LoRaWAN: State of the Art, Challenges, Protocols and Research Issues

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***Abstract*— Low Power Wide Area Network (LPWAN) gaining much attention in the industry as well as in academia due to its ability to communicate over the long-range. Due to this reason, LPWAN is considered one of the favorable technologies for the Internet of Things (IoT). Long Range Wide Area Network (LoRaWAN) is one of the promising technologies of the LPWAN that provide communication with low power, low cost, long-range, and low data rate. This paper covers the state of the art of LoRaWAN technology. Further, this paper discusses the design goal of Long Range (LoRa) technology. Medium Access Control (MAC) layer recent advancements are also part of the paper. Finally, the future research challenges of Physical and MAC layer implementation of LoRaWAN are also highlighted that help researchers and industrialist to implement the concept of LoRaWAN in IoT.**

Keywords—LoRaWAN, IoT, Research Challenges, LoRa

I. Introduction

Low Power Wide Area Network (LPWAN) gaining much attention in the industry as it enables the low power devices to communicate over the long-range. Due to this reason, LPWAN is considered one of the favorable technologies for the Internet of Things (IoT). IoT describes the connectivity of anything, anywhere at any time [1]. Design goals for LPWAN are Long-range (by using sub -1 GHz band or modulation techniques), Ultra-low power operations (through topology, Duty Cycling, Lightweight Medium Access Control, offloading complexity from end devices), Low cost (Due to reduction in hardware complexity, minimum infrastructure or using license-free or owned licensed band), Scalability (by using diversity techniques, densification, and adaptive channel selection and data rate) and Quality of Service (QoS). The propriety technology for LPWAN is SIGFOX, Long Range (LoRa), INGENU, TELENSA, QOWISIO [2].

LoRaWAN is one of the promising technologies of the LPWAN that provide communication with low power, low cost, long-range, and low data rate. LoRaWAN communication system consists of LoRa end devices, LoRa Gateways, Network servers, and Applications of LoRa. Thousands of LoRa end devices connected with Gateways which are further connected to the network server.

LoRaWAN communication system mainly focuses on the Physical and MAC Layers of its protocol stack. Long-Range (LoRa) is the physical layer implementation of LoRaWAN by LoRa Alliance and Long-Range Wide Area Network (LoRaWAN) is the MAC layer protocol promoted by LoRaWAN Alliance [3]. LoRa enables the low power devices to communicate over the long-range with low bitrate. For this reason, it is the most suitable candidate for most of the Internet of Things (IoT) applications like in smart cities, smart metering, smart parking, smart lighting, and smart agriculture. However, the implementation of LoRa is restricted to those scenarios that support low bitrate. Further, the success of the LoRaWAN depends on the security of the network. In the Internet, better security and ease of the management can be obtained by implementing role-based security control focusing on dynamic separation of duty [4, 5]. Further, the success of the LoRa communication system is its openness and the availability of its open-source software support. The Protocol Stack of LoRa technology is shown in figure 1 [6].

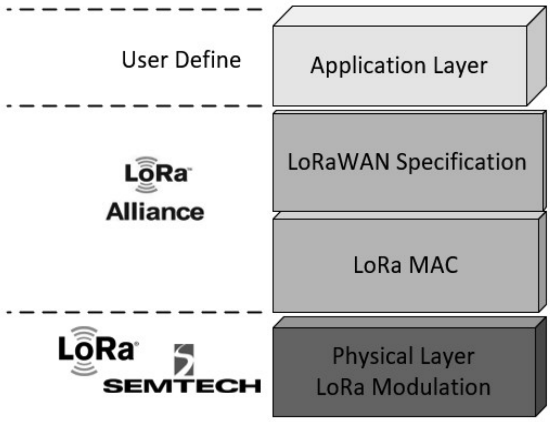

Fig. 1 LoRaWAN Communication Protocol Stack [6]

The organization of the paper is as follows: LoRa technology is defined in section II which is followed by design challenges and issues of LoRa technology discussed in section III. Research challenges of LoRa are highlighted in section IV. Section V discussed the LoRa based MAC Protocols while LoRa based MAC Layer research issues will be highlighted in section VI and finally we conclude the paper in section VII.

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II. LORA TECHNOLOGY

LoRa is the physical layer implementation of LoRaWAN and is a propriety spread spectrum modulation technique Patent by Semtech [7, 8]. It is promoted by LoRa Alliance. It modulates the signals in the SUB-GHz Industrial Scientific and Medical (ISM) band (unlicensed ISM Band) which has regularity constraints over different regions [2, 9]. LoRa uses the Compressed High-Intensity Radar Pulse (chirp [6]) spread spectrum (CSS) modulation technique with integrated Forward Error Correction (FEC) that helps in reducing the interference caused by different data rate. Chirp signal varies their frequencies over time without changing the phase between the symbols. If the frequency change is slow it decodes the transmission even at 19.5 dB that means below the noise level of the floor, to achieve long-range communication, on the other hand, it also permits the recovery of information in the case of transmission errors. LoRa also supports bidirectional communication. The data rate of LoRa ranges from 300 bps to 37.5 kbps that depends on different transmission parameters. Transmission parameters for LoRa can be named Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW) and Coding Rate (CR) [8]. These parameters also affect resilience against interference, bit rate and ease of decoding during LoRa communication.

A. Transmission Power (TP)

The TP can be adjusted within the range of -4 dB to 20 dB. The hardware limitation reduces this range from 2 dB to 20 dB. Further, the power level higher than the 17dB used 1% duty cycling. The duty cycle is the maximum percentage of the time duration in which an end device can occupy a channel. It is the key constraint in the unlicensed band [10].

B. Carrier Frequency (CF)

CF can be programmed in the range of 137 MHz to 1020 MHz with the steps of 61Hz. Due to LoRa Chip limitation, it can be limited to 860 MHz to 1020 MHz Range [10].

C. Bandwidth (BW)

BW is the width of the frequencies in the transmission band. The data rate of LoRa increases with the increase of BW and vice versa. The data rate is the data send out at a chip rate equal to bandwidth (125 kHz corresponds to a chip rate of 125 kcps). The range for BW of LoRa varies from 7.8 kHz to 500 kHz, but normal settings are 500kHz, 250 kHz, or 125kHz.

D. Spreading Factor (SF)

SF is the ratio between the symbol rate and chip rate. The number of chips per symbol can be calculated as 2^{SF} (If SF=6 than Chirps/Symbol will be 2^6=64 chirps/symbol). The range for SF varies over the geographic locations as for European deployments SF is between 6 to 12 represented as [SF6, SF7, SF8,,, SF12] but in the North, America SF range is between the 7-12. Each increase in the SF halves the transmission rate doubles the transmission duration and increases the energy consumptions for LoRa communication. The increase in SF also increases the Signal to Noise Ratio (SNR) that eventually increases the airtime of the packet. The sensitivity of communication also increases with the increase of SF that also increases the range for communication. LoRa uses an orthogonal spreading factor that enables the transmission of multiple packets with different SFs over the same channel concurrently. However, the authors identify another fact that the packets with different spreading factors using the same channel can collide and increase the packet loss. Authors prove their findings through theoretical work and then perform a simulation (theoretical Simulation) using the MATLAB [11].

E. Coding Rate (CR)

LoRa faces a burst of interference while transmitting the data. This interference is controlled by selecting suitable CR. The possible settings for CR are 4/5, 4/6, 4/7, or 4/8. The higher protection can be achieved at the higher CR but with the compromise of the time on an air of the packet. The most robust setting of CR is 4/8. Radios with different CRs can communicate with each other concurrently as the CR is explicitly mentioned in the header of the packet.

F. Adaptive Data Rate (ADR)

In LoRa, ADR features enable the devices and servers to select the transmission parameter settings automatically. The data rate can be managed in two ways either through the device itself or through network servers. It helps in conserving the energy and gives us an improved performance by automatically selecting the settings as per requirements [10]. The authors proposed the two algorithms named EXPLoRa-SF and EXPLoRa-AT that outperform the ADR in terms of efficiency. These algorithms also improve the bit rate especially in the case of high traffic load [12]. It can achieve a speedup of IoT communication. However, there is another solution that speeds up the IoT communication that also considerable in the IoT [13].

III. DESIGN CHALLENGES AND ISSUES OF LORA

The design consideration of LoRa has emphasized the following functionalities/matrices: scalability, throughput, coverage, multipath resistance, energy conservations, and low cost [8].

A. Scalability

The scalability of LoRa can be defined as the maximum number of end devices connected to a single gateway. To measure the scalability of the LoRa, researchers use different mathematical models and simulation tools for theoretical and experimental analysis, respectively. Scalability of LoRa depends on the following factors: Number of channels and their capacity (Regulatory Constraints), traffic load generated by the network, spreading factor, bandwidth, coding rate, Payload size during packet transmission, message inter-arrival time, and QoS requirement.

One of the primary concerns for scalability is the regularity constraints that is the availability of license-free bands within a specific region [14]. In Europe, the available band for LoRa is 863 MHz to 870 MHz and for America, this range is 902 MHz to 928 MHz. It limits the number of

available channels for communications. Gateways capacity increases linearly with the increase in the number of channels.
The transmission parameters settings like spreading factor, bandwidth, and frequency of packets affect the scalability of LoRa. Researchers assess the scalability through the Data Extraction Rate (DER) and Network Energy consumption (NEC) being used as a metric. They reveal through the simulation that the physical layer settings (SF12, 125kHz, CR 4/5) support only 120 nodes which are not enough for IoT applications [15]. In LoRa, if the end device sends the single packet per day then the network may scale up to several million end devices. In addition to this, if the end device sends a single packet per minute then the network can scale up to thousands of end devices [16]. Another research reveals that by increasing the spreading factor, the scalability is reduced. The SF7 (SF=7) supports more devices as compared to other higher SFs. Further, the Authors also disclose the fact that CR has no significant effect on scalability. Co-Spreading Factor interference also plays an important role in the scalability. Authors work on the theoretical model using the stochastic tools and find that co spreading factor also influences the scalability of the LoRa network [17].Scalability can be influenced by the following parameters: regularity authority, duty cycling, bandwidth, data rate, and transmission parameters like spreading factor, coding rate, and co-spreading factor.

B. *Throughput:*

The throughput of LoRa depends on the transmission mode. We define the transmission mode through the LoRa physical-layer settings like bandwidth, spreading factor, and coding rate. There are two approaches to measure the throughput, theoretical and experimental. Theoretical throughput measured as the transmission rate by using the Semtech published specification for LoRa presented in equation 1 [3].

$$\text{Transmission Rate} = SF \times \frac{BW}{2^{SF}} \times CR, \quad (1)$$

The highest and lowest transmission rate depends on the transmission parameters Settings. For example, SF=7, CR=4/5 (5468 bps, Highest), and SF=12, CR=4/8 (610 bps, Lowest) are settings for highest and lowest transmission rates, respectively. The bandwidth was assumed to be the constant, 125 kHz while calculating the transmission rate in both the settings.

C. *Coverage:*

We can measure the coverage range of LoRa by calculating the area covered by its single gateway. Spreading factor, bandwidth, transmission power, and code rate are the parameters that made an impact on the coverage of LoRa technology. Packet Delivery Ratio (PDR) and Packet Reception Rate (PRR) are the main matrices that the researcher uses to measure the communication distance of LoRa technology. Authors take three different measures to effectively calculate the coverage that includes: Outdoor measurement, Indoor measurements, and mobility measurements [9]. Authors conducted different experiments on the real-world testbed for this purpose. In the outdoor measurement, the author's experiments on the stationary nodes, located in the different places of the city. Nodes broadcast their packets to the gateways that forward their messages to a network server. To deploy their setups authors, use commercially used end devices and gateways. The authors measure the throughput of the network under the metric PDR. They suggest that 3 gateways are enough to cover the whole city, more specifically coverage range for outdoor measurement is 10 KM. In their indoor experimental setup, they conclude that building construction material and Line of Sight (LOS) issues are hurdles that affect the coverage in the case of indoor measurement. In the mobility measurement, they conclude that mobility has less effect in the coverage of LoRaWAN as some of the other factors have more effect on coverage like topology, Line of Sight (LOS), and the actual location of devices. Another study conducted that focuses on real-world experiments based on hardware devices to find the coverage of LoRa [16]. They made different experiments on the ground as well as on the water to find the range of LoRa gateway. The coverage in the ground area and water is 15 Km and 30 Km, respectively. Another study was conducted to explore the coverage aspect of LoRa technology by considering the Line of sight communication, outdoor, indoor, and semi indoor environment and concludes that LoRa can communicate up to 10 KM by using the SF12 with a PRR of 70% in LOS communication [18]. In the outdoor urban environment, this range is <3 KM with a PRR of 70%. For the batter coverage, fine-tuning of LoRa communication settings is required. Simulators for LoRa technology to further evaluate its performance is also required that include the simulations support for moving nodes.

D. *Energy conservation:*

One of the application areas of the LoRa technology is the IoT. In IoT, the important challenge is to conserve energy ad provide support for the heterogeneous application. LoRa supports the features that help in conserving the energy during the transmission. One way to conserve energy is to select the transmission parameter settings automatically. The transmission parameters settings can be selected automatically through the ADR feature of LoRaWAN. However, the authors develop the link probing regime that quickly estimates the performance requirement and determines the suitable transmission setting to conserves the energy. The authors calculated that 6720 settings are possible in LoRa transmission [10]. They have designed an algorithm to find the best settings and prove their findings through an experimental setup. They have shown that their settings consume less energy as compared to settings adapted by ADR of the LoRaWAN. Another study was conducted on different physical-layer settings of LoRa that evaluate the impact of different settings on energy conservation through simulations. For this purpose, the authors extend the LoRaSim simulator. Total energy consumption and PDR are the matrices for their experiments. They prove through the experiments that setting combination (SF=6, BW=500, CR=4/5) outperforms the other combinations and gives better results in terms of packet delivery and energy consumption. This combination can also be effective when we consider the IoT uses cases. The combination (SF=12, BW=125kHz, CR=4/8) shows poor results especially considering the IoT use case. Here we can conclude that energy conservation can be achieved by lowering the spreading factors and minimizing the coding rate. Further, the automatic parameter selection can also be helpful in this regard.

IV. Research Challenges of LoRa

Most of the studies conducted addresses the scalability, only considering the single cell or single sink for their experiments, there is a need to address the scalability for multiple sink / multiple Cells. Co spreading factors and SNR effect on scalability is an important research issue.

Reliability and its effect on scalability are also an important area for research in this domain. As we know that scalability can be affected if we increase the acknowledge packets. It will increase the traffic that results in packet loss which ultimately effects on scalability

LoRa based communication should support multi hope communication. We need further investigation in terms of throughput, coverage, and energy consumption. Regularity Authorities should think about the expansion of available band for LoRaWAN. Further, there is a need to conduct the study for a shared band for different technologies of LoRa network

In the future, devices from different vendors that supports the LoRa technology will be operational in the market soon. Further, the devices with different functionalities like their data sending frequency and nature of the job when communicating with each other bring another challenge of how these devices can interact with each other and communicate under the umbrella of IoT.

There is a need to discuss the range of applications and their scalability in terms of their utilization. The security of LoRaWAN on the Internet of Thing (IoT) is also an important factor that needs to be considered in the future to make the concept of successful deployment of this technology. In the Internet, role-based security is affected by the complexity of mutual exclusion and role inheritance [19]. It can be solved by implementing the dynamic separation of duty based on pre-defined permissions [20].

One of the areas that need further exploration is the concurrent transmissions that will not only restricted to the number of devices but also cover the coverage aspect of LoRa transmitters. Coverage, scalability, and performance improvements under the mobility of nodes is also a promising area of research.

V. LoRa Based MAC Protocols

LoRa radio technology is one of the promising technologies to support the multitude of Internet of Things (IoT) use cases. In a LoRa-based communication system, MAC functionalities include connection establishment between devices, managing the transmission and reception of MAC commands [21]. Moreover, it also includes channel access mechanism, adaptive data rate management, and provide interaction mechanism with PHY and networking layer of a networking protocol stack. In this section, we thoroughly discuss existing MAC layer protocols that can be used with LoRa that includes LoRaWAN, MAC on Time (MoT), RPL, and LoRa MAC (RL MAC) Protocol, Adaptive Duty Cycle Medium Access (ADC MAC) Protocol, and Collision Resolving MAC Protocol.

A. LoRaWAN:

LoRaWAN is the standard MAC protocol proposed for LoRa-based networks. The specifications for LoRaWAN are defined by LoRa Alliance. LoRaWAN defines three components: End device, Gateways, and Servers.

LoRaWAN Classes: LoRaWAN specification defines three different classes of end devices, namely: Class A, Class B, and Class C. Class A is intended for low power devices, as it utilizes less energy compared to the other device classes, i.e., Class B and Class C. It also allows the bidirectional communication which means supporting both uplink and downlink communication. Class A functionality must be implemented on all devices of LoRaWAN. In Class A implementation, the transmit window is used for uplink communication followed by two received windows RX1 and RX2 for downlink communication as shown in figure 2. The delay slot time is region-specific, and the data rate is the same for the transmitting window and RX1.

However, the data rate for RX2 can be modified by MAC Commands, available in LoRaWAN Specifications. If the network server wants to send more data after the RX2 window, it must wait for the next transmission call which will be initiated by the end device.

Class B devices have the specifications of Class A devices along with more downlink transmission windows but limited by predefined schedule time. It ensures the availability of end devices at predictable times. All devices connected to a network are joined as Class A devices then application decides either the end device acts as class B or Class A. Class B status is changed by using the Class B bit present in the FCtrl field of MAC Layer message format.

Class C devices are normally powered by the mains supply and consume more energy as compared to other Class devices. Further, class C end devices perform operations under less latency. The philosophy behind the class C device is having the continuous RX2 window which will open until the downlink communication takes place.

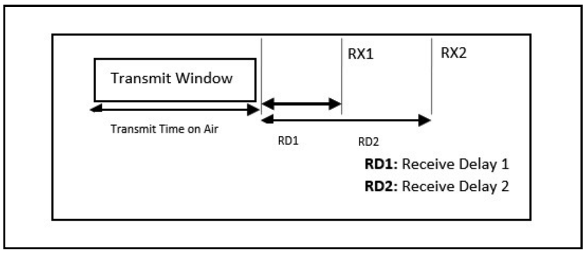

Fig. 2 Class A End Device Receive Window Slot

However, the Class B option cannot be implemented in the Class C devices. Further, there is no specific message for a node that tells the server about the implementation of the device as a Class C device rather application on the server will decide during the join procedure.

In LoRaWAN, some vulnerabilities were found in LoRaWAN specifications v 1.0 which are classified under network availability, data integrity, and data confidentiality. Some are addressed in LoRaWAN v 1.1, but few attacks still need solutions like RJ Jamming attack, Replay attack, and man in the middle attack [22]. Some other security threats include a rogue gateway, self-replay, and end device physical capture discussed in [23].

B. MAC on Time (MoT):

MoT is a hybrid MAC protocol designed for mission critical IoT applications. MoT provides reliable packet delivery, high throughput, energy consumption, ensure fairness, good throughput, scalability, and efficient channel utilization with the benefit of longer battery life. It also calculates the deterministic latency through the effective utilization of bandwidth. MoT supports the star topology in which nodes and base stations exchange the information periodically. In MoT, maximum channel utilization, high throughput, can be achieved through scheduling mechanisms managed by base stations. The base station acknowledging reports generated by nodes for reliable packet delivery. It also ensures the deterministic latency by allowing each node with one report once per frame. Further, a variable packet size can also be allowed in MoT for data transmission. The performance of MoT is measured in the MoTSim simulator, which is a modified form of the LoRaSim. It is a discrete event simulator using Python [24]. Long battery life and good coverage are also important features of MoT. MoT exceeds its performance from LoRaWAN in terms of throughput and latency.

C. RL MAC Protocol

RPL + LoRa MAC (RL MAC) Protocol is the MAC protocol for multi hope communication. It uses spreading factors for available neighbours as the objective function which is used to select the best path that minimizes the time on-air. It is implemented in the Contiki OS and uses the same protocol stack as we use for RPL but replaces the MAC protocol to RL MAC protocol to support the LoRa based as shown in figure 3 [25]. RL MAC works in two phases, neighbour discovery and SF selection. These two phases can be accomplish using the initially use SF12 on all devices, synchronized timeslot, and SF Loops. RL MAC selects the SF Loops as it has less probability of collision as compared to LoRaWAN. Further, it allows building the network with optimal SF. The selected SF results in less time on-air which conserves energy that also effects the battery life of the nodes. The validation of the proposed RL MAC protocol was performed by deploying the RPL network on the campus and found expected results. However, there is a need to build a simulation tool for further investigation before deploying this protocol into the real world.

D. ADC MAC Protocol

Adaptive Duty Cycle Medium Access Protocol (ADC MAC) is a MAC protocol that uses LoRa as the physical layer [26]. This asynchronous protocol enables the nodes to maintain three indicators: node load, network congestion rate, and residual energy. The basic idea behind this protocol is to maintain the minimum interval of the uplink by selecting the different duty cycle by considering the indicators [27]. OPNET simulator is used to simulate the ADC-MAC protocol to check the efficiency of the protocol for LoRaWAN. The nodes that have a high load and have enough energy can dynamically change its duty cycle and uses a large duty cycle. Alternatively, the nodes that have low energy use the lower duty cycle. This protocol reduces the energy consumption by dynamically changing the duty cycle parameter. Due to this reason, the life of the node increases, and the premature death of nodes can be avoided. Further, packet delivery can also improve by using the network congestion indicator. This helps in reducing the interference among the packets by avoiding the transmitting of packets at the same time.

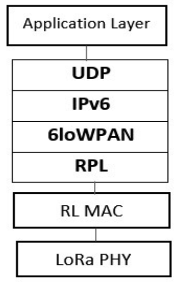

Fig. 3 Protocol Stack for LoRa Based Communication [25]

E. CR MAC Protocol :

Collision Resolving MAC Protocol (CR-MAC Protocol) is used to resolve the Collison issue in LoRa based communication. It maximizes the energy efficiency of nodes. Gateways send the periodic beacons to end devices having each category of SF. After receiving the beacon end devices starts the slots and sub-slots for randomly starting the transmission. The probability of collision is reduced due to the random selection of slots and sub-slot (the possible starting point within each slot). The end device selecting the same slot has the possibility of selecting the different sub-slot to avoid the collision. The collision probability is also affected by the number of slots and sub-slots. CR-MAC Protocol outperforms the conventional LoRaWAN protocol in terms of throughput, energy consumption, and delay. A comparison of both the protocols can be carried out by using the simulator which is designed in Perl [28]. Simulation results showed that LoRaWAN gives the throughput 40% while CR-MAC protocols reach its throughput to 58 %, 78%, and 83% by using the two, four, and eight slots, respectively. CR-MAC also gives better throughput from the LoRaWAN while considering the number of end devices and different spreading factors. We can say that CR-MAC protocol gives higher the network throughput, less delay, and more energy efficiency as compared with LoRaWAN which conventional MAC Protocol by LoRa Alliance is.

VI. LoRa based MAC Layer Research Issues

LoRaWAN is the recommended MAC protocol for LoRa supported devices. However, research has been made to improve its performance in terms of its throughput, energy consumption, delay, and packet delivery ratio [21]. Different MAC protocols have been discussed and found improvement in the performance of LoRa based communication. MoT is used for mission-critical applications but a good candidate for the LoRa communication system due to its energy efficiency. CR MAC and RL MAC are specifically designed for LoRa technology and have shown better results in terms of throughput, energy conservation, and delay compared with traditional LoRaWAN protocol. ADC MAC uses LoRa as the Physical Layer and shows energy conservation and less delay compared with LoRaWAN. Different research areas have been found in the MAC Layer which can be divided into the following categories: MAC Protocol improvements in terms of energy consumption, throughput, latency, and reliability. Study on channel access mechanism, currently, LoRa Supports Aloha, Pure Aloha, Delay Before transmitting (DBT), CSMA. Defining the new channel access mechanism or improving existing is a research direction. However, we cannot separate the security of IoT in the implementation of the new technology especially without considering its security models [29]. Most of the research describes the functionality of class A end devices, only a few papers are available that discuss the functionality of Class B device. So, there is a research potential to work on the class B functionality.

VII. CONCLUSION

LoRaWAN commination is considered the best candidate for future IoT implementation due to its promising features as it provides communication with low power, low cost, long-range, and low data rate. This paper covers the state of the art of the LoRaWAN by considering its physical and MAC layer implementation. Further, we have highlighted different research areas of LoRaWAN that help in its implementation in the near future. Scalability, coverage, optimized parameter selection to cope with the different IoT solutions, energy consumption, throughput, reliability, and security are considered main research areas that attract the researchers for their future work.

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