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A Comprehensive Survey on Mobile Data Offloading in Heterogeneous Network

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Abstract With the explosive increase of smartphones, tablets and laptops, the past few years have witnessed the exponential rise of mobile data traffic. This has already caused data overload on cellular networks. As a result, cellular networks can not offer sufficient capacity to accommodate the numerous mobile data requirements. Therefore, it is an urgent agenda for cellular network operators to find out immediate solutions. As a promising way to tackle this problem, mobile data offloading is considered to transfer traffic which originally generates towards cellular network to complementary networks. This article aims to present a comprehensive overview of mobile data offloading. According to the participation of infrastructure, we classify the existing strategies into two major categories, namely infrastructure-based strategies and infrastructure-less strategies. Then, we review the technical aspects and discuss the state of the art in each category. After discussing advantages and disadvantages of these strategies, we also introduce the performance metrics used in offloading system, as well as the future challenges.

Keywords Mobile data offloading · cellular networks · infrastructure-based networks · opportunistic communication · delay tolerant networks

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1 Introduction

Over the last few years, an increasing number of wireless devices occur in the market, such as smartphones, tablets and laptops. People often use these various intelligent terminals to access the Internet for entertainment and resource consuming services, which is one of the primary contributors to global mobile traffic growth. According to Cisco Visual Network Index, global mobile data traffic grew 63 percent in 2016, reaching 7.2 exabytes per month at the end of 2016, up from 4.4 exabytes per month at the end of 2015 (One exabyte is equivalent to one billion gigabytes, and one thousand petabytes). Additionally, Cisco also forecasts that mobile data traffic will grow at a compound annual growth rate (CAGR) of 47 percent from 2016 to 2021, and reach 49.0 exabytes per month by 2021 [24].

Up to now, there already exist several major concerns to alleviate congestion and make network more efficient. Apparently, the most straightforward one is to install more base stations per area, so that the capacity of networks is increased. As it is known to all, upgrading the cellular network to the next-generation is another promising way such as 5G [7]. For example, it's a novel 5G scenario that vehicle nodes would download interested media while fast moving [28] [11]. Generally, the networks condition can be improved by building extra infrastructures. However, on one hand, it is costly and will inevitably take a long period to upgrade the hardware equipment. On the other hand, whether it can keep the pace with the explosive increasing mobile data is also not guaranteed [34]. Additionally, cellular operators have attempted to formulate rational pricing strategies to limit customers' demand for data usage. For example, Sangtae Ha et al. divided a day into peak hours and off-peak hours [26]. Although such strategies successfully transfer a large quantity of mobile data from peak hours to off-peak hours, they actually degrade user experience and affect the user's satisfaction.

Given these negative factors, we draw our attention to one solution, the mobile data offloading, which recently has been attracting increasing interest from the research community. Although the overall radio spectrum is sufficient, only a small portion can be employed by operators. Fortunately, the offloading plays a significant part in saving cellular infrastructure bandwidth, and makes the spectrum more efficient [15]. Moreover, the increasingly maturity of communication interface technology, such as multiple interfaces and high speed, makes offloading feasible [3,46]. Meanwhile, many mobile data offloading strategies have been proposed, including Wi-Fi access point [2], femtocell [19] and opportunistic communication [43].

The focus of this article is to provide a summary of existing mobile data offloading strategies in detail, by giving a comprehensive elaboration for beginners. The major contributions are three-folded: (a) To categorize the existing mobile data offloading strategies into infrastructure-based and infrastructure-less branches. (b) To provide an up-to-now review on previously published works with a discussion on advantage and disadvantage. (c) To discuss the performance metrics and challenges associated with offloading.

The rest of this article is organized as follows: In section 2, in terms of role that infrastructure plays, we present a classification of existing offloading schemes: infrastructure-based and infrastructure-less. In section 3, we propose an overview with a detailed analysis for each category. A variety of performance metrics proposed in previous literature are introduced in section 4. Finally, we discuss the challenges that may occur in the near future and draw a conclusion of this article in section 5 and section 6, respectively.

2 Review Taxonomies

Up to now, a great variety of offloading trials are implemented in academic and industrial community. Some major worldwide operators such as AT&T, T-Mobile and Verizon have installed more wireless access points (APs) in their networks to promote mobile data offloading. A few works such as literature [23,51] have summarized and categorized existing mobile data offloading techniques. Based on the type of the network frequency resources, Elhami et al. divide existing mobile data offloading strategies into three categories:

- Using unlicensed bands as network resources.
- Using licensed bands as network resources.
- Using combination of unlicensed and licensed bands [23].

They category the offloading methods as femtocell technology in licensed bands, Wi-Fi APs in the un-licensed bands, device-to-device and opportunistic communications in either licensed or unlicensed bands.

In the other paper [51], depending on the time sensitivity of mobile data, Aijaz et al. divide existing schemes into two categories: **non-delayed offloading and delayed offloading**:

- In case of non-delayed offloading, no extra latency is allowed in whole offloading process. For example, it is essentially meaningless for a live video or audio streaming, once it is attached to additional latency. Nobody will be interested in watching a basketball or score game, after the result of game is revealed.
- In contrast to non-delay offloading, delayed offloading is not associated with strict delivery delay constraints, in which users can patiently wait for the data content until deadline reaches.

It is precisely the delay-tolerance feature that ensures the content delivered through multiple methods. In general, most of users can readily accept the a level of condition, e.g., that their acquired music or movies are received with a tolerable delay. If failing to download the content while they are in a congested cellular network, users may prefer to obtain the content through Wi-Fi access point in proximity. In addition, it is also a terrific option to receive cached content shared by other peers.

In this section, we primarily present a comprehensive classification of the existing offloading strategies, and further provide our understanding from another perspective. Throughout the study of existing literature, we found that some offloading methods require assistance of infrastructure, while others not. Thus, according to whether there is infrastructure participating in the offloading process, we briefly classify currently available offloading schemes into two types: infrastructure-based offloading and in-frastructureless offloading. Based on this classification, we bring a much comprehensive understanding on these offloading methods. More specific details of offloading strategies are introduced in next section.

2.1 Infrastructure-based offloading

In infrastructure-based offloading solutions, some infrastructures with communication, computing and storage capabilities are deployed to assist in data transmission, in which Wi-Fi APs and femtocell (as two kinds of efficient complementary access networks) play important roles on guaranteeing mobile data transferred from cellular network. These two main offloading technologies are discussed as follows.

Wi-Fi stands for wireless fidelity, which is a wireless connectivity solution based on IEEE 802.11 standards [2]. It was designed for getting Internet access in indoor environment with a data rate of 1Mbps. In 2003, IEEE developed a new version, 802.11g, raising the data rate to 54Mbps. IEEE 802.11n, presented in 2007, efficiently combine MIMO and OFDM technology improving the wireless communication quality and the date rate was up to 600Mbps [47]. What attracts cellular operators most is that Wi-Fi operates on the free unlicensed frequency bands (2.4GHz UHF and 5GHz SHF) without causing interference to cellular network, which is an economical solution to expand the network capacity. The architecture of Wi-Fi network is shown as Figure 1, the data is transparently transferred to the Wi-Fi network, when they are in Wi-Fi coverage, completely bypassing the cellular core network for data services.

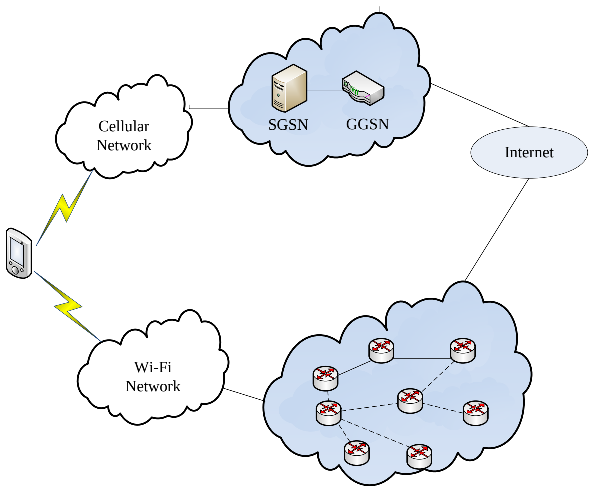

Fig. 1 Mobile data offloading via Wi-Fi network

Wi-Fi offloading is regarded as one of the most promising techniques for dealing with the explosive data increase in cellular networks, due to its high data transmission rate and low requirement on devices [32]. As a natural solution to mobile data offloading, Wi-Fi has limited coverage due to its stationary position and finite transmit power. Although most Wi-Fi works in indoor environment (e.g., office, airport and train station), operators are continuously deploying outdoor Wi-Fi APs in urban area to meed demand of ubiquitous access.

Another infrastructure-based solution for offloading is femtocell which is also known as home base station. Unlike Wi-Fi networks that operate in unlicensed spectrum in which radio interference is not actively managed, femtocell networks will operate in licensed spectrum. In a large content, it is completely considered as a base station with limited coverage, and low power employed by indoor users for getting a better service. Similar with Wi-Fi access point, its transmit power is about 10-100 mW with the capacity of 4-6 users. As shown in Figure 2, the user-installed device communicates with the cellular network over a broadband connection such as digital subscriber line (DSL), cable modem, or a separate radio frequency (RF) backhaul channel [14]. Previous studies have shown that more than 50 percent of all voice calls and more than 70 percent of data usage occurs in indoor environment such as home and office. Therefore, as a potential method of offloading, femtocell can shift a large number of traffic originated in macro cellular network.

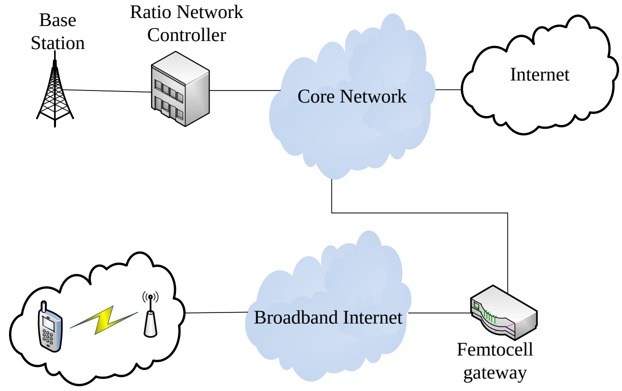

Fig. 2 Mobile data offloading via femtocell

There are several benefits using femtocell to relieve or avoid data congestion in cellular network for both operators and users. Firstly, compared with installing macro cell tower, it is convenient and of less monetary cost for operators to deploy this home base station. Moreover, users can enjoy a better service in terms of seamless experience and higher bite rate. Last but not least, due to not managing another interface and consuming energy to scan available APs, femtocell prolongs the battery life of devices. Nevertheless, due to operating on the same frequency band as cellular network, interference from a nearby macrocell and femtocell may affect the quantity of service. This factor is a reason that prevents femtocell from widespread adoption.

2.2 Infrastructure-less offloading

On one hand, the increasing popularity of smart mobile devices means a huge amount of infrastructures in the infrastructure-based solutions. However, on the other hand, the increasing popularity of smart mobile devices equipped with several alternative communication options makes it possible to transmit data directly between mobile users, without any need for an infrastructure. Thus, some operators propose infrastructure-less solutions.

Here, we mainly discuss offloading mobile data through opportunistic network or delay tolerance network (DTN). Both the terms opportunistic and DTN are completely referring to utilizing opportunistic contacts of mobile terminals to finalize communication, as shown in Figure 3. Opportunistic communication technology makes it possible that mobile terminals communicate with others directly without the involvement of APs or base stations [36]. Recently, the advanced interface technologies of intelligent terminal such as cellular, Bluetooth and Wi-Fi Direct interface boost the development of opportunistic communication. Such a way ensures users access to both cellular network and local network at the same time.

Because most of Bluetooth and Wi-Fi Direct technologies are operated on 2.4G unlicensed frequency band without additional equipment, opportunistic communication as an offloading method means an extremely low monetary cost for operators. Additionally, intelligent terminals with long battery life, accurate GPS and large storage make offloading through opportunistic communication more potential. Nowadays, a large number of mobile data such as multiple-media newspaper, popular videos and music are of common interests among a set of users and most of these contents are not associated with strict real-time constraints. Benefiting from this delay tolerance characteristic, operators can only transfer the content to a small number of users. The contents are going to be further delivered to all subscribers, by those selected users through opportunistic communication.

It is essential for any offloading schemes to select mobile users, with high potential to further spread the contents. The existing offloading strategies can be

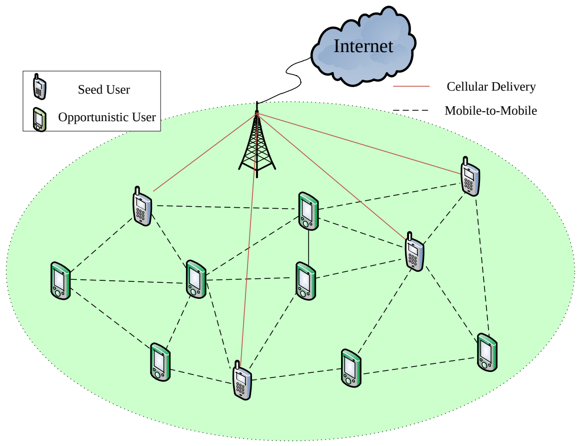

Fig. 3 Mobile data offloading via opportunistic communication

briefly classified into two main types: topology-awareness and social status-awareness. The former makes offloading decision through the real-time topology information, while the latter puts more focus on the social status of mobile users. It is obvious that the connectivity is immediately established, once pairwise users come into the communication range of each other [56].

The topology information here exactly refers to the connectivity between numerous users. In general, users can send contents to their current neighbors who are with good qualification for dissemination. For instance, only a number of neighbors is beyond a threshold can trigger the dissemination process. More topology-awareness algorithms such as Epidemic, Direct Delivery and SnW (Spray and Wait) which are equally efficient in offloading are described in [54].

The social status-awareness offloading strategies exploit influence on social interaction among numerous mobile users to identify the potential helpers. The social status may include the user's mobility pattern, the interacting time, the real-time location and the activity [6]. Universally, such a user who is with a more active mobility and encounters a large number of peers, will be regarded as potential helper. This indicates that helpers, behaving as a source or a relay, are more likely to successfully finalize the delivery. Similarly, a long interacting time means a stable connectivity between users which can achieve large size file transmission. Moreover, the encounter times between two users are also used to identify the user's intimate degree. Imagine that Lily has cached the content required by Bob, but Lily and Bob are far away. Fortunately, Lily encounters Bob's intimate fellow Smith. So, it is very likely that Smith will send the content to Bob eventually after he receives it from Lily. More social status-awareness routing algorithms such as PRoPHET, MaxProp and BUBBLE

Table 1 The main category of the existing works

Classification		Reference	Benefits	Shortcomings
Infrastructure-based offloading	Wi-Fi	[52][4][17] [18][16][19] [45][22][35] [21]	1. Less expensive 2. No interference 3. High data rate and reliability	Limited coverage and mobility
	Femtocell	[62][12][1] [48][9]	1. Easy deplayment 2. Prolong device battery life 3. Capacity gain from higher SINR	Interference from nearby macrocell and femtocell
Infrastructure-less offloading	Topology	[13][59][37] [50][57][42] [49]	1. No monetary cost 2. No extra equipment 3. High efficiency in dense environment	1. Consumption of battery and storage 2. Privacy and security problem
	Social status	[27][25][58] [5][38][41] [33][20][40] [29][61] [31]		

Rap are described in [39,8,30]. Although with the lowest cost, this offloading approach also have some limitation. Here, the classification of existing offloading strategies as well as their benefits and shortcomings are listed in Table 1.

3 Review on existing offloading solution

Following the classification above, a review on previous works in each category is discussed in this section.

3.1 Infrastructure-based offloading solutions

3.1.1 Mobile data offloading via Wi-Fi

As far as mobile data offloading is concerned, utilizing Wi-Fi networks can be the most promising solution that can offer an immediate remedy to this problem. There are many Wi-Fi APs available at many user locations such as homes, shops and universities. Due to various advantages and its promising future, Wi-Fi offloading becomes a hot research topic and has attracted the attention of many researchers.

Nikodin et al. come up with two algorithms for offloading mobile data from 3G networks, called Mix-Zones and HotZones respectively [52]. The latter scheme is Wi-Fi based offloading scheme, where HotZone refers to a cell covered by Wi-Fi APs. With the help of User Mobility Profiles (UMPs), the operator ranks the cells for users according to their average visiting number in a day. The cell with a large visiting number implies that user have obtained the accessing permission (considering many Wi-Fi is not provided for free). Balasubramanian et al. propose Wiffler, a system to improve cellular network capacity through Wi-Fi access point deployed in urban environment [4]. An easy approach is to transfer data with a certain delay via the Wi-Fi interface, until a Wi-Fi AP is available. As a result, the proposed Wiffler has the ability to offload almost 50 percent of total 3G traffic with an average delay of 60 seconds.

With the development of intelligent traffic, Wi-Fi Offloading in Vehicular Environment has attracted attention [17,18,16]. Generally, vehicles signal to nearby WiFi APs when traveling along a road, so that the cellular traffic can be delivered to vehicles. In [17], the authors have provided a overview of the mobile data Wi-Fi offloading in vehicular communication environments, and discussed its unique characterizations, effectiveness, technical challenges, existing solutions, and future research directions. In [18], the authors have proposed an approach to predict Wi-Fi offloading potential and access cost in vehicular environments, and introduced auction game-based and congestion game-based offloading mechanism for vehicular users to effectively offload the cellular traffic through the carrier-WiFi network. In [16], authors have theoretically investigated the performance of vehicular Wi-Fi offloading, modeled the arrivals and fulfillments of data services of a vehicular user as an $M/G/1/K$ queue, derived the probability distribution of the effective service time and analyzed the average service delay and offloading effectiveness by the queueing analysis.

On the other hand, Cheung et al. point out that most of previous works mainly apply as few cellular data as possible, ignoring the quality of service (QoS) of the applications [19]. Therefore, they pay more attention to the usage-based pricing, aiming to trade-off the user's cost and the QoS associated with the transmission deadline. They first analyze a delay-aware Wi-Fi offloading problem as a finite-horizon sequential decision problem. The Delay-Aware Wi-Fi Offloading and Network Selection (DAWN) is presented as a solution, to obtain an optimal QoS under the user's cost constraint. Generally, in the absence of a threshold structure, a sequential decision problem is hard to cope with [44]. Thus, considering the optimal policy has a threshold structure in deadline and file size, they further present a monotone approximation DAWN algorithm to solve more general offloading issues. The insight shows that it is not an optimal choice to offload via Wi-Fi, when deadline is tight and the Wi-Fi network is heavily loaded. On the contrary, users can benefit a lot from the delay-aware fashion when there is long period before the deadline. What inspires is that, persistent effort should be shifted from static offloading schemes to dynamic offloading, in order to adjust to a dynamic network condition.

Energy consumption is another key constraint that affects the performance of offloading scheme. Yoshihisa et al. introduce a predict-based method maximizing the offloading data fraction with the constraint of energy consumption taken into account [45]. Here, by tracking the user's browsing print, the method takes a period to have an intimate knowledge of user's browsing habit and their frequently accessing Web pages. About 11 percent of data can be offloaded with a lower energy consumption, than that required in cellular network. If the predicted accuracy can not be guaranteed strictly, a considerable amount of storage and energy is going to be wasted to cache the content which user will hardly request later. Besides, another energy-aware offloading algorithm is proposed in [22], in order to improve energy efficiency. Throughout prediction, the traffic is offloaded to a Wi-Fi AP, if the energy consumed using the Wi-Fi transmission minus the energy consumed in transmitting the same data volume using the cellular network, is larger than a predefined threshold.

The above articles are mostly tested in the virtual simulation platform, whereas some researchers test Wi-Fi offloading schemes in the realistic scenario. Lee et al. present one of the first quantitative studies on the performance of 3G cellular data offloading via Wi-Fi APs in South Korea [35]. About 100 volunteers implement an iPhone application to track their Wi-Fi connectivity for over two weeks. From the data collected by the application, the authors find that 70 percent of their time is spent in Wi-Fi environment and these users will come back within 40 minutes every time they leave the Wi-Fi coverage. Supported by a real data set recording the mobility of 536 taxis in San Francisco for 30 days, Sevio et al. propose a offloading architecture named MADNet architecture [21]. The users' data requests are classified into Download Requests (DR) and Upload Requests (UR). For DR, each time a data item is required, the user states a "final location" and the time when they will reach there. As long as the time expires, the item will not attract the user's interest anymore. For UR, a user records and uploads content at the time he enters a vicinity of a point of interest. The trace-driven experiment shows 50% of mobile data for both download and upload can be offloaded from 3G network with hundreds of Wi-Fi APs.

3.1.2 Mobile data offloading via femtocell

Compared with Wi-Fi, femtocell is attractive to operators as they provide improvement in both coverage and capacity, especially for indoors. Thus, some researchers have conducted in-depth studies on femtocell. Due to operating on the same frequency band as cellular network, interference from a nearby macrocell and femtocell may affect the quantity of service. Thus, Zhu et al. have proposed an approach to allocate appropriate radio resources for non-CSG UE data packet transmission, in order to mitigate the effect of macro-femto interference without the need of true handover [62]. The key benefit of this proposed mechanism is to achieve highly efficient mobility, by enabling a CSG femtocell base station to relay data without handover and access to the CSG femtocell. This avoids potential interference and saving radio resource and signaling load on the network.

In addition, the dense deployment of femtocell may cause the interference between two nearby femtocells. With the consideration of random and uncontrolled interference, Prabhu et al. propose an analytical model to estimate the capacity enhancement of the OFDMA-based co-channel macrocell-femtocell networks [12]. Based on the mathematical framework structured by expected distance of interfering femotocell, system load and throughput of both macrocell femtocell users, author find that there is a positive correlation between maximum user number accommodated by femtocell and the femtocell density. Additionally, transmit power also plays a significant role in average throughput, which is determined by the macrocell load, femtocell amount and traffic requirement determine. A high transmit power can also lead to a maximum offloading gain.

Considering the interference problem, some researchers explore the combination of femtocell and Wi-Fi networks. Ahn et al. propose a scheme for traffic offloading between femtocell and Wi-Fi networks utilizing software-defined networking (SDN) technology [1]. The proposed scheme utilizes the property of the femtocell, wherein data traffic to the operator's core network is transmitted via the user's broadband network. Using this property, the proposed offloading scheme can reduce the interference level of the femtocell, by offloading traffic to the Wi-Fi networks from the femtocell, meanwhile without performance degradation and connection losses. Experimental results on an actual test-bed showed that the proposed offloading scheme provides seamless connectivity and reduces the femtocell load, by up to 46 percent with the aid of the proposed target selection scheme, while ensuring QoS after offloading. Mahmoud et al. present a generic framework combining mobile femtocell with Wi-Fi networks (MFW) [48]. Contrast to traditional femtocell installed in indoor environment, mobile femtocell is installed in public vehicles, such as city buses and streetcars to offer Internet access for mobile terminals. This kind of mobile femtocell is connected to a Wi-Fi transmitter on the vehicle roof, and this Wi-Fi transmitter connecting to urban Wi-Fi APs offers a backhaul for mobile femtocell. The result reveals that, with a maximum capacity of 40 users, MFW can offload up to 50 percent of data traffic originated in cellular network.

Furthermore, Doru et al. provide an analysis on how to deploy femtocell to maximize the offloading gains in macrocell networks [9]. Due to the existence of propagation losses, the indoor users may suffer from a serve degradation in signal-to-noise ratio (SNR). However, supposing these indoor users be served by femtocell, both the QoS of user and the capacity of macrocell will be improved simultaneously. Throughout the analysis on different SNR values, they find that offloading gain varies with macrocell transmit power in a negative correlation. A higher transmit power results in a higher SNR, thus more users can be supplied service by macrocell. Meanwhile, the mutual interference between macrocell and femtocell becomes more severe, when a high transmit power is configured. Concerning femtocell offloading, how to appropriately deploy femtocells to limit the interference is still worthwhile investigating.

3.2 Infrastructure-less offloading solutions

Offloading traffic through opportunistic communications has been recently proposed, as a way to relieve the current overload of cellular networks. Therefore, an increasing body of work is to investigate the use of infrastructure-free opportunistic networking as a complement for the cellular infrastructure. A number of strategies can be used to disseminate the content among mobile nodes.

3.2.1 Topology-awareness

Chandrasekaran et al. propose an ICN (information centric network)-based offloading architecture that propagate the content already being cached by helpers, to other subscribers in proximity through D2D communication [13]. Such a single-hop scheme indeed degrades the network overhead. But in the sparse environment, this scheme is going to be of less efficiency. Additionally, when several helpers can serve one requester at the same time, how to avoid the transmission conflict is also not discussed. The work in [59] presents a Subscribe-and-Send (SaS) architecture and an opportunistic forwarding protocol called HPRO to determine the message routing. Different from most of offloading solutions, it is the mobile user that decides whether to deliver the content requested by others, instead of the service provider. The content with common interests is to be transferred to a denser region, so that many subscribers can get profit. Nevertheless, the users in a sparse area that is located in the opposite direction of data stream, may fail to obtain the content through this offloading scheme.

As a matter of fact, how to identify the target-users is a NP-hard problem. Li et al. [37] establish a complicatedly mathematical framework to tackle offloading problem. However, unlike some previous works, they consider that 1) users have diverse subscribing preference, 2) the content with various delay sensitizes and size, 3) the storages capacity of terminal limited. Throughout a strict mathematical derivation, they translate this offloading problem into a sub-modular maximization under several linear constraints (including storage capacity, users' preference and heterogeneous content). Three suboptimal algorithms called Greedy Algorithm (GA), Approximation Algorithm (AA) and Homogeneous Algorithm (HA), are proposed to efficiently respond to different network conditions respectively. GA is devised to offload mobile traffic in a generic scenario, while AA performs better than GA, and HA in the situation that content in DTN-based network is configured with short life time. Considering some works do not capture the need to reward seed users, Filippo et al. include a rewarding cost in the design of the opportunistic offloading strategy [50]. They design a global strategy to select which nodes act as seeders and which ones as leechers, in order to reduce the total dissemination cost. In above works, mobile users are assumed to be volunteers, who selflessly deliver the content to every other user in proximity while moving. However, practical users are selfish in the delay tolerant network formed by device-to-device (D2D) communications. Wang et al. take user selfishness into consideration and propose a network formation game to capture the dynamic characteristics of selfish behaviors [57]. Simulation results show that user selfishness highly degrades the data offloading efficiency, compared with ideal volunteer users.

Due to the delay-tolerant nature of some multimedia content, mobile operators can choose a certain number of users, as target users to receive the initial content. Then these selected users will further disseminate the content to all subscribers in the network through opportunistic contacts. Finally, in order to ensure 100% delivery, the operator will directly send the content to the users who are unlikely to fetch it (within the utmost delay they can tolerate). In [42], Mayer et al. propose a routing solution for the offloading of message exchange between end-users. In fact, the protocol initially attempts to transmit messages through opportunistic communications, and switches to the infrastructure-based network only when the probability of delivering the message within the deadline decreases.

Although opportunistic communication between mobile users is a promising alternative in mobile data offloading, designing an efficient solution is not an easy job. Filippo et al. propose and design a framework called DROiD (Derivative Re-injection to Offload Data), of which the core mechanism is to use infrastructure as less as possible [49]. There is no doubt that this framework will be very efficient in a highly dynamic environment.

3.2.2 Social status-awareness

Obviously, how to wisely select the initial users for further dissemination can maximize the offloading gains is a key issue. With the social status of mobile users in mind, Han et al. present three algorithms, Random, Greedy and Heuristic, to investigate the optimal target-user selection [27]. Previous works have shown that there certainly exists regularity in human mobility [25]. With the general knowledge of human mobility, the Heuristic algorithm selects target users by considering historical mobility. The Heuristic outperforms other two algorithms with over 73% of total traffic offloaded.

However, tracking and recording the mobility of numerous mobile users will consume a lot of resource. Furthermore, a dramatically changed mobility pattern inevitably leads to performance degradation. Wang et al. propose the TOSS framework to offload the mobile cellular traffic for social network services, via opportunistic sharing [58]. They present the discussions on the pushing strategies to choose the appropriate initial seeds, depending on their spreading impact in the online social network services (SNS) and their mobility impact in the offline mobile social networks (MSN). Trace-driven evaluation reveals that TOSS can reduce up to 86.5 percent of the cellular traffic, while guaranteeing the access delay requirements of all users. To select the initial users, Barbera et al. establish a social graph between two users if they meet each other frequently [5]. Using the social graph, they apply several well-known social structural attributes to define the social importance of a user, such as betweenness centrality, closeness centrality. Thus, the initial sources can be selected according to the social importance of users. Based on the regularity of human mobility, Li et al. propose NodeRank which uses the encounter characteristics to choose target nodes [38]. The encounter characteristics (include the encounter frequency, contact time and inter-contact time) can ensure the integrity and availability of message delivery to a certain extent.

Apart from the selection of the initial users, how to forward messages is also addressed. Thus, in order to tackle this problem in a large scale scenario, Lu et al. present an offloading framework called Distance-based Opportunistic Publish/Subscribe (DOPS). It exploits distance information to make decision on whether to start offloading process [41]. For example, if a content is associated with a 3 days' delay threshold, the distance provider has travelled in last 3 days is extracted. Another distance-based offloading scheme is proposed by Sun-Hyun Kim et al which uses RSSI (Received Signal Strength Indicator) to roughly estimate the location of message destination [33]. RSSI can be transferred to the distance between a user and the nearest base station.

In particularly, there have been numerous papers on mobile social networks. SimBet adopts the betweenness and similarity for data forward decision [20]. Compared to other centrality calculation methods, betweenness is better to control the spread of the message. SimBetAge introduces the aging factor [40]. It redefines the similarity and introduces flow betweenness, directed betweenness and other metrics, to deal with the dynamics of social networks and adjust social network metrics. BUBBLE borrows the concept of distributed community to bubble message up to the target community of destination [29]. Literature [61] introduces four social-aware date diffusion schemes according to the data similarity of the contacts social relationship. Fruitful works in this field could be referred to [10].

Most of previous works concentrate on the content downloading scenario. In general, the amount of traffic generated in the downloading process is much larger than that in uploading process. Recently, with the popularity of social software and cloud storage technology, people upload the photos and videos more frequently than before. Therefore, the amount of uploading traffic can not be ignored any more. RoCNet exploits opportunistic network for uploading scenario is presented in

[31]. Each mobile user maintains a value called Coefficient Variation (CV) to record the complexity of user's mobility. The user often shuttling back, and forth between high load areas and low load areas, will be attached to a larger CV. It is shown that RoCNet can divert about 20% of traffic from high load area to low load area during peak time. Indeed, what this system actually operates is transferring data from congested cell to another non-congested cell, instead of reducing total cellular data amount.

4 Mobile data offloading metrics

For tackling different offloading problems, existing literature proposes a variety of strategies to evaluate the offloading effect. The improvement on network performance brought by implementing offloading schemes can be reflected in a few aspects. Although both mobile users and operators are benefiting from mobile data offloading, they focus on two essentially diverse views of offloading metrics. In this section, we briefly discuss the performance metrics of various offloading strategies.

From the perspective of operators, mobile data offloading is expected to reduce the traffic load and ease the cellular congestion. As for mobile users, they are more concerned about the energy consumption as well as the delivery delay. Here, we mainly introduce five major evaluated metrics frequently performed as indictors of various offloading scenario in literature.

Offloading efficiency: There are a few previous works using the total offloading traffic amount to evaluate the effect of proposed algorithms and frameworks. However, it lacks stringency on the efficiency, because different frameworks may generate traffic in different amount. Generally, the larger amount of created traffic is, the more offloading amount can be achieved. Therefore, the offloading efficiency is universally considered as the evaluated criterion for any offloading scheme. It is defined as the ratio of total amount of offloaded traffic, to total amount of generated traffic without implementing offloading. It is obvious that a higher offloading efficiency is desirable.

Traffic load over cellular network: The goal of mobile data offloading technology is to relieve the congestion over the cellular network. Hence the traffic load over cellular network is another vital performance metric for operators. Due to the limited capacity, each base station can merely support a certain number of users. Over the same period, excessive users accessing the same base station will lead to overload, which mainly reflects in a low throughput or even no available bandwidth for mobile users. An efficient offloading solution is able to reduce the traffic load over cellular network, especially during the peak time.

Network overhead: This metric chiefly refers to the consumption of network resource. Taking the DTN-based offloading as an example, the flooding routing means that the source user will forward the popular content to every peer user he encounters, regardless of their true requirement. Thus, these peer users may only perform as a relay. On the other hand, there seldom exists a direct path between source user and destination user, so that multi-hops routing is inevitable. The storage and energy of these relay user's device can be regarded as an additional occupation of network resource.

Energy consumption: From the perspective of mobile users, battier energy consumption is a significant issue in offloading. At present, intelligent terminals are generally equipped with multiple interfaces. Searching for other devices or APs will consume a part of energy. However, due to the high bit rate of Wi-Fi and Bluetooth, the energy consumed in offloading process will be less than that consumed in a congested cellular network. Such as, an energy-saving offloading mechanism is more attractive to mobile users.

Delivery delay: Although users can accept the existence of delivery delay, an infinite delay is not necessarily allowed. As previously discussed, the content is always associated with deadline. Such a deadline represents the delay tolerance to the user's greatest extent. In most circumstances, the earlier that users receive the content within the delay-tolerance threshold, the better the offloading mechanism is. If the users fail to receive the content before deadline, they will request rest data over cellular network again. That is to say, the long waiting time is spent meaninglessly, which severely will harm the user's satisfaction.

5 Challenges in mobile data offloading

In this section, we present a discussion on the crucial challenges in mobile data offloading. Although implementing offloading strategies can bring benefits to operators, offloading option will be extensively accepted by mobile users, unless the potential challenges are addressed appropriately. No matter which offloading methods that users choose (Wi-Fi, Femtocell or opportunistic communication), the vital concern is always user's experience.

5.1 Challenges in Wi-Fi offloading

A lot of users are reluctant to spend too much time, on managing how or when to start an offloading process by all means. Thus, the real-time guidance provided by operators is strongly required in terms of users' experience. On another hand, the seamless service which reflects in network handover is also important. The disruption occurring in forwarding or receiving process will cause the strong dissatisfaction of users. For this reason, it is essential to achieve a tighter integration within 3GPP and wireless networks [53]. Wi-Fi offloading solution is to transfer data bypassing cellular network. However, it is absolutely impossible that all of Wi-Fi APs in a city are installed by operators. Of course, there are a considerable number of APs which are completely separated from the core network, whereas may result in the lack of operator's supervision. Moreover, outdoor Wi-Fi APs are not widely available in most of countries. Therefore, there is still a long way for operators to implement offloading solutions via Wi-Fi networks in a large scale. Even if this dream would come true in near future, how to effectively manage the roaming among numerous Wi-Fi APs will be another challenge to address.

5.2 Challenges in femtocell offloading

Due to the feature that femtocell operates on the same frequency as the macro cellular network, the foremost challenge in femtocell offloading solution is interference management. Here, the interference includes two types: interference between macro and femtocells, as well as inter femtocell interference [60]. Different from the macro network, the femtocells are often installed without a considerate plan, thereby leads to the imbalance in development density. In a dense development, a femtocell creates severely mutual interference to the nearby femtocells. Similarly, a femtocell installed in a residence will create downlink interference, to a device that is close but not connecting to it. For more details on downlink and uplink interference, interested readers can refer to [60].

5.3 Challenges in opportunistic communication offloading

The privacy and security is the main challenges in opportunistic communication offloading solutions. A mobile user will never accept a strange peer to arbitrarily search, and obtain the content cached in his terminal without any permission. To this end, future researches could pay more attention to the privacy and security protection. Operators should design an application for users to install on their handsets. This application is responsible to identify the content that user is willing to share with others, so that other users is not able to search the content without a special identification. The flooding-based schemes are not viable in real life. In fact, not everyone is delightful to participate in the offloading process as a relay node, regardless of the energy and storage consumption. Therefore, it is necessary for operators to propose incentive strategies, and reward the volunteer in offloading process. Making the participation more attractive can encourage realizing the potential of offloading. Related study can be seen in [63][55].

6 Conclusion

Mobile data offloading is regarded as the natural alternative to alleviate the congestion on the cellular network. Not only can operators benefit from this emerging technology in terms of low monetary cost, but also users are able to obtain a better experience. In this article, we propose a brief summary on status-of-the-art offloading mechanisms. Two main classifications we present, infrastructure-based and infrastructure-less, can almost cover all emerging use cases driven offloading systems. For each category, the detailed discussion on offloading solutions could provide enlightenment for beginners in this field. Simultaneously, we analyze the performance metrics exploited to evaluate the offloading system. The potential challenges indicate the key issues to be addressed in community.

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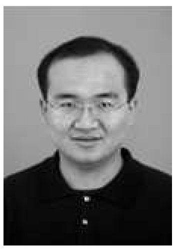
References

1. Ahn, C.W., Chung, S.H.: Sdn-based mobile data offloading scheme using a femtocell and wifi networks. Mobile Information Systems **2017** (2017)
2. Aijaz, A., Aghvami, H., Amani, M.: A survey on mobile data offloading: technical and business perspectives. IEEE Wireless Communications **20**(2), 104–112 (2013)
3. Asadi, A., Mancuso, V.: Wifi direct and lte d2d in action. In: Wireless Days (WD), 2013 IFIP, vol. 143, pp. 1–8. IEEE (2013)
4. Balasubramanian, A., Mahajan, R., Venkataramani, A.: Augmenting mobile 3g using wifi. In: Proceedings of the 8th international conference on Mobile systems, applications, and services, pp. 209–222. ACM (2010)
5. Barbera, M.V., Stefa, J., Viana, A.C., de Amorim, M.D., Boc, M.: Vip delegation: Enabling vips to offload data

in wireless social mobile networks. In: Distributed Computing in Sensor Systems and Workshops (DCOSS), 2011 International Conference on, pp. 1–8. IEEE (2011)
6. Baştuğ, E., Bennis, M., Debbah, M.: Social and spatial proactive caching for mobile data offloading. In: 2014 IEEE international conference on communications workshops (ICC), pp. 581–586. IEEE (2014)
7. Boccardi, F., Heath, R.W., Lozano, A., Marzetta, T.L., Popovski, P.: Five disruptive technology directions for 5g. IEEE Communications Magazine **52**(2), 74–80 (2014)
8. Burgess, J., Gallagher, B., Jensen, D., Levine, B.N.: Maxprop: Routing for vehicle-based disruption-tolerant networks. In: INFOCOM, vol. 6, pp. 1–11 (2006)
9. Calin, D., Claussen, H., Uzunalioglu, H.: On femto deployment architectures and macrocell offloading benefits in joint macro-femto deployments. IEEE Communications Magazine **48**(1), 26–32 (2010)
10. Cao, Y., Sun, Z.: Routing in Delay/Disruption Tolerant Networks: A Taxonomy, Survey and Challenges. IEEE Communications Surveys Tutorials **15**(2), 654–677 (2013)
11. Cao, Y., Sun, Z., Wang, N., Yao, F., Cruickshank, H.: Converge-and-diverge: A geographic routing for delay/disruption-tolerant networks using a delegation replication approach. IEEE Transactions on Vehicular Technology **62**(5), 2339–2343 (2013)
12. Chandhar, P., Das, S.S.: Analytical evaluation of offloading gain in macrocell-femtocell ofdma networks. In: Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, pp. 1–6. IEEE (2013)
13. Chandrasekaran, G., Wang, N., Tafazolli, R.: Caching on the move: towards d2d-based information centric networking for mobile content distribution. In: Local Computer Networks (LCN), 2015 IEEE 40th Conference on, pp. 312–320. IEEE (2015)
14. Chandrasekhar, V., Andrews, J.G., Gatherer, A.: Femtocell networks: a survey. IEEE Communications magazine **46**(9), 59–67 (2008)
15. Chen, Q., Yu, G., Maaref, A., Li, G., Huang, A.: Rethinking mobile data offloading for lte in unlicensed spectrum
16. Cheng, N., Lu, N., Zhang, N., Shen, X.S., Mark, J.W.: Opportunistic wifi offloading in vehicular environment: A queueing analysis. In: Global Communications Conference (GLOBECOM), 2014 IEEE, pp. 211–216. IEEE (2014)
17. Cheng, N., Lu, N., Zhang, N., Shen, X.S., Mark, J.W.: Vehicular wifi offloading: Challenges and solutions. Vehicular Communications **1**(1), 13–21 (2014)
18. Cheng, N., Lu, N., Zhang, N., Zhang, X., Shen, X.S., Mark, J.W.: Opportunistic wifi offloading in vehicular environment: A game-theory approach. IEEE Transactions on Intelligent Transportation Systems **17**(7), 1944–1955 (2016)
19. Cheung, M.H., Huang, J.: Dawn: Delay-aware wi-fi offloading and network selection. IEEE Journal on Selected Areas in Communications **33**(6), 1214–1223 (2015)
20. Daly, E.M., Haahr, M.: Social network analysis for routing in disconnected delay-tolerant manets. In: Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing, pp. 32–40. ACM (2007)
21. Dimatteo, S., Hui, P., Han, B., Li, V.O.: Cellular traffic offloading through wifi networks. In: 2011 IEEE Eighth International Conference on Mobile Ad-Hoc and Sensor Systems, pp. 192–201. IEEE (2011)
22. Ding, A.Y., Hui, P., Kojo, M., Tarkoma, S.: Enabling energy-aware mobile data offloading for smartphones through vertical collaboration. In: Proceedings of the 2012 ACM conference on CoNEXT student workshop, pp. 27–28. ACM (2012)
23. Elhami, G., Zehni, M., Pakravan, M.R.: A survey on heterogeneous access networks: Mobile data offloading. In: Electrical Engineering (ICEE), 2015 23rd Iranian Conference on, pp. 379–384. IEEE (2015)
24. Forecast, C.V.: Cisco visual networking index: Global mobile data traffic forecast update, 2016-2021. Cisco Public Information, February **9** (2017)
25. Gonzalez, M.C., Hidalgo, C.A., Barabasi, A.L.: Understanding individual human mobility patterns. Nature **453**(7196), 779–782 (2008)
26. Ha, S., Sen, S., Joe-Wong, C., Im, Y., Chiang, M.: Tube: time-dependent pricing for mobile data. ACM SIGCOMM Computer Communication Review **42**(4), 247–258 (2012)
27. Han, B., Hui, P., Kumar, V., Marathe, M.V., Pei, G., Srinivasan, A.: Cellular traffic offloading through opportunistic communications: a case study. In: Proceedings of the 5th ACM workshop on Challenged networks, pp. 31–38. ACM (2010)
28. Han, C., Dianati, M., Tafazolli, R., Liu, X.: A novel distributed asynchronous multichannel mac scheme for large-scale vehicular ad hoc networks. IEEE Transactions on Vehicular Technology **61**(7), 3125–3138 (2012)
29. Hui, P., Crowcroft, J., Yoneki, E.: Bubble rap: Social-based forwarding in delay-tolerant networks. IEEE Transactions on Mobile Computing **10**(11), 1576–1589 (2011)
30. Hui, P., Crowcroft, J., Yoneki, E.: Bubble rap: Social-based forwarding in delay-tolerant networks. IEEE Transactions on Mobile Computing **10**(11), 1576–1589 (2011)
31. Izumikawa, H., Katto, J.: Rocnet: Spatial mobile data offload with user-behavior prediction through delay tolerant networks. In: 2013 IEEE Wireless Communications and Networking Conference (WCNC), pp. 2196–2201. IEEE (2013)
32. Kang, X., Chia, Y.K., Sun, S., Chong, H.F.: Mobile data offloading through a third-party wifi access point: an operator's perspective. IEEE Transactions on Wireless Communications **13**(10), 5340–5351 (2014)
33. Kim, S.H., Han, S.J.: Contour routing for peer-to-peer dtn delivery in cellular networks. In: 2012 Fourth International Conference on Communication Systems and Networks (COMSNETS 2012), pp. 1–9. IEEE (2012)
34. Lee, J., Yi, Y., Chong, S., Jin, Y.: Economics of wifi offloading: Trading delay for cellular capacity. IEEE Transactions on Wireless Communications **13**(3), 1540–1554 (2014)
35. Lee, K., Lee, J., Yi, Y., Rhee, I., Chong, S.: Mobile data offloading: How much can wifi deliver? pp. 425–426 (2010)
36. Lei, L., Zhong, Z., Lin, C., Shen, X.: Operator controlled device-to-device communications in lte-advanced networks. IEEE Wireless Communications **19**(3), 96 (2012)
37. Li, Y., Qian, M., Jin, D., Hui, P., Wang, Z., Chen, S.: Multiple mobile data offloading through disruption tolerant networks. IEEE Transactions on Mobile Computing **13**(7), 1579–1596 (2014)
38. Li, Z., Shi, Y., Chen, S., Zhao, J.: Cellular traffic offloading through opportunistic communications based on human mobility. TIIS **9**(3), 872–885 (2015)

39. Lindgren, A., Doria, A., Schelén, O.: Probabilistic routing in intermittently connected networks. ACM SIGMOBILE mobile computing and communications review **7**(3), 19–20 (2003)
40. Link, J.Á.B., Viol, N., Goliath, A., Wehrle, K.: Simbetage: Utilizing temporal changes in social networks for delay/disconnection tolerant networking. In: Mobile and Ubiquitous Systems: Networking & Services, MobiQuitous, 2009. MobiQuitous' 09. 6th Annual International, pp. 1–2. IEEE (2009)
41. Lu, X., Lio, P., Hui, P.: Distance-based opportunistic mobile data offloading. Sensors **16**(6), 878 (2016)
42. Mayer, C.P., Waldhorst, O.P.: Offloading infrastructure using delay tolerant networks and assurance of delivery. In: Wireless Days (WD), 2011 IFIP, pp. 1–7. IEEE (2011)
43. Mehmeti, F., Spyropoulos, T.: Performance analysis of mobile data offloading in heterogeneous networks. IEEE Transactions on Mobile Computing (2016)
44. Ngo, M.H., Krishnamurthy, V.: Optimality of threshold policies for transmission scheduling in correlated fading channels. IEEE Transactions on Communications **57**(8), 2474–2483 (2009)
45. Onoue, Y., Tamai, M., Yasumoto, K.: Energy-constrained wi-fi offloading method using prefetching. In: 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), pp. 1–5. IEEE (2014)
46. Pieterse, H., Olivier, M.S.: Bluetooth command and control channel. Computers & Security **45**, 75–83 (2014)
47. Poularakis, K., Iosifidis, G., Pefkianakis, I., Tassiulas, L., May, M.: Mobile data offloading through caching in residential 802.11 wireless networks. IEEE Transactions on Network and Service Management **13**(1), 71–84 (2016)
48. Qutqut, M.H., Al-Turjman, F.M., Hassanein, H.S.: Mfw: Mobile femtocells utilizing wifi: A data offloading framework for cellular networks using mobile femtocells. In: 2013 IEEE International Conference on Communications (ICC), pp. 6427–6431. IEEE (2013)
49. Rebecchi, F., de Amorim, M.D., Conan, V.: Droid: Adapting to individual mobility pays off in mobile data offloading. In: Networking Conference, 2014 IFIP, pp. 1–9. IEEE (2014)
50. Rebecchi, F., de Amorim, M.D., Conan, V.: Should i seed or should i not: On the remuneration of seeders in d2d offloading. In: World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2016 IEEE 17th International Symposium on A, pp. 1–9. IEEE (2016)
51. Rebecchi, F., De Amorim, M.D., Conan, V., Passarella, A., Bruno, R., Conti, M.: Data offloading techniques in cellular networks: a survey. IEEE Communications Surveys & Tutorials **17**(2), 580–603 (2015)
52. Ristanovic, N., Le Boudec, J.Y., Chaintreau, A., Erramilli, V.: Energy efficient offloading of 3g networks. In: 2011 IEEE Eighth International Conference on Mobile Ad-Hoc and Sensor Systems, pp. 202–211. IEEE (2011)
53. Sou, S.I.: Mobile data offloading with policy and charging control in 3gpp core network. IEEE Transactions on Vehicular Technology **62**(7), 3481–3486 (2013)
54. Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking, pp. 252–259. ACM (2005)
55. Wang, K., Lau, F.C., Chen, L., Schober, R.: Pricing mobile data offloading: A distributed market framework. IEEE Transactions on Wireless Communications **15**(2), 913–927 (2016)
56. Wang, T., Cao, Y., Zhou, Y., Li, P.: A survey on geographic routing protocols in delay/disruption tolerant networks(dtns). International Journal of Distributed Sensor Networks **2016**(6), 8 (2016)
57. Wang, T., Sun, Y., Song, L., Han, Z.: Social data offloading in d2d-enhanced cellular networks by network formation games. IEEE Transactions on Wireless Communications **14**(12), 7004–7015 (2015)
58. Wang, X., Chen, M., Han, Z., Wu, D.O., Kwon, T.T.: Toss: Traffic offloading by social network service-based opportunistic sharing in mobile social networks. In: INFOCOM, 2014 Proceedings IEEE, pp. 2346–2354. IEEE (2014)
59. Xiaofeng, L., Pan, H., Lio, P.: Offloading mobile data from cellular networks through peer-to-peer wifi communication: a subscribe-and-send architecture. China Communications **10**(6), 35–46 (2013)
60. Yavuz, M., Meshkati, F., Nanda, S., Pokhariyal, A., Johnson, N., Raghothaman, B., Richardson, A.: Interference management and performance analysis of umts/hspa+ femtocells. IEEE Communications Magazine **47**(9), 102–109 (2009)
61. Zhang, Y., Gao, W., Cao, G., La Porta, T., Krishnamachari, B., Iyengar, A.: Social-aware data diffusion in delay tolerant manets. In: Handbook of Optimization in Complex Networks, pp. 457–481. Springer (2012)
62. Zhu, Z., Fan, Z., Cao, F., Sun, Y.: Data offloading method for interference and mobility management in femtocell systems. In: Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International, pp. 2115–2120. IEEE (2011)
63. Zhuo, X., Gao, W., Cao, G., Dai, Y.: Win-coupon: An incentive framework for 3g traffic offloading. In: 2011 19th IEEE International Conference on Network Protocols, pp. 206–215. IEEE (2011)



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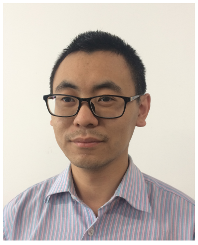

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