A Classification of Cross-Layer Optimization Approaches in LoRaWAN for Internet of Things

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***Abstract*—The Internet of Things (IoT) uses Low-Power Wide Area Networks (LPWAN) for applications that require long-range, energy-efficient, and low-cost end devices. LoRaWAN is one of the most popular LPWAN technologies because of its key features and openness making it highly suitable for IoT. Despite its exceptional features, some challenges faced by this technology are optimizing the protocol used for scheduling, low data rate, and duty cycle restrictions. One possible way to address these challenges is by using cross-layer optimization. This optimization technique violates the restrictions of the traditional OSI protocol stack giving freedom to its protocol layers. However, there is currently no summary of cross-layer methods implemented in LoRaWAN. This paper presents a classification of state-of-the-art cross-layer approaches that were used in optimizing the LoRaWAN technology in IoT. The cross-layer techniques were classified based on the merging of adjacent layers, direct communication between layers, and completely new abstractions. In addition, this paper identified the issues and challenges featured in these state-of-the-art cross-layer approaches. Finally, this paper serves as an overview of the performance of cross-layer optimization in LoRaWAN technology for IoT applications.**

***Keywords*—cross-layer, IoT, LoRaWAN, LPWAN, optimization**

I. Introduction

The Internet of Things (IoT) is increasing in popularity as technology is now giving the ability of "things" to connect to the Internet. IoT can simplify tasks, automate the gathering of information, predict certain activities, monitor events, and data analysis without direct human intervention. The concept of how IoT works can be described into three processes. First is the end nodes or sensors that are placed or installed to gather information like water levels, temperature, sound levels, movements, etc. Second is the connection, it is required to send the data gathered by the sensors to its intended destination to be processed. There are several ways to have a connection, via cellular, Wi-Fi, Bluetooth or LPWAN. Lastly, the connection will link the end device to a processing system to decode the data and be used in certain applications. IoT solutions depend on the specifications of the consumer. If it requires a high data rate with high throughput, Wireless Local Area Network (WLAN) like Wi-Fi (802.11) is one of the popular choices. One of the challenges in using this technology is that it is limited to short-range communication. On the other hand, if one of the requirements is long-range communication, Low-Power Wireless Area Network (LPWAN) can be used. Among several LPWAN solutions, the key features and openness of LoRaWAN technology stand out among others making it highly suitable for IoT implementations [1].

Moreover, this technology is highly suitable for implementations requiring long-range communications since it can reach multiple kilometers depending on the environment. Additionally, it consumes very low power making the end devices' lifetime reach up to several years on a stand-alone battery supply. Other outstanding features of LoRaWAN are low bandwidth utilization, ease of deployment and the low cost of devices. The operation of LoRaWAN starts with the gathering of data by the end nodes. That data then will be forwarded to a gateway. The purpose of the gateway is to connect the network server and the end devices. It then forwards the message to the LoRaWAN network server where an application server is included. It is responsible for processing application-specific data messages received from end devices. Also, a joint server is connected to the network server that assists in key storage, session key creation, and secure device activation.

However, the LoRaWAN technology has several weaknesses. It has a low data rate making it not recommended for real-time data gathering. Another is the scheduling process used that is based on the Pure-ALOHA (P-ALOHA) protocol. Also, it is susceptible to collision which can compromise the reliability of the system. Since it is commonly used in the ISM band, the duty-cycle regulations that are about 1% of the transmission time must be followed. Therefore, it cannot send messages at will [1]. With these limitations, the functionality of LoRaWAN should be further developed and optimized for it to reach its full potential. One of the techniques to improve wireless communications is cross-layer optimization. This optimization process, which is the subject of this paper, gives the layers in its protocol stack the freedom to communicate or collaborate with the other layers.

Paper contributions: The major contributions of this paper are as follows: (1) classification of cross-layer approaches and designs implemented in LoRaWAN for IoT; and (2) identification of the issues and challenges in the implementation of cross-layer optimization based on the state-of-the-art approaches. To the best of our knowledge, there haven't been studies that classified the state-of-the-art cross-layer approaches and designs for optimizing LoRaWAN performance for IoT applications.

II. Related Work

Because of the appealing qualities of LoRaWAN to both academics and industrial applications, it is one of the most favored technologies in IoT implementations. As a result, numerous studies were done to further increase the system's capabilities.

The survey for LoRaWAN for IoT analyzed all the LoRaWAN-related materials that were available in the Google Scholar and IEEE databases and reviewed the available solutions to the system's flaws. However, the gathered research was restricted to the year 2015 to 2018 [2]. For [3], a survey on LoRaWAN was also conducted to discuss the main obstacles and challenges of the technology. Its primary concerns were geared toward scalability issues, coexistence in the RF environment, and a lack of mathematical models and simulators that can help solve the scalability issues. Moreover, a taxonomy of LoRa challenges was constructed by the authors of [4] and categorized into five classifications: energy consumption, communication range, multiple access, error correction, and security. It included existing research that further contributed to the optimization of LoRaWAN. Also, open issues and solutions were discussed and classified into two parts: papers that are related to performance measurements and a summary of papers that gives solutions to the LoRaWAN technology.

Another survey on LoRaWAN focused their study on the LoRaWAN system's security flaws. After discussing several issues related to security, the authors shared how to identify and counteract the most common security attacks that the technology has been subjected to [5]. Another remarkable study involving LoRaWAN was [6], wherein the authors discussed applications where LoRaWAN was implemented. This study featured existing LoRaWAN devices discussing their applications and their respective outputs. However, the study was inclined on studying the feasibility of LoRaWAN implementations in monitoring water-distributed networks. A focus on a Green LoRaWAN protocol was the purpose of the authors of [7]. It was based on energy efficiency, multi-access, and routing protocols. It also added a classification of methods than can guide fellow researchers in designing a new protocol. One of the most recent studies which were published in 2022 examined the current LoRaWAN optimization papers. In this paper, the authors specifically addressed energy efficiency in the network, link, and physical layer [1].

Cross-layer optimization is proven to increase the performance of wireless networks. To name a few examples, several studies conducted utilized this approach to further improve the Quality of Service (QoS) [8], energy consumption [9], routing [10], and scheduling [11] in WSN. However, there is a lack of discussion focusing on classifying the cross-layer optimization approaches for LoRaWAN in IoT applications. Therefore, this paper presents a classification and overview on the performance of state-of-the-art cross-layer approaches that were used in optimizing the LoRaWAN technology in IoT.

III. Classification of Cross-Layer Optimization for LoRaWAN in IoT

This section presents existing cross-layer optimization techniques that were implemented in the LoRaWAN technology. The references gathered either indicated that it utilized the cross-layer architecture or programmed the different combinations of the application, network, link, and physical layer in unison. Also provided in this paper is the classification of cross-layer architecture designs used in optimizing LoRaWAN as shown in Table 1. The table summarizes the cross-layer architecture used by the authors and the layers involved in their optimization design.

As technology develops, several limitations in the OSI protocol stack make it inefficient to deploy technologies like LoRaWAN. Consequently, optimization is now being seen as a necessity in this regard. The cross-layer design can help wireless networks to perform better in contrast to utilizing traditional architecture and protocols. For example, the utilization of TCP in wireless networks. To ensure that the system is efficient and systematic, some rules and conditions must be followed when using this protocol.

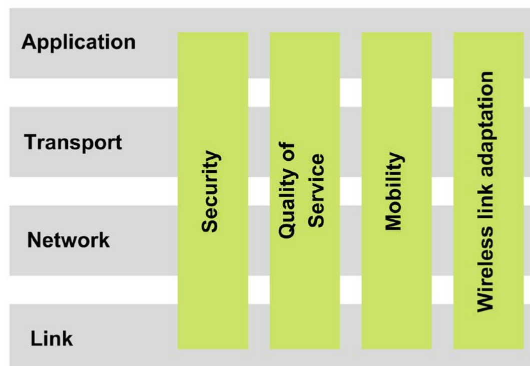
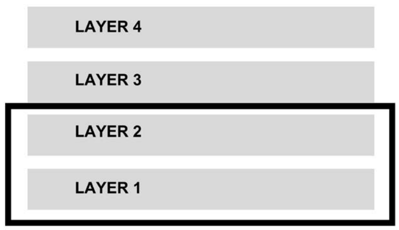


Fig. 1. A cross-layer coordination model (adapted from [12]).

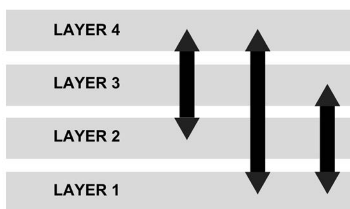
A cross-layer reference model was introduced by Foukalas, et.al. [12] to specify the functionality of each new entity in the proposed cross-layer solution. The model consists of four separate planes that were vertically extended over the layers as shown in Figure 1. The security plane harmonizes the security and encryption protocols across the layers; the mobility plane supports the movement of wireless terminals from one area to another through handovers to appropriate radio access points; the QoS (Quality of Service) plane coordinates the QoS information to the different layers; and the wireless link adaptation plane that assesses the effects of certain parameters to the wireless link.

One of the definitions of cross-layer is the violation of a layered communication architecture to the original architecture [13]. This technique is used to co-relate other layers. For example, there are three layers: Layer 1, Layer 2, and Layer 3. With cross-layering, Layer 1 and Layer 3 can communicate and know each other's information. Layer 1 and Layer 2 can merge into a "super layer" and share their parameters and data. Another option is that Layer 1, Layer 2, and Layer 3 can share and access their data back and forth. To categorize the study in this paper, a variety of design proposals were considered as shown in Figure 2.

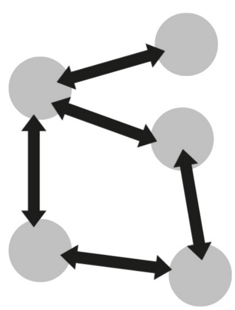
The papers included in this study that used cross-layer architecture are categorized according to how the layers were managed. Either it was the merging of adjacent layers into a super layer, direct communication between the layers, or a completely new abstraction.



(a) Merging of Adjacent Layers



(b) Direct Communication between the Layers



(c) Completely New Abstraction

Fig. 2. Proposal of architectural blueprints (adapted from [13])

A. Merging of Adjacent Layers

The merging of adjacent layers is a cross-layer architecture that combines the adjacent layers to form a "super layer". This design enables both layers to collaborate and access each other's information and status as shown in Figure 2a.

The JMAC protocol [14] was implemented by merging the Network and Link Layer to enable multi-hop in the LoRaWAN communication. The purpose of this is to manage and reuse the limited resources to greatly expand and extend its coverage. This protocol was modeled similarly to Asynchronous Scheduled MAC (AS-MAC) and Receiver-Initiated MAC (RI-MAC). The AS-MAC is a protocol where nodes are aware of their neighbors' wake-up time and not requiring long preambles before stating their transmission [15]. Meanwhile, the Receiver-Initiated MAC (RI-MAC) is a protocol where the sender and receiver find a specific time to exchange data but are still independent with their duty-cycle schedules [16]. The network topology utilized a tree network structure with mesh routing. A "C parameter" was introduced in this protocol. It manages the probability of sending a message to the next hop. This is to avoid potential collisions between the sensors that will transmit at the same time.

Another example where the adjacent layers were combined is the novel MAC protocol called LoRaBlink [17] where it added features that are not implemented by LoRaWAN. It unified the MAC and routing to achieve a multi-hop communication, abide by the duty-cycle requirements, provide a robust and high probability of messages delivery, and low transmission delay. With this protocol, it was tested and proven that it is feasible to conduct concurrent transmissions and deliver messages over great distances when implementing multi-hop routing.

Moreover, the authors of [18] merged the Network and Link layer to produce a protocol that can utilize a tree construction algorithm that can achieve a high balance mode and a timeslot channel assignment algorithm. At the same time, it can support parallel data transmission of nodes. The protocol is based on Time Division Multiple Access to guarantee that no collision will occur with the neighboring nodes during the tree construction period. Nodes in the network can create a schedule just from the information of their neighbor. It also allows parallel transmissions for it to reduce latency. It can also minimize the packet size in the nodes depending on the choice of its parent node.

B. Direct Communication between the Layers

This cross-layer architecture only utilized several needed parameters in each respective layer to further increase the performance of the system as shown in Figure 2b.

A proposal to improve the performance of LoraWAN was presented by Chen, et.al. [19]. In this study, the authors combined the use of rate-less codes which allows decoding with multiple gateways and cross-layer optimization. It explored the effects of two important parameters: The spreading Factor (SF) in the Physical Layer and block length in the Link Layer. Varying the said parameters can achieve a more efficient transmission but requires more energy and larger CRC overheads. The parameter updates and LT code are sent to the gateway to solve specifically the lifetime, communication range, and latency. More importantly, the authors used a high-level programming system to solve the optimization problem where it is addressed in the cloud and send the updated parameter command back to the gateway for it to distribute the settings to the end devices.

The Dual Orthogonal LoRa Modulation [20] was proposed to give freedom to Spreading Factor assignments to further enhance the network. The authors co-optimized the network and link layer in performing this study. This modulation technique is observed to be non-coherent since it does not require the receiver to estimate the phase in the channel in contrast to the standard LoRa modulation. Therefore, it greatly reduces the complexity of the system while being more cost-effective making it more desirable for massive IoT implementations. The existing Adaptive Data Rate used in LoRaWAN was modified and time power multiplexing was introduced instead of using network densification since it has a negative impact on the system. This almost forces all the end devices to utilize a low SF, therefore increasing the offered traffic in those mentioned SFs. The optimization was done by modifying the existing ADR to obtain the same amount of end devices having SF = 7 and SF = 8. Then combining the modulation technique with time power multiplexing to increase the performance of the gateway in two aspects; (a) downlink packets keeping the same transmission time or (b) decreasing the transmission time between 54%-58% compared to the standard modulation.

C. Completely New Abstraction

This cross-layer architecture was a study patterned to the concept of [21] that breaks down the protocol into smaller units called blocks. The network was then described as the interaction between the blocks as shown in Figure 2c.

A study that utilized a completely new abstraction design was the proposal of the authors of [22], which incorporated a software-defined network approach to build access levels for IoT with allowable losses. The purpose of the study was to build a cognitive model to control multiple access in IoT using the LoRaWAN technology. The access network parameters can be created by choosing the best possible parameters based on the probability that data will be delivered, bit error, frame loss, collision, and network parameter selection. The system enables the analysis of the relationship between link-level metrics, traffic user parameters, and network operation quality.

Moreover, a cross-layer simulator where it can assess and co-optimize the MAC, PHY, and NETWORK parameters to a more realistic scenario was proposed by [23]. The framework was split into different modules, the end node, air interface, and gateway. The modules have embedded information containing realistic considerations that can be relevant in the assessment of the energy used in LoRaWAN. For example, the end nodes were incorporated with information regarding location, energy profile, and the LoRaWAN parameters. According to their study, energy consumption in end nodes was not only limited to transmitting, receiving, and sleeping states. There is a further process that consumes energy like a simple process that approximately consumes 15 mW of power, the state related to waking up and setting the radio that approximately consumes 8.25 mW, and executing the MAC-related functionality after receiving the downlink that approximately consumes 8.3 mW of power. These assessment considerations were based on The Things Network. For the air interface, a realistic simulation of a path loss, Received Signal Strength (RSS) translated to SNR and collision model. And for the gateway part, the characteristics of an iC880A LoRa Concentrator. This transceiver can receive multiple LoRa packets with different SFs. In this study, the packet length was considered in assessing the energy consumption by its Data Extraction Rate (DER), energy per payload byte, and variance which is the effect of varying propagation characteristics. During simulation, it was found that turning ON the ADR feature of the LoRaWAN is highly recommended for energy optimization. Also, turning OFF confirmed messages or not requiring acknowledgments from the gateway can also contribute to energy consumption. Lastly, the average energy consumption per payload byte was minimized when sending large packets. Therefore, for applications that do not require immediate actions, data can be accumulated to decrease overheads and less the utilization of the channel.

IV. Summary of Different Cross-Layer Optimization in LoRaWAN for IoT

The taxonomy of LoRa challenges was discussed by Shanmuga, et.al. [4] and was categorized into (a) energy consumption where the LoRaWAN devices need to save as much energy as possible since several of its applications will be implemented in places where accessibility would be difficult and not be practical. The end devices should also be able to operate within years by merely operating on small power supplies, for example, batteries, (b) communication range should also be addressed since the data sent by end devices travels long distances, making it susceptible to attenuation, propagation losses, and fading. The Chirp Spread Spectrum (CSS) modulation used by LoRaWAN is also prone to interference; therefore, it must be properly addressed, (c) multiple access allows to interconnect of perhaps thousands of end devices. Furthermore, challenges in multiple access are divided into two aspects. First is linked coordination for appropriate scheduling since LoRaWAN utilizes the Pure-ALOHA protocol which is very vulnerable to collision. Second, is the resource allocation in which it can enhance concurrent transmissions by varying the controllable parameters like BW, SF, transmission power (TP), and channel, (d) error correction since LoRaWAN technology utilizes SFs (SF7–SF12). It makes signals more resilient to noise. During air transmission, data can get lost or corrupted along the way due to environmental aspects, channel effects, and perhaps collision. Even the strongest spreading factor (SF12) can get corrupted along the way due to the time needed to transmit which is called Time on Air (ToA), and (e) security because computer communications are constantly vulnerable to a variety of security threats like node impersonation, selective forwarding, and eavesdropping [4]. These attacks' purpose is to obtain the key to the encryption. Once obtained, it can compromise the entire system according to its desired purpose. The current LoRaWAN technology security key generator is not updating making this a major concern.

As discussed in the previous section, the cross-layer approach indeed optimized the performance of LoRaWAN. It was evident that it either optimized the system's energy efficiency, communication range, and/or multiple access capabilities. It was also observed that there is no general structure in solving a specific parameter. For example, a combination of NET and LINK, NET and PHY, LINK and PHY, or the combination of all the layers can solve issues regarding energy efficiency optimization. Additionally, [22] cross-layer optimization can collaborate with other network solutions like SDN to produce other results aside from the mentioned LoRaWAN challenges. However, increasing the complexity of the design of the system.

Table II shows the summary of cross-layer-based approaches for optimizing LoRaWAN based on their advantages and disadvantages.

TABLE I. CLASSIFICATION TABLE OF CROSS-LAYER ARCHITECTURE FOR OPTIMIZATION IN LORAWAN FOR IOT

Paper	Classification			Cross-Layer Approach		
	Merging of adjacent layers	*Direct communication between layers*	*Completely new abstractions*	*Network*	*Link*	*Physical*
JMAC Protocol [14]	✓			✓	✓	
LoRaBlink Protocol [17]	✓			✓	✓	
Mai et al. [18]	✓			✓	✓	
Chen et al. [19]		✓			✓	✓
Vangelista et al. [24]		✓		✓		✓
Muthanna et al. [22]			✓	✓	✓	✓
Callebaut et al. [23]			✓	✓	✓	✓

TABLE II. Summary of Cross-Layer Approaches Based on their Pros and Cons

Paper	Pros	Cons
LoRaBlink [17]	Multi-hop capabilities	Inefficient end-nodes power consumption
JMAC [14]	Multi-hop, node scheduling and "C parameter" to manage the probability of sending messages to the next hop	Absence of proposed down-link functionality design
Mai et. al [18]	Multi-hop, distributed aggregation scheduling, and parallel transmissions	Energy consumption during end-nodes joining period
Chen et al. [19]	Optimized parameter (SF and block length) updates to the end-devices	Traffic in the down-link
Vangelista et al. [24]	Non-coherent modulation and link level bit-rate enhancement	Incurring 3dB SNR penalty
Callebaut [23]	ADR ON and confirmed messages OFF for better energy consumption	Scalability and dynamic applications
Muthanna et al. [22]	Leveraging a probability model for bit-error, frame loss, and collision from the quality of the network, link level parameters, and traffic user's parameters	Design complexity

V. Issues and Challenges

With regard to the research efforts, there are still several challenges and issues related to cross-layer-based optimization in LoRaWAN technology.

Lacking assessment approaches: It was observed that there is a lack of real-life implementations for the proposed protocols. It was either analytical, simulations, or testbed experiments. Therefore, it is difficult to assess the actual performance if it is indeed feasible when implemented using thousands of end devices. Some of the studies also lack mathematical models and few parameters used are based on assumptions. Therefore, a comprehensive study of the effects of the layers crossed including complete mathematical models can help to further optimize the system.

LoRaWAN Class C End Devices: Majority of the discussed approaches used the LoRaWAN Class A and B end devices. Knowing that Class C LoRaWAN end devices consume a lot of energy, it was observed that it was seldom used in optimization designs. With the feature of LoRaWAN Class C end devices having the receive link always open (except when transmitting). And as mentioned in [25], this class of end devices does not often rely on batteries but is more often mainly powered. This class of end devices can be used for time-critical and non-delay tolerant IoT applications that require long-range communications, low data rate, and cost-effective to be leveraged with efficient routing and multiple access protocols.

Insufficient Baseline Comparison: The cross-layer optimization technique indeed showed feasibility and commendable results when simulated and tested. Unfortunately, several papers discussed were not compared to the traditional LoRaWAN. Therefore, it is difficult to gauge the efficiency of the results. Also, there are optimization techniques that were addressed with single-layer approaches in other studies that were not included in this paper. It is worthy to look if indeed cross-layer optimization is superior to single-parameter approaches.

Performance Trade-offs: The papers using cross-layer optimization in LoRaWAN either proposed a novel MAC protocol, introduced a new technique to enhance the network capabilities, used different network topologies, or changed the modulation process. It is very important to weigh the trade-offs of such actions. Some network topologies can address routing issues, but they can also compromise the latency and scalability of the network. It is also the same with scheduling techniques which is why the proper trade-off must be considered. The system may be free of the collision but in return, sacrifices energy consumption. The physical layer parameters should also be properly analyzed using optimal parameters that can balance energy consumption, communication range, and multiple access. With this, it is a top priority to select the proper combination of network parameters, adequate protocol, and modulation that would complement each other when using cross-layer optimization. As technology advances, there is new research that can entirely upgrade the network performance operation. One example is the utilization of SDN where the data and control plane can be separated and controlled as different entities.

VI. Conclusion and Future Directions

The majority of long-range IoT implementations use the LPWAN technology due to their ability to communicate over great distances with limited resources, being low-cost, and ease of deployment. Among the LPWAN technologies, the LoRaWAN is one of the most opted technology due to its openness and attractive features that can satisfy the IoT requirements. Numerous studies have been conducted to further enhance the system and several techniques are used for the optimization process. This paper classified several examples of how cross-layering designs optimize the LoRaWAN technology.

Analyzed studies demonstrate that when the cross-layer architecture managed the layers within its protocol stack, specifically for merging and direct communication between layers, it indeed solves the challenges enumerated in the taxonomy of LoRa challenges [4]. Also, when using the architecture that created a completely new abstraction, this architecture can address and solve these discussed challenges. Moreover, it can further extend the existing applications of LoRaWAN.

Going forward, the extension of this work will be gathering more data for evaluation related to cross-layer optimization in LoRaWAN. Also, another is to determine the certain effects in terms of improvement and drawbacks of utilizing the different cross-layer architectures. Another possible extension of this work is to compare if cross-layer optimization is superior to single-layered optimization techniques. There are several studies related to LoRaWAN that enhanced energy consumption, communication range, and other challenges without using the cross-layer architecture. Finally, directing the study towards the exploration of other methods like machine learning, SDN, and Artificial Intelligence that can be collaborated with cross-layer optimization to further exploit the LoRaWAN technology.

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