Chapter 2

Preliminaries and related work

This chapter presents the preliminaries about the LoRa network, devices, and resources. We also present the state-of-the-art work on the effective resource allocation with the interference problem in the LoRa network.

2.1 Overview of LoRa network

Internet of Things (IoT) is envisioned to improve the living pattern of human beings [1, 2, 26, 27]. The introduction of IoT in various sectors, including smart home, healthcare, environment monitoring, agriculture, and so on, experiences exponential growth in the last few years. This growth in the IoT applications generates a considerable amount of data whose processing and transmission is tedious and power-consuming. Therefore, the IoT applications demand a network that incorporates energy-efficient, cost-effective, reliable, and scalable mechanisms for data transmission. One such emerging network technology in IoT is Long Range (LoRa) that works on the physical layer of the network. LoRa uses chirp spread spectrum for a low power wide area network [6]. On top of the LoRa physical layer, LoRaWAN works as a network layer protocol for managing communication among devices. In this section, we discuss the LoRa network devices and their resources.

2.1.1 LoRa network devices

A LoRa network consists of the following devices:

- End Users (EUs) are the leaf devices of the LoRa network. The EUs generate the sensory data and transfer to the LoRa nodes for further processing. Some EUs in the LoRa network are embedded with the LoRa nodes. It is also true that multiple EUs can be connect with a LoRa node. Short-range communication protocols usually perform communication between EUs and LoRa nodes.
- LoRa Nodes (LNs) are the primary devices of the network, which are directly connected with the EUs. The LNs collect the environment data by using the sensors. Such LNs usually consist of low processing and limited storage. The main task of the LNs are collecting sensory data from the EUs and forwarding it to the LoRa gateway.
- LoRa Gateway (LG) forwards the data packets of LNs to the network server without understanding the contents of the packets. A LG can simultaneously connect with multiple LNs by using different SFs. Single-channel LGs support only one channel and multi-channel LGs access and forward the data by using multiple channels. Different from multi-channel LGs, single-channel LGs are the low-cost and low-power consuming devices. However, single-channel LGs are not LoRa-compliant and offer low coverage.
- Network Server (NS) receives the data of LNs from the LGs. It processes the data and identifies the result. The NS acts as the brain of the network for controlling the complete LoRa network. The main tasks of NS are controlling and supervision of the network, management of LNs and LGs, and providing network security.
- The Application Server (AS) is the final destination of the processed data provided by NS. The LoRa network pushes data to the AS by using the existing protocols such as HTTP POST, or MQTT.

2.1.2 LoRa resources

- **Symbol:** LoRa uses Chirp Spread Spectrum (CSS) modulation technique, where the transmitted data is represented by a chirp signal with a given minimum and maximum frequency. Such transmitted data is called *symbol* in the LoRa network.
- **Spreading factor:** Spreading Factor (SF) indicates the number of chirps per second sent from LN to the LG. LoRa network supports six SF, denoted by SF_7 to SF_{12}. The SF_7 and SF_{12} are the lowest and highest SFs of the LoRa network, respectively. A lower SF sends more chirps per second then high SF. For example, SF_7 sends more chirps per second or more symbols than SF_8. The transmission time or airtime in LoRa network indicates the duration of the transmission of data from LN to LG. The transmission time of a higher SF is more than a lower SF. The main advantage of the lower SF is that it takes less transmission time but covers a short distance as compared with high SF. The number of chirps per symbol is given as

$$\text{Number of chirps per symbol} = 2^{SF}, \tag{2.1}$$

  where, $SF \in \{7, \cdots, 12\}$.
- **Bandwidth:** Bandwidth (BW) is the frequency range (minimum frequency to maximum frequency) of the chirp signal used to carry the data from LN to LG.
- **Coding rate:** LoRa network supports the error connection by using a variable known as Coding Rate (CR). The number of CR bits encoded with the transmission data depends on the conditions of the channel. The higher CR implies high protection against burst interference. LoRa supports the following four different CR, $\{\frac{4}{5}, \frac{4}{6}, \frac{4}{7}, \frac{4}{8}\}$.
- **Transmission rate:** Transmission Rate (TR) in the LoRa network indicates the number of bits transmitted per second from LN to the LG. The TR in LoRa

network can be calculated as

$$TR = BW \times \frac{SF}{2^{SF}} \times CR. \tag{2.2}$$

2.2 Overview of Game Theory

This section discusses the basic concepts of game theory and game models that we use in the thesis. Game theory is the study of mathematical models which concerns how rational entities make decisions in a situation of conflict [28]. An entity in a game is said to be rational if it implements the best available strategy to pursue the well-defined objectives over the set of possible outcomes.

A game is defined by the following three objectives:

- A *set of players* is the strategic decision-makers within the context of the game.
- A *strategy of a player* is a complete plan of action the player will take in a setting, where the outcome depends not only on their actions but on the actions of others. The strategy is said to mix if the action is chosen by the player with some probability. On the other hand, a player with pure strategy deterministically chooses an action
- The *utility of a player* receives from arriving at a particular outcome. It depends on the selected strategies of the players.

Definition 2.1 *(Equilibrium strategy) An equilibrium in a game is a stage, where the gain of a player is the optimal utility given the strategies of other players.*

2.2.1 Nash equilibrium

The game-theoretic approaches can be classified as cooperative and non-cooperative approaches. The players can be benefited by cooperating and binding agreements in the cooperative game approach. Players in non-cooperative game approach cannot make binding agreements and make their rational decisions. The decisions of rational players for selecting the strategy in a non-cooperative game approach are independent. The objective of a non-cooperative game approach is to find the equilibrium solution with rational players. Nash Equilibrium (NE) finds the solution of a non-cooperative game which involves two or more players. Each player knows the equilibrium strategies of the other players, and no player has anything to gain by changing only their own strategy.

Definition 2.2 *(Nash equilibrium) Let a game consists of N number of players and the set of such players is denoted by $\mathcal{N}$. Let n be an index of a player, $n \in \mathcal{N} = \{1, 2, \cdots, N\}$. Let $\mathbf{t}_n$ and t_n be the set of strategy and any strategy of the player n, respectively. Furthermore, let $U_n(\cdot)$ denotes the utility of the player n. The NE satisfies the following condition*

$$U_n(t_n^\star, \mathbf{t}_{-n}^\star) \geq U_n(t_n, \mathbf{t}_{-n}^\star), \tag{2.3}$$

where $t_n^\star$ and $\mathbf{t}_{-n}^\star$ are the NE strategy of node $n \in \mathcal{N}$ and strategy vector of all the nodes in $\mathcal{N}$ except n, respectively.

2.2.2 Bayesian game

Based on the sharing of the information among the players, the non-cooperative games can be further classified into complete and incomplete information game. The complete and incomplete information are also known as symmetric and asymmetric information, respectively. As the name suggests, each player in a complete informant game consists of all information (*i.e.*, strategies and utility) of other players of the game. Such a complete information game uses NE for solving the problem or finding the outcome of the game. Each player in an incomplete information game does not have complete information about other players. Bayesian Game (BG) is an example of the incomplete information game, where Bayesian analysis is used to solve the game. Bayesian Nash Equilibrium (BNE) finds the solution of a non-cooperative game which involves two or more players with incomplete information. The rational anticipation regarding the

BG, made by the players, is restricted by the knowledge of the players. Players in the BG do not have exact information about the utilities of other players. It is usually modelled by introducing a *type* of the players and the beliefs associated with these types. Probabilistic distributions represent these beliefs. A BG consists of type sets, action sets, utility functions, and prior beliefs. A strategy for a player in BG is an action set that covers each strategy for all types that player might choose. Type set contains all the possible types of a player. The beliefs of a player describe the uncertainty of that player about the types of the other players.

2.2.3 Stackelberg game

Stackelberg Game (SG) is a strategic interaction among players on which some hierarchical competition takes place [28]. The players of SG are leader and followers. LG and LNs act as leader and followers in the game, respectively. The leader starts the game and selects a strategy. After observing the strategy of a leader, followers respond by choosing their best response strategies. Then the leader re-optimizes its strategy based on the best response strategies of the followers.

2.3 Related work

Scalability in the LoRa network investigated in recent years [8, 9]. The existing work shows that with an increase in the number of LNs, the packet delivery rate, network throughput, and coverage probability drops exponentially, due to the interference. The interference problem in LoRa occurs when two or more nodes use the same or different SFs. It also occurs when the non-LoRa devices use sub-GHz radio technology and other devices use the LoRa network. Due to such an interference problem, the LoRa network is not able to effectively utilize the LoRa resources such as SFs, bandwidth, coding rate. Based on the types of devices (LoRa and non-LoRa devices) and use of the SFs (same or different), the existing work that consider the interference problem can be divided into the following categories:

2.3.1 Interference with same SF (Co-SF interference)

Interference in the LoRa network occurs when signals simultaneously collide in time, frequency, and SF. Such interference problem is known as Co-SF interference. Due to the Co-SF interference, the LNs are not able to transmit the data to the LG even with remaining duty cycles.

The authors in [8] investigated the Co-SF interference in a single LG based network. During Co-SF interference, the receiver signal at the LG can be described by an additional term, denoted by $\chi_k^s(t)$ indicator function, where k LNs are transmitting the data at the same time t using s SF. The authors proved that a signal could successfully occur at the LG if Signal-to-Interference-plus-Noise-Ratio (SINR) is below the specified threshold of SF. The signal can also successfully receive if the received signal is four-time stronger than any other concurrent transmitted of the same SF. Similarly, the work in [9] considered the SINR for successfully receiving the signals in the present of Co-SF interference. An adapted algorithm is proposed for extracting the information from simultaneously received LoRa messages on the same frequency and SF. The algorithm first verified whether the received signals are LoRa-like signals or others. If they are LoRa-like signals, then the algorithm first decodes the strongest signal, reconstruction of the strongest signal and removes its contribution. It further selects the next strongest signal and continues this process until all signals are not decoded. The authors in [10] used an FFT based approach for successfully receiving two signals. The authors assumed that two nodes transmitted the signals at the same time and using the same SF. The authors first decoded the symbols of the first user. Next, the time delay between the first and second user is decoded. Finally, they decode the symbols of the second user. The main limitation in the existing work [8–10] is that they are suitable when the limited number of users are present in the network. The simulation results in [9] also considered only three users. Another limitation in SINR based solutions is that they considered the SINR only because of interference. However, SINR may be affected by other factors, such as non-LoRa communications.

2.3.2 Interference with Co-SF and inter-SF interference

Most of the existing work [8–10, 29] consider only the Co-SF interference, where the authors assumed perfect orthogonality among the different SFs. Recent work [11, 12] disproved the validity of such an assumption and claimed that the interference problem in the LoRa network could also occur by the different SFs. This is because different SFs do not make the transmitted signals perfectly orthogonal. Such interference problem is called inter-SF interference. In this subsection, we present some existing work on inter-SF interference.

The authors in [30] use a single LG based network scenario for estimating the performance of the network in the presence of inter-SF interference. They analyzed the interference problem and concluded that the packet loss is high if the power of the interference signal is high. The work in [30] concluded that the higher SFs also have interference issues even the users far from the LG. Different from this work, the work [17] considered both Co-SF interference and inter-SF interference. The main objective of the work is max-min fairness in terms of throughput, without taking into consideration the energy of end-devices. The authors derived the SINR. If a LN n uses m SF, the SINR of inter-SF and Co-SF are given by $SINR_{nm}^{inter} = \frac{\mathrm{SNR}_{nm}}{\sum_i \sum_j s_{ij}\mathrm{SNR}_{ij}+1}$ and $SINR_{nm}^{co} = \frac{\mathrm{SNR}_{nm}}{\sum_i s_{im}\mathrm{SNR}_{im}+1}$, respectively, where i and j are the LNs and SFs other than n and m, respectively, s_{ij} is binary one if i uses j, and SNR_{ij} is Signal-to-Noise Ratio (SNR). They first formulated the optimization problem by modelling the achievable uplink short term average rate under Co-SF and inter-SF interference. Next, they proposed an SF-allocation algorithm based on matching theory. Here, two sets of players are presented, a set of SFs and the set of end-devices. A LN will prefer to be matched to the SF offering the highest utility, while each SF prefers to be matched with the group of devices with the highest utility.

The authors in [18] considered both Co-SF interference and inter-SF interference with and without perfect orthogonality. They provided a theoretical analysis of the achievable throughput on the uplink of a LoRa network with Co-SF and inter-SF interference. They derived the probabilities of successfully transferring the data when Co-SF, inter-SF, and both (Co-SF and inter-SF). They proved that a packet successfully transfers from LN to LG if the following conditions are satisfied: 1) its SNR is above the reception threshold, 2) its SINR is above the Co-SF capture threshold if there is Co-SF interference, and 3) its SINR is above the inter-SF capture threshold if there is inter-SF interference. Some existing work uses stochastic geometry for solving Co-SF interference and inter-SF interference. The authors in [14] investigated the effect of Co-SF and inter-SF interference. They used the tools from stochastic geometry to model the interference field as a Poisson point process and included MAC and Physical layers features. The authors derived signal-to-interference ratio distributions in the presence of dominant Co-SF interference, cumulative Co-SF interference, and inter-SF interference, under a realistic path loss model and channel fading. Finally, they evaluated the coverage probability by using the derived distributions. The authors in [13] modeled the spatial distribution of LNs by using the stochastic geometry for reducing the Co-SF and inter-SF interference. The main idea of the work is to allocate the SFs based on the existing number of LNs per unit area. They assumed that the LGs are deployed by the Poisson point process and Matern hard-core point process. They numerically illustrated that the work increased the success probability of packet transmission and the throughput of the network. The main limitation in geometry-based approaches is that they considered a fixed process such as Poisson point process and Matern hard-core point. However, such assumptions are not feasible when the devices are mobile and have unequal deployment.

2.3.3 Cross-technology radio interference

A LoRa network also faces the interference problem with non-LoRa devices. Example of such a non-LoRa network is IEEE 802.15.4g. Such interference reduces the utility of LoRa and the non-LoRa network. The authors in [19, 31, 32] considered interference due to the Co-SF and non-LoRa devices.

The work in [19] computed the outage probability due to the Co-SF interference occurred as follow $P_{\text{out:1}} = 1 - \exp\left(-k\lambda r^2 (\beta_{\text{SF}})^{2/\alpha}\right)$, where k being the Gamma function, β_{SF} is minimum SIR, λ is the density of LNs, r is the radius of deployment region, and exponent $\alpha > 2$. The outages probability from other (non-LoRa) users that use the same channel is derived as $P_{\text{out:2,x}} = 1 - \exp\left(-k\lambda_{\text{I}} r^2 (\beta_{\text{SFx}})^{2/\alpha}\right)$, where λ_{I} is the density of non-LoRa devices . Finally, the authors computed the successful transmission probability as $P_{\text{out,x}} = 1 - (1 - P_{\text{out:1}})(1 - P_{\text{out:2,x}})$. The experimental results in [32] illustrated the impact of cross-technology radio interference between LoRa and IEEE 802.15.4g networks. It is shown that as compared with strong IEEE 802.15.4g interference, the LoRa can obtain high packet reception rates. Therefore, when crosse-technology radio interference occurs, the LoRa has less packet loss and throughput as compared with other technology. Similarly, the empirical study on interference [33] investigated the interference when one LoRa and two IEEE 802.15.4g simultaneously send the data. The paper concluded that it is hard to find the effect of interference behavior beyond the specific empirical observations. A measurement study [34] is done in European 868 MHz Band (using SigFox communication technology) and the LoRa network. The authors considered the shopping area, a business park, a hospital complex, an industrial area, and a residential area for this study. The main objective of this study is to find what the interference source may be and how the interference may affect LoRa and SigFox. It shows that there is a 22-33 % probability of interfering signals in a shopping area and a business park. However, the probability of interference is less than 3% in the three other measurement locations. Most of the existing work in this direction measured the interference and did not propose the solution for reducing the interference issue. The authors in [31] investigated the LoRa interference on IEEE 802.15.4 networks. They observed that the IEEE 802.15.4 Clear Channel Assessment (CCA) mechanism does not reliably detect interfering LoRa transmissions. An enhanced CCA mechanism based on a Multi-Layer Perceptron classifier is proposed in the paper for solving such an interference problem. The proposed mechanism reduces the number of unsuccessful transmissions while remaining compatible with the IEEE 802.15.4 standard.

2.3.4 Resource management for interference problem

As we have discussed above several studies have started to address the interference problem (Co-SF, inter-SF, and Cross-technology radio interference), focusing on issues of the scalability of the network. The performance of the LoRa network depends on communication technology (low interference) and the effective use of resources [35, 36]. The authors in [35] illustrated that each LN could successfully transfer the data from the LN to LG by selecting the appropriate SF. The selection of proper SF can be considered to reduce interference among groups of LNs which are assigned different SFs, and therefore improve the total network capacity. However, the authors in [35] ignored the effects of inter-SF interference by assuming the perfect orthogonality among different SFs.

The data rate is an important resource in the LoRa network. The authors in [37] illustrated that the loss of the packets of far LNs is high as compare with near LNs to the LG. Such loss can be reduced by assigning of fair data rate to each LN. The authors also proposed an algorithm for balancing the transmission power control, which overcomes the effect of the strong signal at the LG. Furthermore, in [20] considered the transmission power and SF for reducing the interference. The authors derived the collision probability as $p_{coll,S} = 1 - e^{-2G_S}$, where G_S denotes the amount of generated packets with spreading factor S. The authors proposed an algorithm for solving the fairness optimisation problem $\min \max_S p_{coll,S}$. Different from the other existing work, this paper mainly focused on the edge users. Using simulation results, the authors claimed that around 50% packet error rate could be improved by controlling the power and SFs. The Adaptive Data Rate (ADR) is a mechanism that runs time adapts the data rate of each LNs based on the link conditions and network density. The authors in [38] proposed an ADR algorithm under dynamic link conditions. They changed the network parameters in the ADR algorithm to observe their effects on the convergence time. They concluded that slow ADR increases packet loss and energy consumption. Both work [20, 38] considered the Co-SF interference problem to improve the packet error rate. They assumed that the inter-SF problem could be eliminated by considering unconstrained power control.

The authors in [39] developed a resource scheduling scheme which consists of low overhead. The network server works as the controller in the network for allocating the time and amount of the transmissions of end devices. The network server sends a list slot indexes when an end device can transmit the data. The authors in [40] proposed a protocol which adds the delay before transmitting the data. Such delay is nothing but the waiting time of a LN before transmitting the data. The LN uses IDs to analyze the amount of time it has to wait. The main limitation of work [39, 40] is that they proposed a centralized approach which is suitable for the small size of the network.