REVIEW OF WIRELESS COMMUNICATION LAYER INTERFACE ON ADVANCED METERING INFRASTRUCTURE

R. Ruliyanta[1], I. Kusuma[1] and M. Fathoni[2]

[1]Department of Electrical Engineering,
Universitas Nasional, Jl. Sawo Manila, Pasar Minggu, Jakarta Selatan 12520,
Jakarta, Indonesia.

[2]Department of Electrical Engineering,
Institut Teknologi Budi Utomo, Jl. Mawar Merah, Pondok Kopi, Duren Sawit, 13440,
Jakarta, Indonesia.

Corresponding Author's Email: [1]ruliyanto@civitas.unas.ac.id

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ABSTRACT: Advanced Metering Infrastructure is a technology that will be implemented in Indonesia along with the current growth of information technology. Indonesia has natural conditions consisting of mountains and oceans. The problem of selecting an appropriate network to support AMI conditions in Indonesia is significant. This research will examine the benefits of various existing wireless technologies. We will examine several important parameters such as cost, range, data transfer speed, etc. The review results show it has the best potential among other communication interfaces. This review evaluates LoRaWAN in comparison to other technologies, such as ZigBee, Cellular, Satellite, and Bluetooth. The advantages of LoRaWAN include comprehensive coverage, low energy consumption, low implementation costs, and extensive network scalability. Under line-of-sight conditions, the range can extend to 20 km or more in ideal scenarios, such as when high-mounted gateways and flat terrain are utilized. Transmit power ranges from 14 dBm (25 mW) to 20 dBm (100 mW), depending on regional regulations. The implementation cost of LoRAWAN is much lower, and its network scalability is very high compared to other technologies.

KEYWORDS: *Advanced Metering Infrastructure; LoRaWAN; Communication Layer Interface; Smart Grid; Wireless technologies*.

1.0 INTRODUCTION

Modernization of the energy sector has become a global imperative to address the challenges of energy efficiency, sustainability, and reliability [1]. One of the significant advances in this regard is the implementation of Advanced Metering Infrastructure (AMI) in the Smart Grid framework [2, 3]. AMI represents an essential component of the Smart Grid ecosystem, enabling real-time data collection, improving demand response, accurate billing, and improving energy management [4]. As a rapidly developing country with ever-increasing energy demand, Indonesia urgently needs modern and efficient energy infrastructure [5–7]. The application of AMI is gaining momentum as a strategy to transform traditional energy networks into more innovative and more responsive networks [8–10]. Various studies have highlighted pilot projects and initiatives undertaken by Indonesian utility companies in specific regions or cities to assess the feasibility and impact of AMI [11-16]. The implementation of AMI in Indonesia is faced with several geographical problems that can affect the implementation and effectiveness of the system. Indonesia has significant geographic diversity, including large islands, mountains, forests, and remote areas. This problem can affect the need for communication infrastructure and AMI distribution, considering that some areas may be difficult to access or have challenging topography [5, 17-20]. As an archipelagic country, Indonesia has long distances between islands. This can be a challenge in providing excellent and efficient connectivity between smart meters throughout the country. Some areas, especially inland or remote islands, may be challenging to reach and have limited accessibility. Installation and maintenance of smart meters in such areas can be more complex [14]. Indonesia's diverse topography, such as mountains and highlands, can make installing network and communications infrastructure difficult. Selecting communication technology appropriate to topographic conditions is critical [17].

Several areas in Indonesia experience extreme weather conditions such as heavy rain, strong winds, or long dry seasons [21, 22]. This can impact the reliability of infrastructure and electronic devices, requiring devices and systems that can withstand extreme weather. Remote areas often have more limited energy infrastructure. The existence of development gaps between urban and rural areas can influence the acceptance and sustainability of AMI implementation. Urban areas may be better equipped with better infrastructure than rural areas [5, 17, 19, 23-24]. Different geographical conditions require appropriate regulations and policies. Coordination between central and regional governments in implementing regulations and standards can be problematic. Implementing AMI in Indonesia requires significant investment [18, 25–27]. While some regions may be better prepared economically, others may require more financial support [5, 27].

Indonesia's geographical problem, which consists of thousands of islands, is one of the obstacles to AMI's growth [24]. The AMI communication network at the communication layer is one of the problems. We reviewed various communication layers as AMI interfaces with the control center. In overcoming this problem, collaboration between government, energy service providers and other stakeholders is essential. Selecting technology appropriate to Indonesia's geographical conditions and developing specific solutions for certain regions can also help overcome this challenge. This research will review the AMI technology communication interface most suitable for Indonesian conditions. This research contributes to providing alternative interfaces that are most suitable for AMI. This is adapted for rural, urban, and suburban areas.

2.0 LITERATURE REVIEW

The target for implementing AMI in Indonesia will be completed in 2031 [5]. Researchers such as [26] emphasize that implementing AMI in Indonesia involves technical, regulatory, and socio-economic challenges. Initial deployment of smart meters was primarily focused on industrial and commercial customers, with some gradual expansion to residential consumers [25-26, 28]. This phased approach is a strategic response to managing complexity and resource allocation. Several challenges hinder the integration of AMI into the Indonesian energy landscape. Sinaga et al. [21] pointed out the lack of standard regulations and policies specifically tailored to the implementation of AMI. Regulatory clarity and coordination between government agencies, utility companies, and technology providers are critical for successful implementation [29-30]. The communication interface in AMI is a meeting point between various components in the system. The communication interface in AMI allows data exchange between smart meters, control centers, monitoring devices, and other elements in the network. Communication is carried out in two directions. An outline of the architecture of AMI is given in Figure 1 [31].

Meanwhile, a research conducted a Survey of Threats and Countermeasures on Smart Meters [33]. In a smart grid, AMI is the weakest part of various threats. AMI measures energy consumption and other data periodically. Data generated by smart meters includes information about energy consumption, device conditions, and network status. This data is then stored as a packet ready to be sent. The data generated by smart meters is packaged in data packets that comply with the communication protocol used in AMI. Data packaging includes adding information such as sender address, recipient address, and timestamps. The network access used can be physical or non-physical. The physical network comprises power line communication (PLC), Ethernet, copper cables, fibre optics, and non-physical or wireless networks such as satellite communications, LoraWAN, Wi-Fi, Bluetooth, and cellular communications [5].

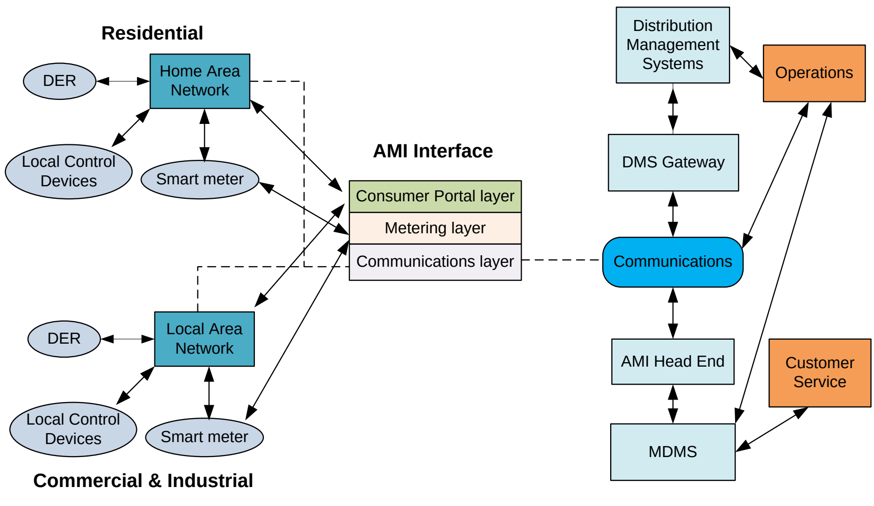

Figure 1: Overview of AMI [32]

Wireless communication is a commonly used choice to support AMI because of its flexibility and ease of implementation. In their research, Ismail et al. designed a prototype EV charging station [34]. However, in his proposal, the connections are TCP/IP, ZigBee, and cellular communication. Because the AMI communication network is short-distance, both wireless and cable communications can be candidates for this network [5]. In their paper, they propose broadband PLC (BB PLC), narrowband PLC (NB PLC), 4G, WiSun, and NB IoT (Narrowband Internet of Things). This is selected and adjusted according to data rate (10-100 kbps/node and 500 kbps for backhaul), data size (100 – several bytes), latency (2-15 seconds), reliability: 99-99.99%, and security factor.

A research group of communication technology is divided into three groups: Power Line Communication (PLC), Radio Frequency (RF), and cellular and non-cellular communication technologies [14]. However, the choice of communication type is adjusted to customer characteristics such as geographic conditions and customer density. Gallardo et al. [35] utilize LoRa for IoT in AMI communications for residential intelligent grids. The advantage of LoRa is that even in low power conditions, it can still transmit information well [36].

2.1 Radio Frequency (RF)

RF is the primary choice for wireless communications in AMI. RF communication systems use radio waves to transfer data between smart meters and network infrastructure. RF advantages include comprehensive area coverage, penetrating obstacles such as buildings, and managing power consumption to extend device battery life. Although radio frequency (RF) technology has several advantages, several disadvantages must be considered when implementing AMI. Radio signal interference is an obstacle in implementing AMI, especially in big cities [4, 36]. RF is susceptible to external interference, such as electromagnetic interference from other devices, inclement weather, or building structures. This kind of interference can cause loss or disruption in data exchange between smart meters and the control centre. In addition, the RF range is limited. Even though RF has a wide range, its maximum distance is still limited [5]. When smart meters are spread over a large or remote area, it may be necessary to install repeaters or signal boosters to extend the range. RF channel capacity can be limited, mainly if many smart meters communicate simultaneously within a given area. This can cause signal overlap and network congestion [31]. RF also has security issues in AMI applications. RF is vulnerable to eavesdropping or data manipulation because its signals can be intercepted or recorded by unauthorised parties [9, 16, 31, 37-38]. Additional security protections, such as data encryption, may be necessary to protect the integrity and confidentiality of information.

Using RF by smart meters can result in significant additional power consumption. If not managed properly, this can shorten the battery life of smart meters that run on battery power. Implementing an RF communications system requires a substantial initial investment in the infrastructure and hardware that supports this technology. Installing repeaters or signal boosters can also add to operational costs. RF requires appropriate frequency allocation for its operation [16, 34, 39-40]. Regulations and restrictions on frequency use by authorities must be followed to avoid interference with other communication systems [13, 30, 37].

Despite several disadvantages, RF is still prevalent in AMI implementations because it provides extensive wireless connectivity and good coverage [4]. However, it is essential to carefully consider these drawbacks and plan appropriate mitigation strategies to minimise their impact on AMI implementation [37]. RF is suitable for networks that cover large areas. RF signals can reach broad areas, including rural or remote areas, that are not easy to reach by cable or PLC technology [16, 37]. Another advantage of RF is that it allows high flexibility and mobility. This allows for easier installation and device changes without changing the cabling infrastructure. RF network implementation can be more economical than cable infrastructure [5, 40]. This is especially true in large areas where building cable infrastructure may not be practical. RF networks can be set up quickly and relatively easily compared to cable infrastructure, which requires excavation and physical installation. RF enables networks that are easily expandable and adaptable to growing needs. Adding devices or coverage areas can be done relatively simply.

2.2 Mesh Networks

A mesh network is a structure where each device can communicate directly with its neighboring devices. In the context of AMI, mesh networks enable smart meters to form a strong and connected network, allowing data to be transmitted over multiple paths [5]. This increases the reliability and speed of communication. In a mesh network, each device can communicate directly with other devices. This means that each smart meter in the network also acts as an access point or network node that can send and receive data. Thus, data can flow through various routes in the network, not just directly to the control centre or gateway [41–43]. Mesh networks have high redundancy, as data can flow through alternative paths if one route is blocked or disrupted. This increases network reliability because disruption to one device or route will not affect the entire network [9, 34]. Mesh networks allow flexibility in adding or removing devices. When additional devices are added to the network, they can automatically join and contribute to the communications infrastructure. Mesh networks can be easily expanded by adding more devices to the network. This makes it suitable for AMI implementations that require increasing the number of smart meters or other devices over time. In a mesh network, devices are only active when needed to transmit or receive data. This can reduce overall energy consumption in the network, mainly if energy-friendly technologies are used. Compared to communication technologies that require expensive central infrastructure, mesh networks can be implemented at lower costs because they utilize existing devices (smart meters) as network nodes.

3.0 RESULTS AND DISCUSSION

3.1 Wi-Fi (Wireless Fidelity)

Wi-Fi technology can support AMI communications, especially in urban environments or areas with good Wi-Fi infrastructure. Wi-Fi offers high data transfer speeds but typically has a shorter range than RF technologies. The advantage of the Wi-Fi Network for AMI is High Data Transfer Speed. Wi-Fi offers high data transfer speeds, enabling fast data exchange between smart meters, gateways, and control centres. This enables accurate real-time energy monitoring and management. Wi-Fi is a commonly used and widely known technology, so installing and configuring Wi-Fi devices is relatively easy. This can reduce the complexity of implementing AMI. Many homes and buildings are already equipped with Wi-Fi networks, so utilising existing infrastructure can reduce the costs of implementing AMI. Most consumer devices, such as smartphones, tablets, and laptops, support Wi-Fi connections. By using Wi-Fi for AMI, users can easily connect and monitor their energy consumption. Some modern Wi-Fi devices support dual-band connections, allowing both 2.4 and 5 GHz frequencies to be used. This can help overcome frequency bottlenecks and improve network performance in congested environments. The main challenge of using Wi-Fi technology for AMI is energy consumption. Wi-Fi devices consume more energy than other communications technologies, mainly in continuous transmission mode. This can be a problem in AMI applications that require energy savings. Wi-Fi has a limited range compared to technologies such as LoRaWAN or mesh networks. This can be a challenge in environments with extensive coverage or if the smart meter is in a location where Wi-Fi signals are challenging to reach.

Although Wi-Fi provides various security features, such as data encryption, there are still security risks associated with using Wi-Fi. Additional steps are required to protect sensitive data transmitted within the AMI network. Building the Wi-Fi infrastructure required to support AMI can require significant investment, especially if upgrading or expanding existing Wi-Fi networks is required.

3.2 Cellular Networks (4G, 5G)

Cellular networks such as 4G or 5G allow smart meters to connect to existing communications infrastructure. Cellular technology provides comprehensive area coverage and high data transfer rates. However, subscription costs and device power consumption must be considered [37]. Cellular networks generally have comprehensive coverage, covering large areas, even in remote areas. This enables AMI communications across multiple geographic locations. 4G and 5G cellular networks offer high data transfer rates, enabling fast data exchange between smart meters, gateways, and control centers [44–46]. This is important to support real-time energy monitoring and management. Most modern cellular networks support both lower frequencies (e.g., LTE at 700 MHz) and higher frequencies (e.g., LTE at 2.6 GHz), allowing dual-band connections [45]. This helps overcome frequency bottlenecks and improves network performance. Mobile networks have built-in security features such as data encryption and strong user authentication. This helps protect data transmitted within the AMI network from security threats. Mobile networks can easily be expanded to handle increasing AMI devices. Adding additional devices to a cellular network can be done relatively quickly with existing infrastructure.

The main challenge of using cellular networks for AMI is operational costs. Using cellular networks for AMI can involve high operational costs, including data subscription, roaming, and device fees. Devices that use cellular connections tend to consume more energy compared to other communications technologies. This can be a problem in AMI applications that require energy savings. The quality of AMI services is highly dependent on the availability and quality of the cellular network provided by the operator. This dependency can cause problems if there is a network disruption or service outage. Cellular networks require adequate infrastructure, including cellular antennas and base stations. Some regions may not have sufficient infrastructure to support AMI implementation with cellular networks.

3.3 Satellite

Satellite communications can be used in hard-to-reach areas or over large areas. Although they typically have higher latency, satellites can be an option for AMI projects in remote areas. The use of satellites in Advanced Metering Infrastructure (AMI) is one communication option that can be used to connect smart meters with control centres and collect energy consumption data [17, 33, 47-48].

Satellites can cover vast areas, including remote or isolated areas that are difficult to reach by other land communications infrastructure. This makes it an ideal choice for AMI in sparsely populated areas or bordering hard-to-reach areas [17]. Satellite connections are often stable and reliable, unaffected by weather conditions or physical obstacles such as buildings or vegetation [47]. This enables consistent and reliable data exchange between smart meters and the control centre. Using satellites allows AMI to be deployed in various geographic environments without depending on existing ground network infrastructure. This allows flexibility in network deployment and expansion. Communications via satellite are often encrypted and heavily protected, offering a high level of security for AMI data exchange. This is important to protect sensitive information about customers' energy consumption.

The challenge of using satellite communications is cost [48]. The use of satellites in AMI is often more expensive than other communications technologies, especially in terms of equipment costs and satellite service subscription costs. This can be a limiting factor when adopting a satellite solution. Communication via satellite can experience delays and latency due to the distance the signal must travel. This can affect responsiveness and response times in data collection and transmission. Although satellite technology has a large bandwidth capacity, certain technical limitations may limit the amount of data that can be transferred efficiently [49]. This problem can be if the AMI requires large or real-time data transfers. The availability of satellite services depends on atmospheric conditions and satellite position. Weather disruptions or technical problems with satellites can disrupt service availability, causing disruptions in AMI communications.

3.4 Zigbee

Zigbee is a wireless communications protocol commonly used in smart home networks. Despite its limited coverage, Zigbee can be used in AMI scenarios where smart meters and other devices are relatively close [34, 40]. Using Zigbee in AMI has several advantages and relevant applications [50]. Zigbee is known for its low power consumption, making it suitable for smart meters operating autonomously on battery power. Zigbee supports a mesh network topology, where each Zigbee device can communicate directly with each other or through neighboring devices, enabling broad coverage and tolerance for device failure—well-established standard ZigBee infrastructure with widely available infrastructure, including various easily accessible Zigbee devices and gateways. ZigBee devices are affordable, making them an economical solution for AMI implementation. ZigBee has good automation capabilities and self-organising capabilities, so it is easy to implement and manage, especially in networks that require regular addition of devices [35, 45, 51-52]. Smart meters use ZigBee technology to communicate with each other in a mesh network, enabling the efficient exchange of energy consumption data. The Zigbee gateway acts as an access point between the smart meters and the control center, collecting data from the smart meters and sending it to the control center for monitoring and analysis. Zigbee is used for AMI network setup and monitoring, including device configuration, meter reading scheduling, and network performance monitoring [9, 14]. Data collected via Zigbee networks can be integrated with energy management systems to optimise energy use, support predictive maintenance, and facilitate other innovative energy services [47, 53-54]. Zigbee enables remote device maintenance and updates, reducing the need for manual intervention and increasing operational efficiency.

3.5 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a wireless technology used in AMI to facilitate communication between smart meters, gateways, and control centers [55]. Smart meters with a BLE module can measure energy consumption and transmit data via Bluetooth Low Energy. A gateway or hub connected to the internet and with BLE features can be an access point between smart meters and the AMI network. Data collected via a BLE connection can be integrated with energy management systems for further analysis, performance monitoring, and better decision-making regarding energy usage [56].

Depending on the physical environment and obstacles, BLE has a limited range, typically tens of meters. Although BLE is suitable for sending small and periodic data, its data transfer capacity is more limited than that of other communication technologies such as Wi-Fi or cellular networks. The effectiveness of BLE in AMI depends on adequate infrastructure, including gateways or hubs connected to the internet. Despite some challenges, using BLE in AMI can enable efficient, energy-saving, and cost-effective communications between smart meters and control centers and provide flexibility in energy management and monitoring. Table 1 summarizes the most used wireless networks for AMI communications at the communications layer.

Table 1: Comparison of wireless technology supported AMI communication layer interface

Interface	ZigBee	Bluetooth	LoRaWAN	Cellular	Satellite
Frequency	2.4 GHz, 868 MHz, 915 MHz	2.4 MHz	915 MHz, 868 MHz, 433 MHz	2G: 850 MHz, 900 MHz, 1800 MHz, 1900 MHz 3G: 850 MHz, 900 MHz, 1700/2100 MHz, 1900 MHz 4G LTE: 700 MHz, 850 MHz, 1700/2100 MHz, 1900 MHz, 2300 MHz, 2500 MHz, 2600 MHz 5G: 600 MHz, 700 MHz, 3.5 GHz, 26 GHz	- L-band (1-2 GHz) Ku-band (12-18 GHz) Ka-band (26.5-40 GHz)
Power	Low	Very Low	Very Low	High	Very High
Range	10 m – 30 m	10 -240 m	Urban: 1–3 km Suburban: 3 - 5 km Rural: 5–10 km	2G: 10 – 100 km 3G: 10 km 4G LTE: 5 – 10 km 5G: < 5 km	
Security	High	Low-High	High	High	High
Rate	250 kbps – 2 Mbps	50 Mbps	< 1Mbps	9 kbps – 200 Mbps	Some Mbps
Scalabilities	Good	Very Low	Very High	Good	Medium
Stability	Low	Very Low	Very High	Low	High
Cost	Low	High	Very Low	High	Very High
Infrastructure	High	High	Easy	Easy	Easy
Reference	[13], [14], [19], [36], [37], [57],	[55], [38], [57], [59]	[3], [4], [47], [49], [52]–[54], [56]–[58], [60],	[14], [45][37], [69]–[71]	[3], [20], [51], [63]

	[58]		[61], [13], [62]–[68], [14], [17], [19], [20], [35]–[37]		

Table 1 shows LoRaWAN as the superior network for AMI communication interfaces. Several advantages are wide range, low energy consumption, low cost, scalability, flexibility, security, and simple management. There are several disadvantages to consider: limited data throughput, high latency, capacity limitation, dependency on infrastructure, interference, and limitation in customization. Nevertheless, by considering these drawbacks in network planning and design and selecting the right technology for specific application needs, LoRaWAN remains an attractive solution for AMI implementation in many scenarios. Advantages of LoRaWAN Compared to ZigBee, Bluetooth, Cellular, and Satellite for AMI Interface Layer show in Table 2.

Table 2: Advantages of LoRaWAN Compared to others Technologies

Technology	**LoRaWAN Advantages**
ZigBee	• Coverage Range: LoRaWAN supports long-range communication (up to 10-15 km in open areas), while ZigBee is limited to short distances (around 100-200 meters). • Power Consumption: LoRaWAN is more energy-efficient, ideal for battery-powered devices like AMI sensors. • Scalability: LoRaWAN can support a much larger number of devices compared to ZigBee.
Bluetooth	• Coverage Range: LoRaWAN offers significantly wider coverage compared to Bluetooth, which is limited to 10-100 meters. • Node Capacity: LoRaWAN can handle thousands of devices, whereas Bluetooth is constrained to fewer connections. • Interference Resistance: LoRaWAN operates in frequency bands less susceptible to interference than Bluetooth’s 2.4 GHz band.
Cellular	• Operational Cost: LoRaWAN utilizes unlicensed bands, making it more cost-effective compared to Cellular, which requires licensed bands and subscription fees. • Power Consumption: LoRaWAN is far more power-efficient, suitable for battery-powered IoT devices. • Deployment Flexibility: LoRaWAN enables users to build private networks without relying on Cellular operators.
Satellite	• Cost: LoRaWAN has significantly lower operational and infrastructure costs compared to Satellite communication. • Power Consumption: LoRaWAN is much more energy-efficient than Satellite systems, which typically require high power • Latency: LoRaWAN offers lower latency than Satellite communication for certain distances.

LoRaWAN has a range of 2–5 km in urban areas due to building obstructions and interference. In rural or open areas, it can reach up to 10–15 km, depending on environmental conditions and antenna height. Under line-of-sight (LoS) conditions, the range can extend to 20 km or more in ideal scenarios, such as when high-mounted gateways and flat terrain are utilized. LoRaWAN devices can operate for 5–10 years on a single battery under typical usage conditions. Transmit power ranges from 14 dBm (25 mW) to 20 dBm (100 mW), depending on regional regulations. In sleep mode, the current can be as low as 1 µA, which is significantly lower than that of other communication technologies. The implementation cost of LoRAWAN is much lower, and its network scalability is very high compared to other technologies.

4.0 CONCLUSION

With these advantages, LoRaWAN becomes an attractive solution for AMI implementation, especially in large and distributed areas. LoRaWAN has the best potential among other communication interfaces. The advantages of LoRaWAN include comprehensive coverage, low energy consumption, low implementation costs, and extensive network scalability. Apart from that, LoRaWAN has better flexibility, security, and management.

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