Performance evaluation of communication technologies and network structure for smart grid applications

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Abstract: The design of an effective and reliable communication network supporting smart grid applications requires the selection of appropriate communication technologies and protocols. The objective of this study is to study and quantify the capabilities of an advanced metering infrastructure (AMI) to support the simultaneous operation of major smart grid functions. These include smart metering, price-induced controls, distribution automation, demand response, and electric vehicle charging/discharging applications in terms of throughput and latency. OPNET is used to simulate the performance of selected communication technologies and protocols. Research findings indicate that smart grid applications can operate simultaneously by piggybacking on an existing AMI infrastructure and still achieve their latency requirements.

1 Introduction

Nowadays, the electric power grid is transitioning into an intelligent grid, which is called the smart grid [1]. The key to realising smart grid applications, such as demand response (DR), real-time pricing, automated metering, and electric vehicle (EV)-related applications, is to appropriately choose corresponding network structures and communication technologies that provide bidirectional end-to-end data communications [2]. Communication networks for smart grids can be presented as a hierarchical multi-layer architecture, which include a wide area network (WAN), a neighbourhood area network (NAN), and a customer premises area network [3]. WAN provides backbone communication for a smart grid [4, 5]. NAN manages information flow between WANS and customer premises area networks [6]. Customer premises area networks can be further classified as a home/building/industrial area network [7]. They enable communications within customer premises [8].

Popular WAN communication technologies are fibre optic, powerline communications (PLCs), and wireless media using cellular [9]. Popular NAN technologies are ZigBee, wireless local area network (WLAN), PLC and some long-distance technologies, such as cellular and data over cable services interface specification [10]. Various communication technologies, such as ZigBee, WLAN, Z-Wave, and PLC, are widely used [11–14]. Fibre-optic communication is one of the fundamental communication technologies for WANS due to its high data rate and immunity to noise [15]. However, it has high upfront investment and maintenance costs [16]. While PLC is a very good candidate for home automation and street light control applications [17, 18], its drawbacks are the inability to transmit signals cross a transformer, power line channel distortion, interference, noise, and harsh conditions of the power line environment; these are significant technical issues which affect its implementations [19, 20]. ZigBee, on the other hand, is a cost-effective, low-power, high-efficiency communication technology [21], but interference problems can be a challenge as it shares the same channel spectrum with some other protocols [22]. WLAN, well-known as Wi-Fi, is reliable, secure, and high speed. As a result, it is good at supporting short-range communications [23]. However, it is costly and has power consumption as compared with ZigBee and Z-wave [24]. The cellular network is one popular radio network, such as 3G and 4G (WiMAX and LTE). WiMAX natively supports the quality of service and real-time two-way broadband communications between nodes [25]. However, WiMAX is expensive and high-power consumption [26]. LTE is a high-speed, low-latency, secure, and long-distance wireless communication technology [27]. However, it shares the cellular services with other mobile customers which may lead to congestion and reduce the network performance [28]. As summarised above, each type of communication technology has its own advantages and disadvantages. In addition, different smart grid applications have specific communication requirements in terms of their data rate, latency, reliability, coverage range, and security requirements. Hence, it is extremely necessary to conduct the performance evaluation of communication technologies for smart grid applications.

As far as the literature review is concerned, there is plentiful research work on the performance comparison of communication technologies supporting smart grid applications. In [29], the authors compared different communication technologies (i.e. ZigBee, Wi-Fi, Ethernet etc) and assess their suitability for deployment to serve smart grid applications, focusing on home automation within a premises area network. In [30], the authors proposed and analysed the use of LTE multi-cast between the aggregator and residential (or official) premises for efficient DR management in smart grids. Effects of communication network performance on dynamic pricing in smart grid are discussed in [31]. In [32], the authors provided a comprehensive review of possible communication network infrastructures for metering based on real-world smart grid projects and analyse their advantages/disadvantages in terms of deployment costs, communication range, and reliability. Yuan et al. [33] and Ouya et al. [34] proposed EV charging management systems comparing between ZigBee and LoRa communication technologies. In [35], the authors proposed a communication network model for smart grids considering application requirements, link capacity, and traffic settings. Zaballos et al. [36] and Aggarwal et al. [37] proposed a heterogeneous communication architecture for smart grids with the detailed analysis of communication requirements. However, these works do not take into account the practical network infrastructure. In fact, advanced metering infrastructure (AMI) is one of the most commonly implemented network infrastructures with extremely wide coverage (from WAN to NAN). According to the U.S. Department of Energy’s Smart Grid Investment Grant Program (SGIG), a majority of the SGIG projects (65 out of 98) are categorised as AMI [38]. Using the existing AMI network to...
support other smart grid applications besides the meting has drawn lots of attention recently. These include applications, such as the supervisory control and data acquisition-based distribution automation (DA) [39], demand side management [40], transmission expansion with a phase-shifting transformer [41], forced oscillation source locating [42], cooperative control for micro-grid [43], transformer identification and phase identification [44], smart energy management [45], and stability analysis for the distribution control of micro-grid estimation [46]. In addition, Bian et al. [47] discussed a centralised demand curtailment allocation algorithm that can be implemented by piggybacking on AMI. Renewable energy resources can also be monitored and managed via AMI through an hourly DR programme [48]. Similarly, smart pricing, smart metering, and optimal EV charging using AMI are introduced in [49–51]. However, these studies, while focusing on proposing algorithms applications, do not investigate whether an existing AMI network can actually support simultaneous operations of different smart grid applications. In [52], the authors discussed technical requirements imposed on the communication network for AMI. Then they examined each of the AMI application standards found in the open literature based on these requirements. However, this paper does not provide simulation, not to mention the analysis for the simultaneous operation of different applications. Kulkarni et al. [53] carried out an extensive performance evaluation through simulations of current technologies delivering traffic from multiple AMI applications but only focuses on NAN. Zhou et al. [54] discussed scalable distributed communication architectures to support AMI. In [55], a bi-directional communication protocol was introduced considering the effect of the AMI environment. The discussion of ZigBee and PLC technologies for AMI is presented in [21, 56, 57]. Khan and Khan [58] discussed a heterogeneous WMAX-WLAN network for AMI communications. A novel path-sharing scheme for an AMI network is presented in [59]. Vaidya et al. [60] developed a multi-path routing method for AMI networks in a smart grid.

To fully realise benefits of AMI, it is necessary to appropriately choose communication technologies and associated communication networks that provide two-way communications. The comprehensive simulation and analysis of the ability of AMI network to support multiple smart grid applications are still a knowledge gap. To bridge the gap, the objective of this paper is to substantiate the claim that AMI network can support the simultaneous operation of other smart grid applications using simulation studies. Considering the extensive literature in this area, the main contributions of this paper are as follows:

- Firstly, popular communication technologies supporting AMI network operation, i.e. fibre optic, WiMAX, LTE, and 900-MHz radio frequency (RF) mesh network, are discussed and their performance is simulated in OPNET, commercial software that provides accurate communication simulations [61].
- Secondly, the performance of these communication networks is evaluated considering the simultaneous operation of popular smart grid applications in both NAN and WAN.
- Lastly, the conclusion from this paper provides a comprehensive analysis discussing the ability of AMI to support multiple smart grid applications.

The rest of the paper is organised as follows. Section 2 summarises network structures and technologies for smart grid applications. Technical requirements of smart grid applications are summarised in Section 3. In Section 4, case studies are discussed, and AMI communication network capability is then evaluated.

2 Review of communication technologies and network structures for smart grid applications

With the rapid transition from a traditional power system into a smart grid, smart metering applications have become widespread. There are a number of AMI rollouts, providing reliable two-way communications between an electric utility and end-use customers. This section provides a comprehensive review of communication technologies deployed in real-world AMI projects in the United States, as well as discusses typical AMI components and communication network structure.

2.1 Review of communication technologies for AMI

Based on a survey of real-world AMI projects in the United States [32], Table 1 summarises relevant information of selected AMI projects, including their number of smart metres and communication technologies deployed as the backbone network (in WAN, connecting a control centre and base stations) and the smart metre network (in NAN, connecting base stations, data concentrators, and smart metres). From Table 1, it can be seen that fibre optic and WiMAX/LTE are the most popular communication technologies for the AMI backbone network. Between the two choices, the fibre-optic option has an advantage over the WiMAX/LTE option in that it can provide a higher bandwidth. This is because the bandwidth of a WiMAX/LTE network needs to be shared with other customers in the same cellular network. Furthermore, the fibre-optic technology can provide a higher reliability level than 4G/LTE during inclement weather conditions. The 900 MHz RF mesh network appears to be the most popular technology choice to support communications for smart metre networks. This is because it has the good reliability of connection and signal penetration. Also, 900 MHz RF has a farther reach.

2.2 Typical AMI components

Important components that support AMI applications, as well as other major smart grid applications may comprise the following: Control centre is responsible for supervising overall smart grid operation. For example, it automates the data-collection process from smart metres, evaluates the quality of the data, generates estimates where errors and gaps exist, and broadcasts the price information or DR event commands. Base station communicates wirelessly with smart metres and field devices using fibre optic and connects directly with the control centre. Data concentrator is a combination of the software and hardware units that collects information from smart metres and forwards the information to the utility. Data concentrators are popularly used in densely-populated areas. Field devices are devices that allow remote control from a central location to accomplish selected smart grid applications, such as DA. Example field devices include remotely controllable voltage regulators, capacitor banks, switches etc.

A smart metre is a digital metre that can be used to record consumption of electric power/energy and transfer the consumption information to a utility. It can also be used to receive commands or price signals from a utility.

2.3 AMI communication network structure

The network, as shown in Fig. 1, illustrates a possible network structure supporting the AMI application (and perhaps others, such as pricing, EV and DA applications). In this figure, a group of smart metres and field devices are connected to one data concentrator, and then all data concentrators are connected to the control centre through the base station. Having data concentrators increases the numbers of smart metres and field devices that can be connected to a base station. The communication between a control centre and a base station can be based on fibre optic, between a base station and data concentrators can be based on WiMAX/LTE, and between a data concentrator and smart metres can be based on RF 900 MHz (per Table 1).

2.3 Technical requirements of selected smart grid applications

Since different smart grid applications have different characteristics, e.g. data size, data sampling frequency, latency, and reliability requirements, it is, therefore, necessary to ensure proper operation of all smart grid applications, especially those sharing the bandwidth with an AMI network. Characteristics of selected smart grid applications are as follows:...
Two types of DR applications are considered: on-demand DR and real-time DR. While on-demand DR schedules a demand reduction at least two hours ahead, real-time DR sends a request to participating customers for a demand reduction in real time. The pricing application broadcasts time-varying pricing information to end-users. Two types of metering applications are considered: on-demand meter reading and meter reading with scheduled time intervals. While on-demand meter reading is used to gather customer meter information as needed, the other kind of meter reading application is to read customer meter data at every fixed time intervals (e.g. 15 minutes or an hour). EV application controls the EV charging. DA includes sensing the operating conditions of the distribution grid and allows making adjustments to improve the overall power flow and distribution-level performance by controlling field devices such as capacitor banks and switches.

The package size shows a number of transmitted/received bytes typically involved in each smart grid application. Data-sampling frequency decides the number of packages needed. Latency is the total delay from both the algorithm and communication network.

4 Case studies

This section discusses case studies simulated in OPNET to analyse the throughput and latency of different communication options supporting smart grid applications.

4.1 CenterPoint energy: a reference smart grid project

Based on the AMI deployment reference scenario of the CenterPoint Energy Smart Grid Project [62], the service area (square miles), number of WiMAX towers, data collectors, and smart meters are summarised in Table 3.

It can be seen that the density of smart meters in the CenterPoint Energy's service area is 440 m per sq. mile (2.2 million/5000 sq. mile). The ratio of the WiMAX tower to metre

| Table 1 Selected real-world AMI deployments |
|--------------------------------------------|
| Project name | Number of metres | Backbone network | Smart metre network |
|--------------|------------------|------------------|-------------------|
|              | Fibre | WiMAX/LET | RF | 900 MHz | PLC | Others | WiFi | ZigBee | 900 RF | PLC | WiMAX/L TE |
| Knoxville smart grid community project, TN | 3393 | X | | | | | | | | | |
| customer driven design of smart grid capabilities, WI | 4355 | | | | | | | | | |
| AMI pilot, LA | 4855 | | | | | | | | | |
| smart grid modernisation initiative, OH | 5033 | | | | | | | | | |
| smart grid project, IN | 7474 | | | | | | | | | |
| AMI and smart grid development programme, LA | 10,596 | | | | | | | | | |
| connected grid project, OH | 12,575 | | | | | | | | | |
| Woodruff electric AMI project, AR | 14,450 | | | | | | | | | |
| Leesburg smart grid investment grant project, FL | 16,683 | | | | | | | | | |
| Connecticut municipal electric energy cooperative project, CT | 23,449 | | | | | | | | | |
| Pacific NW division smart grid demonstration project, WA | 30,722 | | | | | | | | | |
| smart grid team 2020 programme, MD | 38,551 | | | | | | | | | |
| AMI/metre data system, CO | 44,920 | | | | | | | | | |
| Urbank water and power smart grid programme, CA | 51,928 | | | | | | | | | |
| smart grid programme, CA | 52,257 | | | | | | | | | |
| Lafayette utilities system smart grid project, LA | 63,967 | | | | | | | | | |
| AMI/metre data system, SD | 68,980 | | | | | | | | | |
| front range smart grid cities, CO | 85,328 | | | | | | | | | |
| AMI smart grid initiative, CA | 85,582 | | | | | | | | | |
| smart grid initiative, FL | 124,000 | | | | | | | | | |
| smart grid project, NY & NJ | 170,000 | | | | | | | | | |
| IPC smart grid programme, ID | 380,928 | | | | | | | | | |
| central main power (CMP) AMI project, ME | 622,000 | | | | | | | | | |
| smart currents, MI | 688,717 | | | | | | | | | |
| smart grid initiative, MD | 1.3 million | | | | | | | | | |
| smart grid project by Centerpoint energy, TX | 2.1 million | | | | | | | | | |
| energy smart Florida, FL | 3 million | | | | | | | | | |

Fig. 1 Communication network supporting smart grid applications
data collectors is 112:5200 or 1:46, the ratio of the data collector to smart metres is 5200:2.2 million or 1:423, and the ratio of a WiMAX tower to smart metres is 112:2.2 million or 1:19,642. These ratios are used to set up the simulation case study as discussed below.

4.2 Case study I: performance analysis of the hybrid fibre-optic-WiMAX option as the backbone network

4.2.1 Service area assumption: The service area of interest covers around 600 sq. miles which is shown in Fig. 2. Based on the CenterPoint Energy service area discussed above, it is assumed that 15 WiMAX towers are used to support up to 290,000 smart metres within the service area. The service area of each WiMAX tower is 40 sq. miles. Using (1), the radius \( r \) of one WiMAX tower coverage area (hexagonal shape) is calculated to be \( \sim 4 \) miles. In each WiMAX cell, assuming that the ratio of the WiMAX tower to metre data collectors is 1:46 and the ratio of the data collector to smart metres is 1:423, thus, there are 46 data concentrators in each WiMAX cell, and each data concentrator is connected to 423 smart metres.

Note that 423 smart metres per data concentrator are used in this case study, which creates the worst-case scenario when simulating AMI performance. That is, it can be seen from Table 1 that the density of the smart metres for each data concentrator is much <423. Additionally, it is to be noted that smart metre locations within each cell are randomly distributed which is comparable to the real-world environment:

\[
\text{Area} = \frac{3}{2} \times \sqrt{3} \times r^2
\]

4.2.2 Communication technology and network structure of the hybrid fibre-WiMAX option: The hybrid version of fibre-optic-WiMAX technologies is used as a basis to simulate the backbone AMI traffic. That is, fibre optic is selected to serve between the control centre and 15 WiMAX base stations, and WiMAX is selected to provide coverage from base stations to data concentrators. The simulation is conducted in OPNET to evaluate the performance of this communication network to support smart grid applications in terms of latency.

To analyse the performance of this network in OPNET, data concentrators are simulated by using subscriber stations; the BS block is used to simulate the base station; the control centre is simulated by using a server station. A detailed case study is simulated in the OPNET with 15 WiMAX towers and 690 data concentrators within the 600 sq. mile area. Fig. 3 illustrates how the system is set up in OPNET.

The WiMAX technology used in Case Study I is wireless orthogonal frequency division multiplexing access (OFDMA) 20 MHz. For this type of WiMAX, the frequency band is 2.3–2.5 GHz and the bandwidth is 20 MHz. The WiMAX technology provides two-way communications which are uplink (UL) and downlink (DL). The UL transfers the information from smart metres to base stations; the DL transfers the information from base stations to smart metres. Both UL and DL are FreeSpace models.

For WiMAX technology, both UL and DL are split into multiple subcarriers with a narrow bandwidth. There are four kinds of subcarriers assigned to different functions. Guard subcarrier provides ‘guard interval’ which helps minimise the channel interference. Data subcarriers are used to transfer data. Pilot subcarriers are used for the synchronisation. The DC (direct current) subcarrier marks the centre point of the channel.

The 20 MHZ OFDMA WiMAX has 2048 points of fast Fourier transform which means that it has 2048 subcarriers in both UL and DL. The detailed classification of subcarriers is summarised in Table 4.

The maximum transmission data rate \( R \) that can be achieved in the WiMAX physical layer is defined in the IEEE 802.16 standard as

\[
R = \frac{N_{\text{data}} \cdot b_m \cdot c_t}{T_s}
\]

where \( N_{\text{data}} \) is the number of data subcarriers, \( b_m \) is the number of bits per modulation symbol (bits), \( c_t \) is the coding rate of the

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**Table 2** Characteristics of selected smart grid applications

| Package size, bytes | Data sampling frequency (time per day) | Latency, s |
|---------------------|----------------------------------------|------------|
| on-demand DR [44]   | 100                                    | <60        |
| real-time DR        | 100                                    | <5         |
| pricing             | 100                                    | 2–6        |
| on-demand metring   | 100                                    | <15        |
| metring with scheduled time intervals | 1600–2400 | 4–6 per residential; 12–24 commercial | <4h |
| EV application      | 100                                    | 2–4        |
| DA                  | 100                                    | as needed  |

**Table 3** Detail of the CenterPoint energy's AMI project

| Service area (sq. mile) | Reference case |
|-------------------------|----------------|
| Data collector          | 5200           |
| M2M tower               | 112            |
| Data collector          | 5200           |
| smart metre             | 2.2 million    |

Fig. 2 Northern Virginia service area

Fig. 3 Simulation of Case Study I in OPNET
modulation (bits/s), and $T_s$ is the CP-OFDM symbol time (seconds).

In OPNET, $T_s$ is 100.8 ms, and $N_{data}$ is 1120 for UL and 1440 for DL for the 20 MHz OFDMA. The parameters $b_m$ for Quadrature Phase Shift Keying, 16-QAM, and 64-QAM are 2, 4, and 6, respectively. In this case, the 64-QAM modulation method with the 3/4 coding rate is used.

### 4.2.3 Assumptions on smart grid applications:
For each application, assumptions on customer participation ratio, the start time of the operation, and the operation duration are summarised in Table 5.

For the real-time DR, metring, and pricing applications, the participation ratio of the end-user is assumed to be 100%. It means that all end-users are involved during the operation of these smart grid applications. It is assumed that there are five field devices located in each cell. For the EV application, it is assumed that half of the end-users have EVs, and the participation ratio of the EV application is thus 50%. For the DA application, only field devices can participate.

In this case study, the simulation lasts for 60 min. The metring application's operating frequency is 15 min. Thus, it operates four times during the simulation interval at the minute 1, 16, 31, and 46. For other four smart grid applications, it is assumed that they function only one time during the 60-min simulation period.

For the real-time DR, its operation duration is assumed to be 3 min. For all other smart grid applications, the operation duration is <5 s.

### 4.2.4 Scenario description:
In both scenarios, five kinds of smart grid applications (real-time DR, metring, pricing, EV application, and DA) function in a queue.

In the first scenario, it is assumed that there is no overlap between any two smart grid applications. In the second scenario, different from the first scenario, there is an overlap in operation between real-time DR and pricing applications.

### 4.2.5 Simulation results:
Simulation results of the first and second scenarios are shown in Figs. 4 and 5, respectively. In all case studies, the 'seed' which creates the random number generation is set as 20. As a result, simulation results presented in this paper are average of 20 simulation runs. Since the operation of the real-time DR requires real-time communications, the volume of data exchanging is large. See Fig. 4a at $t=50$ and Fig. 5a at $t=20.8$. As a result, the latency of this application is a little longer than other smart grid applications.

In scenario one, when there is no overlap in operation between any two smart grid applications, the longest latency is $\sim 40$ ms, as shown in Fig. 4b, which is an acceptable latency per the requirement specified in Table 2.

In scenario two, the operation time of the real-time DR application overlaps with that of the pricing application. As a result, the latency of the entire network increases (see Fig. 5b) to a little longer than 50 ms. This is an $\sim 10$ ms increase when running both the real-time DR and pricing applications simultaneously. This implies that an application that sends a 100-byte package to each customer adds $\sim 10$ ms delay on average to this particular network. Thus, for such applications as metre reading that also sends a 100-byte package, another 10 ms delay can be expected if it operates together with both real-time DR and pricing applications. For others, such as EV customers which has lower participation and DA which has a limited number of device...

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**Table 4 Classification of subcarriers**

|                  | UL  | DL  |
|------------------|-----|-----|
| guard subcarrier from left | 184 | 184 |
| guard subcarrier from right  | 183 | 183 |
| data subcarrier       | 1120| 1440|
| pilot subcarrier      | 560 | 240 |
| DC subcarrier         | 1   | 1   |
| total                | 2048| 2048|

**Table 5 Operations of smart grid applications**

|                  | Participation | Operation begin time, min | Operation duration, s |
|------------------|---------------|--------------------------|-----------------------|
|                  | 1st scenario | 2nd scenario             |                       |
| real-time DR     | 100%         | 50                        | 180                   |
| metring          | 100%         | 1, 16, 31, 46             | 5                     |
| pricing          | 100%         | 21.6                      | 5                     |
| EV               | 50%          | 55                        | 5                     |
| DA               | 5 devices in each cell | 45                        | 5                     |

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**Fig. 4 Simulation results:**
(a) Throughput (Mbps) and (b) Latency (seconds) when there is no overlap in operation of different smart grid applications.

**Fig. 5 Simulation results:**
(a) Throughput (Mbps) and (b) Latency (seconds) when there is overlap in operation among smart grid applications.
participation, these applications do not contribute much to added delay due to much lower bandwidth requirements. This implies that if all selected smart grid applications operate simultaneously, the maximum latency will be <80 ms. This latency is still much lower than the lowest latency requirement of all smart grid applications, i.e. <5 s specified in Table 2. Therefore, it can be concluded that all smart grid applications function properly when operating simultaneously.

4.3 Case study II: performance analysis of the hybrid fibre-optic–LTE option as the backbone network

4.3.1 Service area assumption: In the Case Study II, same assumptions as the Case Study I are implemented. Instead of 15 WiMAX base stations used in Case Study I, 15 LTE base stations are used.

4.3.2 Communication technology and network structure of the hybrid fibre-optic–LTE option: The hybrid version of fibre optic and LTE technologies is used as a basis to simulate the communication traffic between the control centre and data concentrators. Fibre optic is selected to serve as between the control centre and 15 LTE base stations. LTE is selected to support the smart metre network which covers from base stations to data concentrators.

The simulation is conducted in OPNET to evaluate the performance of smart grid applications in terms of its latency. A detailed case study simulated in the OPNET with 15 LTE towers and 690 data concentrators within the 600 sq. mile area is shown as Fig. 6.

The LTE 20 MHz frequency division duplexing (FDD) communication technology is applied in Case Study II. For this LTE technology, FDD is used as the duplexing scheme. The LTE technology also provides two-way communications which are UL and DL. In this case study, the UL transfers the information from smart metres to base stations, whereas the DL transfers the information from base stations to smart metres. The multi-path channel model for LTE’s UL is single-frequency division multiple access. The LTE frequency band of UL is at 1920 MHz and the bandwidth of UL is 20 MHz. The multi-path channel model for LTE’s DL is OFDMA. The frequency band of DL is 2110 MHz and the bandwidth of DL is also 20 MHz. Both UL and DL are the FreeSpace models.

The modulation type and coding scheme index for the LTE applied in this case study is 12, which means the 16-QAM modulation method with the 3/4 coding rate. The 2 × 2 multiple-input and multiple-output (MIMO) is applied as the MIMO configuration method for the LTE technology used in this case study. Throughputs of DL and UL can be calculated using

\[ R_{\text{peak}} = N_s \times N_m \times N_b \times T_s \]  

where \( N_s \) is the number of data stream, \( N_m \) is the number of modulation symbols per subframe, \( N_b \) is the number of bits per modulations symbol (bits/s), and \( T_s \) is the time duration of a subframe (second).

In this case study, \( N_s \) of 2 Nm is 100 for DL and 50 for UL, \( N_b \) is 64 bps, \( T_s \) is 71.4 ms, and based on the modulation method, the peak data rate provided by OPNET is up to 86.7 and 180 Mbits/s.

4.3.3 Simulation results: Similar to that of Case Study I, two scenarios are simulated using the fibre-optic–LTE network. Simulation results are shown in Figs. 7 and 8, respectively. The same as Case Study I, the ‘seed’ is set at 20, and all results shown below are average of 20 simulation results.

Similar to the fibre optic and WiMAX cases, ~10 ms increased when two applications overlapped. It can be concluded that when
all five smart grid applications overlap at the same period, the maximum latency will be <80 ms. This latency meets the smart grid application requirements specified in Table 2.

4.4 Performance analysis of 900 MHz RF to support smart grid applications from data concentrator to smart metres

This subsection discusses the latency from a data concentrator to smart metres. Using the data from Section 2, each data concentrator is connected with 423 smart metres, and assuming the radius of the WiMAX/LTE coverage area is 4 miles. For each customer, the size of data package is 100 bytes which is equal to 800 bits. Similarly, two scenarios are considered: non-overlapping and overlapping of operation of any two smart grid applications.

For the communication network connecting smart metres and data concentrators, RF technology is widely used in real-world AMI projects. Therefore, the RF mesh network is used as the smart metre network under study. Since RF provides very high reliability, the major consideration of the RF mesh network is its latency.

According to [63], the total delay of an n-hop routed path for one packet sent from one smart metre to the data concentrator can be calculated as

\[
T = \left[ n \times \left( T_{\text{prop}} + \frac{L}{R} \right) \right] + \left[ (n - 1) \times T_{\text{proc}} \right]
\]

(4)

where \( n \) is the number of hops for one packet, \( T_{\text{prop}} \) is the propagation delay (second), \( L \) is the length of the packet (bits), \( R \) is the data rate, and \( T_{\text{proc}} \) is the time spent processing the packet before forwarding it (second).

According to Gungor et al. [64] and Power Engineering International [65], the 900 MHz RF network has the data rate of up to 13.5 Mbps with the coverage of up to 25 miles and allows up to 1000 customers to access. Its coverage and access ability can be implemented to support communications of the AMI smart metre network connecting a number of smart metres to a data concentrator. In this section, the package size is 800 bits and the data rate is set as 10 Mbps which is popularly used.

Equation (5) shows the total latency of an RF network (\( T \)), comprising

\[
T = \sum (T_{\text{tran}} + T_{\text{prop}} + T_{\text{proc}})
\]

(5)

where \( T_{\text{tran}} \) denotes the delay from pushing the data into a communication channel, \( T_{\text{prop}} \) is the delay from data travelling from a sender to a receiver, and \( T_{\text{proc}} \) is the delay from collecting data at the receiver.

To calculate the latency, it is assumed that a smart metre and a data concentrator have the same access speed. Equation (6) shows the calculation of transmission and processing delays:

\[
T_{\text{tran}} = T_{\text{proc}} = \frac{S_p \times N_c}{R}
\]

(6)

where \( S_p \) is the size of the package (bits), \( N_c \) is the number of customers, and \( R \) is the data rate (bps).

To calculate the propagation delay, the distance between each access points and the base station is assumed to be a Gaussian distribution. Also, the propagation speed of the signal in free space is the same as the light which is \( 3 \times 10^8 \) m/s. Equation (7) shows the propagation latency:

\[
T_{\text{prop}} = \frac{D}{S_{\text{prop}}}
\]

(7)

where \( D \) is the distance (m) and \( S_{\text{prop}} \) is the propagation speed (m/s).

4.4.1 Non-overlapping scenario: When there is no overlap operation period between any two smart grid applications, the transmission, propagation, and total latency are calculated as shown in (8)–(10), respectively:

\[
T_{\text{tran}} = \frac{S_p \times N_c}{R} = \frac{800 \times 423}{10 \times 10^3 \text{(bps)}} = 0.03 \text{ s}
\]

(8)

\[
T_{\text{prop}} = \frac{D}{S_{\text{prop}}} \leq 0.01 \text{ s}
\]

(9)

\[
T_{\text{scenario}} = T_{\text{tran}} + T_{\text{prop}} + T_{\text{proc}} \leq 0.03 + 0.01 + 0.03 \leq 0.2 \text{ s}
\]

(10)

4.4.2 Overlapping scenario: When there is one overlap operation period between any two smart grid applications, communication traffic throughput is doubled, and the latency of the worst case is two times of the non-overlapping scenario. The total latency is calculated using

\[
T_{\text{scenario}} = T_{\text{tran}} + T_{\text{prop}} + T_{\text{proc}} \leq 0.03 + 0.01 + 0.03 \leq 0.2 \text{ s}
\]

(11)

4.5 Summary of the case study results

Table 6 summarises overall case study results on the AMI network latency. As shown, the overall latency of the operation of all five smart grid applications under the overlapping scenario is <0.06 s in the backbone network with fibre-optic WiMAX/LTE, and is <0.4 s in smart metre networks with 900 MHz RF. The overall latency thus meets the latency requirements specified in Table 2. In the real world, the density of smart metres is much less than the assumption used in the case study. The operation frequency for each smart grid application is also smaller than the number used in the case study. As a result, the actual overall latency is expected to be much less than the results shown in Table 6.

5 Conclusion

With the rapid development of the smart grid, there are different aspects of market opportunities and technological applications being deployed simultaneously. For example, there are two demand side management programmes that may overlap: one that operates on pre-defined schedules and the other that operates dynamically based on price. In this paper, the capability of an existing AMI communication network to support multiple types of smart grid applications is evaluated. The observation is that popular communication technologies (i.e. hybrid fibre-optic—WiMAX, hybrid fibre-optic—LTE, and 900 MHz RF) implemented with proper communication network structures can support simultaneous operations of programmes with predefined schedules and those which operate dynamically based on price.

6 References

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Table 6 Summary of case study results

| Latency       | Backbone network, s | Fibre-optic WiMAX | Fibre-optic LTE | Smart metre network, s | 900 MHz RF |
|--------------|----------------------|------------------|----------------|------------------------|------------|
| non-overlap  | <0.05                | <0.04            | <0.05          | <0.2                   | <0.4       |
| overlap      | <0.06                |                  |                |                        |            |

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