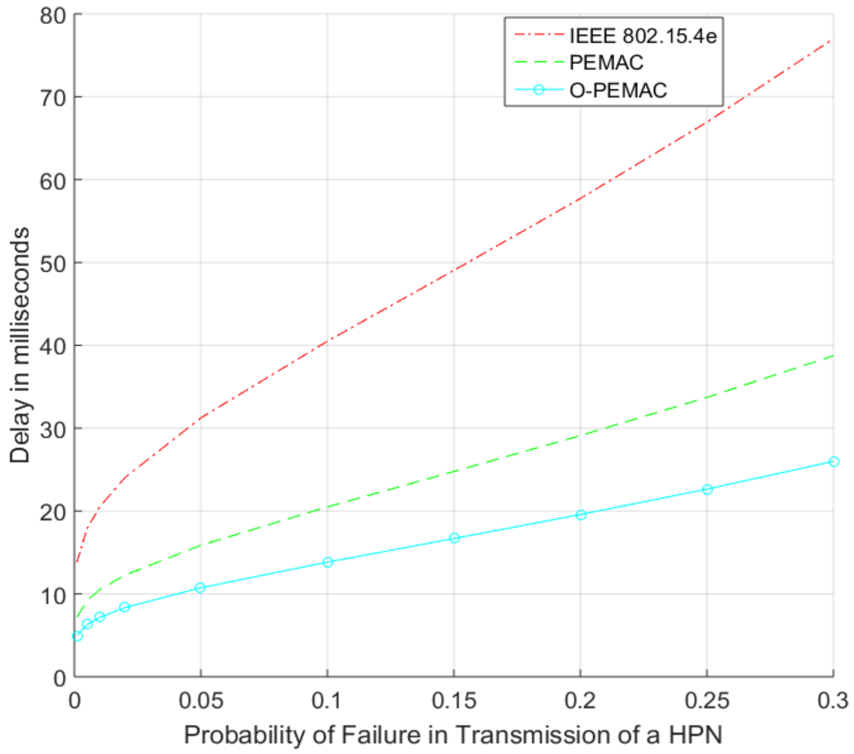

Figure 4.12: Maximum delay encountered in 99.99% traffic delivery to control system

for the poor channel conditions (i.e. successful packet communication drops to 85% under normal conditions), the process control can effectively work with the integration of suitable control blocks like smith predictor to establish a stable controlled environment in case of both PE-MAC and O-PEMAC.

4.3.1.5 Performance analysis of LPNs

The incorporation of PE-MAC and O-PEMAC in the existing IEEE802.15.4e, improves

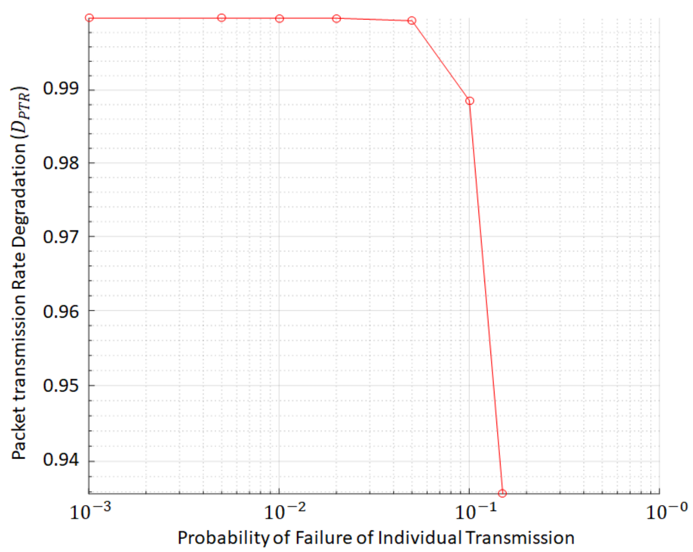

Figure 4.13: Performance degradation in LPNs w.r.t the probability of failure in wireless communication

reliability of HPNs and reduces average delay. However, it also affects the performance of LPNs. Since the transmission slots of LPNs are occasionally used by the HPNs, some of the communications of LPNs are postponed to next superframe or sometimes discarded. It results in reduction of packet transmission rate of LPNs. The overall degradation in packet transmission rate for LPNs in case of PE-MAC / O-PEMAC is represented in Figure 4.13. Although, the communications in LPNs are not as critical, however, in poor channel conditions the drop in packet transmission rate becomes more notable. It was observed that the reliability in PE-MAC and O-PEMAC was increased at the cost of reduction in the packet transmission rate of LPNs. For PE-MAC and O-PEMAC, the communications error was reduced from 15% to 1% and

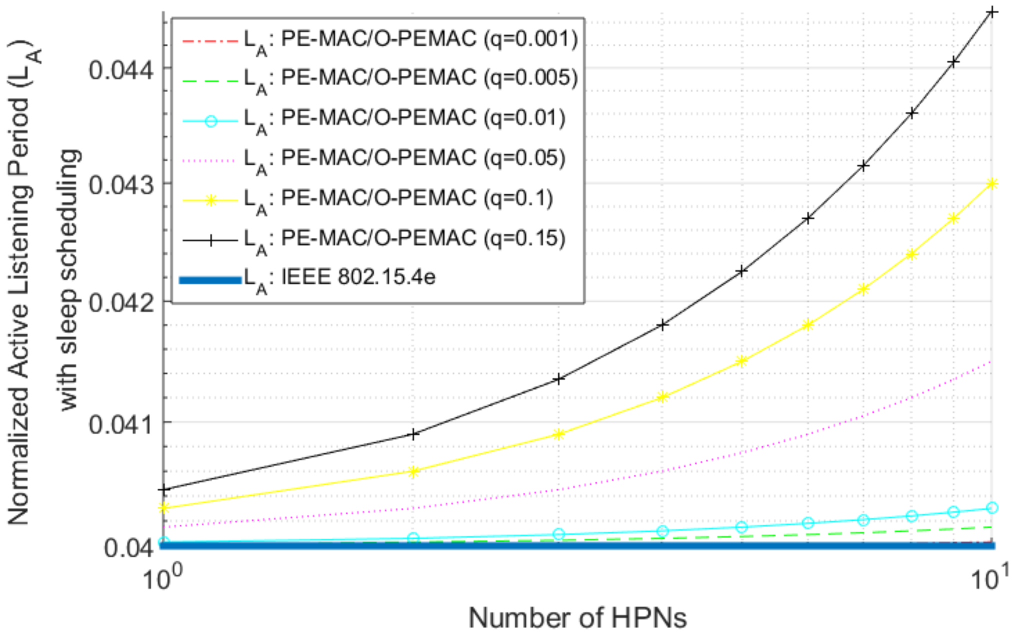

Figure 4.14: Active listening period of LPNs in IEEE 802.15.4e in comparison to PE-MAC/O-PEMAC

0.001% respectively at the cost of 7% reduction in the packet transmission rate of LPNs (for q=0.15, m=10).

It was also observed that the reduction in the communications error and delay in PE-MAC/O-PEMAC (see Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12) was also dependent on additional active listening period of LPNs. In Figure 4.14, the normalized active listening period of LPNs for IEEE 802.15.4e and PE-MAC/ O-PEMAC is presented. As shown in the figure, the average active listening period is comparable in IEEE 802.15.4e and PE-MAC/ O-PEMAC for lower number of HPNs but becomes notable as the number of HPNs increase. Overall, up to 10%

increase in the active listening period of LPNs is observed in PE-MAC/O-PEMAC in comparison to IEEE 802.15.4e.

4.3.1.6 Performance analysis of QES and PQES

In this section, the results presented regarding QES and PQES are divided into two parts. The first part discusses the overall impact of the proposed QES and presents reliability of the QES in comparison to the IEEE 802.15.4e LLDN. It also discusses the cost paid to ensure the desired QoS. In the Second part, the overall network load optimization is analysed when the proposed dynamic priority system is embedded into the QES (PQES) in comparison to QES.

To maintain a desired rate of successful communication in a superframe, as a function of estimated PRR, an empirical form of scheduled slots (c) to total slots (n) ratio is represented in Figure 4.8. In this figure, set of three curves is presented which suggests the ratio of scheduled slots to total slots to achieve the desired QoS of 99.9%, 99.99% and 99.999% for selected values of 's'. In Figure 4.8, three sets of QoS curves are presented with $s = 20, 100\ and\ 200$ respectively. Note that the empirical curves in this figure, suggest a ratio that will ensure the desired QoS for network communication. For evaluation purposes the ranges of p is used as 0.001 to 0.1. These paramerter values are chosen based on channel conditions and successful communication ratio in industrial environment for a relatively suitable channel condition to poor channel conditions. $(T_{deadline} - t)$ is in a range between 10 milliseconds to 100 milliseconds depending on the size of the superframe. δ_1 and δ_2 (Eq. 4.2) are adjusted to 0.6 and 1/25 respectively to establish 60-40 contribution ratio based on time deadline and PRR.

The overall PRR for communication of QES and IEEE802.15.4e LLDN are presented in Figure 4.15. It can be seen that the QES (following proposed k/n ratio curves in Figure 4.8) notably improves the QoS compared to IEEE 802.15.4e as presented in Figure 4.15 (a). Figure 4.15 (b) shows the magnified view of the QES and it can be seen that in accordance with the curves provided in Figure 4.15 (b), for all three of the presented cases, (99.9% QoS, 99.99% QoS and 99.999% QoS) the QoS threshold is not violated, ensuring higher QoS than the selected QoS threshold. However, the cost paid for improved QoS is represented in Figure 4.8, and plot in

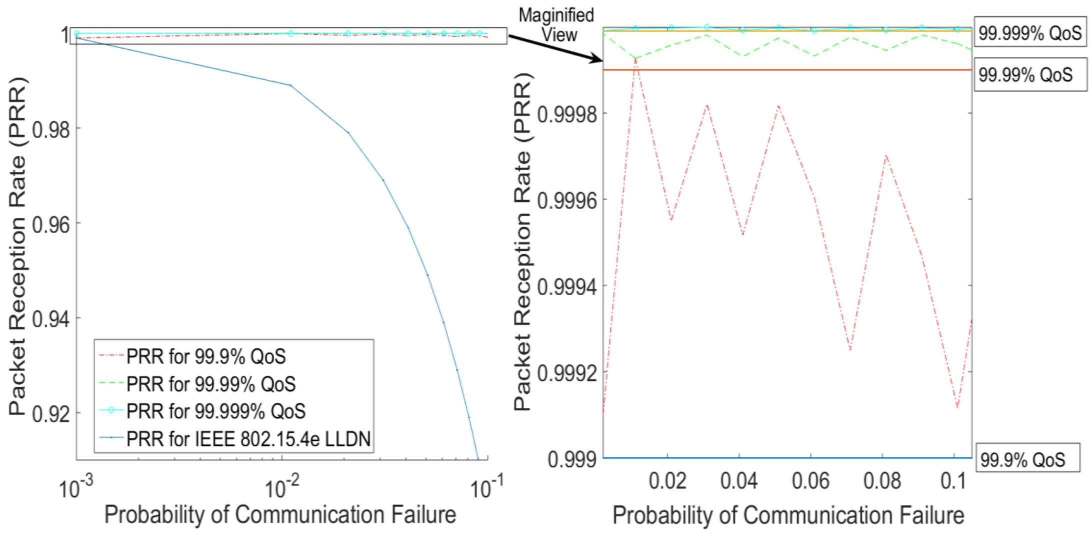

Figure 4.15: Packet Reception Rate (PRR): (a) PRR for the desired QoS cases in comparison to IEEE802.15.4e LLDN; (b) Representation of the QoS aware communication: PRR in comparison to QoS bounds.

Figure 4.16 (See red line with marker), where the number of scheduled slots are reduced notably to sustain desired QoS at poor channel conditions. It was also noted that for larger superframe sizes, the overall communication efficiency was improved under similar channel condition.

It is noted that the communication in IWSNs is only critical for selective nodes comprising 5% (or at max. 10% of total load). The implementation of proposed priority system allows to identify the high priority nodes, facilitating higher reliability for selected nodes' communication. The

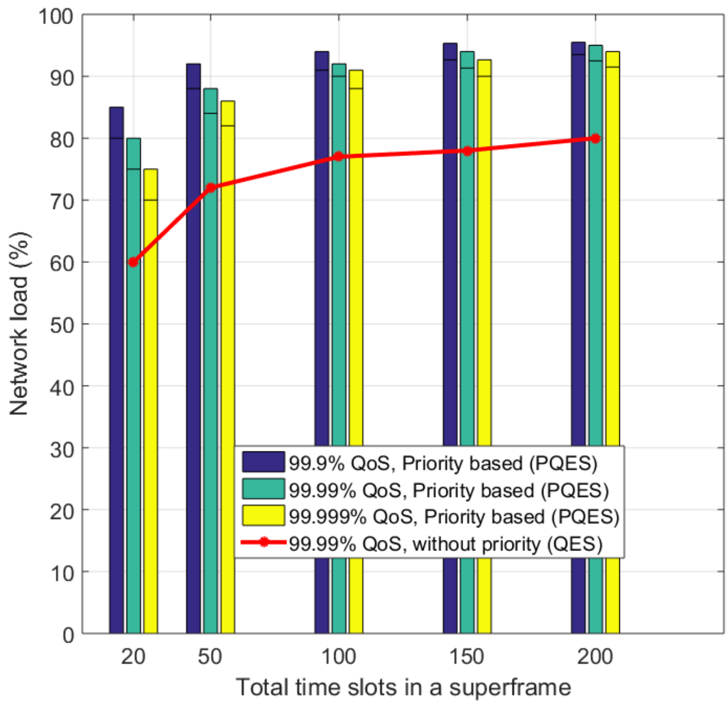

Figure 4.16: Maximum network load for achieving desired QoS with 10% critical information content per superframe

implementation of the priority system with 10% critical information content per superframe resulted in an increase of up to 20% additional load management capabilities of the network while maintaining the desired QoS. The percentage of the scheduled nodes for PQES in comparison to non-priority based QES is presented in Figure 4.16, where the presented results cover various QoS requirements and superframe sizes.

4.4 Summary

This chapter presented a dynamic priority based communication system for real-time and reliable communication of critical sensory information in IWSNs. A dynamic priority system was introduced which evaluates priority of collected information within the industrial processes. The proposed priority system classified various communications taking place within the industrial environments. This classification helped in prioritizing the communication of critical nodes/data.

Four MAC protocols were also introduced, developed and thoroughly evaluated in this chapter. PE-MAC and O-PEMAC offered an enhanced reliability and low latency for highly critical communication within the industry standards. These schemes implemented adaptive channel assignment to improve the communication of high priority nodes. Both the schemes offered notable improvements in the reliability and latency of HPNs communication in the network. In the results, it was observed that PE-MAC in comparison to IEEE 802.15.4e LLDN offered 75% reduction in error for critical cases. Whereas O-PEMAC offered 99.999% successful frame rate for critical channel conditions. The reliability was further improved in less critical cases

The chapter also introduced QES and PQES which targeted the regulatory control applications which required more deterministic reliability constraints. QES maintained up to 99.999% successful PRR under diverse channel conditions. Both QES and PQES adaptively adjust scheduled to shared slots ratio to offer a pre-specified PRR. In addition, PQES integrated the proposed priority system with QES to offer an improved network efficiency and load management.

5 MULTI-CHANNEL SCHEME FOR URLLC IN IWSNS

5.1 Introduction

The past couple of decades have witnessed a relatively perpetual rise in industrialization and automation of the processes [1]. In the competitive industrial world, automation is the key to cost reduction whether it is a production, nuclear power, oil refinement or chemical plant [2]. These industrial plants can greatly benefit from technological advancements and can implement successful process control with efficient and effective formation of a close loop control system. However, to introduce a suitable process control, a reliable communication infrastructure is needed which should also offer scalable architecture for future enhancements and permits infrastructural extension in the ever-changing industrial plants [162-165]. To cope with the first objective (reliability), wired networks offer suitable solution but some intrinsic properties of these networks do not sit well with the present-day industries. The lack of scalable architecture and flexibility of industrial wired networks pose serious limitations for dynamic industrial environments. On top of that, the high price in the wired networks also comes as a setback. IWSNs are sometimes considered as an alternate for the wired networks, however, un-predictable wireless communication links in IWSNs appears to be a major challenge [16]. Therefore, in order to establish a wireless feedback network, the reliability and real-time data delivery must be ensured.

The IWSNs offer a suitable reduction in the deployment cost as well as the maintenance cost of the feedback communication [15, 164] along with the benefits of, scalability, self-healing ability, reduced planning overload and installations time minimization [16]. All these benefits have encouraged the use of IWSNs in industries, eventually leading to an extensive increase in research and development activities to ensure suitable IWSN solutions for wider variety of applications in the industries.

The present day IWSNs are capable of taking in account, the channel conditions, sensor readings, network specifications and suitable responses to the sampled sensor data. These abilities if properly utilized can also serve as a tool to overcome uncertainty in wireless links and timely delivery of the information. All these improvements in IWSNs encouraged their use in industrial environments.

Despite these benefits and the recent improvements, the researchers are still struggling to offer substantial solutions for the improved reliability and real-time data delivery in IWSNs to match the strict deadlines as needed for the close loop process control and Ultra Reliable Low Latency Communication (URLLC) [58, 166]. URLLC is mandatory for IWSNs, especially when dealing with the emergency communication and regulatory and supervisory control feedback systems. To improve the overall acceptability of IWSNs, and to cope with fast paced improvements in industry, protocol stack developments, restructuring and procedural changes for URLLC in IWSNs are very important. The research in URLLC in IWSNS aims to accomplish: 1) support for large number of low data rate network devices, 2) sustaining a minimal data rate in all circumstances to satisfy the feedback control requirements and 3) very low-latency data transfer [167].

In this chapter, a multi-channel TDMA based hybrid scheme is introduced, which benefits from the use of multiple-channels and short frame communication for time critical data. The proposed scheme targets real-time data delivery with improved data reliability. The effectiveness of the scheme is demonstrated with a test case with two frequency channels: one is used for the slotted access of the communication medium for low latency networks, second channel is used for the communication of the urgently required or critically needed information to be delivered to the control center within a specified time deadline. The second channel is also used for the retransmission of the failed communications to improve reliability. The time deadlines enforced by the control society are taken in to consideration to offer reliable solution for close loop control systems in industrial plants.

Most of the industrial protocols presently used in the industry are CSMA/CA based and the core functionalities of Physical and MAC layer are inherited from the IEEE802.15.4. Zigbee and 6LoWPAN are examples of such protocols. Although the specified protocols offer flexibility of operation and can be used to establish ad-hoc on-demand network with the ability of active network formation and handling runtime changes. However, these protocols are more suitable for monitoring and traditional WSN applications.

On the other hand IEEE 802.15.4e standard targets the critical applications of WSNs, primarily focusing industrial environments where time sensitive and information critical data are to be routed [17]. It uses TDMA based channel access to ensure collision free access to the wireless resources on pre-specified and dedicated time slots. This standard also takes into consideration the low latency demands of the industrial processes. Hence, a special LLDN framework is introduced to meet the critical time deadlines for the emergency and close loop control applications. Some widely used industrial protocols, ISA100.11a, WirelessHART etc. also use TDMA based channel access.

The multichannel schemes in IWSNs for MAC optimization offer improved medium utilization. Many schemes are presented in literature which use multi-channels to offer improvements in the existing scenarios. Some of the well-known developments are listed as follows.

5.2 Multi-channel schemes

In [168], authors have demonstrated the effectiveness of the multi-channel schemes in improving throughput over other schemes. In [169], authors have taken into account the benefit of the availability of multiple channels, defined a scalable media access and considered the limitation of the presently available sensor nodes. However, this scheme requires frequent channel hopping and has relatively high scheduling overhead. In [170] authors use TDMA based channel access in a multi-channel scenario. The scheme is relatively static and does not exploit the available resources. In [171], a pseudo random scheduling is introduced where each node randomly decides two factors, the wakeup time and the channel sequence. The primary aim of the protocol is to distribute the traffic in the available communication resources. However, the scheme fails to offer an efficient traffic scheduling and resource sharing mechanism. In [138], authors use multiple channels to increase the network throughput. The proposed algorithm eliminates collisions by establishing coordinated transmissions. The scheme schedules both periodic and event based traffic using reinforcement learning to establish collision free transmissions on parallel data streams using multiple channels. However, the scheme fails to offer a differentiated treatment for different datasets of different priorities. It also fails to suggest a suitable alternate in case of communication failure. In [172] the authors propose a multichannel scheme where the network is divided into sub-trees. Once divided, each sub-tree is allocated a unique channel. In [103], authors present a multichannel scheme for the static networks . The scheme benefits from the TDMA based source aware scheduling. However, the scheme fails to give satisfactory assurance on reliability of the scheme. In [105], the multichannel overhead reduction is achieved using regret matching based algorithm. For the evaluation of the proposed scheme both software and hardware based analysis were presented. In [173] authors propose a hybrid scheme which uses both TDMA and CSMA/CA for communication purposes. The proposed work offers a mechanism to switch between the two access schemes based on the traffic density. The proposed protocol also considers multichannel scenario. However, in this scheme suitable reliability and QoS can only be achieved using much higher delays unacceptable in critical industrial processes, making the scheme unsuitable for time critical and information sensitive industrial processes.

The discussed schemes, though offer a suitable improvement in the existing scenarios, almost all of the encountered schemes fail to offer suitable plans for retransmission of failed communication. In most of the cases, the importance of retransmission is ignored, which results in extended delay and failure in deterministic behavior of the network. The proposed scheme focuses on how to ensure the retransmission of the failed communication up to certain desirable extent within the superframe, time deadline which helps in not only improving the overall delay but also the communication reliability.

In this chapter, a hybrid multi-channel scheme for performance and throughput enhancement of IWSNs is proposed. The scheme utilizes the multiple frequency channels to increase the overall throughput of the system along with the increase in reliability. A special purpose frequency channel is defined which facilitates the failed communications by retransmissions where the retransmission slots are allocated according to the priority level of failed communications of different nodes. A scheduler is used to formulate priority based schedule for retransmission in TDMA based communication slots of this channel. Furthermore, in CSMA/CA based slots, a frequency polling is introduced to limit the collisions. Mathematical modelling for performance metrics is also presented. The performance of the proposed scheme is compared with that of IEEE802.15.4e, where the performance is evaluated on the basis of throughput, reliability and the number of nodes accommodated in a cluster.

5.3 System Model

Feedback control systems play a very important role in automation and process control. In such applications, the IWSNs serve as the feedback path for the sensory information. For better control of the processes, the reliability of the feedback link is very important. The deadline in the discrete feedback systems also alters the performance of the implemented process control, hence, making the processes more time sensitive.

The proposed scheme uses TDMA based channel access to minimize interference and to ensure URLLC. Apart from this the scheme also considers multiple channels scenario where channels are effectively used to offer improved throughput, reliability and timely delivery. The proposed scheme focuses on short burst communication where a dedicated channel is used to facilitate the transmissions of urgently required data. A detailed description of the network topology, superframe structure, channel specifications and system modelling is presented as follows, whereas the frequently used parameters in the discussion are first listed in Table 5.1**.**

Table 5.1: Description of frequently used variables

Parameters	Variable(s)	Value(s)
Superframe duration	T_{sf}	*10 ms*
Total Nodes	W	*20, 60, 100, 200*
High Priority Nodes	m	*1, 2, ...10*
Time slots in a superframe	n	*20*
Total RC channels	H	*1, 2, ...10*
Total high priority nodes communicating in a single superframe	w	*1, 2, ...10*
Frequency bands for RC channels	$f_1, f_2, \dots, f_H$	2.4 Ghz-2.4835 Ghz
TDMA based time slots in SP channel	$n\text{-}b$	
Probability of successful communication of a node	p	*0.9-1*
Probability of failed communication	q	*0-0.1*

5.3.1 Superframe structure

The proposed scheme targets improvement in MAC layer architecture by taking in account the availability of multiple channels. More specifically, the frequency and time division multiple access is utilized so as to improve the QoS and meet the time and reliability requirements of critical industrial processes. From the available frequency channels, a Special Purpose (SP) channel is specified which is dedicated for the short frame communications for highly time sensitive or erroneous packet communications. Any failures in transmissions from Regular Communication (RC) channels which require urgent retransmission due to sensitive nature of the data are facilitated by the SP channel. Superframe structure for the proposed system is presented in Figure 5.1, where the superframe structure for RC and SP channels are presented. Except for the SP channel, all the channels use TDMA based access scheme for the collision free communication. The SP channel, however, implements a hybrid scheme using both CSMA/CA

Figure 5.1: Superframe Structure (a) TDMA based (RC) channels, (b) SP channel

as well as TDMA based channel access.

5.3.2 Network architecture and multi-channel scenario

In the proposed scenario, a star topology is considered, where the coordinator (cluster-head) considers the nodes' suitability for association and disassociation with a cluster (See Figure 5.2). Each node affiliated to a cluster is assigned a local id starting from 1 to *w*, where '*W'* is the maximum number of nodes in the cluster. All the TDMA based channels maintain a uniform superframe duration (T_{sf}) where the synchronization takes place at the start of every frame with a synchronization beacon transmitted by the cluster-head. In each superframe the communication takes place in *n* time slots, each of duration *t*. These time slots are pre-assigned to the nodes in the cluster in sequence of highest priority node to lowest priority node. Each time slot is further divided into data transmission and acknowledgement section. Note that in Figure 5.2, the cluster represented with *n* nodes and a cluster-head uses one frequency channel for communication. The incorporation of multiple channels can be used to either improve the data rate of the individual nodes in a cluster or increase the number of affiliated nodes to the cluster head.

The SP channel is used to offer both, contention based and TDMA based channel access where the initially first *b*-slots are used for contention based access and the remaining (*n-b)* slots are used for the TDMA based communication. In the contention based time slots, the nodes in the cluster get the flexibility to transmit time sensitive information by using CSMA/CA scheme. As

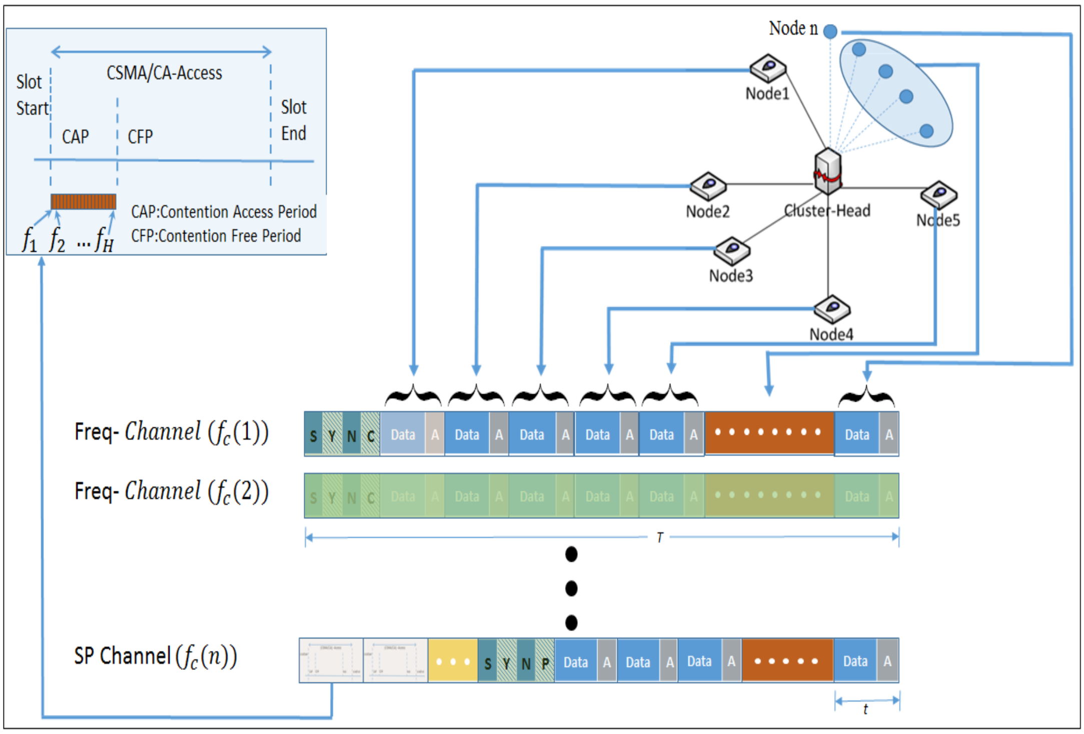

Figure 5.2: Superframe Structure, channel Distribution and Cluster representation

multiple channels can be used, therefore, multiple nodes can transmit data simultaneous and if communication from one or more nodes is failed it can be retransmitted using contention based slots. To keep congestion to the minimum, the contention based access on SP channel is only allowed during first *b* time slots as the retransmission requests are relatively less at the start of communications. However, as the time in superframe increases, there are more nodes communicating and hence higher chances of communication failures which will results in more attempts to access the channel. Therefore, the last *n-b* slots in the SP channel superframe are TDMA based to ensure collision free communications. The TDMA based retransmission schedule of selected nodes is communicated to the network during the Synchronization beacon (SYNP).

An effective retransmission mechanism for failed communications in RC channels using the

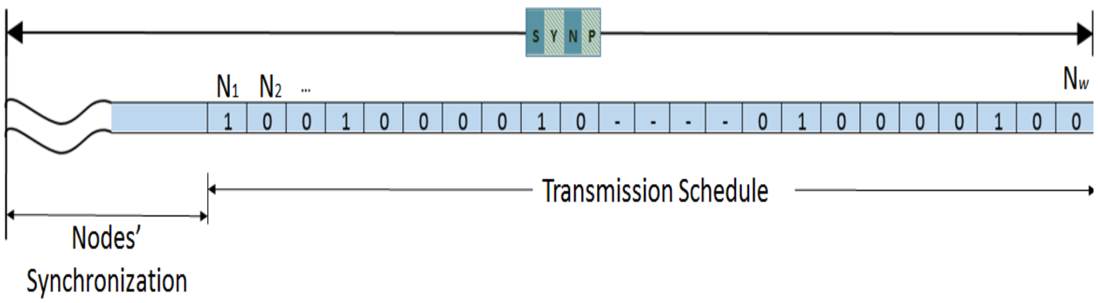

Figure 5.3: Schedule of the Nodes transmitting in TDMA slots of SP channel

SP channel is implemented. The delayed synchronization beacon in SP channel serves to synchronize the upcoming TDMA based communications in this channel. Along with synchronization the transmission schedule of urgently required or failed communications in last *k* time slots are also broadcasted. In other words, the TDMA based time slots of SP channel are used for rescheduling failed communication in the other RC channels. In Figure 5.3, a broadcast schedule for retransmission of selected nodes' information is presented. The schedule is part of SYNP as represented in Figure 5.3. The schedule consists of a sequence of 0's and 1's, where one bit is specified for each node. The position of the bit from left to right is assigned as per the nodes' id. In this sequence, the left most bit is for node 1, next for node 2, and so on until the rightmost bit specified for node *w*. *For instance, in* Figure 5.3, N_1 will communicate in timeslot b+*1*, N_4 will communicate in slot *b+2 and so on*. The total 1's in the sequence cannot exceed *n-b*, the total number of TDMA based slots in the current superframe of SP channel.

In the proposed scheme, a hierarchical architecture is used to offer suitable scalability features. The number of RC channels (H) are also limited to a maximum of 10 with one SP channel. Each superframe in RC channels is divided in twenty time-slots and the time duration of the superframe is limited to 10 milliseconds to establish low latency and deterministic networks. Apart from this, the communication from all the RC channels and the SP channel are aligned as represented in Figure 5.4 and all superframes are of the same duration. Note that the start of the superframe in case of SP channel is shifted by exactly one time slot (t duration) after the beacon of all the RC channels. In this way, every node in the cluster is synchronized with SP channel. For the evaluation purposes, the effect of multiple channels is investigated in terms of number of nodes that can affiliate to a single cluster-head.

The superframes at different frequency channels are synchronized in a manner represented in Figure 5.4, which allows the allocation of first three time slots in superframes of all RC channels to highest priority nodes in the cluster. Furthermore, the priority of these nodes is also distinguished by affiliating a priority factor based on frequency of the channels. To further elaborate, please consider the scenario where, after the beacon synchronization, the communication of first time slot in superframe of all RC channels takes place. In this time slot, all the nodes to whom this time slot is allocated try to communicate. Out of these communications, one or more communications can fail. As represented in Figure 5.4, nodes with unsuccessful communication (communicating at f_2 and f_H) will try to access the CSMA/CA based time slot of the SP channel (marked with ✓) and try to get hold of it during CAP. A magnified view of this slot is also presented in the figure, where based on frequency, the access to the slot is divided. Each node based on its channel frequency will sense the channel first and if vacant, it will initiate its access beacon giving a signal for the rest of the nodes that the CFP of this slot is reserved for its communication. In the presented case, the node operating at frequency channel f_2 will sense the channel and finds no other access beacons, so its beacon is broadcasted. The node communicating at frequency f_H, due to higher frequency is allowed to access the channel later in CAP and finds beacon of node operating at f_2 and hence withdraws its access till the next time slot. Any node which fails to access CSMA/CA based communication slots for retransmission of its information, is scheduled for transmission by the coordinator and its transmission schedule is included in the SYNP for retransmission on TDMA based time slots in SP channel. Doing so improves the communication reliability and timely delivery of information to the coordinator. Since this scheme tries to improve the reliability and real time data delivery of high priority nodes, the total number of nodes benefitting from this scheme are limited to w where $w = m \times H$. Here m is the number of high priority nodes and H is the number of RC channels used.

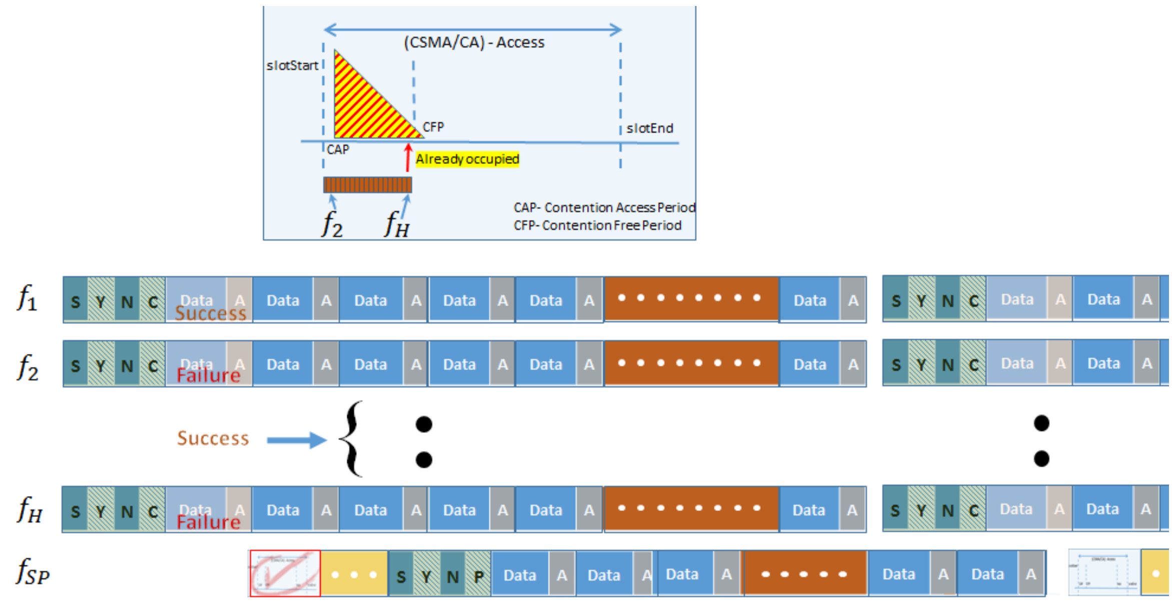

Figure 5.4: Synchronized superframe structure for NC and SP channel and priority based access

5.3.3 Mathematical formulation

The proposed scheme considers the impact of multiple channels compared to single channel schemes and evaluates improvements in number of nodes per cluster, communication reliability and overall throughput. To evaluate the performance of the proposed scheme, a mathematical formulation of the possible scenarios for typical IWSN as well as for the proposed scheme in IWSNs is presented as follows.

The communication from all the affiliated nodes in a cluster periodically originates in specified time slot of every superframe. The success of each individual communication is dependent on the channel conditions and probability of success of an individual communication, which is represented with p whereas the total successes in every time slot are modelled as binomial (p, w)

distribution.

To demonstrate the frame error rate for various number of high priority nodes a mathematical formulation is presented in Eq. 5.1, where, *m* is the number of high priority nodes and can change from 1 to 10. The total communications in a single frame are limited to *n* and *H* specifies number of RC channels.

$$P(frame\_error\_rate|H = 1) = \sum_{x=1}^{m} \binom{m}{x} (1-p)^x p^{m-x} \tag{5.1}$$

The use of multiple channels introduces a significant improvement in the throughput of the system but the reliability in such cases is dependent on the number of RC channels and ratio of RC and SP channels. A mathematical expression for the frame error rate in case of multiple channel scenarios is given in Eq. 5.2, 5.3 and 5.4. The maximum number of high priority nodes are limited to *k* per RC channel. Based on the total number of high priority nodes permitted (*m*) and total communications in a single frame (*n*) limits for high priority nodes are generalized to w_1 and w_2 for Eq. 5.2, 5.3 and 5.4. Where $w = k \times H$, $w_1 = \frac{n}{2}$ and $w_2 = n$.

$$P\big(frame\_error\_rate \,\big|\, (H > 1)\&(w \le w_1)\big) = \frac{\left[\left(\sum_{x=1}^{w}\left(\binom{w}{x}(1-p)^x p^{w-x} \times \left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^y p^{x-y}\right)^2\right)\right)\right]}{H} \tag{5.2}$$

$$P\big(frame\_error\_rate \,\big|\, (H > 1)\&(w_1 < w \le w_2)\big) = \frac{G}{H} \; where$$

$$\begin{aligned} G = &\left(\sum_{x=1}^{w_1}\left(\binom{w}{x}(1-p)^x p^{w-x} \times \left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^y p^{x-y}\right)^2\right)\right) \\ &+ \left\{\sum_{x=w_1+1}^{w}\left(\binom{w}{x}(1-p)^x p^{w-x} \right.\right. \\ &\left.\left. \times \left\{\left(\sum_{y=1}^{z=n-x}\binom{x}{y}(1-p)^y p^{x-y}\right)^2 + \left(\sum_{v=z+1}^{x}\binom{x}{v}(1-p)^v p^{x-v}\right)\right\}\right)\right\} \end{aligned} \tag{5.3}$$

$$P\big(frame\_error\_rate \,\big|\, (H > 1)\&(w > w_2)\big) = \frac{L}{H} \; where \tag{5.4}$$

$$L=\left[\left\{\sum_{x=1}^{w_1}\left(\binom{w}{x}(1-p)^x p^{w-x}\times\left(\sum_{y=1}^{x}\binom{x}{y}(1-p)^y p^{x-y}\right)^2\right)\right\}+\left\{\sum_{x=w_1+1}^{w_2}\left(\binom{w}{x}(1-p)^x p^{w-x}\times\left\{\left(\sum_{y=1}^{z=n-x}\binom{x}{y}(1-p)^y p^{x-y}\right)^2+\left(\sum_{v=z+1}^{x}\binom{x}{v}(1-p)^v p^{x-v}\right)\right\}\right)\right\}+\left\{\sum_{x=w_2+1}^{w}\left(\binom{w}{x}(1-p)^x p^{w-x}\right)\right\}\right]$$

All three equations (Eq. 5.2, 5.3 and 5.4) are defined on the basis of certain ranges affiliated to number of high priority nodes in the system.

5.4 Results and Discussion

The performance of the proposed multiple channel scheme with a dedicated retransmission channel (SP channel) is evaluated as a function of probability of successful communication of an individual node, total number of parallel data streams, i.e. the number of communication channels (RC channels) and the number of high priority nodes (*m*) trying to communicate in a single superframe duration. For the evaluation purposes the maximum number of RC channels (*H*) and number of high priority nodes (*k*) are limited to 10. Twenty transmissions in a single superframe are used (*n* = 20) so w_1 and w_2 are set to 10 and 20 respectively.

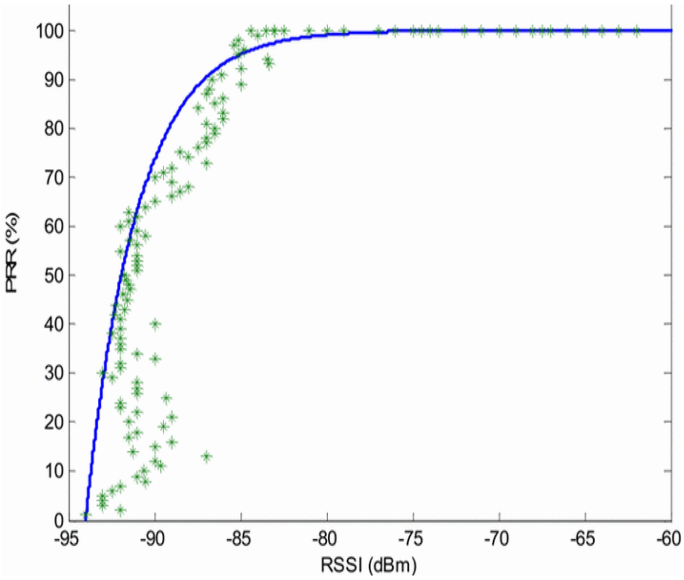

Figure 5.5: PRR as a function of RSSI using CC2420 [40]

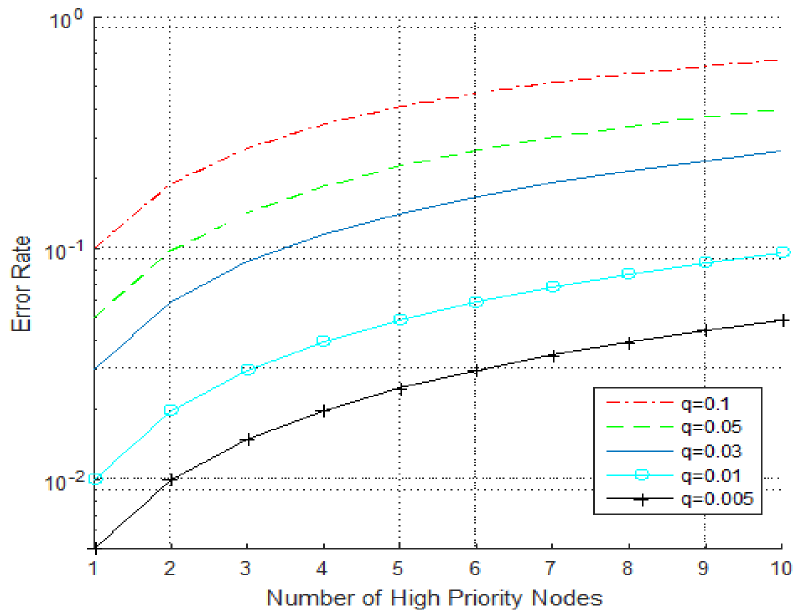

Figure 5.6: Frame Error Rate for Typical IEEE802.15.4e LLDN with one RC Channel and No SP Channel

In Figure 5.5, the probability of successful communication of a node is presented as a function of RSSI. In this figure, PRR is plotted against the RSSI. The plot is acquired using a communication established between SunSPOT sensor node and the SunSPOT base-station. The nodes use CC2420 radio, which operates at 2.4 GHz and uses OQPSK modulation with chip rate of 2Mchips/sec. The plot in Figure 5.5 represents the percentage of successfully received packets for different values of Radio Signal Strength Indicator (RSSI), with blue line representing polynomial curve fitting of scatter plot. As can be seen in the figure, if the received RSSI is

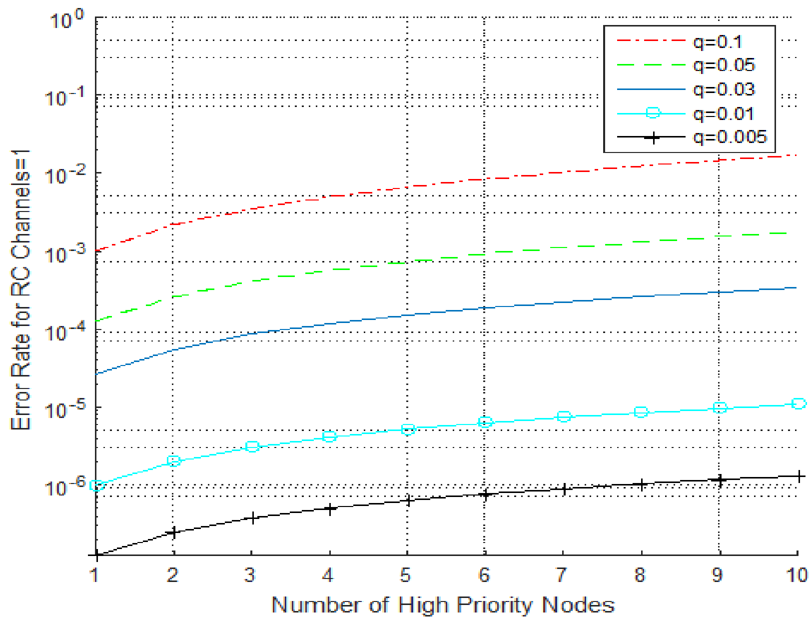

Figure 5.7: Frame Error Rate for proposed scheme with one RC Channel and One SP Channel

maintained above -87dBm, 90% or more successful transmissions are expected. To counter the

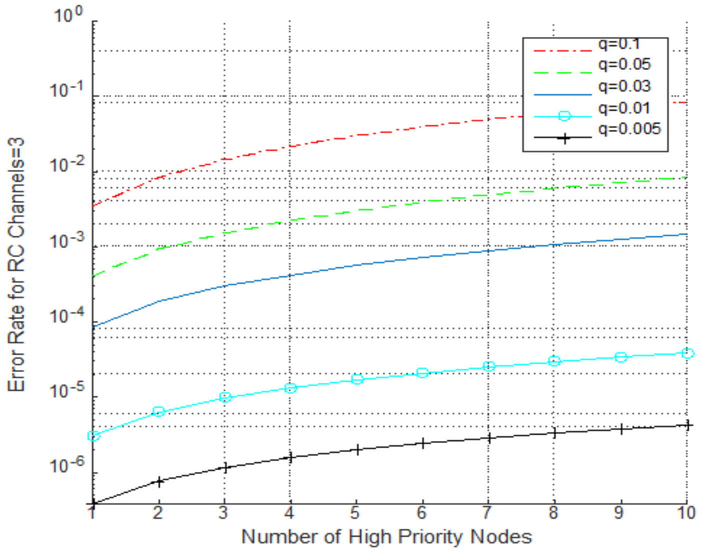

Figure 5.8: Frame Error Rate for proposed scheme with Three RC Channels and One SP Channel

effect of uncertainty of the wireless channel, 10dB margin is suggested when establishing a link between the coordinator/cluster-head and sensor nodes. For communication, a superframe duration of 10 ms is used. The maximum number of parallel data streams are limited to ten, and

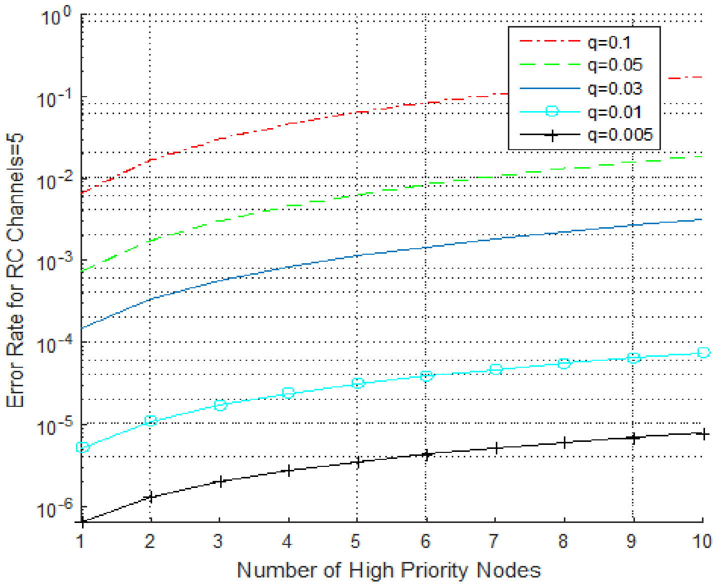

Figure 5.9: Frame Error Rate for proposed scheme with five RC Channels and One SP Channel

are synchronized in time domain. To evaluate the performance of the proposed multi-channel scheme, the performance of typical IEEE802.15.4e with single channel is presented as a reference in Figure 5.6. The performance is evaluated, based on the number of high priority nodes (m) communicating within the superframe where the total number of nodes trying to attempt a communication in a single superframe are limited to twenty. The frame error rate is evaluated for different channel conditions where the probability of communication failure is represented by q.

By introducing a SP channel in the typical IEEE 802.15.4e as expressed in the proposed scheme a significant error rate reduction can be seen in the communication of high priority nodes. Since

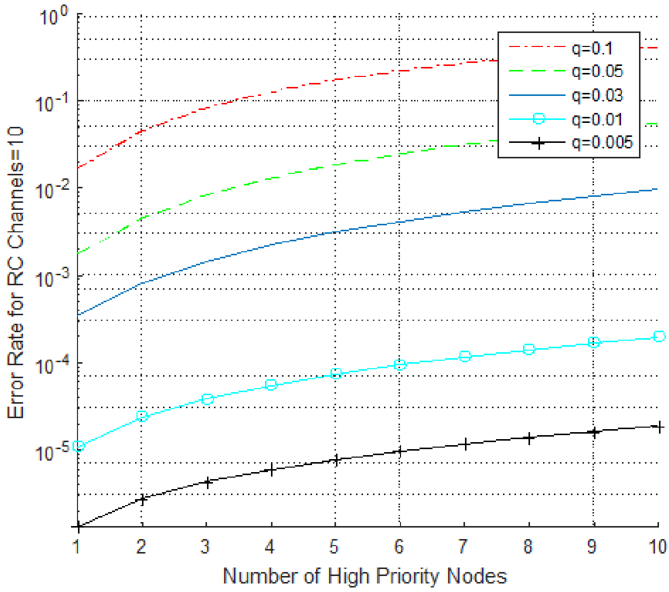

Figure 5.10: Frame Error Rate for proposed scheme with ten RC Channels and One SP Channel

the rest of the *n-k* nodes communicating in the network are considered as low priority nodes so the failure in communication of these nodes is not that critical and will not affect the performance of feedback control systems. With the retransmission of failed communication in RC channel through SP channel, a significant improvement in the reliability of communication can be seen. Similar conclusion can be deducted by comparing the error-rate of IEEE802.15.4e presented in Figure 5.6, and proposed multi-channel scheme with one RC channel and one SP channel,

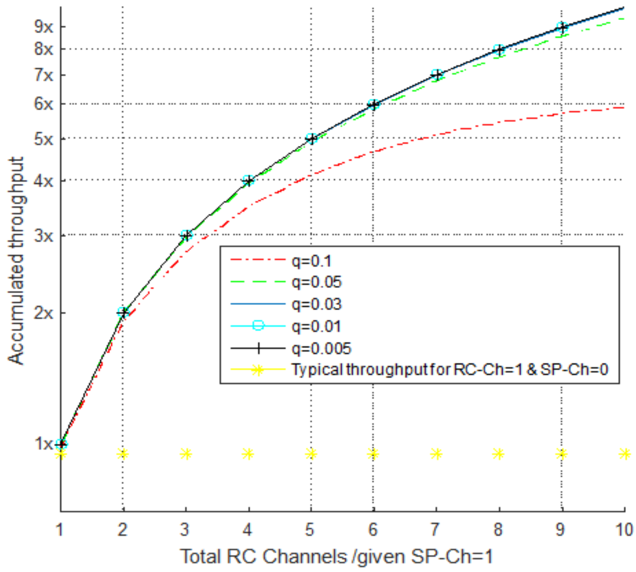

Figure 5.11: Accumulated throughput of the proposed multi-channel scheme with reference to single channel Low data-rate WPAN

presented in Figure 5.7 . To further evaluate the effect of using multi-channel scheme for higher number of parallel data streams the error rate is evaluated for the cases with one SP channel and 3, 5 and 10 RC channels, as presented in Figure 5.8, Figure 5.9, Figure 5.10 respectively. The proposed scheme, due to the incorporation of SP channel, offers notable improvement in the reliability. The observed improvement results from the efficient scheduling of the failed transmissions using the SP channel. The results show than under normal channel conditions and average number of high priority nodes, the scheme offers upto 99.999% successful frame communication rat which further improves for more suitable channel conditions.

Due to the introduction of multi-channel scheme the overall throughput of the network greatly increases along with the potential rise in the total number of nodes which can affiliate to a single cluster. However, in a scenario where single channel scheme is compared with the two-channel scheme (one SP and one RC channel), the improvements observed are focused on reliability improvements, where notable improvement in the communication reliability can be seen. The use of more than one RC channels, however, strongly influence the overall throughput and with the increase in these communication channels the throughput is increased several times. The overall throughput for different number of frequency channels is represented in Figure 5.11. As represented in this figure the overall throughput of the network can increase up to 900 percent with additional ten frequency channels in use. Apart from the throughput, as discussed earlier the reliability of the communication also improves along with the throughput.

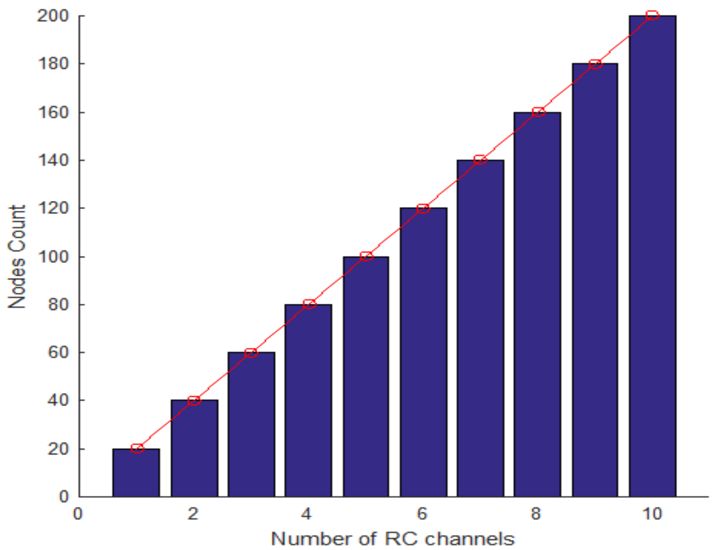

Figure 5.12: Total Number of affiliated nodes to a cluster-head

The total number of nodes that can communicate to the cluster-head in time T with different number of frequency channels is presented in Figure 5.12. Since the short-burst communication is used for urgent delivery of information, T, the time duration of superframe is limited to 10 ms. A communication overhead of 3.84 ms is considered, leaving the connected nodes a relatively short duration for communication. Each node in a cluster is assigned at least one time-slot in the 10 ms window enabling fast, frequent, and reliable communication to the central control unit, well within the specified times.

5.5 Summary

The chapter proposed a multi-channel hybrid access scheme for optimized communication retransmission for the failed communications. The scheme offered both throughput and reliability enhancement with primary objective to establish selective communication optimization for critical nodes. In the proposed scheme, the performance was evaluated using throughput, reliability and number of nodes accommodated in a cluster. The scheme offered notable increase in the reliability and throughput over the existing IEEE802.15.4e standard. The overall improvement in reliability was directly dependent on the SP channels to RC channels ratio. The throughput however is more dependent on the number of RC channels and the probability of successful communication.

For the evaluation purposes, the scheme considered one SP channel and hence can further be realized for multiple SP channels and can give a more suitable venue for performance improvement. In this investigation, the SP/RC channels ratio is limited to the cases ranging from 1:1 to 1:10. However a more generic approach may be considered which seems very suitable, where ratios 1:1 to 10:1 are evaluated for study purposes. Investigating the whole range of channels ratio will enable the use of the scheme in different challenging scenarios and a predefined projected or predicted output can also be formulated to better meet the desired requirements.

6 PERIODIC INITIALIZATION IN GRADIENT ROUTING PROTOCOLS

6.1 Introduction and Relevant Developments

The ability of distributed collection from multiple sites [174], enables WSNs to work as an effective solution for a wide variety of applications. The applications involving industrial automation and process control require improved reliability, and extended network life time due to the presence of inaccessible sensor nodes in the network [175, 176]. Hence, energy efficient and reliable routing plays an important role in deciding the network lifetime. A wide range of these protocols can be characterized as gradient-based routing protocols. In gradient-based routing protocols, a cost field is established where zero cost is set at a sink (serving as centre of the network) and as we start moving away from a sink, cost will be increased. This allows the data accumulation from farther ends of the network to the sink [177, 178] as each node routes its data to a lower cost neighbour eventually allowing data to reach at the sink. The conventional gradient-based routing protocols use setup phase, which is executed at the time of sensor nodes' deployment [154] to establish a cost field using a cost function. The cost function, based on some of the performance metrics including time delay, reliability, RSSI values, energy of the node, congestion, distance from sink and the number of hops from sink etc., will assign a cost for each node, which will be used to define compute communication path from a source to a sink. Typically, an appropriate weight affiliated to each performance metric in cost function defines the data routing behaviour of the gradient-based routing protocols. However, due to the uncertainty in WSNs, especially when operating in harsh industrial environments, cost of nodes can change drastically in runtime, requiring to updates for the node's cost regularly. Failure in updating nodes' cost may result in lack of accuracy, causing performance degradation and data loss.

This chapter proposes two primary update mechanisms, Periodic Setup (PS) and multiple-setup. These primary update mechanisms are further strengthened with secondary update schemes used to keep the nodes and networks updated for improved energy utilization and network reliability. The secondary update schemes reduce the communication overhead where adaptive route maintenance is also introduced to keep the network updated for efficient and reliable data routing. To verify the performance, the proposed schemes were embedded in two well-known gradient-based routing protocols, Gradient Cost Establishment for an energy aware routing in WSN (GRACE) [153] and Gradient Broadcasting (GRAB) [152]. The incorporation of PS and multiple-setup in gradient-based routing protocols resulted in an observable impact on network lifetime and communication reliability. Further to this, the paper also proposes a dynamic and application specific gradient cost function for effective cost field establishment within the network.

6.2 System Model

6.2.1 Gradient Cost Function (GCF)

In gradient-based routing protocols, the selection of the gradient cost function has a notable significance in ensuring communication reliability and energy efficiency in IWSNs. The cost function can be modelled to optimize certain elements of the data communication as detailed in (i) to (v) below. A proposed generic demand-based optimizable GCF C_{grad} (which gives a cost value) is given by;

$$C_{grad}(k) = \min_{i=1 \to a}\big(\alpha \times H_{count}(i) + \beta \times delay(i\,) + \gamma \times \varDelta E(i) + \\ ʒ \times \text{Ɛ}n(i) + \xi \times LQ(i)\big) \tag{6.1}$$

Here, a is the maximum number of nodes from which a node k can receive the cost values, and i is one of the intermediate nodes among m. The key elements in Eq. 6.1 are described as follows:

(i) $H_{count}(i)$ is number of hops to the sink from node i, which if being prioritized, allows shortest routing time. The normalized H_{count} is $\frac{No.of\ hops\ to\ sink}{H_{max}} \times 100$ where H_{max} is the maximum number of hops in the network.

(ii) $delay(i)$ can be modelled as a recursive function which updates the delay value based on an accumulated average delay at a node i. A $delay$ function can be generally described as: $delay(i) = f(i, d_{avg}, d_{max})$, where the values of average and maximum delays (d_{avg} & d_{max}) for individual nodes are updated frequently.

(iii) $\varDelta E(i)$ is an estimated power consumption per link and is given in Eq. 6.2. $\varDelta E(i)$ is normalized (0-100%) and depends on the electrical assembly and transmitter/receiver on-time and the output power of the transmitter.

$$\varDelta E = \sum_{i=1}^{H_{max}} N_t(i) \times \{P_{VCS} \times (t_{st}(i) + t_{tx}(i)) + P_{out}(i) \times \\ (t_{tx}(i))\} + N_r \times \{P_r(t_{st}(i) + t_{tx}(i))\} \tag{6.2}$$

In Eq. 6.2, N_t and N_r are the number of times transmitter and receiver switch on per unit time. P_{VCS} is the power consumed by synchronizer and Voltage Controlled Oscillator (VCO), P_{out} is the transmitter output power, P_r is the power consumed by the receiver, t_{rx} and t_{tx} represent the active time and t_{st} denotes the start time of transmitter and receiver [49].

(iv) $\text{Ɛ}n(i)$ is a node's remaining battery level, represented in percentage.

(v) LQ(i) is a link quality based on RSSI. It is evaluated in reference to the receiver sensitivity (ζ) of node i, which is evaluated to be -80 dBm using Sun SPOT nodes (It was also observed that under ideal cases the maximum RSSI value was found to be -25dBm) [179]. It can be modelled as a non-linear function as $LQ = 110 - \left[10 * \left(\zeta/_{RSSI}\right)^2\right]$, where the relationship for LQ is formulated using empirical data.

Furthermore, the cost coefficients defined as α, β, γ, ʓ and ξ can be customized to specify contribution from each performance metric to achieve solution for each of specific applications.

The cost function presented in Eq. 6.1 is applicable for an entire network, however it is also scalable to fulfil the objectives needed for application specific design. The GCF is used to setup gradient cost field for the network which builds the data flow path from farther ends of the network to the sink. The operation of the gradient-based routing protocols can be divided in setup phase and data communication phase, where each phase is described in accordance with the proposed scheme.

6.2.2 Setup phase

In a setup phase, a cost field is established throughout the network. Initially at a given sink node, cost value is set to zero; however, cost at all other nodes is set to infinity. The cost field using broadcast signal is started from the sink. Afterwards each node broadcasts its cost once it has calculated its own. A node calculates its cost by selecting a neighbour with minimum cost value i.e. zero in case of sink being the neighbour and adds its own cost function to form a final cost. Later, if any more cost values from its neighbours are received, the neighbour with minimum cost value is selected. In this way, each node in the network has a routing table and it maintains a least cost neighbour from itself to the sink. Whenever a node needs to send data to the sink, it selects a neighbour that has minimum cost. The process continues until the data reaches to the sink. Furthermore, a back-off based cost field establishment mechanism is implemented which allows the nodes to postpone their cost message broadcast until the lowest possible cost value is received which reduces the initialization overhead.

As an example, consider Figure 6.1 which represents cost field setup of selected section of an IWSN. In Figure 6.1, letters 'I' to 'P' are used to label the nodes. It can also be seen that node I, J and K can directly communicate with sink whereas the rest of the nodes have to convey information in two steps. Firstly, to send information to either of the nodes I, J or K and then from there to sink. As soon as the nodes are deployed, the setup phase is run. Setup phase is initiated by the sink, which broadcasts an advertisement packet. Here $C_{Sink} = 0$; i.e. cost of advertisement packet sent by sink is zero. The cost of node I, J and K can be defined as

$$C_I = C_{i\text{-}sink} + C_{sink} \tag{6.3}$$

$$C_J = C_{j\text{-}sink} + C_{sink} \tag{6.4}$$

$$C_k = C_{k\text{-}sink} + C_{sink} \tag{6.5}$$

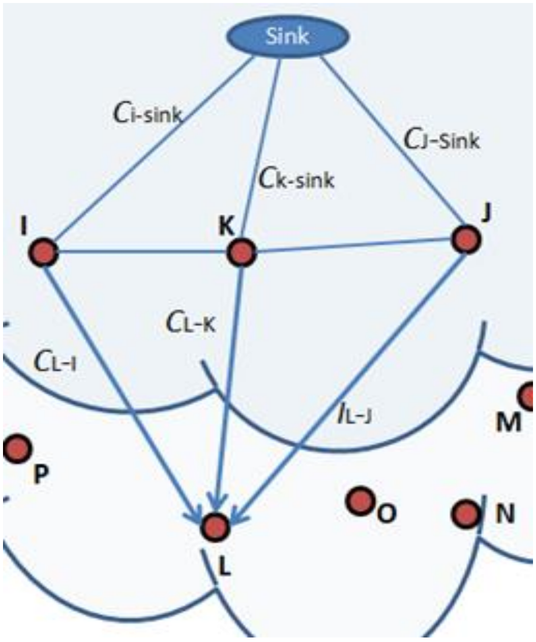

Figure 6.1: Cost Field Establishment

Where $C_{x\text{-}sink}=g(\mathcal{E}_n, LQ)$*, and* $\mathcal{E}_n$ and LQ are evaluated on the basis of received cost value. As for the nodes I, J and K, since they received advertisement packet directly from sink, they evaluate their own cost and broadcast it. However, node L will receive three cost packets one from each of the nodes I, J and K. For such cases, it will have to select the minimum cost path. The cost function of node L (C_L) is therefore defined as:

$$C_L = min\{(C_{L-K} + C_k), \quad (C_{L-J} + C_J), \quad (C_{L-I} + C_I)\} \tag{6.6}$$

After the selection of minimum cost path, the evaluated cost of node L will be broadcasted.

Note that the function C_{L-X} (where X could be I, J or K) can depend on a number of factors including: link quality from node X to L, delay measure, received RSSI, energy left in node L, channel characteristics, congestion, deferral probability etc. The setup phase terminates once the gradient cost field for entire network is established.

6.2.3 Data communication phase

After the setup phase, since the cost field is established throughout the network, any node can send data to the sink through the least-cost path. However, due to dynamic nature of these networks, the cost can be changed, hence an adaptive updating mechanism is required to maintain energy efficiency and communication reliability while minimizing the update overhead. To reduce this overhead and to maintain uniform network-energy deterioration for an extended network operation, two primary mechanisms for updating gradient cost along with some low power secondary update modes are introduced.

6.2.4 Periodic Setup (PS) Initialization and modes of operation

In conventional and industrial WSNs, the energy level of each wireless sensor node and link quality of data relay path can change rapidly especially if the node is a part of an active routing path. To update the status information of the nodes i.e. node energy and link cost, the setup phase must be initiated more than once. The frequency of running setup phase depends on a number of factors including communication overhead, energy consumption during gradient cost update, frequency of cost update, network conditions etc. However, it can result in notable improvement in network lifetime and communication reliability if the setup is carefully planned. In the proposed PS initialization, even though the setup phase runs periodically to update the routing tables, yet in between the two setup initializations, the elected path will not change. Therefore, certain other modes are introduced which will update the status of stressed nodes in between the two PS initializations and will also serve as a marker to force the setup phase to trigger or postpone if the link quality degrades or energy levels of the nodes in path deteriorate significantly or vice versa.

Furthermore, these modes help prolonging the delay between two update phases which reduce update overhead.

Algorithm 6.1: Algorithm for the Proposed PS initialization

Initialization: (setup Phase)

1

- **Sink**:
- Timer0.set();
- Broadcast cost (C_{sink} = 0, ch1) // Broadcasting sink cost at channel 1
- Go to '3';

2

- **Network Nodes**: (x=1,2, … n) // n=Total nodes in the network
- Nodes.listen(ch1);
- If (Broadcast_received== C_{sink}) {
- $C_{x\text{-}sink}=g(\mathcal{E}_{rv}, LQ)$;
- $C_x = C_{x\text{-}sink} + C_{sink}$;}
- *else{ wait[rand* $(\delta)\pm(H_{count}\times\Delta)$*];* // Backoff based wait for certain duration
- $C_X = min\{\forall(C_{X-Y} + C_Y)\} \mid Y \in W_x$; where W_x is set of all nodes whose cost is received by node x} // Routing tables formulated
- Broadcast cost($C_X, ch1$); // Broadcasting the cost of the node at channel 1.
- If(node==Relay){Go to 4;}
- Else{go to 5;}

Data communication and Periodic update with Broadcast Acknowledgement Mode

Sink

3

- Timer0.start() // Used to trigger periodic update (listed in '1')
- Timer1.start();
- Sink.openRxConnection(ch2); // Opening a connection to receive data from the sensor and relay nodes at channel 2.
- While (true){
- While (Sink.listen() == 0); // Holds until data packet not received at sink
- Store/Respond to the received input
- If (timer0==0)
- Go to '1'; }

Relay Nodes

4

- Observing (Ch1.Broadcast)
- Timer1.start();//Timer 1 started, entering DC mode
- Relay.openRxConnection(ch2);
- Relay.openTxConnection(ch2); // Allows both transmission and ack reception with this connection
- While(true){
- While (Relay.listen() == 0); // Holds until data packet not received
- rcvPacket= Relay.listen();
- if (timer1 == 0){Broadcast_Ack+Node's cost}
- else{ Unicast_Ack}
- Relay.transmit(rcvPacket, LCN); // Transmits the received packet to lowest cost neighbour (LCN)
- listen(Ack, t1); // Try to wait for ack for prespecified time
- Update LCN;
- if (Ch1.Broadcast==true)
- Go to '2';}

Sensor Nodes

5

- Observing(Ch1.Broadcast)
- Timer1.start(); //Timer 1 started when entering DC mode
- Sensor.openTxConnection(ch2);
- Sensor.openRxConnection(ch2); // To operate as a relay
- while(1){Sensor.transmit() // Sensor information transmitted to least cost neighbour
- listen(Ack, t1); // Try to wait for ack for prespecified time
- Update LCN;
- if (Ch1.Broadcast==true) Go to '2';}

The algorithm for PS initialization in terms of triggering primary and secondary cost update mechanisms is presented in Algorithm 6.1. Note that the algorithm is divided in two phases: i) Setup phase and ii) Data communication and periodic update phase. A modular approach is used where nodes in the network are divided in sensors, relays and sink. The algorithm presents the operation of the nodes in terms of relay, sensor and sink in the two phases. Timers are used to initiate secondary cost update and periodic cost update. In the presented algorithm (see Algorithm 6.1), the broadcast acknowledgement is used as a secondary update mechanism.

The PS based update mechanism along with the embedded cost update modes keeps the routing table of the nodes in network updated. The up-to-date cost information in the network not only offers improved reliability but also reduces overall network power consumption hence compensating the energy overhead due to additional control information.

Six modes of operation are also introduced [153] along with the proposed PS as follows:

(i) PS Alone Mode (i.e. PS without acknowledgment or correction procedures)

(ii) PS with Unicast Acknowledgement Mode (PS (U-ack))

(iii) PS with Broadcast Acknowledgement Mode (PS (Back))

(iv) PS with Correction Mode, starting from the sink (PS(C-sink))

(v) PS with Correction Mode, starting from the intermediate node (PS (C-intr))

(vi) PS with Hybrid Mode, 'Correction + Acknowledgement' (PS (C+A))

6.2.5 Multiple-setup initialization

As discussed earlier, sensor motes are energy constrained, therefore, the proposed protocol focuses on efficient energy usage without undermining the reliability. Although the PS initialization results in an increased network lifetime, the periodic nature of the proposed protocol can further be modified to achieve better network performance. In contrast with PS, the multiple-setup, route maintenance, do not run after a predefined interval of time. Since, at the beginning, nodes have enough battery power, therefore, there is no need of running setup phase after short intervals of time. However, as the time progresses battery depletes and hence, the status of nodes start changing frequently. It is when a more frequent cost update is needed. Therefore, in multiple-setup, the frequency of running setup phase increases with the depletion of the nodes. In other words, unlike any other static scheme the update frequency changes adaptively as a function of collective nodes' energy and packets received. The conditions and dependency for route maintenance phase execution is expressed as:

$$R_{update}\big(\mathrm{C} \times \mathcal{E}_{frequent-node}(t-1) > \mathcal{E}_{frequent-node}(t-1) \mid\mid pkt\_rcv\_count \\ = G \times last\_count\big) \tag{6.7}$$

Where

(i) $\mathcal{E}_{frequent-node}(t-1)$ is the energy cost value (as given in the 4th term in Eq. 6.7) of most frequently used node since last route maintenance phase

(ii) $\mathcal{E}_{frequent-node}(t)$ is current energy cost value of the most frequently used node.

(iii) The $last\_count$ is the count of packets received up until previous route maintenance phase.

(iv) pkt_rcv_count is the total count of packets received since last triggered multiple setup route maintenance.

Table 6.1: Simulation Parameters

Parameters	Value (s)
Total Nodes	250
Node Battery Specs	3.7V, 770mAh
Battery Model	Non-Linear
Node transmission power (P)	*0 dBm*
Nodes Deployment	*Random*
Tool Used	*MATLAB*
Channel Access	CSMA/CA (Slotted)
Data Generation	Periodic
Path loss exponent (n)	3.5

(v) $\complement$ and G define the frequency of the route maintenance phase, where increase in $\complement$ and G, reduces frequency of triggering route maintenance phase and decrease - in $\complement$ and σ increases the frequency of route maintenance phases.

To implement MSI, the algorithm presented in Algorithm 6.1 is changed accordingly where the timers are controlled using Eq. 6.7.

6.3 Simulation Results and Discussion

6.3.1 Simulation setup

A network consisting of 250 nodes is used for simulation based evaluation of the proposed schemes. Details of the simulation parameters are listed in Table 6.1.

In the proposed application area, since the network lifetime enhancement and communication reliability are the primary objectives, therefore, the proposed gradient cost function is customized for the application at hand. To meet the specified objectives, a subset (LQ and $\mathcal{E}n$) of the proposed gradient cost function (in Eq. 6.1) is selected. With the incorporation of LQ and $\mathcal{E}n$ as the primary elements of the routing cost function, link quality and energy efficiency primarily influence data routing. For the evaluation purposes, the proposed PS and multiple-setup along with the specified six modes of operations are implemented. The performance of the proposed schemes is thoroughly evaluated with rigorous simulations. The performance of the proposed approaches, once being incorporated in GRACE and GRAB are also compared with the both of the parent schemes GRACE, and GRAB through simulation results. Metrics used for performance evaluation are listed as follows.

6.3.2 Investigation of network energy (ε) vs. connectivity

During the operational network lifetime, the energy of individual nodes is not equally utilized and at the end of network lifetime, a number of nodes might have energy leftover whereas other

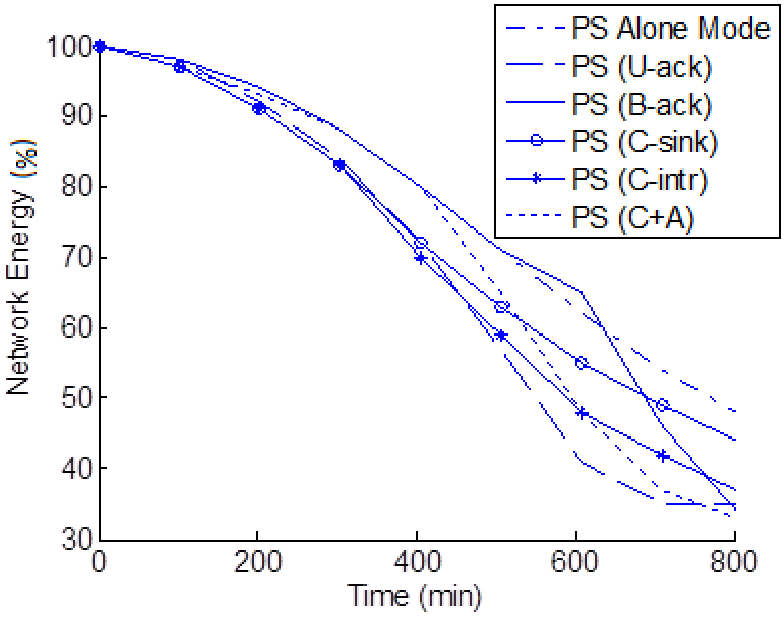

Figure 6.2: Network Energy Depletion PS-Modes

nodes are depleted. Ideally, one should manage the network so that energy of all nodes is uniformly used in order to prolong the network connectivity, hence ensuring continuous communications. Therefore, collective energy leftover in the network gives a measure of wasted energy which should have been used to increase network lifetime.

In Figure 6.2, the amount of energy leftover (from all nodes) is represented. Here, network energy depletion is plotted for different modes in the PS initialization. After 800 minutes, the network energy is least depleted for 'Alone mode', then 'C-sink' and then 'C-intr'. The other three modes have almost the same level of energy depletion. However, it is worth noticing the PS (B-ack) mode offers energy depletion pattern resembling non-linear battery curve implemented for simulation. It shows that in PS (B-ack), the energy consumption is more effectively maintained. The primary reason for efficient cost maintenance in PS (B-ack) is the wider dissemination of the cost due to broadcast nature of cost update. In addition, PS (U-ack) and PS

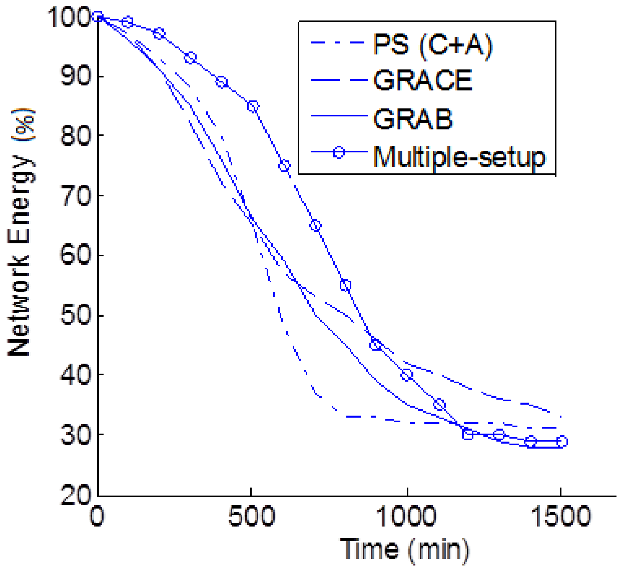

Figure 6.3: Network Energy Depletion Gradient Protocol with improved schemes

(C+A) also efficiently utilize the network energy.

Figure 6.3 presents the network energy consumption patterns of GRACE, GRAB, multiple-setup and PS over time. PS (C+A) is considered as an approach with efficient energy utilization, as it outperforms the rest of the modes of PS initialization in terms of energy consumption (see

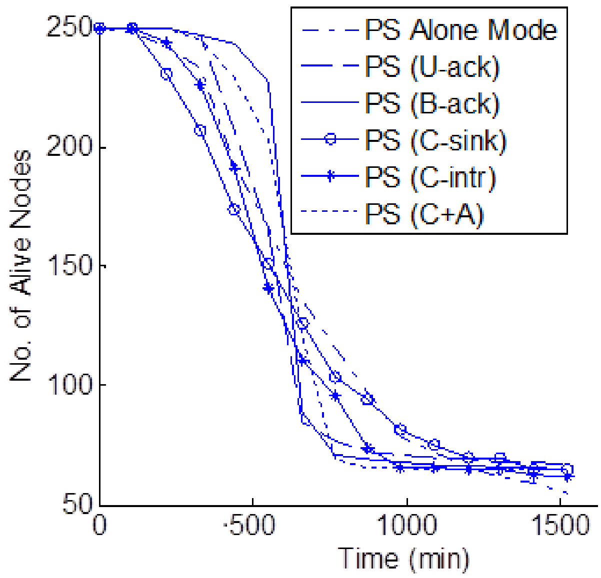

Figure 6.4: Network Lifetime PS-Modes

Figure 6.2). In Figure 6.3, the GRAB and multiple-setup offer better network energy utilization. Each of these utilize over 70% of the network energy (Figure 6.3, 1500 min elapsed) which is relatively higher than both GRACE and PS(C+A). However, from the first look, it seems that PS has effectively handled the Network energy, which is not the case. In fact, when compared with multiple-setup, the energy depletion in other schemes is much faster because of the higher update overhead. This justifies that the multiple setup also keeps the data routing tables of the nodes updated for better communication efficiency. Also, in GRAB, though the energy utilization shows promising outcomes yet, the overall performance is compromised due to redundant transmissions in GRAB.

6.3.3 Network lifetime

In Figure 6.4 and Figure 6.5, number of alive nodes is plotted against time. While comparing, it is clear that in case of PS, PS (B-ack) keeps higher number of nodes alive for longer duration compared to any other mode. The steeper fall in the PS (B-ack) curve indicates that the battery of individual nodes is uniformly utilized, hence prolonging the network lifetime. PS (C+A) also shows acceptable results compared to other modes of PS. It is therefore, recommended that these two modes must be particularly considered if the network lifetime enhancement is the primary

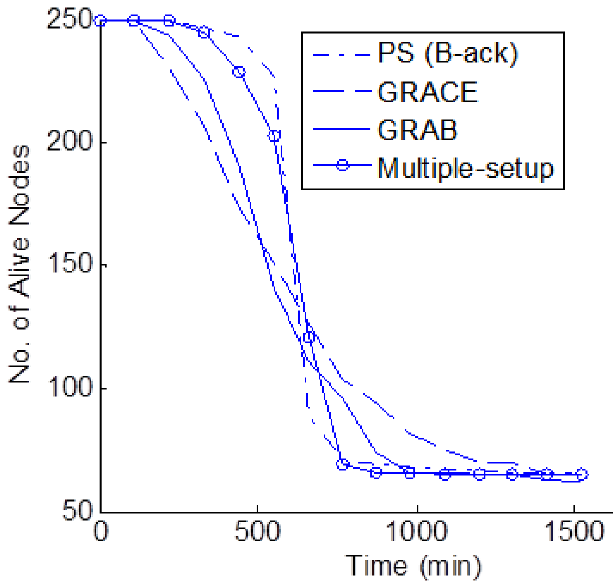

Figure 6.5: Network Lifetime Gradient Protocols

objective. In Figure 6.5, comparing the plots of GRACE, GRAB, PS (B-ack) and multiple-setup it can be seen that the multiple-setup and PS offer significant increase in network lifetime compared to the GRACE and GRAB. Although the multiple-setup offers extended network lifetime, the updates at the start of the network operation are less frequent (see Eq. 6.1 & Eq. 6.7), resulting in early drop in multiple setup plot. However, it regains with PS, rather outperforms at

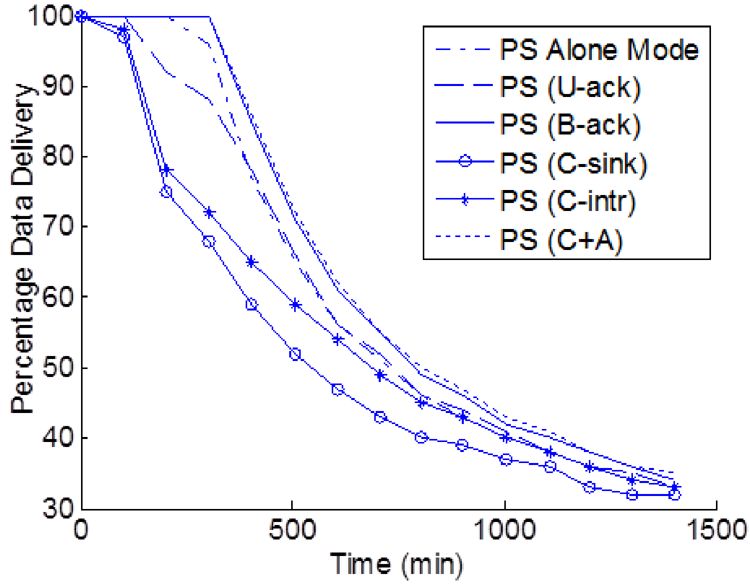

Figure 6.6: Percentage data delivered PS-Modes

the later stages. The adaptive update mechanism in multiple setup allows an increase in network lifetime due to the relatively lower control overhead.

6.3.4 Successful packet transmission and data reliability (μ_r)

In energy-efficient routing protocols for IWSNs, reliability is a crucial attribute. Any extended

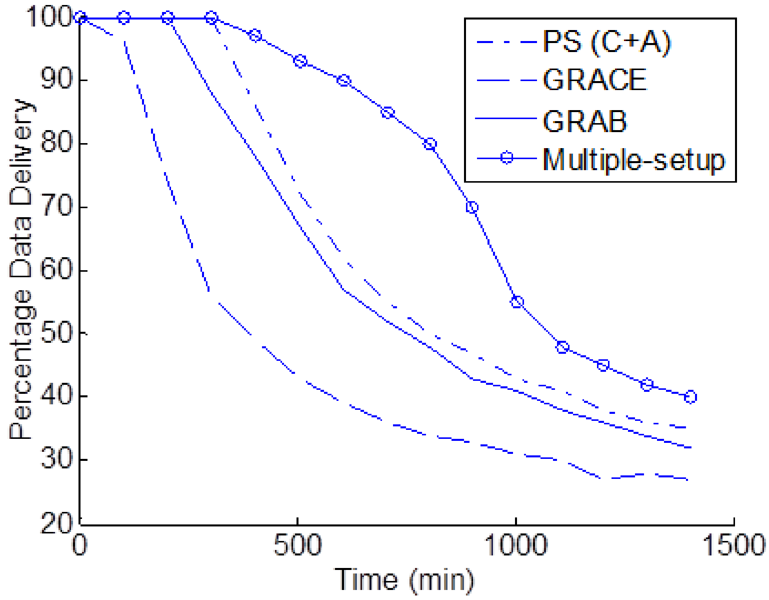

Figure 6.7: Percentage data delivered in gradient protocols

lifetime is only valid when a successful packet transmission rate remains acceptable. Data reliability is measured by the ratio of the end-to-end received, transmitted packets. The

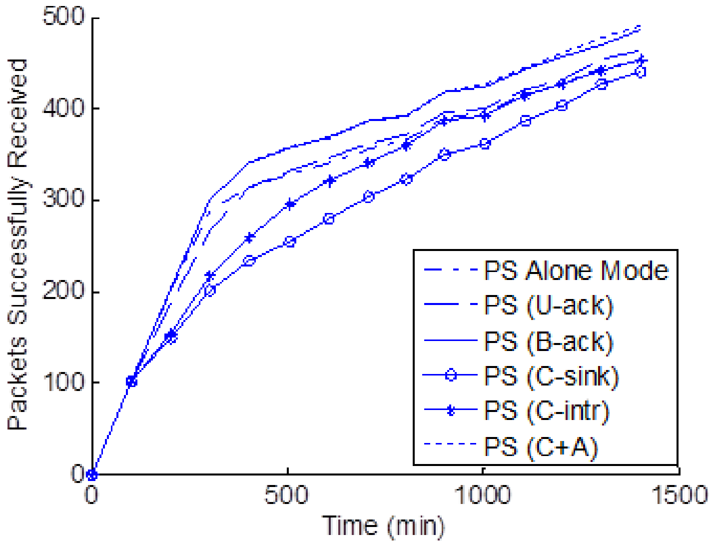

Figure 6.8: Packets successfully received in network life-time, PS-Modes

reliabilities of proposed schemes and parent protocols are represented in Figure 6.6 to Figure 6.9. In these figures, interval based successful packet transmission ratio, data (percentage) received and the count of successful packet delivery in entire network lifetime are represented. In Figure 6.8, the total number of packets delivered in a network lifetime for various modes of PS is represented. It gives a clear indication that the PS (C+A) offers higher number of packets

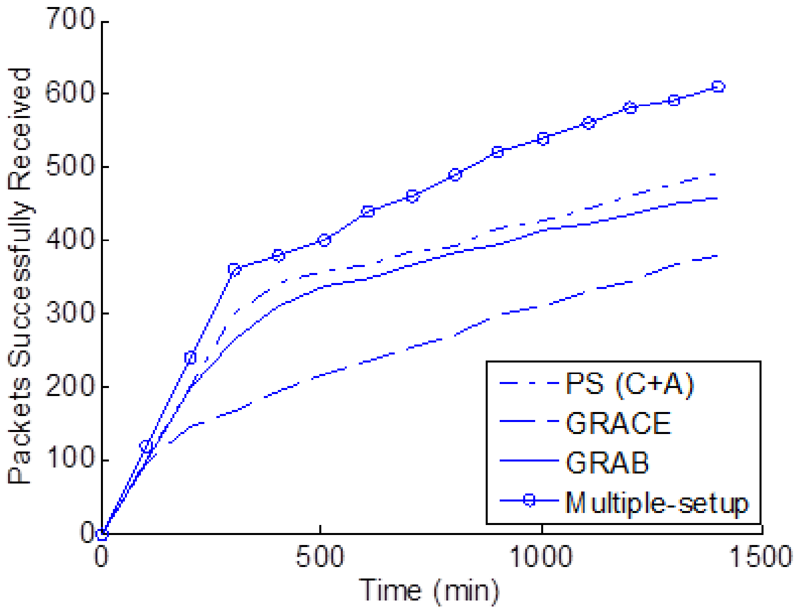

Figure 6.9: Packets successfully received in network life-time, Gradient protocols

delivered, closely matched with PS (B-ack). In Figure 6.9, PS (C+A) shows a modest improvement of 5% and 25% in GRAB and GRACE, respectively. However, multiple setup offers 20% (over 600 vs 500 packets) increase in packet delivered by GRAB where as a significant 55% (over 600 packets vs 400 packets) increase in the total packets delivered in the network lifetime

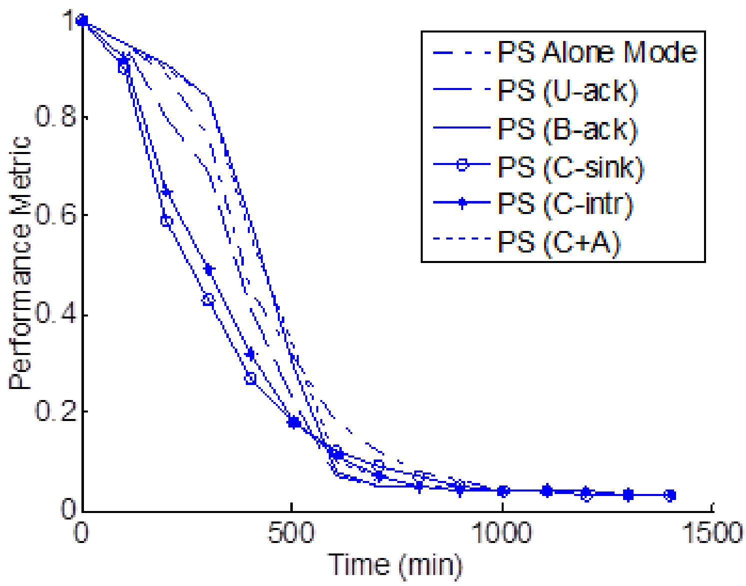

Figure 6.10: Collective Performance Metric (k) PS-Modes
of GRACE.

6.3.5 Collective performance metric, $k = (\varepsilon \times \mu_r \times e_a)$

The Collective Performance Metric k reflects the combined effect of the remaining network energy (ε), reliability (μ_r) and the nodes alive (e_a). Figure 6.10 shows the collective performance metric for different modes of PS against simulation time whereas Figure 6.11 shows collective performance metrics for GRACE, GRAB, PS (C+A) and multiple-setup against simulation time. Based on collective performance metric, the broadcast acknowledgement and hybrid modes (Figure 6.10), both depict almost similar behaviour and can be alternatively used as an efficient solution for energy efficient and reliable network formation. In Figure 6.11, the normalized

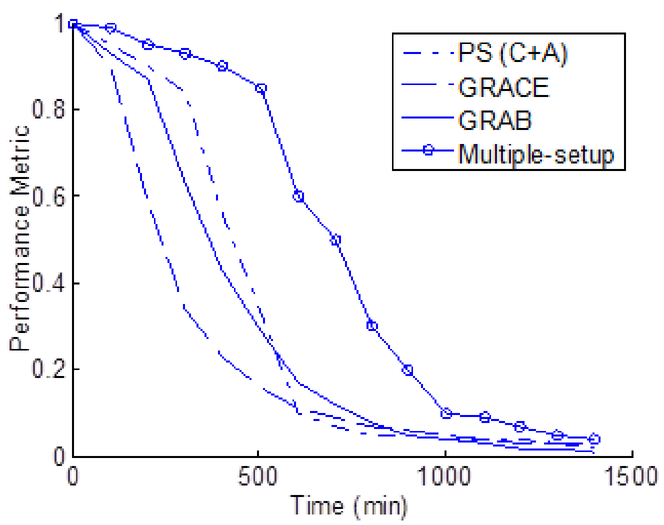

Figure 6.11: Collective Performance Metric (k) Gradient Protocols

performance metric in GRACE, GRAB and PS (C+A) show a significant decrease in longer run, however the multiple-setup maintains high performance for much longer duration. An energy-efficient and more reliable performance for longer duration can be expected when a multiple-setup is considered as a cost update scheme. The better performance in multiple-setup can be attributed to the reduced update overhead and well-updated nodes' routing tables.

6.4 Experimental Results and Discussion

To validate the simulation results discussed in last section, Sun SPOT wireless sensor motes are used to formulate the practical testbed. The experimental evaluation was used to investigate network energy depletion, network lifetime, and communication reliability.

6.4.1 Experimental setup

The wireless sensor test bed taken for the experimental setup comprises of 9 Sun SPOT [24] nodes including a source and a sink. In Figure 6.12, the energy consumption of each node used in the experiment is represented where the unique address of each node is represented on y-axis. The selection

Table 6.2: Sun SPOT Specifications [37]

Hardware Parameters	Values
IEEE standard	802.15.4
Frequency	2.4GHz
Processor Speed	180MHz
Radio	CC2420
RAM	1MB
Flash memory	8MB
Battery	3.7V Lithium-ion battery 770mAh

of Sun SPOTs among other commercially available sensor nodes is primarily inspired due to its high processing capabilities and compact design, suitable for majority of applications. Key specifications of a typical Sun SPOT mote are shown in Table 6.2.

The Sun SPOT based testbed is used to replicate the real-world scenario and to practically verify the observed improvements from the simulations of the proposed schemes. Both PS and multiple-setup are implemented on Sun SPOT testbed, along with GRACE and GRAB to compare the overall performance improvement while using PS and multiple-setup. For the evaluation

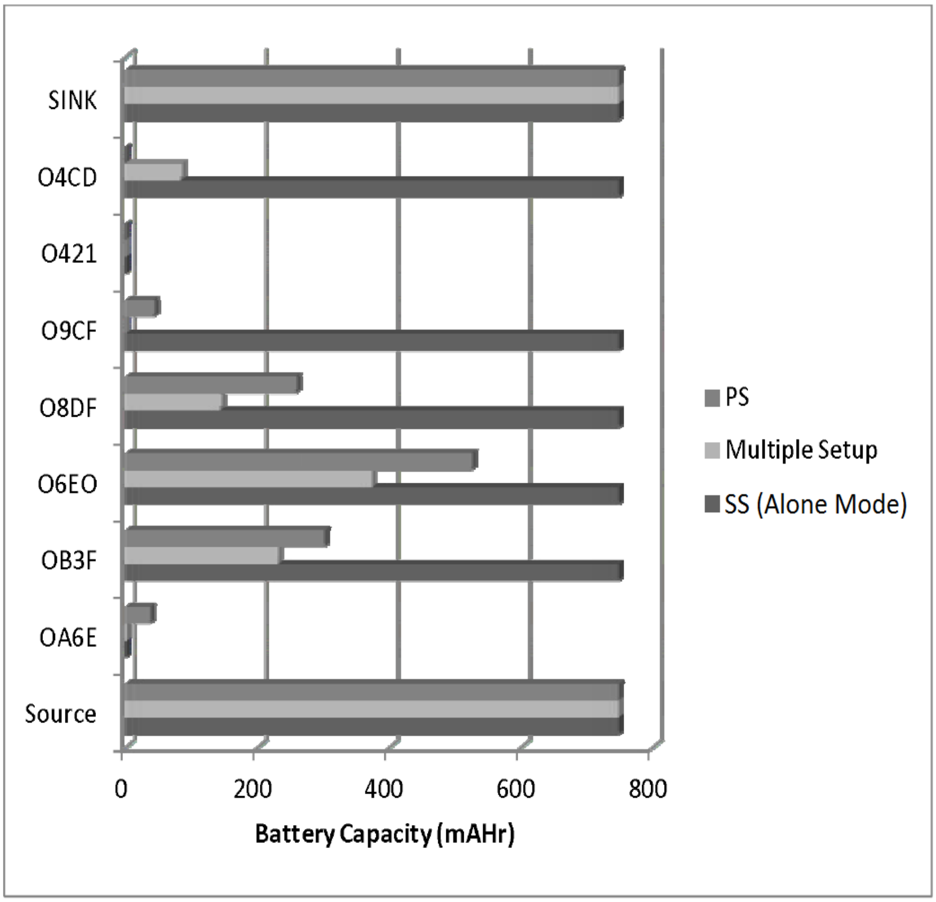

Figure 6.12: Nodes' Energy Left after Network Failure

purposes random deployment is used. Once the nodes are deployed, it is maintained for evaluation of all the schemes to achieve comparable results. The algorithm implemented for a specific scenario is presented in Algorithm 6.1. Note that the experiments are conducted under uniform circumstances to evaluate realistic improvements. The gradient cost function, presented in Section 6.2.1, is customized as specified in the simulation results (Section 6.3.1) to attain the desired improvements in communication reliability and network lifetime. In accordance with the simulations, the experimental evaluation also uses the same metrics for performance evaluation. Details of the observed results are listed as follows.

6.4.2 Node energy leftover after network failure

The term network failure is associated with the state where the sink stops receiving data from the network primarily due to the energy depletion of several nodes in the network causing failure in link from source to destination. Note that, PS(C+A) mode is used in the experimental evaluation

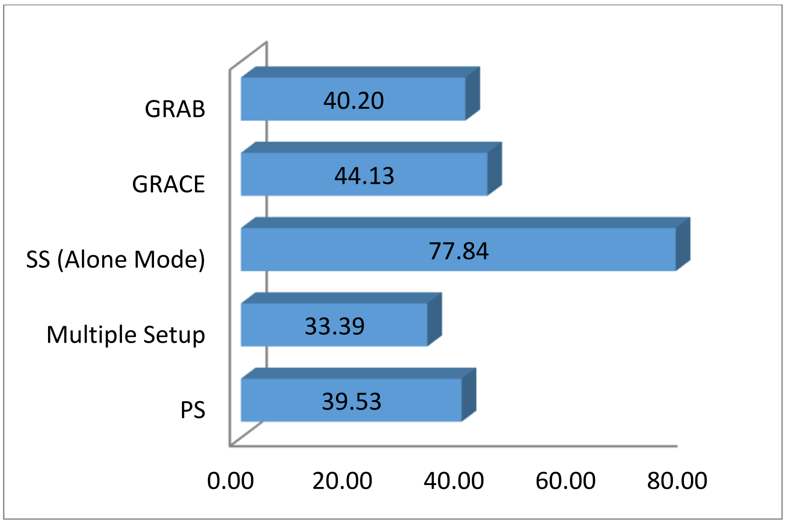

Figure 6.13: Accumulative Network Energy Left after Failure

due to the better performance of this mode compared to the rest of the modes. For generalization, the term PS is used instead of PS (C+A).

In Figure 6.12, it can be seen that the multiple-setup, due to its dynamic update scheme, utilizes the nodes' energy more efficiently compared to PS and single setup (alone mode) phases, therefore, it offers a longer network lifetime. Note that the source and the sink are kept fully charged throughout the experiment to investigate the network lifetime until the failure within the network occurs.

6.4.3 Network energy leftover

In Figure 6.13, the percentage energy leftover after the network failure is represented. The

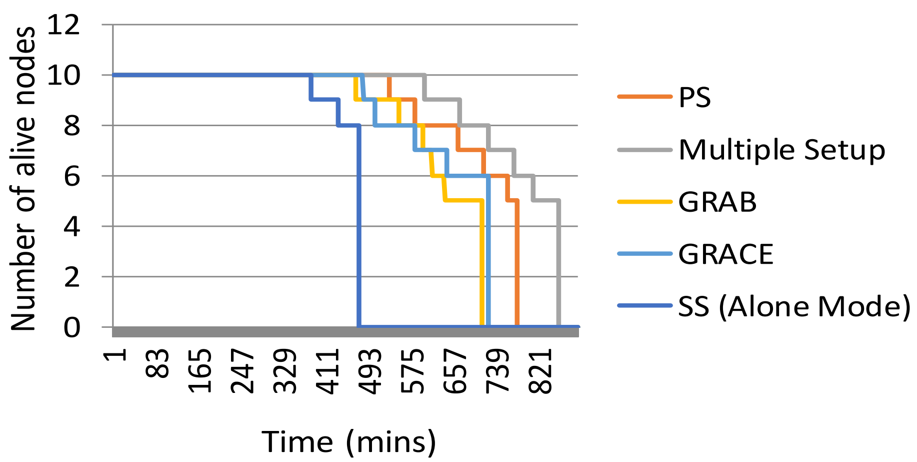

Figure 6.14: Network Lifetime

figure shows that multiple-setup offers more energy-effective utilisation compared to GRACE, GRAB and PS. The efficient and balanced energy utilization enables the network to keep the operation for a longer duration (up to 20% increase).

6.4.4 Network lifetime

Figure 6.14 shows the network lifetime of GRACE, GRAB and proposed Periodic & multiple-setup. The test was performed under uniform circumstances on a pre-installed WSN test bed to offer unbiased evaluation. It is observed that multiple-setup offers extended lifetime compared to other schemes.

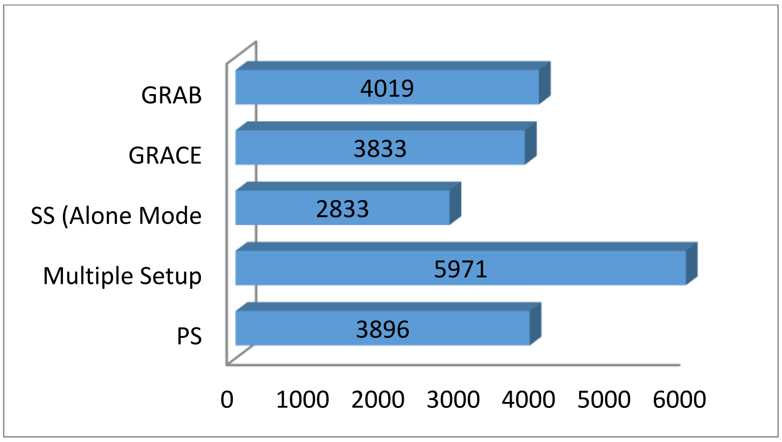

Figure 6.15: Successful packet transmission in network lifetime

6.4.5 Successful packet transmission and data reliability

The number of data packets transmitted by single-setup (Alone Mode), GRACE, GRAB and the proposed update schemes are represented in Figure 6.15. From the obtained data, the extended lifetime allows multiple-setup to deliver the maximum number of packets. Other protocols do not perform that well because in PS, most of the energy is wasted in transmitting control packets, whereas in single-setup protocols, status information is not updated regularly. In multiple-setup, less energy is utilized in sending control packets, while most of the energy is used for sending data packets. The dynamic update procedure in multiple-setup enables over 30% increase in overall count of packets delivered in network lifetime in parent protocols GRACE and GRAB.

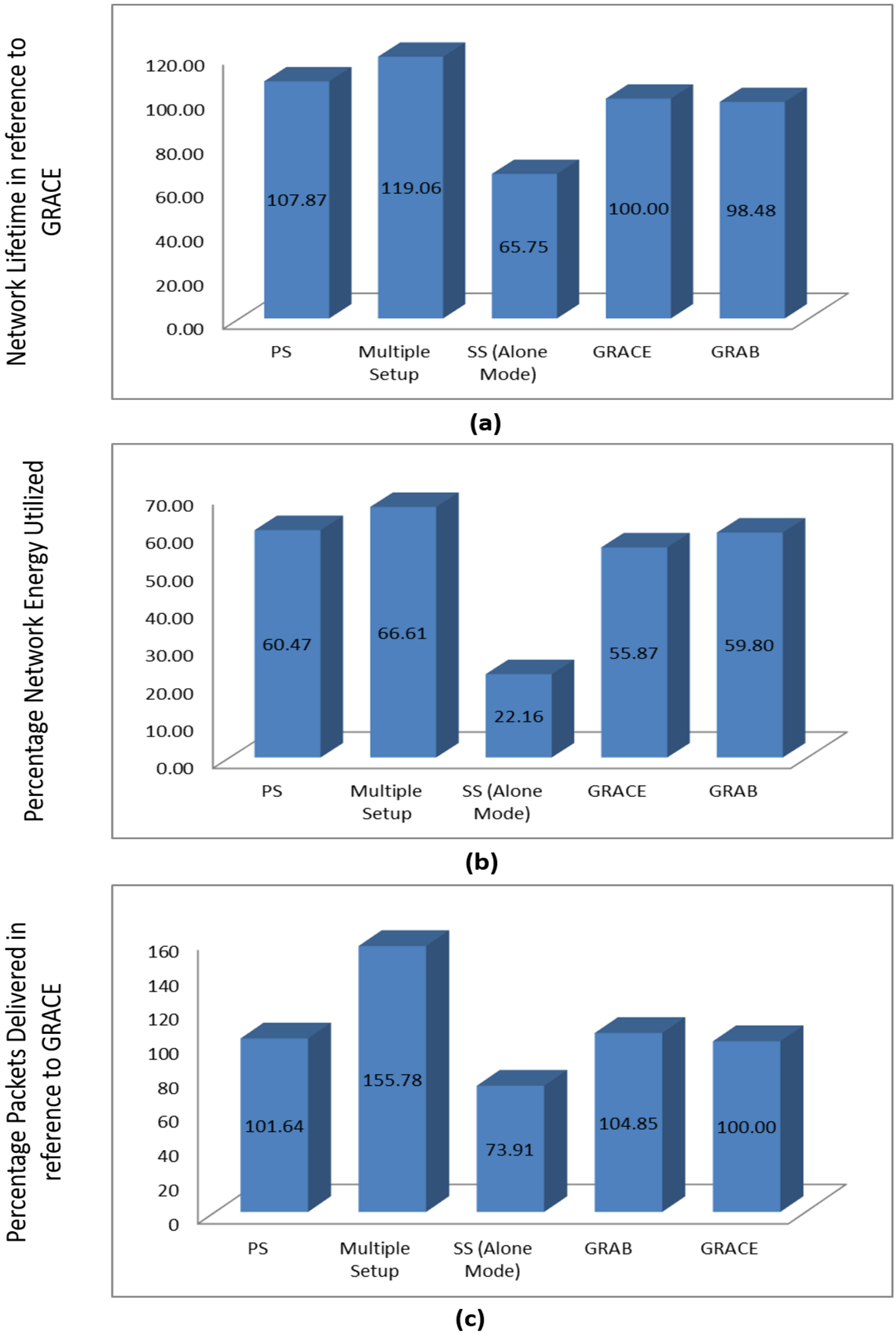

Figure 6.16: (a) Network Lifetime, (b) Percent network energy utilized, (c) PRR

6.4.6 Efficiency

The network efficiency of the gradient-based routing protocols and proposed schemes is evaluated using three key indicators, network lifetime, percentage network energy utilized and successful packet transmission percentage as represented in Figure 6.16 (a), (b) and (c) respectively. Network lifetime of all the schemes are expressed with reference of GRACE. Figure 6.16 (a) shows that the multiple-setup offers 20% increase in lifetime compared to GRACE and 81% compared to SS. It also enables higher packet delivery ratio compared to other schemes.

6.5 Analysis of Results

6.5.1 Analysis of simulation results

The results of the simulation setup show that the PS performs very well in broadcast acknowledgement and hybrid modes. Broadcast acknowledgement and hybrid modes show significant difference compared to other modes. Simulations show that PS (C+A) brings notable improvements in gradient-based routing protocols GRACE and GRAB in network energy utilization and network lifetime. It also gives a marginal improvement in the packets delivered in network lifetime. Improvements from multiple-setup, on the other hand, were very prominent in network lifetime extension and efficient energy utilization. The multiple setup offered an increase of 20% and 55% in the packets delivered in a network lifetime by GRAB and GRACE respectively. The adaptive nature of multiple setup allows efficient use of resources along with the reliability improvements.

6.5.2 Analysis of experimental results

The results of the experimental setup show that the multiple-setup offers a notable improvement in the performance of gradient-based routing protocols. The multiple-setup offered an increase of 51% and 55% in the packets delivered in a network lifetime by GRAB and GRACE respectively. Whereas, the lifetime with multiple-setup showed an increase of around 20% in both GRACE and GRAB and 81% compared to SS. PS, on the other hand offered marginal improvements in network lifetime, network energy utilization and packets delivered.

Results from simulation as well as experiments suggest notable improvements in the network lifetime, efficiency, network energy utilization and reliable packet delivery in gradient-based routing protocols when multiple-setup was used. The scheme provides a low complexity solution for the improvements in the network lifetime and overall data delivery.

6.6 Summary

The proposed schemes address the problem of data routing between sensor nodes and the sink, keeping in view the energy awareness and reliability. The proposed schemes are tested through simulation as well as experimental results. After thorough evaluation of the proposed schemes using various performance metrics including PRR, lifetime extension and energy utilization patterns it can be seen that the proposed schemes once embedded in gradient-based parent protocols, outperform both well-known routing protocols GRACE and GRAB. Multiple-setup offers notable improvements in network lifetime, packet delivery and efficient network energy utilization of the parent protocols. On the other hand, some modes of PS also exhibit potential for improvements.

7 COMMUNICATIONS SCHEDULING IN IWSNS

7.1 Introduction and Relevant Developments

The industrial systems with incorporated automation and process control require a wide range of simultaneously running processes [30, 35]. Each of these processes depends on the information sampled from a number of sensors which plays critical role in the satisfactory operation of these processes. Depending on the significance of the system, feedback requirements and allowable deadlines, each of these sensors may have different sampling times [180]. Therefore, sensors involved in different processes and applications, embedded in the industrial automation and feedback control systems might have very different update frequencies.

The time deadlines of the sensors involved in the regulatory feedback, open loop control and monitoring systems could therefore vary significantly [35]. Since the sensors in the industrial environments belonging to these systems (regulatory, open-loop and monitoring systems) can exist in the same locality and cannot be isolated based on geographic placement. Therefore, scheduling for sensing data from all these systems (having heterogeneous time deadlines) must be performed. In typical WSNs, the communications of such diverse deadlines is mostly handled by adopting the CSMA/CA based channel access schemes [19], which allows the individual nodes to access the channel on the need to need basis or when the communication deadline is approaching. However, due the lack of reliability in CSMA/CA based channel access schemes, its use is not much appreciated in IWSNs. The critical nature of the information [34] in industrial applications and severity of the consequences of failed communications, more reliable channel access schemes are preferred. Hence, the TDMA based channel access scheme serves as a more suitable alternate compared to CSMA/CA based channel access in IWSNs. Furthermore, high dependability of QoS on number of nodes in CSMA/CA based schemes also limits its scope for dense networks. To overcome the issues posed by CSMA/CA based schemes, TDMA based channel access was introduced in IEEE802.15.4e, (industry oriented WSN communication standard) for improved reliability and acceptable QoS [18]. Since TDMA based channel access schemes involve prior scheduling, solutions are proposed to offer runtime schedule, which takes into account the deadlines of the affiliated nodes in every superframe and formulates a schedule for the nodes for each superframe. Although the runtime scheduling offers a deadline-based schedule, the information to control bits ratio is decreased due to the need for increased number of control bits (used for schedule update in every frame). The affiliated nodes also need to stay in active listening mode during control and schedule exchange periods to ensure whether their communications is scheduled or not. Given the importance of long lifetime of the sensor nodes, aforementioned scheduling solution, due to longer active listening periods, degrades the battery life significantly, resulting early depletion of node's energy. Apart from this, since the TDMA based channel access schemes require prior assignment of time-slots to the network nodes, the symmetrical access of the nodes cannot always be ensured in runtime scheduling.

The shortcomings of the opportunistic approach (CSMA/CA) and runtime scheduling can be addressed with the symmetric scheduling. However, for diverse time deadlines, the formation of symmetric schedule using TDMA based channel access mechanism is a very challenging task. The schedule complexity further increases with the increase in the variations in the deadlines and number of nodes to be scheduled.

In this chapter, a novel low complexity scheduling scheme is presented which takes into account the abovementioned issues and formulates a static schedule for TDMA based communication. The scheme uses IEEE802.15.4e superframe as a baseline and proposes a new superframe structure. The static schedule generated by the scheduling algorithm offers reduced energy consumption, improved reliability, efficient network load management and improved information to control bits ratio

7.2 System Model

Due to a wide variety of applications in the industrial environments, ISA has divided industrial systems into six different types [35]. Each of these offers the services for specific areas of applications including emergency, regulatory control, supervisory control, open loop control, alerting and monitoring. Based on the class of application and the sensitivity of the observed

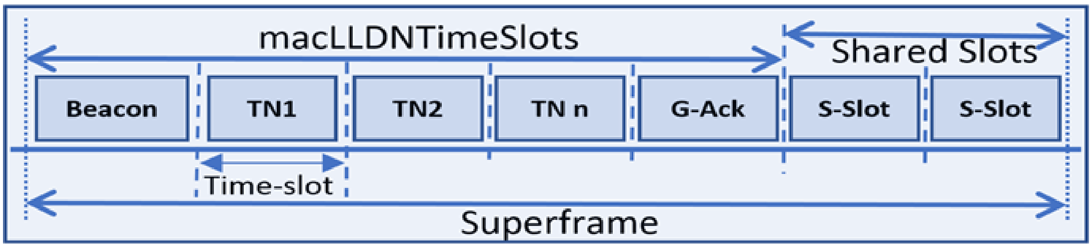

Figure 7.1: IEEE 802.15.4e Communication Frame structure with Group acknowledgement and shared slots

parameter, a deadline is usually affiliated with all sorts of periodic communications in industrial environments. As IWSNs serve as a mean to communicate the generated traffic from various sensing nodes, it should also ensure the timely scheduling of communications to avoid unwanted delays.

7.2.1 Network architecture and proposed superframe structure

The proposed system uses TDMA based channel access and basic frame structure of IEEE802.15.4e, LLDN. The superframe structure for LLDN is represented in Figure 7.1. A cluster based approach is considered where star topology is implemented to connect sensor nodes with the cluster-head. The pre-specified schedule is used for the TDMA based communications

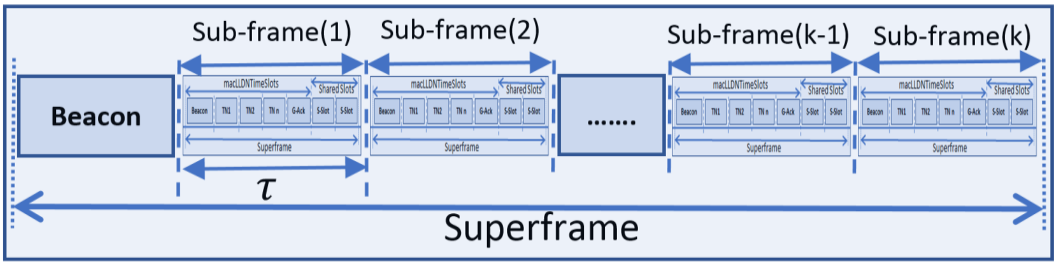

Figure 7.2: Superframe structure for the proposed scheduling algorithm slots

within the cluster with GAck based confirmation and shared slots for retransmission of the communication. The communication of data to the destination is supported by the hierarchical architecture.

To schedule large number of transmitting nodes, with desynchronized time deadlines, the modified superframe is presented in Figure 7.2. In this case, each superframe is divided in sub-frames, each of duration τ. The sub-frame replicates the IEEE 802.15.4e frame structure presented in Network initialization and information communication

The duration of the superframe is controlled by the lowest sampling frequency (f_{min}) of all the nodes in cluster and is given by $T_{sf} = 1/f_{min}$. The duration of the sub-frame, τ is given by: $\tau = \frac{T_{sf}}{sfCount}$, where $sfCount$ is the number of sub-frames in a superframe. A sub-frame duration can also be represented as: $\tau = 1/f_{max}$, where f_{max} is the frequency of the most frequently communicating node. The sub-frame duration is carefully selected so that the most frequently communicating nodes only communicate once during each subframe. The total transmissions that can take place during a superframe are denoted by n and is presented in Eq. 7.1.

$$n = j \times \frac{T_{sf}}{\tau} \tag{7.1}$$

Here j is the number of time-slots per sub-frame.

In any possible scenario, the total time slots required for a proper communications of every node in the cluster is defined by the number of nodes in a cluster and time delay between two consecutive transmissions, i.e. frequency of transmission of the nodes. A generalized equation for total number of required transmission slots, z, is presented in Eq. 7.2.

$$z = \frac{\left(\sum_{i=1}^{s} f\_bits_i \times Sym(r_i\,,\ \ sym\_dl)\right) \times T_{sf}}{B_\Delta} \tag{7.2}$$

Here s is the total number of sources, f_bits_i is the number of bits to be transmitted by the source i in every communication, r_i is the sampling rate of the node i, B_Δ is the number of bits communicated in single transmission and sym_dl is the vector of all possible symmetric deadlines for the values of T_{sf} and τ. The $Sym(r_i,\ sym\_dl)$ is a function which approximates the communication frequency (sampling rate) to nearest repeatable value from the sym_dl vector. This allows nodes to have symmetrical communication patterns within each superframe. The symmetrical deadline selected is either lower than or equal to r_i to ensure the in-time delivery of the information from all the affiliated nodes.

To evaluate the scheduling efficiency of the algorithm, the overall load of the network is also evaluated. Here the Network Load (NL) is defined as the ratio of the required transmission slots (z) to the total available slots (n) and is presented in Eq. 7.3.

$$NL = \frac{z}{n} \tag{7.3}$$

The information provided in Eq. 7.3 gives a measure of the network load handled by the algorithm and saturation point of the algorithm.

The communications between the cluster-head and the source nodes is established in two phases. In first phase (setup phase) the nodes send a request to affiliate with a cluster-head depending on the received RSSI values. The request message also includes the data requirements of a particular node, specifying the details of number of transmission slots needed per unit time. Once the requests are received the cluster-head acknowledges the affiliation of the nodes to the cluster. It is assumed that the load on the cluster-head is shared with the neighboring clusters if the data requirements for all the requests approach to the maximum load limitation of the cluster-head (i.e. $\sigma \rightarrow n$). Along with the confirmation of the affiliation to a cluster, the cluster-head also assigns localized identification numbers to the nodes. Once the nodes are associated to the relevant cluster-heads, each cluster-head broadcasts a communication schedule.

In the second phase (data communication phase), based on the shared schedule the transmission of the sensed data from the sensor nodes to the cluster-head takes place. Any new nodes trying to affiliate with the cluster-head after the setup phase use control channel. The affiliation is provided based on the availability of vacant transmission slots for communication of upcoming node.

7.2.2 Communication Scheduling

The communication schedule evaluated at the cluster-head based on the received transmission requirements of the nodes provides a static schedule, which requires no modifications unless a new node sends affiliation request to the cluster-head or the association status of one or more associated nodes is changed over time. In addition, with the new association or disassociation of nodes, the schedule of the already affiliated nodes does not change, enabling the undisturbed nodes' operation for longer duration. Two primary benefits are achieved using deterministic schedule:

(i) Improved reliability due to less frequent changes in the nodes' transmission schedule and stability in communications

(ii) Improved energy efficiency due to the extended sleep periods and reduced idle listening periods

As stated earlier, the sensed information from different nodes, with communication frequencies ranging from f_{min} to f_{max}, defines the duration of superframe (T_{sf}) and sub-frames (τ). Furthermore, $T_{sf} = N \times \tau$, is also ensured, where N is a positive integer, so that each superframe has *N* sub-frames.

The scheduling of heterogeneous sensing deadlines is considered highly complex; therefore, some non-conventional means are proposed for the efficient schedule generation. Since the target application areas for the proposed scheme are regulatory feedback, open loop control and alerting traffic, therefore, all the nodes need to be scheduled can be categorized as periodic communication sources.

To reduce the scheduling complexity, the sources in the IWSNs are divided into four categories, based on their communication intervals. This division allows more efficient scheduling of each category and finally these four schedules can easily be combined. These categories are:

(i) T_A: sources with communication frequency, f_{max}, which communicate during every sub-frame i.e. in every τ.

(ii) T_B : sources communicating once every $(2 \times Q) \times \tau$ intervals (where Q is a positive integer and $Q < N/2$) This category deals with nodes with time deadlines which are even multiples of τ.

(iii) T_C: sources communicating in every $((2 \times Q) + 1) \times \tau$ intervals (where Q= 1, 2, $\ldots, \frac{N}{2} - 1$). This category deals with the nodes having time deadlines as odd multiples of τ. Therefore, each communication from these nodes will take place after odd number of sub-frames. For example, A node which needs to communicate after every 50ms in a superframe of duration $400ms$ ($T_{sf} = 400ms$) and sub-frame duration of $10ms$ (τ = 10ms) can communicate in sub-frame 1, 6, 11, 16, 21, 26, 31 and 36 in each superframe.

(iv) T_D: sources with communication frequency, f_{min}, which communicate once every superframe.

The total number of source nodes in each category T_A, T_B, T_C and T_D are w, b, c, and d

	T_A				T_B				T_C				T_D	*Unscheduled*
Timeslot → / Subframe ↓	Slot 1	Slot 2	Slots ...	Slot w	Slot w+1	Slot w+2	Slots ...	Slot p	Slot p+1	Slot p+1	Slots ...	Slot s	Slot s+1	Slot s+2
Subframe 1	N1	N2	...	Nw	Nw+1	Nw+3	...	Nw+11	Nw+14	Nw+19	...	Nw+24	Nw+26	...
Subframe 2	N1	N2	...	Nw	Nw+2	Nw+4	...	Nw+12	Nw+15	Nw+20	...	Nw+25	Nw+27	...
Subframe 3	N1	N2	...	Nw	Nw+1	Nw+3	...	Nw+13	Nw+16	Nw+21	...		Nw+28	...
Subframe 4	N1	N2	...	Nw	Nw+2	Nw+5	...		Nw+17	Nw+22	...		Nw+29	...
Subframe 5	N1	N2	...	Nw	Nw+1	Nw+3	...		Nw+18	Nw+23	...		Nw+30	...
...	N1	N2	...	Nw	Nw+2	Nw+4	...		Nw+14	Nw+19	...			...
...	N1	N2	...	Nw	Nw+1	Nw+3	...		Nw+15	Nw+20	...			...
...	N1	N2	...	Nw	Nw+2	Nw+5	...	Nw+11	Nw+16	Nw+21	...	Nw+24		...
...	...	...	...	...	...	Nw+3	...	Nw+12	Nw+17	Nw+22	...	Nw+25		...
...	...	...	...	...	...	Nw+4	...	Nw+13	Nw+18	Nw+23	...			...
...	...	...	...	...	...	...	...		Nw+14	Nw+19	...			...
...	...	...	...	...	...	...	...		...	...	...			...
Subframe N-1	N1	N2	...	Nw	Nw+1	Nw+3	...		...	...	...	Nw+24		...
Subframe N	N1	N2	...	Nw	Nw+2	Nw+5	...		...	...	...	Nw+25		...

Unscheduled slots   Traffic Type T_A scheduled   Traffic Type T_B scheduled   Traffic Type T_C scheduled   Traffic Type T_D scheduled

Figure 7.3: Superframe communication schedule for nodes affiliated to cluster-head

respectively. The scheduler first schedules T_A then T_B then T_C and at last T_D. The scheduling algorithm is presented in Algorithm 7.1, whereas an example scenario for the scheduling is presented in Figure 7.3.

Algorithm 7.1: Schedule formation for communication of heterogeneous sensor sampling in IWSNs.

Input: $(\mathrm{f_i}, \mathrm{f_{bits_i}}, sym_{dl}, B_\Delta, \mathrm{k}, \mathrm{s}, \mathrm{i} = 1, 2, \dots, \mathrm{s})$

Output: (Sch) //Transmission Schedule

1. sortAscending ($\mathrm{f_i}$); /* sorting sampling rate/communication frequencies ($\mathrm{f_{min}} = \mathrm{f_1}$ & $\mathrm{f_{max}} = \mathrm{f_s}$) */
2. $T_{sf} = 1/f_{min}$;
3. $\tau = 1/f_{max}$;
4. $sfCount = T_{sf}/\tau$; /*Total Sub-frames per superframe*/
5. $n = k \times (T_{sf}/\tau)$;
6. $\sigma = (\sum_{i=1}^{s} f\_bits_i \times Sym(r_i\,,\ \ sym\_dl)) \times (T_{sf}/B_\Delta)$;
7. $NL = \sigma/n$;
8. *If(NL≥1) {Re-run Setup Phase/Selected nodes; Go to 1;}*
9. *else*
10. *Sch_ T_A =scheduleAll{T_A (sub-frame(1→ $sfCount$),time-slot(1→ s))};*
11. *Sch_ T_B =scheduleAll{T_B (sub-frame(1→ $sfCount$),time-slot(1→ s))},{circShift&adjust};*
12. *Sch_ T_C =scheduleAll{T_C (sub-frame(1→ $sfCount$),time-slot(1→ s))},{circShift&adjust};*
13. *Sch_ $T_{B,C}$ =circShift&adjust (T_B ,T_C)*
14. *count(sch_Slots/sub_frame);*
15. *Sch=merge(Sch_T_A, Sch_ $T_{B,C}$);*
16. *Sch=Adjust {T_D(1→ $total$) ⇒Min(count (sch_Slots/ sub_frame))};*
17. **Return** Sch;

Based on the transmission requirements from all the affiliated nodes to the cluster-head, a transmission schedule is defined for a period of T_{sf} (the duration of the superframe). The same schedule is repeated for every superframe. A map of the superframe schedule is presented in Figure 7.3. As seen in the figure, each row represents sub-frames and columns represent the time slots in each sub-frame where each block identifiable with a sub-frame and time-slot can facilitate communication of one sensor node. Note that N1 to Nw+30 are node IDs used to refer to scheduling of nodes. Since T_A represents the nodes which communicate in every sub-frame so out of n time slots first w time slots in every sub-frame are reserved for type 'T_A' nodes (as represented in Figure 7.3, 'slot 1' to 'slot w' and Algorithm 7.1 [Lines 1-10]). Nodes in Category T_B, on the other hand, do not transmit in every subframe, rather, nodes in this category transmit once every few subframes and need to be arranged in order to maximize scheduling efficiency. As an example, see scheduling of nodes for 'Slot w+1' in Figure 7.3. Two nodes are scheduled in this column, i.e. 'Nw+1' and 'Nw+2'. Nodes Nw+1 and Nw+2 are scheduled alternatively as both of the nodes transmit in alternative sub-frames. To schedule these nodes, the scheduler will firstly schedule both nodes in two separate columns but since both the columns have vacant slots so one of the columns is circularly shifted and then merged together with the other column as they do not have overlapping scheduled information. Note that the circular shift to the columns is limited by:

$$L_{shift} = \left({}^{T_{deadline}}/_{\tau} \right) - 1 \qquad (7.4)$$

Table 7.1: Delay and update requirements for industrial processes [15, 34, 69]

Update frequency and deadlines for control applications in IWSNs			
Control Process	Application Type	Update Frequency	Battery lifetime
Close Loop Control	Control valve [19, 20]	10 − 500 ms	5 years
	Pressure sensor [19, 20]	10 − 500 ms	5 years
	Temperature sensor [20]	10 − 500 ms	5 years
	Variable speed drive [20]	10 − 500 ms	5 years
Interlocking and Control	Proximity sensor [19, 20]	10 − 250 ms	5 years
	Valve [19, 20]	10 − 250 ms	5 years
	Machinery and tools	10 ms	3 years
	Motion Control	10 ms	3 years

In this case as the time deadline of both 'Nw+1' and 'Nw+2' is $2 \times \tau$, only one shift is performed. Similarly, in case of 'slot w+2', three nodes are scheduled 'Nw+3', 'Nw+4' and 'Nw+5'. See that 'Nw+3' has time deadline of 2τ whereas 'Nw+4' and 'Nw+5' have time deadline of 4τ respectively. First 'Nw+3' is scheduled. Since 'Nw+4' cannot be scheduled in same slot unless circularly shifted so the ‘Nw+4’ was placed in the same column with one shift. Since there are still vacant slots in ‘slot w+2’ The scheduler schedules ‘Nw+5’ and checks if it can be adjusted in ‘slot w+2’ by giving up to three shifts ($L_{shift} = 3$, see Eq. 7.4) and checking if there is overlapping schedule or not. As there is no overlapping after three shifts so the scheduler schedules ‘Nw+5’. Nodes belonging to category T_C are scheduled in a similar way. After nodes belonging to both T_B and T_C are separately scheduled, there could be some partially scheduled columns left. In Figure 7.3, columns referred as ‘Slot p’ and ‘Slot s’ still have unscheduled slots so the scheduler can merge these two by circularly shifting Slot p twice. Any remaining available free slots are filled with the schedule of nodes in category T_D. The final schedule is circulated to the nodes in the cluster before the data communications can start.

7.3 Results and Discussion

The performance of the scheduling algorithm is evaluated in terms of the schedule efficiency and energy efficiency. For the evaluation purposes, the deadlines of the nodes are generated within a random range of 10 milliseconds (ms) to 400 ms. As a reference, the desired update frequency/deadlines for selected control applications in industrial environments are presented in Table 7.1. The time deadlines of the individual nodes in one of the evaluated scenarios is presented

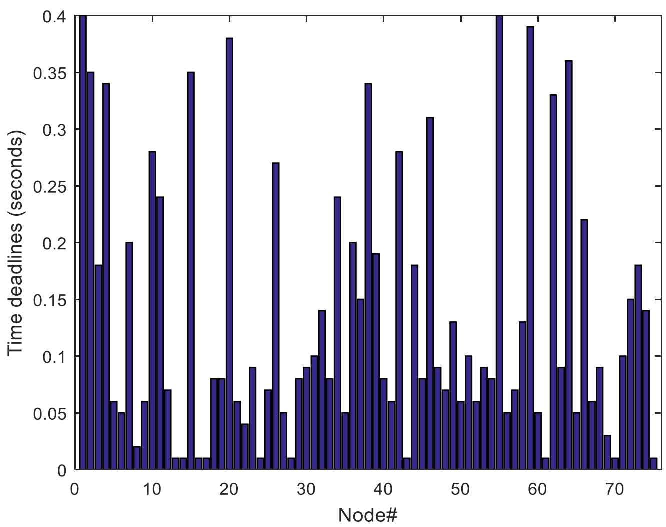

Figure 7.4: Time Deadlines of the Nodes affiliated with a cluster-head

in Figure 7.4. Based on the defined range of deadlines, the values of T_{sf} and τ are evaluated whereas twenty time slots are allocated to a sub-frame. Furthermore, the number of generated information bits per sample, f_bits_i, for node i is assumed to take one time slot for communication.

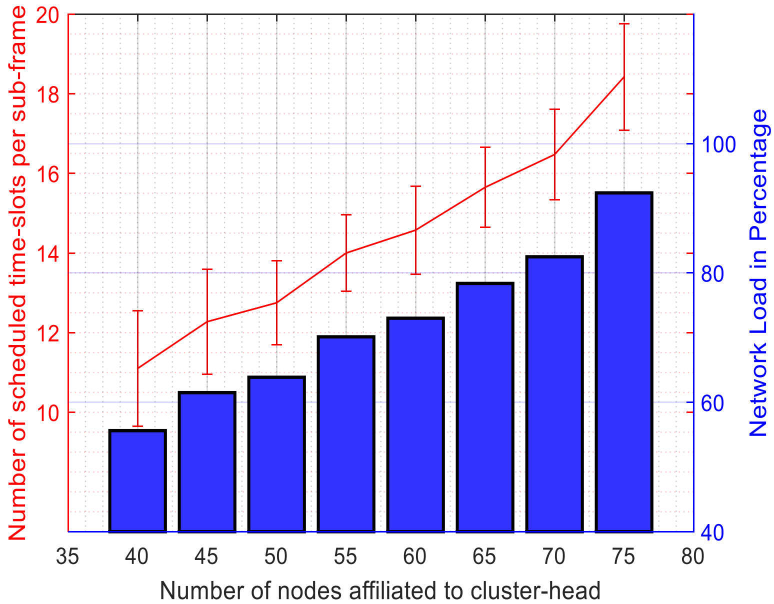

Figure 7.5: Scheduled slots per sub-frame as a function of Network load and number of affiliated

The performance of the scheduling algorithm is evaluated for different loads. This is achieved by increasing the number of affiliated nodes to the cluster-head. In Figure 7.5, the bar graphs represent the traffic load in percentage (right side y-axis) as the number of affiliated nodes are increased from 40 to 75. In extreme cases (nodes=75), the traffic load reaches to 92.4%. The error bars, represented in the second plot in Figure 7.5 (w.r.t left Y-axis) present the average number of scheduled slots per sub-frames, with error bar presenting deviation from the mean value for one complete superframe duration. It can be seen that for loads up to 92.4%, the scheduler still manages to schedule nodes with diverse deadlines. Furthermore, the deviation in number of scheduled slots per sub-frame is well within the maximum number of slots that can be scheduled per sub-frame and since deviation is relatively small, deterministic performance can be ensured due to minimal variations in scheduled slots to shared slots ratio.

Since the proposed scheduling scheme offers a deterministic schedule, therefore, instead of listening to the beacon of each sub-frame (which would be considered as a superframe in traditional cases), the nodes with less frequent communications can choose to listen to the beacon of superframe. For instance, a node transmitting only once in the superframe does not need to listen to the beacon of each subframe. However, it will just listen to the superframe beacon and then to the subframe beacon in which it is communicating in order to ensure time synchronization over time. Listening to the beacon of the sub-frame in which node is scheduled to transmit is used for fine tuning.

Since the active listening mode consumes a reasonable amount of energy, it is therefore, important to optimise the active listening period. In Figure 7.6, the overall active listening period of the nodes in the proposed scheduling scheme as well as the traditional schemes is presented. It can be seen that with the deterministic schedule the overall active listening period during a superframe of duration T_{sf} is notably reduced. This is primarily possible due to fixed schedule generated by the scheduler, which allows nodes to stay in deep sleep mode for longer duration. The nodes with less frequent communications do not need to synchronize and update regularly rather can benefit from the consistent nature of the schedule. The static schedule also allows to minimize conflicts of communications which indirectly improves reliability.

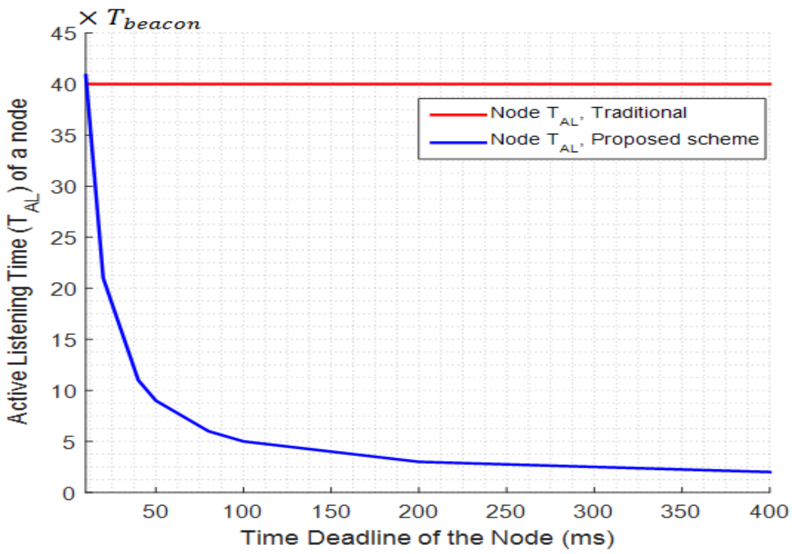

Figure 7.6: Active Listening time of a node in a superframe of duration (T_{sf})

7.4 Summary

Industrial systems have diverse requirements and therefore nodes in IWSNs will have varying and desynchronized time deadlines. Therefore, a deterministic schedule formation for TDMA based communication in IWSNs, is a very challenging task. The proposed scheduling algorithm offers a symmetric and fixed schedule for desynchronized node deadlines. The performance of the algorithm is evaluated based on the scheduled slots in each frame and scheduling ability of the presented scheme under high network loads. Furthermore, the generated schedule is used to improve the lifetime of the wireless nodes by minimizing active listening periods in communications of these nodes.

8 CONCLUSION AND FUTURE WORKS

8.1 Conclusion

In recent years, WSNs have been considerably investigated to evaluate its suitability for industrial applications. The intrinsic flexibility, lower costs of communications, higher market potentials and possibility of reliable, stable, efficient, flexible, and application-centric IWSNs have attracted researchers' attention. The improvements witnessed in this field have been very influential in ensuring wider acceptability of this technology. IWSNs have emerged as a more effective and efficient solution for communications feedback in industrial automation, robotics, manufacturing, facility operation, emergency systems, process control and monitoring applications.

Some of the widely acknowledged advantages of IWSNs are flexibility, self-organization, low cost of installation, self-healing abilities, localized processing, interoperability and ease of deployment. However, this technology also suffers from unpredictability, delay, reliability issues and limited battery capacity. Further research in these areas can assist in exploiting the full potential of the technology. Moreover, the technology also lacks a dedicated research to address industry specific issues, needed to be addressed to ensure acceptable performance of IWSNs within the widespread industrial applications.

This thesis presented a thorough investigation of different classes of industrial systems and highlighted the communication requirements for present and future industries. A detailed discussion on the suitability of different wireless communications standards and technologies, to cope with the challenges in industrial environments, is presented. The research developments in IWSNs to overcome limitations of the technology and to cope with the dynamic industrial requirements, have been thoroughly investigated and a detailed discussion was presented. A comprehensive investigation of the possible research gaps was presented and relevant contributions of this research were highlighted.

The conducted research was mainly targeted to six areas within the industrial networks where suitable improvements have been suggested to overcome reliability, latency, energy efficiency and scheduling issues within IWSNs. The main contributions of the thesis, to ensure ultra-reliable and low latency communications within the IWSNs, included 1) MAC optimization for emergency communications, 2) Reliability enhancement for regulatory and supervisory control information 3) Priority enabled communication in industrial applications, 4) Multi-channel communication for reliability and throughput optimization, 5) Energy efficiency and effective information routing and 6) Deterministic communication scheduling for heterogeneous sensing environments. Further details of each of the above listed contributions are summarised as follows.

A MAC protocol was proposed to ensure time delay minimization and optimal channel access assurance for emergency communications. The proposed scheme allowed to integrate emergency communications within the regular communications channels with optimized access to channel resources for delay minimization and improved reliability. The proposed scheme also eliminated the need for dedicated channel. In the investigations, it was observed that the proposed scheme offers 50% to 92% reduction in communication delay in comparison to IEEE802.15.4e LLDN. The reliability and timely delivery of the communications were also ensured with 31% to 91% reduction in time to successfully transmit packets.

The reliability and real-time data delivery in regulatory and supervisory control system communications were improved using proposed scheme, CF-MAC. CF-MAC ensured time bounded communications for regulatory control processes, where variable superframe durations were introduced to compensate for communication failures. A careful modelling for communications in supervisory systems was also presented to offer bounded delays and improved reliability. The performance of the proposed scheme was verified using mathematical modelling and simulation based performance evaluation. The results have shown that CF-MAC offered a notable improvement in reliability along with 60% to 85% improvement in channel access delay in comparison to IEEE802.15.4e LLDN.

To offer priority based communications in IWSNs, a dynamic priority system was proposed which evaluated priority in real-time. The proposed priority system classified various communications taking place within the industrial environments, which was used to prioritize the communication of critical nodes/data. To ensure the optimal performance, four protocols were introduced where two protocols (PE-MAC and O-PEMAC) targeted the reliability improvement and delay minimization of the high priority communications within the industrial wireless networks, whereas QES and PQES proposed adaptive schemes to ensure a desired successful packet communications ratio. The simulations showed that PE-MAC offered 75% reduction in communications failure of high priority nodes and O-PEMAC ensured successful frame communications of 99.999%. QES and PQES also maintained the pre-specified successful packet communications ratio, where a consistent 99.999% PRR was achieved under diverse channel conditions.

A multi-channel performance and throughput enhancement scheme for IWSNs was proposed. In this scheme, the performance was evaluated using throughput, reliability and number of nodes accommodated in a cluster. The scheme offered a notable increase in the reliability and throughput over the existing IEEE802.15.4e LLDN standard. Whereas a notable improvement in capacity was also observed.

To optimize multi-hop communications in the IWSNs an incremental work has been presented where gradient-based routing protocols are optimized to offer improved energy efficiency and reliability. Two update mechanisms, PS and MS were introduced which kept the network updated and offered optimized throughput, reliability and energy efficiency. A GCF was also proposed which can be optimized as per the network and routing requirements. The simulations and experimental evaluations of schemes using various performance metrics including PRR, lifetime extension and energy utilization patterns were performed. Investigations revealed that the proposed schemes once embedded in gradient-based parent protocols, offered notable improvements in network lifetime, packet delivery and efficient network energy utilization.

To address the issues of coexistence of various industrial processes and communications of various sensory data with diverse time deadlines over same wireless communications channels, a scheduling algorithm was proposed. The proposed scheduling algorithm offered a symmetric schedule for desynchronized node deadlines. The main contributions in this work included the low complexity of scheduler and reliable deterministic schedule formation. The accuracy and scheduling ability of scheduler was tested under various load and network conditions. Furthermore, the generated schedule was used to improve the lifetime of the wireless nodes by minimizing active listening periods using static schedule formulated at the start of communications.

The work summarized in this thesis targeted the industrial applications where the main focus was the reliability improvement and delay minimization. The research mainly targeted the critical industrial processes including emergency systems, regulatory control systems, supervisory systems and open-loop control systems. In these systems, the feedback communications played a very important role in ensuring the effectiveness and accuracy of the running processes. Therefore, the work summarized in this thesis, targeted the improvements in the communications link in the aforementioned systems. Some of the secondary objectives including enhancing network capacity, ensuring co-existence of processes, energy efficiency and scheduling of information were also achieved.

8.2 Future works

In IWSNs, continuous research has provided desirable improvements in past few years. It is because of the efforts of many individuals and some joint ventures that IWSNs have recently witnessed much wider acceptability in all sorts of industrial applications. Due to the broader scope of the potential applications of IWSNs, it is becoming difficult to cope with the rising challenges.

In this section, to resolve prominent and still prevailing challenges in IWSNs, certain future directives are listed.

Since IWSNs are not yet considered as a mature technology in industrial automation and control, ensuring deterministic behaviour in IWSNs will be receiving great significance in the next few years. It is very important to offer deterministic behaviour in IWSNs to assure proper working in harsh environments and industrial processes. Despite a lot of work in Physical, MAC and Network layer optimizations, there is still a need for a single converged platform to offer consolidated solution in the formation of deterministic networks where one could predict the operation with certainty.

Interoperability and transformation of existing structure to wireless with minimal variation in the existing setup will greatly assist the transformation. Moreover, there is a gap of demand for a system offering wireless solutions with more flexibility and ability to embed in the existing wired networks, as it is strongly desirable for future improvements. Although some industrial protocols offer interoperability in IEEE802.15.4 and TCP/IP operated devices, yet it only accounts for the Ethernet based wired networks. In addition, the need for translation from full duplex (wired setup) to half duplex (wireless setup) is strongly desirable. Apart from these, many wireless technologies are predicted to collaborate in industrial automation and process control. Unfortunately, scarcity of the radio band would demand operation of various wireless technologies in overlapping spatiotemporal regions which demand expansion of IWSNs to other technologies to assist in future industrial automation and process control.

The emerging IoT can improve interconnectivity, flexibility, scalability, time efficiency, cost effectiveness, security, productivity and operational efficiency in the industries. IoT can also serve as a platform to establish intelligent network of devices which can interrelate data and processes to effectively establish feedback control systems for industrial automation. Similarly, the continuous increase in the use of wireless technologies in various applications are and will be soon leading to overlapping wireless spectrum access where the opportunistic spectrum access would be inevitable. Examples of such cases can be seen in Wi-Fi, Zigbee, Bluetooth and Wi-MAX, where all of these uses overlapping spectrum. To avoid the interference under similar circumstances, the use of cognitive sensor networks for opportunistic spectrum access is a suitable alternative solution. Moreover, cognitive radios will also offer a bandwidth extension and multichannel utilization by opportunistic tapping in unused spectrum which is otherwise not usable in traditional IWSNs. Cognitive radio sensor networks are also suitable for handling nonlinearly distributed sensors for reliable data delivery under unfavourable propagation conditions.

All these technologies are still in the early stage of development, and there is a need to be thoroughly investigated for modernising industrial environments. Furthermore, the integration of different researches, benchmarking and standardization for industrial communications technologies is very important.

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