Using LoRaWAN Infrastructure in a Smart Grid

Siddhant Khera
Department of Electrical Engineering
University at Buffalo
skhera2@buffalo.edu

***Abstract*—The current power grid was designed in the 20th-century. The grid landscape is changing and we are advancing towards a smart-grid infrastructure. This paper explores how the current grid operates on a very high level, and compares it to a future smart-grid. Smart-grids support bi-directional flow of power and information. Then, three different communication protocols are considered: Zigbee, WiMAX, and LoRaWAN. One of the concerns on a technical level is the feasibility of the network in terms of congestion and the appropriate requirements of the end-device and the communication system. For smart-grid applications, there are varying requirements from different end-devices, with a sole focus on low power, long range transmission in it's current implementation. LoRaWAN is discussed in detail since it supports low power, long range applications with a different variety of end-devices which are suited to a smart-grid ecosystem.**

***Index Terms*—Challenges, Communication, LoRaWAN, Smart Grids**

I. Introduction

The current electrical grid was designed in the 1920s [24]. The grid was originally designed for a small area near the generation plants. It was subsequently expanded over the years to the national scale. The industry has innovative technology in the current grid, although, it suffers from uni-directional flow of power and the information. We have the ability forecast the expected usage for a given hour by the users in the grid system, but we do not have a forecasting model that can precisely predict the load, either long-term or short-term because of lack of real-time data. There is lack of an automated analysis; it simply works on how we program generation. This brings to fore another major issue. Lack of automated analysis or real-time information of the use of power leads to an under-generation or over-generation of electricity. The present electric grid relies mostly on energy generated by fossil-fuel sources such as natural gas and coal [24]. The current grid is unable to react quickly because fossil fuel generation sources are typically slow to power up [24]. They can take as much as 45 to 60 minutes to turn on [24]. Even with recent efforts to keep the grid stable, we could utilize a bi-directional flow of power and information to better predict load and program the generation in the grid.

Smart-grids have the potential to solve this issue, and also increase the possibility of better integration of users within the grid. Most importantly, a smart grid has bi-directional flow of information about the users the grid, and how the current load is distributed. We can then rely on automated analysis to balance load and generation. Finally, smart grid primarily uses renewables like Solar, Wind, etc [11].

A communication network is required to facilitate the data-collection. To facilitate a smart-grid communication network, we need a network back-haul that can support the needs of smart-grid end-devices. We will stick with wireless for simplicity of discussion in this paper. In a smart-grid infrastructure, we desire a network that has a long range while keeping power consumption to a minimum. To accomplish that, this paper will discuss technologies including Zigbee, WiMAX and a focused discussion on viability of LoRaWAN in a smart-grid infrastructure. LoRaWAN has a wide variety of specifications that allow it to be used in very different types of end-devices.

Fig. 1. An image depicting fossil-fuel powered generation plants in a Conventional Grid [10]

II. Smart Grids

A smart-grid primarily uses renewables like Solar and Wind with grid-scale battery storage [11]. Renewables, in their design, can be intermittent. There could be strong solar days while there could be a cloudy day that inhibits their potential to perform at their highest capacity. Likewise, some days are windier than others. To add stability in the renewable generation, we need to add a form of energy storage. Smart-grid is more a marketing term than a technical one. Pseudo-technically, a smart-grid will fully exploit the communications network to cost-efficiently integrate the actions of all direct and indirect users of the load sources, while maintaining low losses and high levels of quality [8]. Battery storage is a viable option. Smart-grids utilize grid-scale battery storage in the Megawatts range.

Another benefit to using battery storage is that the stored energy could be accessed and supplied to the grid on-demand

Fig. 2. Grid-scale battery deployment with Wind generation in Australia [4]

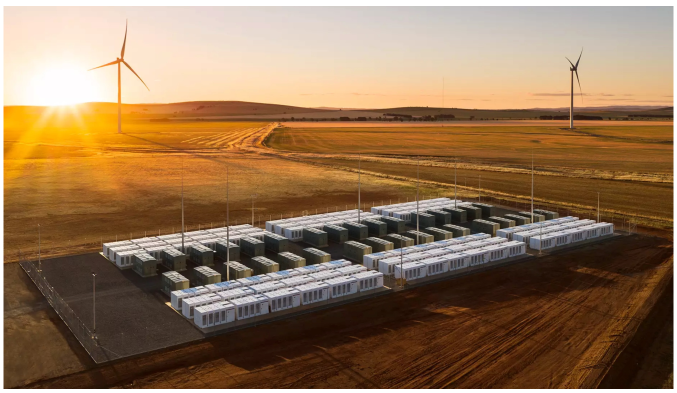

Fig. 3. Grid-scale battery deployment with Solar generation in Australia [5]

and in real-time. Using battery storage allows a smart-grid to react to load changes almost instantly [8]. In Fig. 2, we see a grid-scale battery system with a Solar deployment operated by Tesla in Australia [4]. This deployment was attached to the conventional grid. It was realized in real-time that when the grid is under stress due to heavy load, the solar deployment can instantly add extra generation capacity to the grid — avoiding a blackout since fossil-fuel generation sources usually take at least 45 to 60 minutes to add power to the grid.

With the ability to add load quickly, a smart-grid can also benefit from real-time data to react to the present usage as well as adjusting for upcoming predictions. Likewise, micro deployments within the community could be brought together to add capacity to the grid on-demand. Since a smart-grid ecosystem can support a two-way information flow — it could theoretically know the status of the users of the grid in real-time.

I propose that instead of building just a simple smart-grid infrastructure that replaces the current conventional grid, we build a smart-grid ecosystem. A smart-grid ecosystem will add awareness to the grid. With a strong communications back-haul, each direct and indirect device connected to the grid can transmit it's current state to a central server. A direct user/device connected to the grid is one that remains connected to the grid at all times for it's operation. An indirect user/device of the grid is one that connects to the grid for a period of time and then has it's own energy storage that it uses to operate later. Examples of indirect users/devices include cellphones, electric vehicles and anything with it's own energy storage.

If everything that is connected to the grid has the ability to communicate it's state to the generation side, we can add a data-analytics component that can help optimize generation versus load and result in a more reliable grid. For example, if there are 400 electric vehicles plugged in a given area: if all 400 electric vehicles are sending their state-of-charge and expected time of completion back, the grid can better plan the short-term generation. Likewise, if we perform data-analytics on the data that is coming then we can even predict that a particular car will plug-in to charge at a given approximate time — allowing the grid to optimize the generation automatically before load increases on the grid.

Furthermore, if sensors are added to mundane every-day appliances like stoves, washing machine and dryers — we can track the general pattern and how long they are used over the weeks. A real-time connection to the grid allows us to add intelligence to the grid to manage itself.

Finally, we can even train Artificial Neural Nets to understand patterns in human lives and look for these data-sets to manage the grid and optimize. Using a combination of Neural Nets and Machine Learning techniques, an Artificial Intelligence (AI) can be trained to handle the grid and it's requirements. Before these can be used, a constant data source is required. To accomplish a constant stream of data sources, we need a communications back-haul that will be used. The two-way power-flow and information flow in a smart-grid is represented in Fig. 4.

III. Communication Requirements and Technologies

Smart-grids require a robust communication platform to fulfill their potential. Multiple data streams are only possible with a communications network that can support it. The chosen communication back-haul must also have ease-of-use features for manufactures and users alike. Long range features will simplify the deployment of the network, since it leads to fewer gateways to create a dense network of end-devices. Let's also consider factors like data-rate and battery life.

A. ZigBee

Zigbee is quite common in smart-homes as of 2019. It is based on the IEEE 802.15 standard [6]. Zigbee is suited for use in applications where a low data rate is required, and it has a moderate battery life. A Zigbee network is also secured with 128-bit symmetric encryption keys [6]. Although, one caveat is that the range is short, usually only up to about 100m [12]. Low-range and a low data rate with a moderate

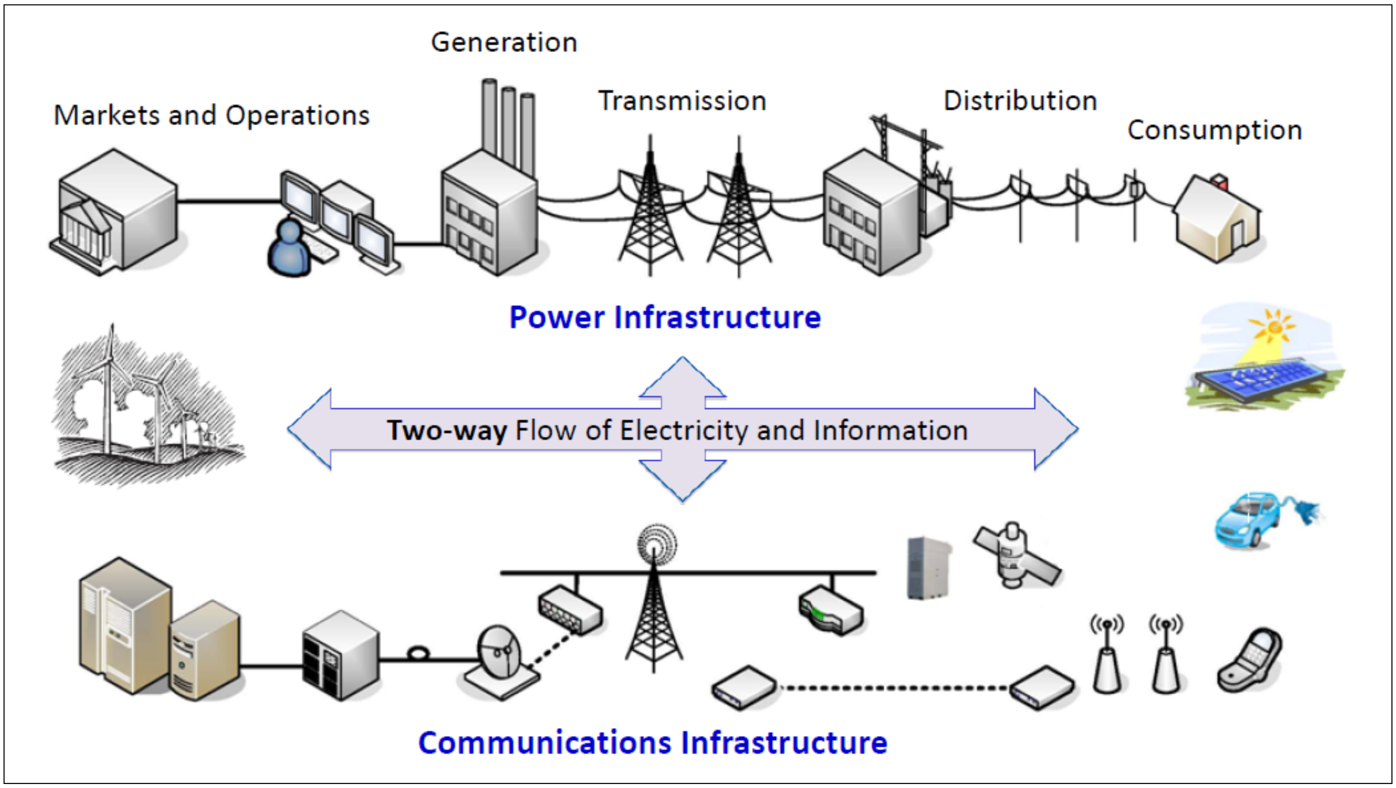

Fig. 4. Two-Way Power/Information Flow in a Smart-Grid [13]

battery life severely limits it's use case in an expansive smart-grid ecosystem. Low data rate is appropriate for intermittent transmissions or a one-shot transmission to the end-device or gateway [6]. Another drawback of Zigbee is that it operates in the 2.4Ghz frequency range — making it susceptible to interference from microwave signals, as well as WiFi and Bluetooth.

One benefit to utilizing Zigbee in a smart-grid ecosystem is that there are multiple Zigbee end-devices already available, which could potentially integrate with a smart-meter application [6]. Smart-meters can then collect information from within the house, and pass it on the gateway to deliver real-time information to the grid. Although, short-range and low data rate with a moderate battery life makes this technology hard to scale.

B. WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a cellular network technology. It is currently not as widespread as Zigbee. Since it is a cellular network, much of the network infrastructure is already built for a future application [11]. There are several existing technologies for cellular communication such as GSM, GPRS, 2G, 3G, 4G with WiMAX that fit into a similar category [6]. Another benefit to using WiMAX is that the data-rate is extremely high and the area covered is also high — up to 75Mb/s for up to 50kms (31 miles) [16]. Although, with such a high data-rate, WiMAX also needs a significant amount of battery power to operate. Therefore, even though we get the required range and a sufficient data-rate from this technology, it is not viable because not all end-devices will always remain mains-powered at all times.

C. LoRaWAN

Long Range WAN (LoRaWAN) is a network technology aimed at lower energy-usage and greater communication distances.

As a technology, LoRaWAN has been designed keeping energy efficiencies in mind, as well as scalability over a long range. It is designed on the basis of a low data bandwidth, and operates in the frequency range that's typically less than 1GHz [25]. Specifically, it operates in bands 433MHZ, 868MHz and 915MHz (depending on the region) [25], which are license-free industrial, scientific and medical (ISM) [15] radio bands. The bandwidth that LoRa operates in are 125 kHz, 250 kHz or 500 kHz [14].

The main priority for LoRaWAN is longer range, and ultra-low power consumption. Devices can theoretically remain powered for up to 6 years on a 2400mAh battery and other factors [9]. As a consequence, the bandwidth could sometimes be a limiting factor [9]. The LoRa communication is well encrypted and it is implemented using AES-128 (Advanced Encryption Standard) [23]. Using AES-128, each message is encrypted and a Message Integrity Code is generated that can be verified. That makes LoRaWAN much stronger encryption-wise as compared to platforms which use a single authentica-

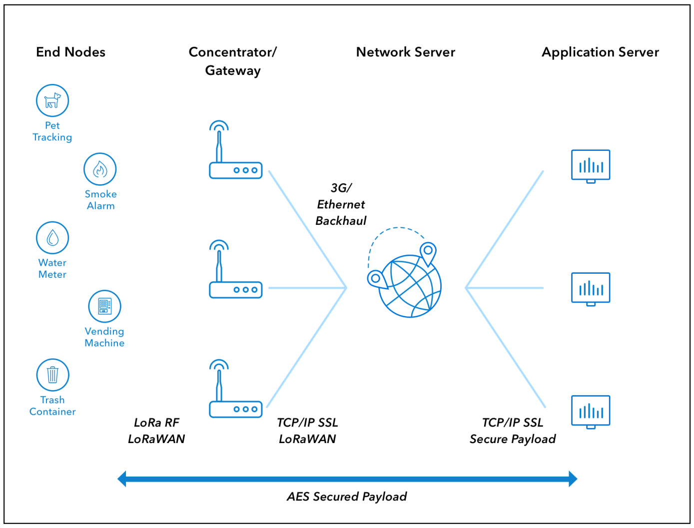

Fig. 5. Network Architecture of a LoRa Network [17]

TABLE I
CHARACTERISTICS OF LORAWAN

Characteristic	LoRaWAN
Topology	Star on Star
Modulation	SS Chirp
Data Rate	290bps-50kbps
Link Budget	154dB
Battery Life	8 to 10 Years
Power Efficiency	Very High
Security	Yes, AES-128
Range	Urban = 2km to 5m Suburban = 15km Rural = 45km

Note: Table data referenced from [23], [25]

tion key [23]. AES-128 is extremely secure and will take more than 2,000 years to crack using a brute-force method [23].

IV. CONSIDERING LORAWAN

LoRaWAN consists of mainly three device types: end-devices, gateways and an application server which is facilitated by a network server. A representation of the network can be seen in Fig. 5.

End-devices can only communicate with gateways, and the gateway then communicates with the application server through a network server. The primary communication between the gateway and the devices are primarily single-hop, and completed at scheduled intervals in a few bits of data [18]. Doing so saves bandwidth, less energy is used since less data is transmitted, and avoids network congestion [23].

LoRaWAN also employs a star-topology in it's application. [15]. Since end-devices can only connect to other gateways, such a system conserves energy across the network.

LoRaWAN uses LoRa modulation layer that is based on FM called Chirp Spread Spectrum (CSS) [15], [23]. It is one of the primary reasons LoRAWAN is not affected Doppler's time shift and can avoid network interference, which leads to a more robust network.

Finally, LoRaWAN also has the highest link budget, at 154dB, among all standardized IEEE communication technologies [3]. The link budget, typically given in decibels (dB), is the primary factor in determining the range in a given environment, and it factors in transmitted power and losses within the transmission.

In Table I, some important characteristics of LoRaWAN are mentioned.

A. ALOHA vs Listen Before Talk (LBT)

In ALOHA, devices transmit whenever they have something to transmit or in a given slot [1]. There are two types of ALOHA: Pure and Slotted. In Pure ALOHA, the device randomly sends the data whenever it has something to send. If there is a collision, it waits for a random time before transmitting again [1]. It also expects an acknowledgment from the receiver [1].

In Slotted ALOHA, the air-time for each device is divided into slots. If the end-device misses the transmission in a given slot, it must wait for it's turn for the next slot. In general, ALOHA networks are less efficient due to large number of collisions as the network size scales up [20].

Listen Before Talk (LBT) is an encoding scheme where the device scans the channel before transmitting [19]. If channel is busy, then the device waits for $[0, 2^{BE} - 1]$ Note that BE is the back-off exponent that goes from $[m_{min}, m_{max}]$. Generally, a network with an LBT encoding scheme leads to fewer collisions.

Although, interestingly, simulations have proven that LoRaWAN has the least collisions when 50% nodes transmit based on ALOHA and 50% on Listen Before Talk [20].

B. ISM Bands and Regions

Even though LoRaWAN uses ISM bands, they still vary across regions. For example, North America uses the the frequency range from 902Mhz to 928Mhz [17]. That means that the network gets it's own dedicated up-link and down-link channels during transmission. On the other hand-hand, the frequency bands allowed in Australia are only 915Mhz to 928Mhz [3]. So, up-link frequencies are a little higher than in the States.

Europe has a more developed set of rules for LoRaWAN. In Europe, LoRaWAN uses the frequency bands from 863Mhz to 870Mhz [3] with a few limitations:

- 0.1% to 1% Duty Cycle when running ALOHA protocol [17]. This severely limits the data that can be transferred as well as the up-time of the device.
- No duty cycle limitation when using Listen Before Talk protocol [6]. This is helpful since it preserves the band-width that is transmitted.

Moreover, the end-devices can communicate over different data-rates and avoid interference within the same band [2]. In Europe, 868.1Mhz, 868.3Mhz and 868.5Mhz are mandatory channels that a gateway must scan [15]. Using these, the data can be transferred at different data rates and avoid interference even when at the same frequency band. [18]

C. Classes of Devices

There are three classes of devices: Class A, Class B and Class C; Each one serves a different purpose.

1) Class A: Class A devices only operate during scheduled time intervals [2] and it mainly focuses on up-link transmission [18]. An up-link transmission is followed by two receiving windows of short length [15]. The first point of communication to Class A devices are always initiated by the end-devices. Importantly, the gateway can only push a down-link to the end-device after a successful up-link transmission [2]. Finally, Class A is mandatory for any LoRa node [2], and classes B and C are optional. Class A is also the most power-conservative of all the three classes [9].

Fig. 6 represents a typical up-link/down-link transmission. After an up-link transmission, there are two receive windows. The first one is opened at T_1 [7], or at RECEIVEDELAY1 [22]. The second one is opened at T_2 [7] or at RECEIVEDELAY2 [22], which is 1s after T_1. Therefore, total time for receive windows for Class A is $T = T_1 + T_2$.

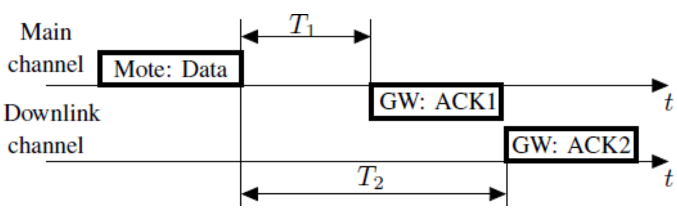

Fig. 6. Communication cycle for the first connection between Class A end-device and gateway [7].

2) Class B: Class B devices are optional and not a requirement of LoRa. As such, they are designed for more focused implementations. They are designed with greater down-link transmission speeds in mind where required [18]. These devices can be communicated by the gateway on-demand as the down-link channels are open even without a successful up-link handshake [23].

Since Class B end-devices have a greater up-time for receiving than Class A, they open their receiving windows for larger amounts of times. Class B opens it's windows as *ping slots*, at pre-determined and expected time intervals. Use of this allows the gateway to initiate predictable down-link messages. Since there is a need to match the time intervals, these time intervals are agreed upon when the first handshake between an end-device and a gateway occurs using periodic beacons [2]. This is visually represented in Fig. 7.

3) Class C: Class C devices are always listening for a down-link transmission, unless when transmitting an up-link communication channel [2]. Subsequently, these devices also consume the most amount of energy. Class C is also the least efficient type of mode. These devices are usually mains-powered.

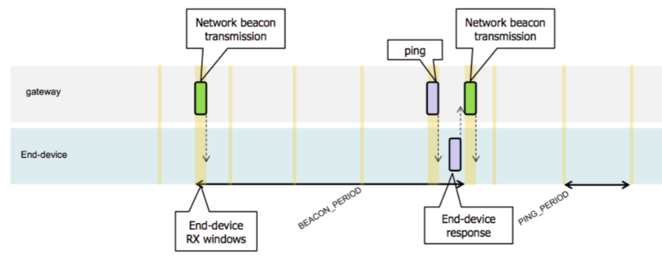

Fig. 7. Receiving windows cycles for a Class B Device [22].

Theoretically, Class C devices are the same as Class A. They have two open receiving windows and the second one is 1 second apart. However, the second receiving window which is opened at time T_2 is not closed [22]. The receiving window is only closed to complete a periodic up-link transmission [22]. This allows a Class A device to switch between Class C and Class A. The timing diagram for a Class C device is visually represented in Fig. 8

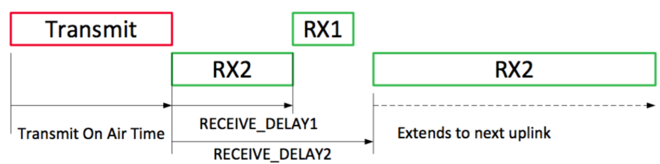

Fig. 8. Receiving window cycles for a Class C Device [22].

Finally, a visual representation of communication latency and battery consumed across Class A, Class B, and Class C devices in represented in Fig 9. We can see that Class A is the most efficient, while Class C is the least efficient but also has the least communication latency.

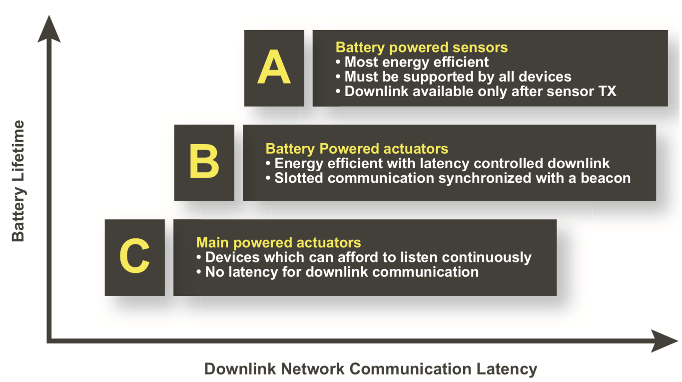

Fig. 9. Characteristics of each class in LoRaWAN [3].

D. Spreading Factor and Range

Spreading Factor is used to define the communication distance as well as the data rate of the transmission [14]. The Spreading Factor can be tweaked to match the design requirements. Generally, using a higher Spreading Factor means a higher communication range but a drop in the data rate [14].

The transmission power is also directly dependent on the SF used. A higher SF results in more power being consumed, but the result is greater range. Likewise, a lower SF results in less power being consumed, but also results in lesser range. A representation of how the SF affects other factors is given in Fig. 10.

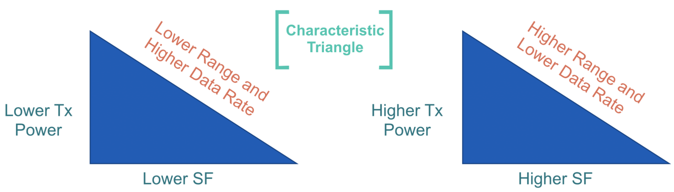

Fig. 10. Characteristic Triangle between SF, Tx Power, Range and Data-Rate

Table II provides a brief overview of the data transmission rates at various SF's, along with range and transmission power used [14].

TABLE II
BITRATE, TX POWER AND RANGE AT GIVEN SFS

SF	Bitrate (bps)	Tx Power	Range
7	11,000	Very low	Very low
8	6,100	Low	Low
9	3,400	Moderate	Moderate
10	2,000	High	High
11	1,100	Very High	Very High
12	400	Extremely High	Extremely High

Note: Data for table referenced from [14]

E. Chirp Spread Spectrum and Doppler Effect

Chirp Spread Spectrum (CSS) was developed by the military in 1960s. Chirp stands for 'Compressed High Intensity Radar Pulse'. CSS is a technique that uses chirp signals in a linear FM signal to transmit whole bandwidth, and have constant amplitude during the transmission. The importance of this will be clearer after the following discussion.

Doppler Effect is when the source of a wave is moving relative to an observer, and the observer receives a frequency different from the one that radiated by the source [21]. Doppler Effect time-shift is defined as:

$$T_d = \frac{\omega_d}{\mu} \text{ [22]} \tag{1}$$

- T_d = Doppler Time Shift
- ω_d is the angular frequency shift by Doppler Effect
- μ is the chirp rate of the signal.

Since chirp rate is high in LoRa, Doppler time shift is minimized according to Eq. 1. Therefore, it adds to the robustness to the network and improves the network performance significantly [2]. An example of an Up-Chirp FM Wave is referred to in Fig. 11

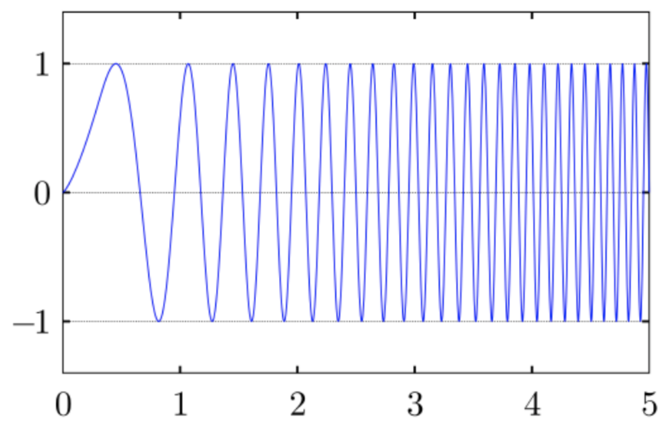

Fig. 11. Up-Chirp FM Wave

F. Star Topology vs Mesh Topology

Between Star Topology and Mesh Topology, LoRaWAN uses Star Topology. There are benefits and drawbacks to each, but generally using Star Topology reduces complexity in a network. Examples of both are referred to in Fig. 12

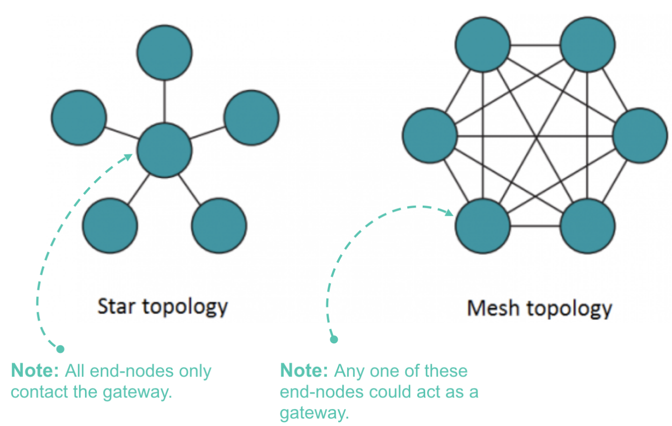

Fig. 12. Star Topology and Mesh Topology [26]

1) Mesh Topology: In a mesh system, all end-devices are connected to each other and can relay to the furthest available connection in the network through simple message relays. From Mesh Topology in Fig. 12, we can infer that two devices at opposite ends of the circle may be unreachable directly, but can be reached through the network of other-end devices. This enables phenomenal range of a given system, since one can go as far as maintaining link with at least one-device in the network. It also enables the gateway to be a part of the system rather than being central to the system.

While great in theory, it adds complexity to the network. The extra end-devices that are used to relay messages use *more* energy than they need to. Therefore, it also reduces network capacity and bandwidth because of the added complexity in the network. Finally, all these factors together reduce the battery-life of end-devices in this topology. While range is great, battery life and bandwidth suffers.

2) Star Topology: In a star topology system, all end-devices can only directly communicate to a gateway. From Star Topology in Fig. 12, we can infer that two devices at opposite ends of the circle may *not* be reached directly even if they are in range, since they can only communicate to the gateway. The gateway remains central to the system. This setup reduces range when compared to a system that uses mesh topology.

The benefit of such a network is that each end-device can only send messages to the gateway thereby maintaining the capacity of the system in terms of range and bandwidth as compared to mesh topology.

One of the biggest benefits of mesh topology is increased range. Since LoRaWAN already has great range, it can solely rely on star topology for a simpler network with less strain on end-devices, leading to a increased battery-life per node.

Finally, another important characteristic of LoRa is that end-devices are not single gateway-dependent — the network server has the freedom to choose the closest gateway that gives the the most optimal set-up [23]. The network infrastructure for LoRa is setup to use Adaptive Data Rate (ADR), which basically allows the end-device to optimize the gateway in use and conserve energy through a lower RF output [23]. Likewise, an end-device can transmit to all gateways in range that can then relay the message to the network server; LoRaWAN nodes are gateway agnostic and do *not* associate themselves with a particular gateway. A visual representation is referred to in Fig. 5. This also allows the end-devices to maximize the battery life.

V. Future Research

While benefits of using LoRaWAN in a smart-grid ecosystem are great, it requires greater attention before a real-world system is built around it. Specifically, future research should focus on simulating city-scale LoRaWAN networks with parameters that match the real world. Once simulated, the results should be tested in the real-world to model a system for an even larger area.

Specifically in America, LoRaWAN needs to be adopted further so that more edge-cases are detected as we use the technology more. Europe uses LoRaWAN more widely than the in the US — so they have more established regulations and rules on it's usage, as noted in Section IV-B. Perhaps with greater usage in North America, research can be performed further to understand the local network environment affects LoRaWAN.

Finally, future research needs to be completed in modeling actual end-devices that can be used in a smart-grid ecosystem. The ecosystem that can be built is vast so there is a great need for research in this area.

Conclusion

Setting up smart-grids are the next big step for the power industry. A smart-grid utilizes the power of two-way power and information flow. Smart-grids can benefit from distributed generation or renewables with storage that can react to load changes quickly. They also need a reliable communications network to for bi-directional data flow. LoRaWAN is an excellent candidate for a communications network due to it's characteristics. It supports a variety of devices through different classes, a variable data-rate with years-long battery life and city-scale range with a single gateway to connect to multiple end-devices.

References

[1] Norman Abramson. The aloha system: Another alternative for computer communications. In *Proceedings of the November 17-19, 1970, Fall Joint Computer Conference*, AFIPS '70 (Fall), pages 281–285, New York, NY, USA, 1970. ACM.

[2] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne. Understanding the limits of LoRaWAN. *IEEE Communications Magazine*, 55(9):34–40, 2017.

[3] LoRa Alliance. A technical overview of LoRa® and LoRaWAN, November 2015. https://lora-alliance.org/.

[4] Simon Alvarez. Tesla's big battery in Australia is starting an energy storage movement, September 28 2018. https://www.teslarati.com.

[5] Christopher Arcus. Wind & Solar + Storage Prices Smash Records, January 11 2018. https://cleantechnica.com/.

[6] D. Baimel, S. Tapuchi, and N. Baimel. Smart grid communication technologies- overview, research challenges and opportunities. In *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pages 116–120.

[7] D. Bankov, E. Khorov, and A. Lyakhov. Mathematical model of LoRaWAN channel access. In *2017 IEEE 18th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pages 1–3.

[8] R. Bucher. Smart grid functionality for the high-voltage transmission grid: On the market readiness of Digital Substation 2.0 technology. In *2017 Saudi Arabia Smart Grid Conference, SASG 2017, December 12, 2017 - December 14, 2017*, 2017 Saudi Arabia Smart Grid Conference, SASG 2017, pages 1–4. Institute of Electrical and Electronics Engineers Inc. Compilation and indexing terms, Copyright 2019 Elsevier Inc. 20182405307844 Digital substation Grid control High voltage transmissions Smart grid Wide area monitoring.

[9] Lluís Casals, Bernat Mir, Rafael Vidal, and Carles Gomez. Modeling the energy performance of LoRaWAN. *Sensors*, 17(10):2364, 2017.

[10] Jordan Davidson. Scientists Show How Fossil Fuel Industry Deceived the Public About the Climate Crisis, October 21 2019. *https://www.ecowatch.com/*.

[11] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke. Smart Grid Technologies: Communication Technologies and Standards. *IEEE Transactions on Industrial Informatics*, 7(4):529–539, 2011.

[12] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke. A Survey on Smart Grid Potential Applications and Communication Requirements. *IEEE Transactions on Industrial Informatics*, 9(1):28–42, 2013.

[13] Dharmesh Kavaiya. What is smart power grid?, October 28 2018. https://www.quora.com/.

[14] A. Lavric and V. Popa. A LoRaWAN: Long range wide area networks study. In *2017 International Conference on Electromechanical and Power Systems (SIELMEN)*, pages 417–420.

[15] Konstantin Mikhaylov, Juha Petaejaejaervi, and Tuomo Haenninen. Analysis of capacity and scalability of the LoRa low power wide area network technology. In *European Wireless 2016; 22th European Wireless Conference*, pages 1–6. VDE.

[16] O. Neagu and W. Hamouda. Performance of WiMAX for smart grid applications. In *2016 International Conference on Selected Topics in Mobile & Wireless Networking (MoWNeT)*, pages 1–5.

[17] The Things Network. LoRaWAN. 2018. https://www.thethingsnetwork.org/.

[18] P. Neumann, J. Montavont, and T. Noël. Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study. In *2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pages 1–8.

[19] J. Ortín, M. Cesana, and A. Redondi. How do ALOHA and Listen Before Talk Coexist in LoRaWAN? In *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 1–7.

[20] J. Ortín, M. Cesana, and A. Redondi. Augmenting LoRaWAN Performance With Listen Before Talk. *IEEE Transactions on Wireless Communications*, 18(6):3113–3128, 2019.

[21] Juha Petäjäjärvi, Konstantin Mikhaylov, Marko Pettissalo, Janne Janhunen, and Jari Iinatti. Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. *International Journal of Distributed Sensor Networks*, 13(3):1550147717699412, 2017.

[22] Alessio Sanfratello. Enabling relay-based communication in LoRa networks for the Internet of Things: design, implementation and experimental evaluation. *IEEE Communications Magazine*, 55(9):34–40, 2019.

[23] J. de Carvalho Silva, J. J. P. C. Rodrigues, A. M. Alberti, P. Solic, and A. L. L. Aquino. LoRaWAN — a low power WAN protocol for Internet of Things: A review and opportunities. In *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*, pages 1–6.

[24] Wikipedia. Electrical grid, October 2019. https://en.wikipedia.org/.

[25] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, and N. Strachan. Evaluation of LoRa and LoRaWAN for wireless sensor networks. In *2016 IEEE SENSORS*, pages 1–3.

[26] George Zerveas. One to Rule Them All?, November 2015. https://ict.swisscom.ch/.