Chapter 1

Introduction

Growth of Internet-of-Things (IoT) network facilitates various applications and services such as smart home, smart healthcare, smart meter, automated transportation, *etc.* [1]. The main characteristics of IoT services are seamless wireless communication and low power consumption [2]. Traditionally, IoT services employ long-range communication protocols to ensure long coverage and high transmission rate. However, such protocols suffer from high power consumption [3]. As, the IoT devices are battery-powered; therefore, it is challenging to realize the demand for services, *i.e.*, energy efficiency and long-range communication.

A wireless technology called Low Power Wide Area Network (LPWAN) provides a suitable solution for IoT services, as it allows low power devices to communicate at long-range wirelessly. The Long-Range (LoRa) standard is a typical LPWAN specification that has gained a broad interest in IoT applications [4]. Figure 1.1 illustrates a scenario of a smart home in an urban area using a LoRa network having different IoT sensors to collect sensory data. The network consists of various LoRa devices such as LoRa Nodes (LNs), LoRa Gateway (LG), Network Server (NS), and Application Servers (AS).

The LNs collect the data from sensors and send to the LG, which forwards to the NS. The NS processes the data and sends the result to the AS. LoRa uses LoRaWAN communication protocol that is based on the Chirp Spread Spectrum modulation technique [5]. LoRa supports high-density deployment of LNs because of its physical layer which offers degrees of freedom in Channel Frequency (CF), BandWidth (BW), Coding Rate (CR), Transmission Power (TP), and Spreading Factors (SFs).

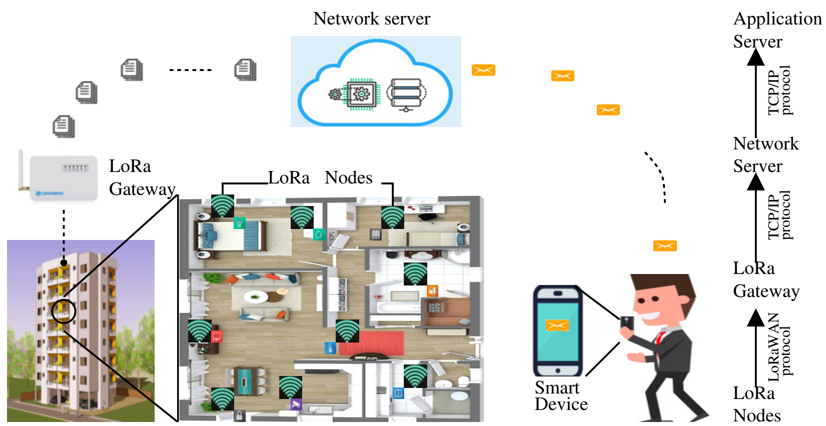

Figure 1.1: A smart home scenario using LoRa network.

The SFs act as the virtual channels between LNs and LGs for given CF, BW, CR, and TP. Multiple LNs with different virtual channels can, simultaneously, use the network for transferring the data to the LGs. LoRa network uses six different SFs, ranging from 7 to 12 [6]. By increasing the SF from 7 to 12, the number of chips per symbol increases, thereby decreasing the nominal data rate [7]. The selection of a SF is a trade-off between coverage range and data rate. The higher the SF results in a higher coverage range and a lower the data rate.

LoRa network consists of different types of network topologies based on the demand of the network. For example, a single LG based LoRa network is suitable for the scenario, where the density of the LNs is low. Multiple LGs in a given region is required when the number of LNs in a region is high. In some network scenarios, LGs assign the SFs to the LNs, while in some cases LNs have fixed SFs. Some network applications require multiple services, simultaneously, by the same LGs to the LNs. Due to the private and other issues in some LoRa networks, all LNs may not share the complete information with each other. Such network demands (*i.e.*, high density or low density of LNs, multiple services or single service, and information sharing), require different approaches for allocating the LoRa resources.

1.1 Motivation of the research work

LoRa finds its applications in various domains due to its low power consumption and long range communication. LoRa covers the advantages of both short-range and long-range communication protocols, *i.e.*, it consumes low energy and provides long distance communication. Despite the above advantages, LoRa suffers from the interference problem. The interference problem occurs when multiple LNs are connected with a LG using the same or different SFs that are subject to collisions. The interference problem also occurs when LoRa and non-LoRa devices communicate simultaneously.

The impact of interference problem can be reduced, if each LN rationally uses the allocated SF, *i.e.*, to free the allocated SF once its transmission is over. Specifically, the network performance can be significantly enhanced by the efficient allocation of the network resources. In this section, we illustrate the major limitations in the existing work, which is the motivation of the research work.

The existing work [8–12] addressed the interference problem in LoRa, while allocating the SFs to the LNs. The authors in [8–10] considered interference when the LNs use the same SF. Since the SFs are not perfectly orthogonal, the LoRa also has an interference problem when LNs use the different SFs [11, 12]. Moreover, the authors in [13] illustrated the impact of the interference on data rate, but they do not solve the interference problem. Some existing work [14] considered the interference among the LNs with same and different SFs. However, such work are suitable only for the limited number of LNs. Authors in [15] designed a full MAC protocol enabling collision resolution, whereas authors in [16] proposed interference model for the LoRa modulation with different coding rates and SFs. As these work considered ALOHA MAC protocol for transmission, increasing the number of LNs leads to frequent collisions. The authors in [8, 9, 17, 18] have proposed the solutions of interference problem by considering single LG-based network topology. Single LG-based network topology is suitable only for a limited number of LNs.

Next, most of the existing SFs allocation approaches are based on the area of the deployment region, path-loss, constant interval, and random [19, 20]. The main drawback of such approaches is that they do not consider the load imbalance on SFs. Allocation of SFs without considering the load will increase the packet loss, packet retransmission, and reduce the throughput of the network. Furthermore, the existing work have also not considered the effectiveness of data. Therefore, existing solutions miss some important data.

Further, the existing work [5, 20] on the allocation of SFs do not consider the other resources of the LoRa network. The resources of the LoRa network are linked with each other. For example, if a LN has a limited remaining duty cycle, then it is beneficial if it transmits the data by the SF, which has a higher data rate.

Finally, in the LoRa network, it is tedious to communicate a large volume of data to the NS. The communication of such data consumes not only considerable energy but also incurs significant communication delay and generates substantial network traffic. Recent studies on communicating large volume of data, such as smart metering applications have considered the use of technologies like Zigbee, Bluetooth, and WiFi for short-range [21–24], and cellular networks (3G and LTE) for long-range [3, 25] communications. However, the long-range communication protocols suffer from colossal power consumption, while short-range communication protocols have limited coverage. Another limitation in existing work [3, 25] is that they did not considered data reduction before communication, so that energy consumption can be minimized.

1.2 Contributions of the thesis

In this thesis, we investigate efficient resource allocation in the LoRa network. We consider the interference problem among the LNs using same or different SFs for data transmission while estimating the transmission time duration on SFs. The main research questions addressed by the thesis are summarized below:

- How long a LN uses the allocated SF from a given LG such that the LN satisfies its service requirement and the network maximizes its revenue?
- How long can a LN be scheduled on a given SF so that the utility of the LN can be maximized and minimizes waiting time of the network?
- How long can a LN associate with the best available LGs to transmit the data of users given that the LNs have incomplete information about other LNs in the network?
- How to efficiently transfer the multivariate time series data to the operator in a given time period with minimum energy consumption?

The rest of the thesis is organized as follows:

Chapter 2: The next chapter presents the preliminaries about the LoRa network, devices, and resources. The chapter also presents the state-of-the-art work on the effective resource allocation with interference problem in LoRa network.

Chapter 3: The impact of the interference problem can be reduced if each LN rationally uses the allocated SF, *i.e.*, to free the allocated SF once its transmission is over. Chapter 3 proposes centralized and distributed approaches to estimate the time duration for the effective use of the spreading factor by the LNs. We refer to it as (n,m,s,c)-Time duration Allocation problem, where n, m, s, and c denote the LN, LG, service, and coding rate, respectively. We consider a LoRa network scenario, which consists of multiple LGs and LNs, where each LN takes services from the same or different LGs. We first formulate the interaction among the LNs as a Nash Equilibrium game to allocate the time duration of using the spreading factors. We consider the interference by using the effective transmission rate, which is less than the default transmission rate due to the interference problem, for estimating the utility of each player. Next, we formulate the interaction between LNs and LGs as a Stackelberg game to balance the load on the LGs that reduces the effect of the interference. Finally, we propose distributed and centralized approaches to run the game model for estimating the time duration to use the SF. We also provide proof of the existence and uniqueness of the Nash equilibrium and Stackelberg equilibrium for the games. The simulation results validate the analysis and demonstrate the significance of the number of LNs, LGs, services, and transmission rate in the estimation of time duration for using the different SFs.

Chapter 4: Multiple LNs can be associated with a LG having the same and different SFs. LNs that are allocated with the same SF have to wait for the availability of the SF, as at a time only one LN can transmit data to the LG using the SF, which increases the waiting time of data transmission by the LNs. Scheduling of the LNs can reduce the data transmission waiting time. We consider a LoRa network scenario which consists of multiple LNs and single LG. In this work, we first propose a Hasse diagram based procedure for finding the subsets of the SFs for each LN, called feasible subsets of SFs, on which they can successfully transfer the data to the LG. Next, we propose a follower game that models the interactions among LNs connected to the LG by using feasible subsets of SFs. The LNs coordinate among each other to decide their optimal time duration such that the network interference reduces. Further, we formulate a Stackelberg game among the LG and LNs to model the interactions between them. Finally, we present an algorithm for scheduling the transmission of LNs on SF to minimize the waiting time of the network. We also prove the existence of Stackelberg equilibrium and derive the sufficient conditions on the uniqueness of the Stackelberg equilibrium.

The simulation results validate the analysis and demonstrate the impact of network parameters on the performance of the network.

Chapter 5: Association of a LN to the suitable LG in the LoRa network improves the packet delivery ratio and packet delivery delay. Such association requires the complete information of the LNs shared among each other, for example, the level of the transmission power of LNs in the LoRa network. However, this assumption is impractical because of the LNs that are not interested in sharing complete information or minimum information for reducing the network load. In this work, we propose an approach for the association of the LNs to the suitable LG with incomplete information. We consider a LoRa network scenario which consists of multiple LNs and LGs. We propose a reputation model using feedback mechanisms which help to select the suitable LGs from the available multiple LGs inside the communication range of a given LN. We use the reputation model and present an approach for estimating the association time duration between each LN and the LGs for transmitting the data of users to the LGs. The approach uses Bayesian game strategy, which is played among the LNs. The Bayesian game accommodates unknown private information of players (*i.e.,* transmission power of a LN which are unknown to other LNs). We also prove the existence of Bayesian Nash Equilibrium and derive the sufficient conditions for the uniqueness of the equilibrium. The simulation results validate the analysis and demonstrate the impact of the number of users, various game parameters, and network topology on the performance of the network. We also demonstrate an application of the proposed work in deployment of a **T**raffic **I**nformation acquisition system based on **L**ong **R**ange network called TILR.

Chapter 6: The transmission of massive data using the LoRa network requires extensive time and energy because of its small packet size and fixed duty cycle. In this work, we address the problem of energy minimization in the LoRa network with deadline constraint. Especially, we consider an application scenario of the smart metering application. In this work, we propose an Compression-Decompression model that uses Long Short Term Memory (LSTM) for lossless compression and decompression of the smart meters data. The transmission of compressed data from LN preserves energy and the LSTM model helps in retrieving original content with maximal accuracy at LG. The system is capable of transmitting data even with an unequal sampling rate of different consumer devices. The LoRa network in this work incorporates multiple LNs that transmit smart metering data to the LG on different SFs within a specified deadline. We derive the expressions for the compression and communication delay and compression and communication energy consumption for formulating the energy efficient data transmission problem.

Chapter 7: The last chapter summarizes the main findings of the thesis. We also discuss some future directions on resource allocation in the LoRa network with different scenarios. Our main contributions are put into a global perspective in this chapter. The publications of the research work presented in this thesis are listed in the List of Publications.