Distributed Communication Architecture for Smart Grid Applications

Jing Jiang, *Member, IEEE,* and Yi Qian, *Senior Member, IEEE.*

Abstract

One big challenge in building a smart grid arises from the fast growing amount of data and limited communication resources. The traditional centralized communication architecture does not scale well with the explosive increase of data and has a high probability of encountering communication bottlenecks due to long communication paths. To address this challenging issue, this article presents a distributed communication architecture that implements smart grid communications in an efficient and cost effective way. This distributed architecture consists of multiple distributed operation centers, each of which is connected with several data concentrators serving one local area and only sends summary or required integrated information to a central operation center. Using this distributed architecture, communication distance is largely shortened and thus data will be delivered more efficiently and reliably. In addition, such a distributed architecture can manage and analyze data locally, rather than backhaul all raw data to the central operation center, leading to reduced cost and burden on communication resources. Advanced metering infrastructure is chosen as an example to demonstrate benefits of this architecture on improving communication performance. The distributed communication architecture is also readily applicable to other smart grid applications, e.g., demand response management systems.

Index Terms

Smart grid, distributed communication architecture, advanced metering infrastructure, large-scale antenna array, demand response.

J. Jiang is with the School of Engineering and Computing Sciences, Durham University, Durham, DH1 3LE, UK. (Email: jing.jiang@durham.ac.uk)

Y. Qian is with the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, Peter Kiewit Institute, Omaha, NE 68182-0572, US. (E-mail: yqian2@unl.edu)

I. Introduction

Smart grid is defined as a modernized power grid that uses information and communications technologies to gather and act on information for improving the efficiency, reliability, economics, and sustainability of the generation, transmission, and distribution of electricity [1] [2]. Data plays an important role in smart grid, such as metering data, renewable energy data, customer data, energy storage data, and control data. The data, if efficiently collected and processed, could provide much insight to smart grid stakeholders: On the operational side, equipment failures can be intelligently managed, and thus power system reliability and market flexibility can be significantly improved. On the consumer side, both the user experience and billing system can be enhanced. A significant challenge in building a smart grid arises from the fact that the volume of smart grid data may increase dramatically, leading to many difficulties in managing the data communications and processing in order to provide intelligence.

The traditional communication architecture of power grids is constructed in a centralized topology where the data generated from various data sources are typically delivered to and analyzed at a centralized control center. Taking advanced metering infrastructure (AMI) as an example, it acquires metering data (including voltage amplitude, active/reactive power, current, quality-of-supply information, etc.), delivers them to a data concentrator and then to a operation center where meter data management system (MDMS) and other applications will be used to process the data [3]. With this centralized communication architecture, the management systems receive and processe metering data from all customers, which seems an easy way of managing data. However, with the number of smart meters increasing, it is highly likely that this traditional centralized communication architecture reaches its physical limit of handling these data and can no longer meet the service requirements in terms of data rates, latency and reliability, which will ultimately cause data congestion, serious latency, or even data loss [4]. Such effects can significantly impair smart grid services. What is worse, the data collection frequency is likely to improve further (e.g., from 15-minute interval to 30-second interval) for achieving advanced smart grid functionalities, such as advanced distribution automation and advanced asset management [5]. More frequent meter readings could make the management system more accurate and help prevent any missed power outages. However, a larger scale of metering data will need to be delivered to and processed at the operation center, which will cause greater burdens to the AMI communication architecture. That is, the vast amount of smart meters, more frequent meter readings, and the handling of large-scale metering data have posed a big challenge on the centralized communication architecture, particularly considering practical obstacles of communication bandwidth limitations and costs.

To address these problems, the concept of distributed communication architecture was firstly proposed by Zhou et al. in [5], where multiple distributed MDMSs are deployed and connected to a central MDMS to provide efficient smart grid AMI services. In [4], a tree-structure communication architecture was introduced, where metering data is aggregated in a tree-like manner. This article shares the same motivation as in [5], and presents a distributed communication architecture that consists of multiple distributed operation centers with each distributed center serving one local area and reporting to a central operation center. Different from previous work, this article focuses on practical realizations of the distributed communication architecture, including deployment of distributed operation centers, candidate communication technologies, and performance evaluations. Large-scale multiple antenna technology is considered at base station of a distributed operation center to further improve communication performance. Different from [5] where a constant data rate is assumed on each concentrator, this article shows that the average achievable data rate is highly related to the transmit distances from data concentrators to the operation center, and demonstrates to what extent the distributed communication architecture can benefit the system communication performance in terms of data rates and cost efficiency. In addition, we note that the distributed operation center is capable of collecting and analyzing data locally, and can autonomously make decisions (with localized goal settings) rather than backhauling all data to the central operation center. Such localized intelligence helps reduce large volumes of raw data to smaller amount of valuable and manageable data, and thus reduce communication burden and cost.

The rest of this article is organized as follows: We present the distributed communication architecture for supporting AMI in smart grid. The deployment of distributed management system servers and communication technologies used for the distributed architecture are also discussed. The benefits of this distributed architecture are demonstrated focusing on the communication performance of achievable data rate and system cost efficiency. This distributed communication architecture is then discussed to be extended to demand response, and finally this article is concluded.

II. Distributed Communication Architecture

This Section introduces a distributed communication architecture for supporting smart grid applications and compares it with the traditional centralized case. To make it more concise, AMI is chosen as one example to demonstrate the setup of distributed communication architecture.

A. Traditional AMI

In smart grids, AMI typically acquires metering data from smart meters, delivers the data to a operation center, and then uses analytic tools for extracting useful information to support various smart grid services. In AMI, smart meters are required to measure energy consumption values (per 15 minutes or in a shorter interval), voltage amplitude, current, active power, reactive power, frequency rating, temperature, alarms, etc. MDMS is a key component of AMI; it is a system or application that maintains all data to be able to calculate the energy bills for customers, analyzes metering data for specified time frames (yearly, monthly, or daily), remotely operates smart meters, automatically identifies new meters, provides data search functions, etc. In particular, MDMS also provides interfaces with other meter data management related applications and returns the validated results. Other meter data management related applications include geographic information system (GIS) that provides geographic information related to the smart grid, consumer information system (CIS) that manages billing and consumer information to enable utilities to exploit the metering data and develop new products/services, distribution management system (DMS) that provides power quality control and load forecasting based on the extracted metering data, outage management system (OMS) that enables utilities to discover and resolve power outages sooner and with greater precision, and asset management systems (AMS) that provides property management, risk assessment, maintenance planning, etc. [6].

The traditional communication architecture for AMI is centralized where MDMS and all other managements and operations are performed at the central server. With the explosive increase of metering data, this centralized architecture dose not scale well and has serious communication bottlenecks due to long communication paths. Thus, a distributed scalable communication architecture is essential for handling the growing amounts of data and communication nodes in smart grids.

B. Distributed Communication Architecture for AMI

A distributed communication architecture for AMI is presented in Fig.1, that involves multiple distributed operation centers each of which serves one local area. In this distributed communication architecture, MDMS and all other meter data management related applications (including GIS, CIS, DMS, OMS, AMS, etc.) are fully decentralized. At one distributed operation center, these data management applications are physically co-located and connected, and communication cost among them can be neglected. The distributed operation center is capable of managing and analyzing data locally, and can autonomously make decisions (with applications' settings) rather than backhaul all data to the central operation center.

This distributed communication architecture consists of two layers as follows.

- Lower layer: With public or private communications, each distributed operation center communicates with several data concentrators via wireless links, and then the metering data is stored and processed locally at the distributed operation center.
- Upper layer: With private communications, the distributed operation center communicates with the central operation center through a backbone network. With localized intelligence at the distributed operation center, only summary information and required integrated information is transmitted to the central operation center.

In the lower layer, compared to the centralized architecture, this distributed architecture has much shorter communication distance (from data concentrators to operation centers), thus the metering data will be delivered more stably and efficiently. With MDMS equipped at one distributed operation center, the data needed for energy cost calculation will be stored and maintained locally. In addition, metering data analysis, remote operations of smart meters, automated smart meter provisioning, data search functions, and other managements enabled by MDMS can all be performed locally at the distributed center. Please note that there does exist information exchange among distributed operation centers and the central operation center: The distributed MDMS accepts management tasks assigned from the central MDMS and returns validated integrated information as required; the distributed MDMS also reports summary information (e.g., data analysis results and updates on smart meter provisioning) daily or for a time frame specified by the central MDMS. The communication resource needed for the upper layer is not sensitive to the number of smart meters or data reading frequency, and thus can be viewed as almost constant. Similar localized processing is applicable to other meter data management related applications:

The summary and/or required information could be defined by the central applications and carried out by distributed applications. For instance, the distributed OMS can handle most abnormal situations locally, and report the summary information (e.g. cost of an interruption for utilities and quality of service for consumers) periodically to the central OMS. With localized intelligence at distributed operation centers, we consider the communication resource needed in the upper layer as almost constant.

Compared to the traditional centralized architecture, the advantages of distributed communication architecture are threefold.

- Saving communication resources: In the centralized architecture, raw data is collected from smart meters and then sent through a long distance to the central operation center. In contrast, in the distributed communication architecture, data is processed locally and only summary information or required integrated information is sent to the central operation center. With much shorter transmission distance in the lower layer and much less information transmitted in the upper layer, the distributed communication architecture reduces the communication resources significantly.
- Enabling more efficient data processing: The complexity of data processing always increases dramatically with the increasing amount of smart meters and growing frequent data readings. This distributed architecture helps to reduce the burden by breaking the large data loads into several streams and processing data locally.
- Achieving better communication performance: With shorter transmission distances, the communication delays and losses of data will be reduced, and the communication Quality of Service will be improved. With the same communication performance requirements (e.g. data rate, latency, and reliability), this distributed communication architecture can cover much larger area than the centralized one.

C. Deployment of Distributed Operation Centers

Since the distributed communication architecture is planned to provide communication coverage for smart meters across a large area, the locations of distributed operation centers should be well planned. It is noteworthy that the coverage of AMI area and the locations of data concentrators are normally accessible as prior knowledge for designing the locations of distributed operation centers. Here, we propose to use Voronoi tessellation to decide the locations of distributed centers, because it is optimal in the sense of minimizing average transmission distances from data concentrators to distributed centers [7]. To solve the minimization problem, the locations of distributed operation centers must satisfy two criteria, nearest neighbor condition and centroid condition. The first condition says that the specific distributed region should consist of the data concentrators that are closer to the corresponding distributed center than any of the other distributed centers. For those data concentrators lying on the boundary, any tie-breaking procedure will do [8]. The second condition says that the locations of the distributed operation centers should be the average of locations of all those data concentrators that are in the corresponding region. To realize this Voronoi tessellation, the Linde-Buzo-Gray algorithm is adopted.

Two examples are given in Fig.2 to illustrate the deployment of distributed operation centers by using Voronoi tessellation and the corresponding Voronoi cells. In Fig.2 (a), 2500 random data concentrators are set to be uniformly distributed in a 20×20 Km^2 area and 8 distributed operation centers are selected using Voronoi tessellation. This diagram consists of 8 Voronoi cells and each cell encloses the data concentrators that are closer to the corresponding distributed center in the cell than to any other distributed centers. The data concentrators in a particular cell will only report to the corresponding distributed center. Another example is given in Fig.2 (b), where the data concentrators are normally distributed to simulate an urban network, and ultimately 16 distributed operation centers are selected using Voronoi tessellation.

D. Communication Technologies

We now consider communication technologies that can be used for supporting the distributed architecture. Communications could be either wired communications and wireless communications. Wired communications are typically mature and stable, e.g., fiber-optic can be used in the private backbone networks to provide high speed, secure, and reliable communications between the distributed operation centers and the central operation center; but it is expensive. Power line communications (PLC) can exploit the existing electrical infrastructure and thus save the deployment cost for an extra communications channel [9]. There are a variety of PLC technologies, from Narrowband to Broadband, where Narrowband-PLC (NB-PLC) operating in the frequency bands below 500 kHz are characterized by rather low attenuation compared to broadband alternatives and can thus reach longer distances [10]. International standards (including ITU-T G.9903, ITU-T G.9904, and IEEE 1901.2) have recommended the specifications of multicarrier-based NB-PLC transceivers and have pointed out the important role of NB-PLC technologies in smart metering systems. Considering the distributed communication architecture in this article, NB-PLC technologies can be used for communications between data concentrators and smart meters.

Compared to wired solutions, wireless communications offer many benefits, such as lower cost of equipment and installation, quicker deployment, wider spread access, and greater flexibility. WiMAX and cellular network communications (3G or 4G) can provide wireless communication solutions for distributed operation centers communicating with data concentrators [1]. Table I shows a comparison among various wired and wireless communication technologies that can be used to enable the distributed communication architecture. Their suitable domains, benefits, and drawbacks are also discussed.

Focusing on the communications between distributed operation centers and data concentrators, this article exploits the use of massive multiple-input and multiple-output (MIMO) technique for further improve communication performance. Massive MIMO has recently emerged as a promising solution of providing high data rates and reliable communications for next-generation multi-user wireless communication systems [11]. A block diagram is shown in Fig.3 where large-scale mutiple antennas are deployed at the base stations of distributed operation centers. The idea of massive-MIMO is that very large number of low-power antennas located at a base station node (or distributed geographically) serves the users (i.e. the data concentrators) concurrently in the same frequency band. Some possible deployment scenarios for massive MIMO base stations, such as distributed antenna array, uniform linear or square antenna array, and circular antenna array are also illustrated in Fig.3. With the antenna array growing large, massive MIMO systems have the channels with asymptotic favorable propagation characteristics. That is, the channel vectors between one base station and the users become mutually orthogonal. As a result, the effect of small-scale fading can be averaged out [12]. In addition, with simple matched filter processing at the base station, many random harmful effects, e.g. uncorrelated noise and intracell interference can be eliminated [12] [13]. These benefits enable massive MIMO systems have higher data rates compared to normal MIMO systems that only have limited antennas equipped at the base station.

III. Communication Performance Evaluations

It is important to understand to what extent the distributed communication architecture can benefit the system communication performance. To this end, this section will demonstrate the effects of distributed architecture on the achievable data rate of a data concentrator and that on the system cost efficiency.

A. Achievable Data Rates

As illustrated in Fig.3, we consider the system including N distributed operation centers. In one local region where the i-th distributed operation center is deployed, the distributed operation center is equipped with M-antenna and the value of M is large. The i-th distributed operation center communicates with K_i single-antenna data concentrators, and $\sum_{i=1}^{N} K_i = K$. The communication is operated on a time-division duplexing mode with channel reciprocity. It is shown in [11] that when the antenna arrays grow large, linear precoding methods with perfect channel state information perform fairly well, which are comparable to the capacity-achievable nonlinear precoding strategies (e.g. dirty paper coding). We thus consider a linear precoder, matched filter, at the distributed operation centers. Then the received signal-to-interference-plus-noise ratio (SINR) γ_{im} at the m-th data concentrator can be obtained and formulated; it is related to the values of M and K_i, transmit signal-to-noise ratio, channel conditions and intra-cell interferences. Since massive MIMO technique is considered at the distributed operation center, we can use large-dimensional random matrix theory to provide asymptotic analysis on γ_{im}. When the value of M grows infinitely large, the channel vectors between the i-th distributed operation center and data concentrators asymptotically become mutually orthogonal, and things that were random before start to look deterministic [12]. Many random effects, e.g. small-scale fading, uncorrelated noise and intra-cell interference can be averaged out and eliminated. We thus have the following asymptotic approximation of γ_{im} when the value of M is large

$$\gamma_{im} \approx \frac{MP_t}{\sigma^2 K_t d_{im}^{\xi}}, \tag{1}$$

where d_{im} denotes the distance from the i-th distributed operation center to the m-th data concentrator, ξ is the path loss exponent, and K_t denotes a constant indicating the physical characteristics of the channel and the power amplifier. The scaler $K_t d_{im}^{\xi}$ characterizes geometric attenuation and shadow fading, which is assumed to be constant over many coherence time intervals and known as prior knowledge [12]. The average transmit power at the distributed operation center is denoted by P_t, and σ^2 is the noise variance of the additive white Gaussian noise at the receiver side. Then according to Shannon's channel capacity theorem, based on the asymptotic approximation of γ_{im}, we will know the approximation of average achievable data rate on a data concentrator as below

$$R_i \approx \frac{1}{K_i}\sum_{m=1}^{K_i} B_i \log_2\left(1+\frac{MP_t}{\sigma^2 K_t d_{im}^{\xi}}\right), \tag{2}$$

where B_i denotes the average communication bandwidth allocated per data concentrator in the i-th cell. From (2), it is obvious that increasing the value of M and/or reducing the distances from data concentrators to the distributed operation center will help to improve R_i. We note that although the asymptotic approximation of R_i in (2) is derived using the large-dimensional random matrix theory, this approximation exhibits a very good accuracy compared to simulation results for a wide range of M (even when M is not large, i.e. for realistic system dimensions) as demonstrated in [13], and thus provides analytical insight into how the transmission distance affects the achievable data rates.

To illustrate to what extent the distributed communication architecture can benefit the communication performance, we consider a simulation scenario with a 20×20 Km^2 urban area having 2 million populations. We assume each family (with average size is 4 persons/family) owns a smart meter, and each concentrator covers 200 smart meters on average. This means K = 2500 random data concentrators are distributed in this simulation area. We note that the population density of this simulation area is 5,000/Km^2, which corresponds to a dense urban area with a similar population density of London[1]; and thus the data concentrators are reasonably assumed to be uniformly distributed over this dense urban area. Distributed communication architecture is deployed with one central operation center. Distributed MDMSs directly communicates with local data concentrators, and report summary power and grid information to the central operation center via private networks. The channels of the lower layer communications are modeled as Rayleigh fading channels, and the physical channel propagation parameters are adopted from the 3GPP LTE standard models. The path loss exponent is set to 3.5 to reflect an urban area, and the constant indicating the physical characteristics of the channel and the power amplifier is set to 10^3 [14]. We consider the noise power density as -174 dBm/Hz, and data channel is 10 MHz. We select the Micro type of transmitter and assume P_t = 38 dBm = 6.3 W. The locations of distributed operation centers are selected via Voronoi tessellation.

[1]London covers 1,572 Km^2 area and had a population of 8,174,000 at the 2011 census; its population density is around 5200/Km^2.

The average achievable rate on a concentrator versus the number of distributed centers N is shown in Fig.4. Two cases of M i.e., 256, 128 antennas per distributed center, are considered and compared. The traditional centralized architecture is also shown in the figure as a special case where the value of N equals 1. From the figure, we can see that increasing the number of antennas equipped at the distributed operation center (i.e. increasing the value of M) will result in a higher data rate and thus help to improve communication performance. In addition, compared to the traditional centralized architecture with $N = 1$, the proposed distributed architecture (regardless of the number of antennas) can provide much better communication performance in terms of achievable data rate per concentrator; this demonstrates the analytical results in (2). From another perspective, if a same value of data rate (achievable by the centralized architecture), the distributed communication architecture will be able to cover much larger area than the centralized case. Thus the proposed distributed architecture is capable of handling the fast growing amounts of metering data and improving the scalability of future smart grid communications.

B. Cost Efficiency Evaluations

Even though the proposed distributed architecture offers many benefits in terms of saving communication resources and improving communication performance, it cause additional cost for deploying corresponding equipment for distributed operation centers. As shown in Fig.1, the distributed communication architecture consists of two layers. The additional cost for deploying this architecture thus includes two parts:

- Deployment cost of distributed operation centers: We define F_d as the cost of deploying one distributed operation center in a local region and F_c as the deployment cost of the central operation center. In addition, deploying large-scale antenna arrays in practice could increase the complexity and cost for operating extra hardware at the base station, e.g. for multiple radio-frequency chains. We thus define L as the extra cost per antenna when massive MIMO technique is used.
- Communication cost from distributed operation centers to the central operation center: We define C as the constant data rate needed for exchanging information between a distributed operation center and the central operation center. As discussed in Table I, fiber-optic can be used in this private backbone communications. We need to consider the additional communication cost and define f as the unit communication cost of this backbone network (in the unit of Euros/Mbps/Km).

The total cost of the distributed communication architecture is thus given by $F_c + N(F_d + LM) + NfCD$, where D is the average distance from a distributed center to the central operation center in the unit of Km. For the centralized communication architecture where massive MIMO technique can also be used, the total cost reduces to $F_c + LM$.

We define the cost efficiency as the achievable system throughput over the total cost (with the unit of bps/Euro). For the distributed architecture, we obtain the cost efficiency $\sum_{i=1}^{N} R_i/[F_c + N(F_d + LM) + NfCD]$, where R_i can be approximated by (2) and $\sum_{i=1}^{N} K_i = K$.

Using the same simulation settings as in Fig.4, the total cost and cost efficiency of the distributed communication architecture versus the number of distributed operation centers N are shown in Fig.5 (a) and Fig.5 (b), respectively. We assume L = 10 Euros, f = 50 Euros/Mbps/Km, F_c = 200,000 Euros, and F_d = 100,000 Euros [5]. Two cases of M, i.e., 256 antennas and 128 antennas, are considered. $C = 20$ Mbps and $C = 10$ Mbps are also considered for variety. As expected, the total cost increases dramatically as the value of N increases. A smaller value of C (which can be realized by reducing information exchange between distributed operation centers and the central operation center) will help to reduce the increasing speed of the total cost. Fig.5 (b) shows that with more distributed operation centers deployed, the system cost efficiency increases but finally decreases. The reason is that the benefits obtained by the distributed architecture are not sufficient enough to redeem the additional cost when too many distributed operation centers are deployed. By carefully selecting the number of distributed operation centers, this distributed communication architecture is shown to be very cost efficient. There exists an optimal region of N in terms of maximizing the cost efficiency, which provides insight for designing the distributed communication architecture in practice.

IV. Discussion and Conclusions

In this article, a distributed communication architecture has been introduced to provide more efficient communications in smart grid applications. This distributed architecture is capable of not only overcoming the challenge of communication resources shortage but also leveraging the data processing locally. The implementation of distributed communication architecture has been demonstrated in the AMI scenario, where the use of large-scale antenna arrays at distributed operation centers has also been studied. Our results have validated significant advantages of the distributed architecture over the traditional centralized one in terms of communication performance and scalability. Even though deploying distributed operation centers causes additional deployment cost and communication cost, by carefully selecting the number of distributed operation centers, this distributed communication architecture has been shown to be cost efficient.

Moreover, the aforesaid distributed communication architecture is not only applicable to AMI, but also readily useful for other smart grid applications, e.g., demand response management system (DRMS). We can deploy several distributed centers where DRMS functionalities will be partially operated, thus achieving the benefits of reduced communication resources and localized data processing. The functionalities supported by DRMS could include customer management, program management, resource management, provision of flexibility, event management, etc. Different from AMI scenarios, the DRMS functionalities may not be fully realized at distributed centers: For instance, the functionality of flexibility provision includes demand response capacity calculation and market bid calculation. The capacity calculation process takes into account status and availability of resources, as well as energy forecasts and evaluation metrics. Bid calculation takes into account, besides the projection of demand response capacity, a projection of market spot prices. These calculations are more oriented for centralized operation, considering that sufficient information should be provided to guarantee calculation accuracy [15]. In this case, raw data can be processed and consolidated at the distributed centers to make maximum savings of communication resources, and then smaller amount of valuable and manageable data will be sent to the central center. Some other functionalities, such as customer management, program management, and resource management, can be performed locally at the distributed centers, with summary information reported to or required information exchange with the central center. Although the DRMS functionalities may not be fully realized at the distributed centers, the benefits of reduced communication resources and localized data processing are still very attractive and worthwhile further investigations, which is left as future work.

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Biographies

Jing Jiang (jing.jiang@durham.ac.uk) is a Research Associate in the School of Engineering and Computing Sciences, Durham University, UK. In 2011, she obtained her Ph.D. degree from the University of Edinburgh, UK. During 2011-2014, she was a Research Fellow with the Centre for Communication Systems Research, University of Surrey, UK. Her recent research interests include smart grid, next generation wireless communications, massive-MIMO and MIMO techniques, cognitive radio, relay and cooperation techniques, and energy efficient system design.

Yi Qian (yqian2@unl.edu) is a professor in the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln (UNL). Prior to joining UNL, he worked in the telecommunications industry, academia, and the government. His research interests include information assurance and network security, network design, network modeling, simulations and performance analysis for next generation wireless networks, wireless ad-hoc and sensor networks, vehicular networks, smart grid communication networks, broadband satellite networks, optical networks, high-speed networks and Internet.

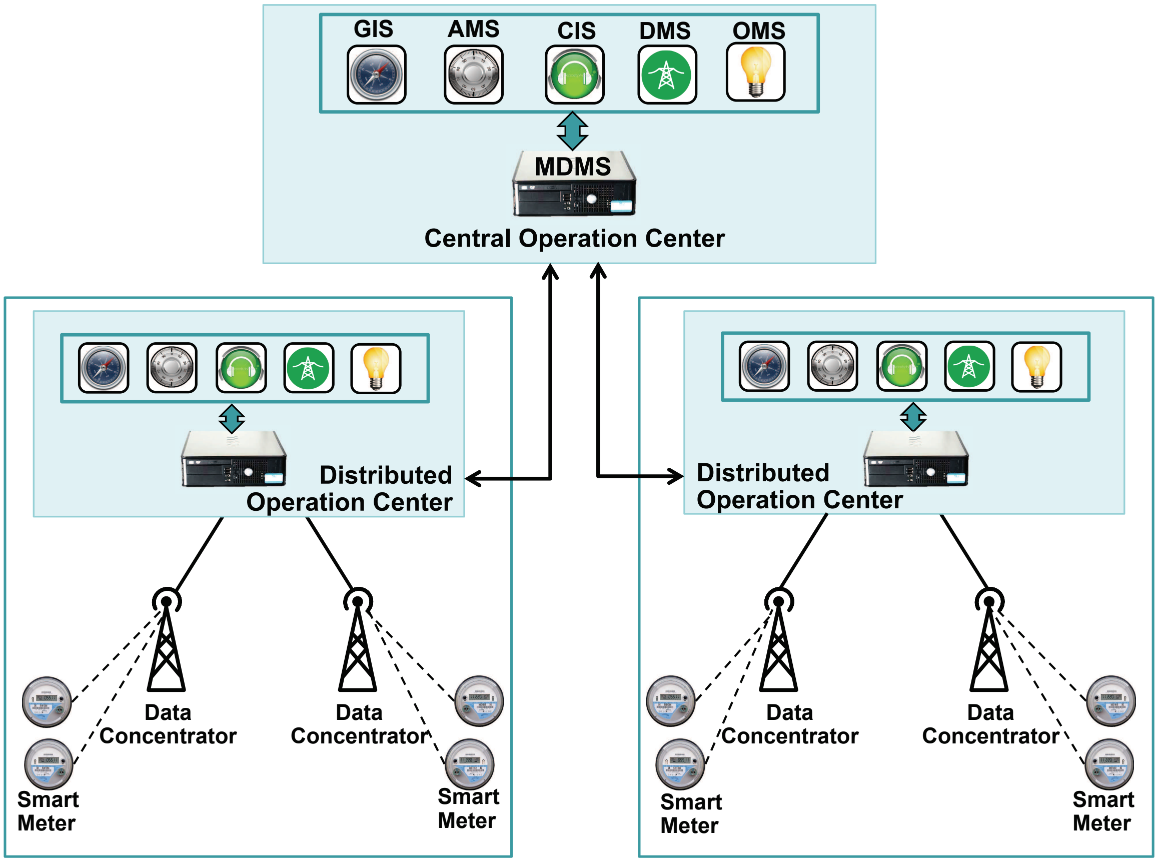

Fig. 1. Illustration of a distributed communication architecture for supporting AMI in smart grid.

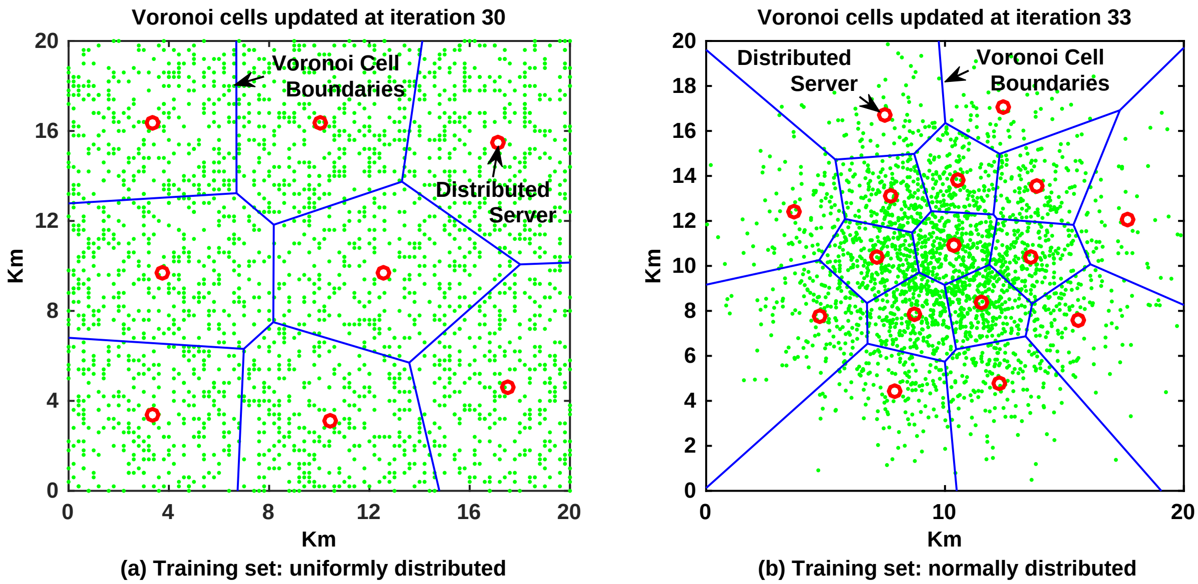

Fig. 2. Locations of distributed operation centers selected using Voronoi tessellation and the corresponding Voronoi cells (2500 random data concentrators are uniformly distributed in a 20 $\times$20 Km^2 area, and 8 distributed operation centers are selected in (a); data concentrators are normally distributed and 16 distributed operation centers are selected in (b).)

TABLE I
COMPARISON OF COMMUNICATION TECHNOLOGIES FOR SUPPORTING THE DISTRIBUTED COMMUNICATION ARCHITECTURE

Technology	**Domains**	**Benefits**	**Drawbacks**
Fiber-optic	Distributed operation centers communicating with the central operation center	High speed; high secure; reliable	Expensive
WiMAX IEEE 802.16	Distributed operation centers communicating with data concentrators	Simple and low latency; fast speed; proper security	User shared bandwidth; spectrum leasing required
Cellular Network (3G or 4G)	Distributed operation centers communicating with data concentrators	Widely adopted; well standardized; low latency	Utility must rent the infrastructure from a cellular carrier
Narrowband PLC	Data concentrators communicating with smart meters	Allow exploiting the existing electrical infrastructure	Low data rate; not long range

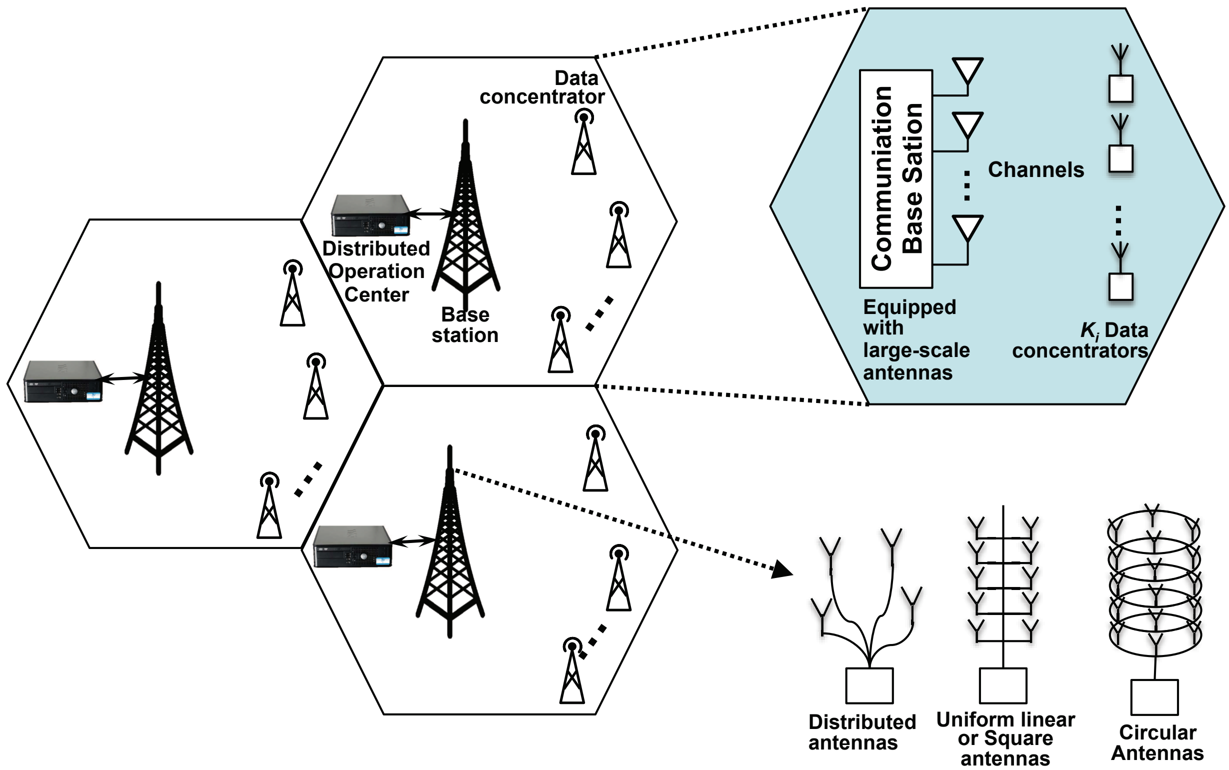

Fig. 3. Illustration of the distributed AMI communication network with large-scale antennas at the base station of distributed operation center, and some possible antenna deployment scenarios.

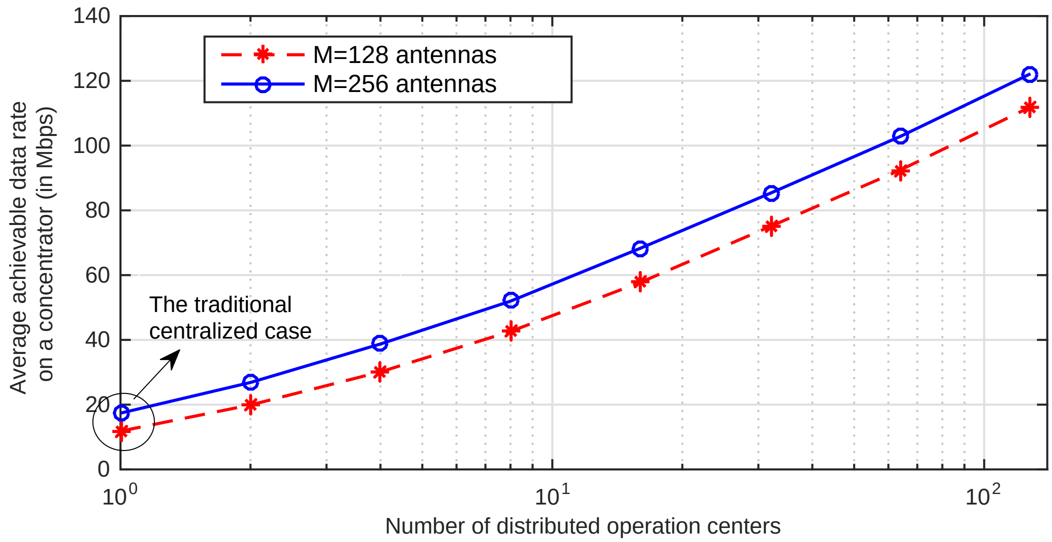

Fig. 4. Average achievable rate on a data concentrator versus the number of distributed operation centers, where two cases of M (i.e. 256, 128 antennas at one distributed operation center) are considered.

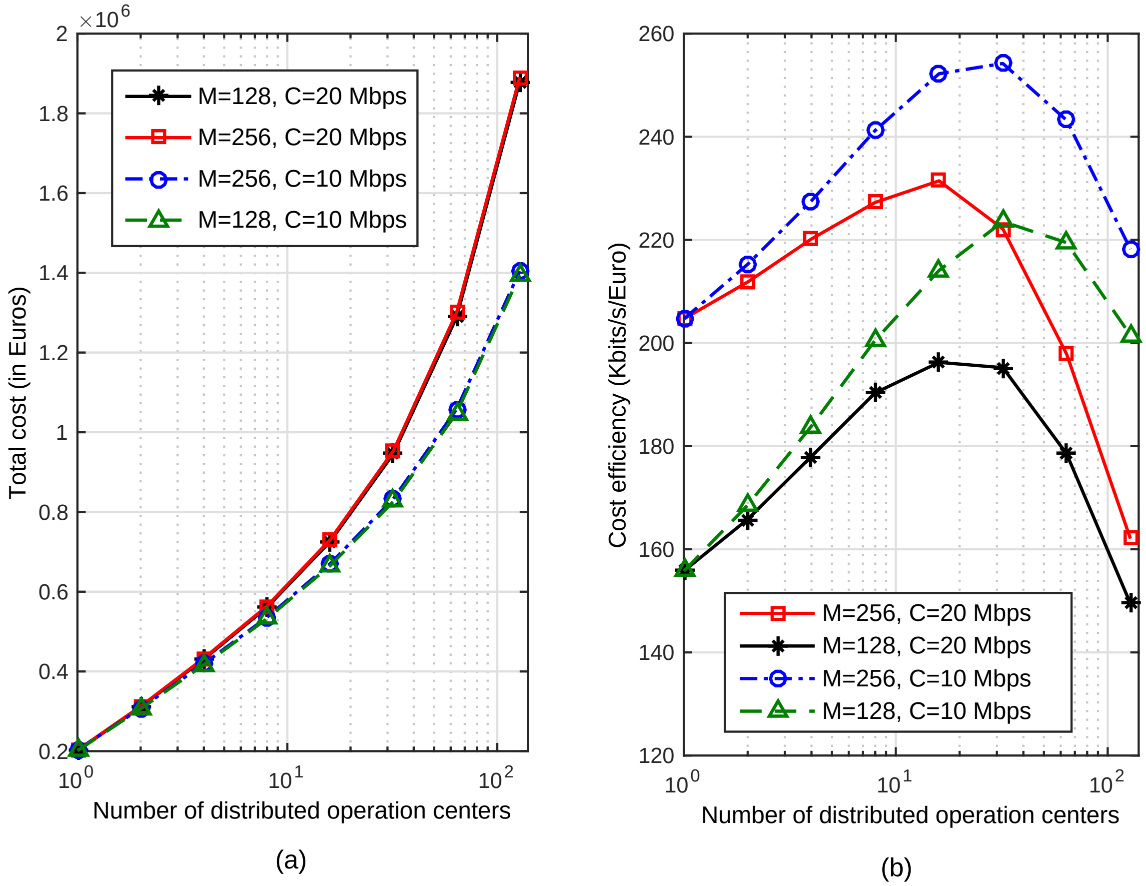

Fig. 5. Total cost and cost efficiency of the distributed communication architecture versus the number of distributed operation centers, where F_c = 200,000 Euros and F_d = 100,000 Euros are considered.