



저작자표시-비영리-변경금지 2.0 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:



저작자표시. 귀하는 원저작자를 표시하여야 합니다.



비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.



변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 [이용허락규약\(Legal Code\)](#)을 이해하기 쉽게 요약한 것입니다.

[Disclaimer](#)

공학석사학위논문

LoRa 네트워크에서 에너지 효율성을 위한 노드 기반 ADR 메커니즘

A Node-based ADR Mechanism for Energy
Efficiency in LoRa Networks

2020 년 8 월

서울대학교 대학원

컴퓨터공학부

박 건 호

LoRa 네트워크에서 에너지 효율성을 위한 노드 기반 ADR 메커니즘

A Node-based ADR Mechanism for Energy
Efficiency in LoRa Networks

지도교수 김 종 권
이 논문을 공학석사 학위논문으로 제출함

2020 년 6 월

서울대학교 대학원
컴퓨터공학부
박 건 호

박건호의 공학석사 학위논문을 인준함
2020 년 8 월

위 원 장 : 전 화 숙 (인)

부위원장 : 김 종 권 (인)

위 원 : 권 태 경 (인)

Abstract

A Node-based ADR Mechanism for Energy Efficiency in LoRa Networks

Kunho Park

Department of Computer Science & Engineering

The Graduate School

Seoul National University

Recently, as Internet of Things (IoT) systems have increased and Wireless Sensor Network (WSN) has been expanding, studies related to them are increasing. Among them, the interest in long range communication technologies has increased. In this regard, Low Power Wide Area (LPWA) network technologies such as Long Range (LoRa), Weightless, and Sigfox have emerged. Also, various studies related to LoRa and LoRaWAN, which are available in Industrial Scientific and Medical (ISM) bands, are being conducted. In LoRa networks, the nodes are connected to the gateway by one hop to form a star topology. LoRa nodes use the transmission parameters such as Spreading Factor (SF), Transmission Power (TP), Bandwidth (BW), Coding Rate (CR), and Carrier Frequency (CF) to transmit frames. In this process, the frame losses and the collisions between frames may occur because of the channel condition and transmission timing. To alleviate this problem, LoRaWAN utilizes the ADR mechanism to select appropriate transmission parameters considering the channel condition on the node side. In addition, there is the ADR mechanism for allocating the transmission parameters on the server side. The ADR

mechanisms maintain the connection between the server and the nodes, and set appropriate transmission parameters. However, these existing ADR mechanisms have some limitations. First, the server side ADR mechanism increases the overhead of the server in proportion to the transmitted frames. Second, it is difficult to quickly and efficiently respond to dynamic channel. Third, the transmission parameters selected by these ADR mechanisms may not be the optimal transmission parameters for energy efficiency. These problems cause large energy consumption of the battery-powered nodes and decrease performance when the channel condition changes dynamically. In this paper, we propose a Node-based ADR Mechanism (NbADR), which is the ADR mechanism for Class A nodes in confirmed mode to minimize the server load and maximize energy efficiency. The proposed mechanism responds quickly to the channel condition based on the downlink pattern and selects the transmission parameters for efficient energy consumption by utilizing Efficiency of Energy (EoE) metric. We analyze the efficiency of the transmission parameters selected through EoE, and conduct extensive experiments. In conclusion, NbADR is more effective in terms of energy efficiency than the existing ADR mechanisms. Additionally, NbADR guarantees throughput of LoRa networks even in dynamically changing channel environments and improves fairness between the nodes.

Keywords: Internet of Things, Wireless Sensor Network, Low Power Wide Area Network, LoRa, LoRaWAN, ADR mechanism, Resource allocation

Student number : 2018-26264

Contents

Abstract	i
Contents.....	iii
List of Figures	v
List of Tables	vi
Chapter 1 Introduction	1
Chapter 2 Related Work	4
Chapter 3 Preliminaries	7
3.1 LoRa/LoRaWAN	7
3.2 Transmission Parameters	8
3.3 ADR Mechanism.....	9
Chapter 4 Channel Modeling	10
4.1 Loss	10
4.2 Collision.....	12
Chapter 5 Node-based ADR Mechanism.....	14
5.1 Approach for Energy Efficiency	15
5.2 Node-based ADR Mechanism (NbADR)	17
Chapter 6 Evaluation	21
6.1 Simulation Settings	22

6.2 Simulation Results	23
Chapter 7 Conclusion	33
Bibliography	35

List of Figures

Figure 6.2.1 SF allocation when using (a) ADR, (b) NbADR, (c) NbADR (SNR), and (d) Server (EoE) for 1,500 nodes.....	26
Figure 6.2.2 Delivery ratio for number of nodes.....	27
Figure 6.2.3 Total energy consumption for number of nodes.....	27
Figure 6.2.4 Energy efficiency for number of nodes.....	27
Figure 6.2.5 Delivery ratio of 1,800 nodes for arrival rate.....	28
Figure 6.2.6 Total energy consumption of 1,800 nodes for arrival rate..	28
Figure 6.2.7 Energy efficiency of 1,800 nodes for arrival rate.....	28
Figure 6.2.8 Delivery ratio of 500 nodes for standard deviation of path loss.....	30
Figure 6.2.9 Energy efficiency of 500 nodes for standard deviation of path loss.....	30
Figure 6.2.10 Fairness for delivery ratio of 1,800 nodes in the network for arrival rate.....	32

List of Tables

Table 6.1.1 Transmission parameters.....	22
--	----

Chapter 1

Introduction

Internet of Things (IoT) related technologies are increasing and its applications are expanding. In addition, long range communication technologies such as Low Power Wide Area (LPWA) network have recently emerged. LPWA network technologies enable long distance communication using resources efficiently. There are Long Range (LoRa) [1], Weightless [2], and Sigfox [3] in LPWA network. Each technology has a feature of being able to transmit frames over long distance but has different characteristics in the modulation method and the available frequency spectrum. This paper focuses on the promising technology, LoRa, which enables low power and long range communication in Industrial Scientific and Medical (ISM) bands. The LoRa network consists of a star topology with one hop between the gateway and the node. Each node sets the transmission parameters such as Spreading Factor (SF), Transmission Power (TP), Bandwidth (BW), Coding Rate (CR), and Carrier Frequency (CF) to transmit signals as needed. The success or failure of the frame transmission depends on the transmission parameters and the channel

conditions. During transmission of frames, the collisions between frames occur because each node cannot accurately know the network condition. The collisions occur in the process of attempting the frame transmission because the nodes use the same CF and SF during air time of each frame. Therefore, the success of the frame transmission is determined by signal strength of frames and transmission timing. Because of these problems, the reliability of the network and the energy efficiency of the nodes get worse. In this regard, LoRaWAN [4] and TTN [5] provide the ADR mechanisms. The ADR mechanisms maintain the connection between the server and the node and adjust the transmission parameters based on the channel state on the server side, thereby increasing the probability of successful frame transmission. However, the ADR mechanisms are not sensitive to the channel condition and does not guarantee good performance in an environment where the channel is dynamically changing. Many studies have been conducted to improve the ADR mechanism or allocate the transmission parameters efficiently. In some studies of LoRa and LoRaWAN, schemes for allocating the transmission parameters [6-10], methods for improving performance in specific situation [11], or specific performance improvement methods [12-14] are proposed. However, there are limitations in selecting the optimal transmission parameters in an environment where the channel condition is constantly changing. Also, some methods focus on only one transmission parameter such as or are for limited environments.

In this paper, we propose a Node-based ADR Mechanism (NbADR) for Class A nodes in confirmed mode. NbADR improves the energy efficiency and can operate even in a dynamic environment without significant performance

reduction. In addition, the proposed mechanism reduces the overhead of the server. NbADR predicts the channel condition and adjusts the transmission parameters using the pattern of downlinks because the SNR information of uplinks is not available. In addition, this ADR mechanism selects the transmission parameters considering the probability of frame transmission and energy consumption of the node.

The main contributions in this paper are as follows.

1. We propose an enhanced ADR mechanism that ensures energy efficiency for Class A nodes in confirmed mode. Also, we conduct extensive experiments to confirm the performance of this ADR mechanism.
2. We describe a new approach to selecting the transmission parameters and apply it to the proposed ADR mechanism. Through this approach, the proposed mechanism can allocate the optimal transmission parameters for energy efficiency.
3. We analyze a wide range of performance evaluations such as delivery ratio, energy consumption, energy efficiency, and fairness between the nodes.

The rest of this paper are organized as follows. Chapter 2 provides related work of the research being conducted in LoRa and LoRaWAN. In chapter 3, the channel is modeled. Chapter 4 describes NbADR. Chapter 5 presents performance of NbADR and other ADR mechanisms through simulation. Chapter 6 concludes paper.

Chapter 2

Related Work

LoRa technology enables long range communication with efficient energy consumption. Therefore, its application fields are expanding and the research has been actively conducted. Many studies of LoRa and LoRaWAN are being conducted in many ways such as features of LoRa technology and performance improvement of LoRa networks.

Researches on the characteristics of LoRa and LoRaWAN and researches on scalability were conducted. M. Bor et al. [15] analyzed the characteristics of LoRa using actual LoRa transceiver device. Also, M. Bor et al. [16] measured the capacity of LoRa networks and the authors modeled LoRa communication behavior and developed a LoRa simulator. In [17], M. Bor et al. analyzed the impact of the transmission parameters used in LoRa. In addition, D. Bankov et al. [18] described the channel access of LoRaWAN. Also, the authors developed a mathematical model considering the capture effect in [19]. F. Adelantado et al. [20] analyzed the capability and scale limitations of LoRaWAN. T. Voigt et al. [21] investigated performance analysis for the directional antennae and the multiple base stations. There are some studies on scalability of LoRa network. F. Van den Abeele et al. [22] conducted scalability analysis using a LoRa error

model in ns-3. Also, O. Georgiou et al. [23] analyzed the scalability of LoRa network related to the effects of interference. A. Mahmood et al. [24] described an analytical model based on the imperfect orthogonality considering quasi-orthogonality of SF.

In LoRa networks, the collisions may occur in the frame transmission process like pure ALOHA network. The collisions between frames and the losses have a significant impact on performance. In this regard, some studies have been conducted to improve network performance. The performance can be directly improved by selecting the proper location of the gateway and using multiple gateways. B. Ousat et al. [25] proposed the gateway placement in LoRa network. Also, the performance of multiple gateways is studied in [16] and [21]. In addition, it is possible to form an efficient and collision-resistant LoRa network while properly allocating transmission parameters. F. Cuomo et al. [6] proposed EXPLoRa-SF based on total number of nodes and RSSI of the connected node and EXPLoRa-AT based on the air time of the node. In addition, F. Cuomo et al. [8] described EXPLoRa-KM for improving the performance of critical area by utilizing K-means technique. Also, they proposed EXPLoRa-TS to balance traffic load of the SF channels. Both schemes are aiming for efficient allocation of SF. In [7], M. Slabicki et al. improved network performance through the ADR mechanism using the average SNR value instead of the max SNR value of the existing ADR mechanism and a network-aware approach utilizing the network information. In addition, B. Reynders et al. [26] proposed the scheme to optimize the packet error rate fairness. J. –T. Lim et al [9] formulated the optimization problem of the average system PSP and proposed SF allocation scheme to achieve maximum connectivity. L. Amichi et al. [10] proposed an

algorithm that solves SF allocation optimization considering interference by focusing on max-min fairness. Also, N. Benkahla et al. [11] proposed the ADR mechanism considering position of mobile nodes.

Some studies have suggested methods to improve specific performance such as energy, fairness, or Quality of Service (QoS). B. Su et al. [12] proposed resource allocation algorithm for energy efficiency by decomposing the nonconvex problem into three sub-problems. K. Q. Abdelfadeel et al. [13] proposed Fair Adaptive Data Rate (FADR) for fair data rate of all nodes regardless of the distance from the gateway. Also, W. Gao et al. [14] proposed a networking solution of resource allocation for fair energy consumption. Also, U. Coutaud et al. [27] presented a channel coding approach for improving Quality of Service (QoS).

Chapter 3

Preliminaries

3.1 LoRa/LoRaWAN

LoRa is a physical layer technology by Semtech [28] to enable efficient power consumption and long range communication. LoRa utilizes Chirp Spread Spectrum (CSS) modulation and Forward Error Correction (FEC) for robust communication. In CSS modulation, each symbol is composed of a number of chips based on predefined patterns such as upchirp and downchirp. It enables the frame transmission even in poor channel condition. In LoRa, the frame is transmitted based on the transmission parameters such as SF, TP, BW, CR, and CF.

LoRaWAN is a protocol for LoRa technology provided by LoRa Alliance. In LoRaWAN, there are Class A, Class B, and Class C [4]. The characteristics of each class can be classified according to the pattern of downlink receive windows after an uplink. In Class A, the node sends the uplink to the gateway as needed, and then receives the downlink through two downlink receive windows. Class B is an extension of Class A and additionally uses the downlink receive windows according to scheduled time. In this class, time is synchronized by using a beacon. Class C is also an extension of Class A. Most

of the time except the uplink time is used for the downlink receive windows.

3.2 Transmission Parameters

In LoRa networks, the server and the node can select the transmission parameters appropriate to the channel condition. The transmission parameters consist of SF, TP, BW, CR, and CF and each parameter can vary depending on the type of device and the region.

- Spreading Factor (SF): SF means the number of chips per symbol. It can indicate the degree of noise resistance. Also, higher SF is more resistant to noise in proportion to the number of chips. It can be selected from SF7 to SF12. In addition, nodes using other SF can avoid collisions due to the orthogonality of SF.
- Transmission Power (TP): TP is the power of the transmitted signal, and nodes select TP in consideration of the transmission distance and the channel condition. The success or failure of the frame transmission is determined according to the sensitivity at the gateway. TP can be set from 2dBm to 14dBm. There are some TPs that can be used outside this range and there may be restrictions for their use.
- Bandwidth (BW): BW means the capability of transmission. It can be set to 125kHz, 250kHz, or 500 kHz.
- Coding Rate (CR): CR is used for robust transmission. CR can be selected to 4/5, 4/6, 4/7, or 4/8. According to CR, extra bits are added to

enable strong transmission against errors.

- Carrier Frequency (CF): CF means the center frequency at which the frame transmission occurs. The range of CF varies depending on the region.

3.3 ADR Mechanism

The frame transmission depends on the channel condition in LoRa networks. The ADR mechanism is used to set the appropriate transmission parameters. In [4], the nodes change SF, TP, and CF by sending the ADR acknowledgement request. If a response is not received from the server within the given count, the transmission parameters are adjusted according to the predetermined order. In [5], the transmission parameters are adjusted from the server. When the uplinks are transmitted, the server detects SNR of each uplink, calculates SF and TP for the channel condition by using the SNR information, and transmits the selected transmission parameters to the corresponding node. In this server side ADR mechanism, the server load occurs in proportion to the number of frames sent by the nodes. These ADR mechanisms make it difficult to quickly adjust the transmission parameters depending on the channel condition and degrade performance when the channel condition changes dynamically.

Chapter 4

Channel Modeling

In this chapter, the channel of LoRa network is modeled. Based on the channel modeling, the extensive experiments are conducted later. The channel is modeled focusing on the urban environment. We consider that there is one gateway, and all nodes in the network have at least one transmission parameter combination that allows the signal to reach the gateway. That is, all nodes can be connected to the gateway. The success of the frame transmission is determined by the channel state and the collisions between the transmitted frames.

4.1 Loss

We use the log-distance path loss model [29] related to densely populated areas, considering our experimental environment among signal propagation models. This model can be expressed as:

$$L_{pl}(d) = \overline{L_{pl}}(d_0) + 10\gamma \log \frac{d}{d_0} + X_\sigma.$$

$L_{pl}(d)$ means the path loss of the channel condition. The values of parameters are configured as follows [16]. $\overline{L_{pl}}(d_0)$ is the path loss when the reference distance d_0 is used. In our experiment, d_0 is $40m$, and it results in $\overline{L_{pl}}(d_0) = 127.41dB$. In addition, γ is 2.08, and X_σ follows a normal distribution with mean of 0 and standard deviation (σ) is from 1.0 to 3.0 in 0.5 intervals. We do not consider other loss or gain. In other words, the signal power can be represented by the TP and $L_{pl}(d)$.

In order to model the probability of a successful frame transmission, we define Frame Success Rate (FSR). In this regard, the analytical expression for FSR is as follows:

$$FSR = (1 - BER)^L.$$

It represents the probability of successful transmission for L bits packet based on the error probability for each bit. In FSR, we calculate BER as [30]:

$$BER = Q\left(\frac{\log_{12} SF}{\sqrt{2}} \cdot \frac{E_b}{N_0}\right).$$

In this equation, $Q()$ means Q-function. $\frac{E_b}{N_0}$ is the energy per bit to noise power spectral density ratio for CSS modulation of LoRa. It is expressed as:

$$\frac{E_b}{N_0} = SNR - 10 \cdot \log\left(\frac{RS \cdot SF \cdot CR}{BW}\right).$$

RS stands for $\frac{BW}{2^{SF}}$. Through this equation, we express the probability for transmission of the frame for the given transmission parameters.

4.2 Collision

In LoRa networks, each node operates like pure ALOHA, where the nodes transmit frames as needed. Therefore, when one node attempts to transmit a frame, the collision may occur because of transmission of other frames. The collision occurs when a frame that is already being transmitted exists in the channel or another frame is transmitted while the frame is being transmitted. In this situation, the frame is transmitted depending on transmission power due to the capture effect. Also, when 5 preambles of the frame are transmitted, the frame can be transmitted. In other words, the power of the frame and the transmission time have to do with whether the frame is lost. There are the transmission parameters related to orthogonality to minimize the collisions and transmit multiple frames at the same time. SF and CF are related to the

orthogonality, so efficient allocation of two transmission parameters can reduce the collisions.

Chapter 5

Node-based ADR Mechanism

The ADR mechanisms set the effective transmission parameters according to the network state and channel conditions. However, the existing ADR mechanisms have some limitations. First, the transmission parameters selected by the existing ADR mechanisms are not necessarily the optimal transmission parameters. Second, when the number of transmitted frames increases, the overhead of the server increases. Third, it is difficult to respond quickly to the channel condition. We propose a Node-based ADR Mechanism (NbADR) that can select the transmission parameters considering energy efficiency. NbADR is the ADR mechanism for Class A nodes operating in confirmed mode. Also, NbADR uses a method for predicting channel condition indirectly through downlinks considering the characteristics of the node-based ADR mechanism. Because it is not possible to know the number of other nodes, distribution of the nodes, transmission period of other nodes, and transmission parameters of other nodes, etc. on the node side. Also, the nodes cannot directly know SNR of the uplink.

5.1 Approach for Energy Efficiency

There is a trade-off relationship between frame success rate and energy efficiency in the performance of LoRa networks. In order to improve the frame success rate, nodes can minimize collisions by using all possible SFs. However, nodes using relatively high SF have negative impact on overall energy efficiency of LoRa network. Because high SF causes large energy consumption. On the contrary, in order to improve the energy efficiency, nodes may use lower SF that consumes less energy. This method increases the nodes using the same SF and thus lowers the frame success rate by increasing the probability of the frame collisions. Therefore, we define Efficiency of Energy (EoE) considering both energy efficiency and frame success rate and use it to select the transmission parameters. EoE can be expressed based on FSR and energy consumption as:

$$EoE = \frac{FSR}{NEC}.$$

A high value of EoE means low energy consumption or high frame success rate. Normalized Energy Consumption (NEC) is the normalized energy consumption value of the nodes between 0 and 1 and is expressed as:

$$NEC = \frac{I_{tp} \cdot V \cdot ToA_{sf}}{I_{tp_{max}} \cdot V \cdot ToA_{sf_{max}}}.$$

Time on Air (ToA) means air time at which a frame is transmitted. ToA_{sf} is the ToA of the selected SF and $ToA_{sf_{max}}$ is the ToA of maximum SF. Also, I_{tp} is the current of the selected TP and $I_{tp_{max}}$ is the current of maximum TP. V is the voltage and we use 3 as the value of this parameter. We can select the transmission parameters as the way to find the largest value of EoE among all selectable combinations of SF and TP. In this regard, we define an EoE function as:

$$F_{EoE}(SF, TP, snr) = \underset{sf \in SF, tp \in TP}{\operatorname{argmax}} EoE(sf, tp, snr).$$

In this function, the parameters of the input are a set of SF, a set of TP, and SNR and the outputs are the optimal SF and TP selected based on the EoE function. SF means the set of SF that can be selected and TP is the set of TP that can be selected depending on the type of node device. In addition, $EoE(sf, tp, snr)$ is expressed as:

$$EoE(sf, tp, snr) = \frac{(1 - f_{BER}(sf, snr))^L}{f_{NEC}(sf, tp)}.$$

f_{BER} is a function of BER and f_{NEC} is a function of NEC. Both functions compute the value of BER or NEC for the given input.

5.2 Node-based ADR Mechanism (NbADR)

NbADR is an ADR mechanism that utilizes the approach of Auto Rate Fallback (ARF) [31], one of the rate adaptation algorithms. In ARF, the appropriate data rate is selected based on the success or failure of the transmitted frames. The pattern for the success of frame transmission is used as the information to select the next data rate and adjustment timing. Similarly, NbADR use an approach checking whether a frame is transmitted through the downlink and adjusting the transmission parameters through downlinks pattern. Therefore, this ADR mechanism operates for Class A nodes in confirmed mode. NbADR consists of two main parts to select the transmission parameters. One is to predict SNR. In this part, the more accurately SNR is predicted, the better the performance can be. However, it is difficult to accurately predict SNR based on the pattern of the downlinks, so methods for predicting SNR will help improve performance. The other is to select transmission parameter combination based on EoE for energy efficiency.

Algorithm 1 NbADR Algorithm

Input: sf_c, TP, snr_c **Output:** sf_n, tp_n, snr_n

```
1:  $SF \leftarrow \{7, 8, 9, 10, 11, 12\}$ 
2: if  $uplink_i$  Transmission then
3:    $count_u \leftarrow count_u + 1$ 
4:   if  $downlink_i$  Reception then
5:      $count_f \leftarrow 0$ 
6:   end if
7:   if  $downlink_i$  Absence then
8:     if  $count_f == 1$  then
9:        $count_f \leftarrow 2$ 
10:    end if
11:     $count_f \leftarrow count_f + 1$ 
12:  end if
13: end if
14: if  $count_u == N_p$  then
15:    $snr_n \leftarrow snr_c + u_1$ 
16:    $(sf_n, tp_n) \leftarrow F_{EoE}(SF, TP, snr_c)$ 
17:    $count_u \leftarrow 0$ 
18:    $count_f \leftarrow 0$ 
19: end if
20: if  $count_u < N_p$  then
21:   if  $count_u == 1$  and  $count_f == 1$  then
22:      $snr_n \leftarrow snr_c - d_1$ 
23:     if  $tp_{max} == tp_c$  and  $sf_{max} > sf_c$  then
24:        $sf_n \leftarrow sf_c + 1$ 
25:     end if
26:     if  $tp_{max} > tp_c$  then
27:        $sf_n \leftarrow sf_c$ 
28:     end if
29:      $SF \leftarrow \{sf_n\}$ 
30:      $(sf_n, tp_n) \leftarrow F_{EoE}(SF, TP, snr_c)$ 
31:      $count_u \leftarrow 0$ 
32:      $count_f \leftarrow 0$ 
33:   end if
34:   if  $count_f == 2$  then
35:      $snr_n \leftarrow snr_c - d_2$ 
36:     if  $sf_{max} == sf_c$  then
37:        $sf_n \leftarrow sf_c$ 
38:     end if
39:     if  $sf_{max} > sf_c$  then
40:        $sf_n \leftarrow sf_c + 1$ 
41:     end if
42:      $SF \leftarrow \{sf_n\}$ 
43:      $(sf_n, tp_n) \leftarrow F_{EoE}(SF, TP, snr_c)$ 
44:      $count_u \leftarrow 0$ 
45:      $count_f \leftarrow 0$ 
46:   end if
47: end if
```

The algorithm of NbADR is described in Algorithm 1. Overall, the node determines the newly predicted SNR value (snr_n), SF (sf_n), and TP (tp_n) for the next uplink transmission through the current predicted SNR value (snr_c), the currently used SF (sf_c), and the set of TP available at the node (TP). First, the node transmits the uplink and checks the result of the corresponding downlink (line 2-13). NbADR determines that if the first or 2 consecutive downlinks absence do not occur during a certain period (N_p), the channel condition may be improved or there may be more suitable transmission parameter combination. Accordingly, the predicted SNR is increased by u_1 , and then transmission parameters are selected based on EoE (line 15-16). However, if the first or 2 consecutive downlinks absence occur before N_p , it means that the predicted SNR does not reflect the current channel condition and current transmission parameters are not appropriate for current channel condition. Accordingly, the predicted SNR is changed and new transmission parameters are allocated. First, when the first downlink absence occurs, NbADR returns to the value similar to the previously predicted SNR. Because the predicted SNR was evaluated better than actual channel condition. It allows node to quickly return to the appropriate transmission parameters. The method of operation is to reduce SNR by d_1 , use current SF if current TP is not the maximum TP, and reassign TP based on EoE. If TP is the maximum TP and SF is not 12, NbADR increases SF by 1 and reallocate TP through EoE. (line 22-30). Next, when 2 consecutive downlink absence occurs, it means a situation in

which the current channel condition is not good or collisions occur. Therefore, in order to prevent the frame losses or the collisions, robust transmission parameters are required. NbADR reduces the predicted SNR by d_2 , increase SF by 1 if current SF is not 12, and reassign TP through EoE (line 35-43). In this mechanism, N_p , u_1 , d_1 , d_2 can be adjusted. In this paper, N_p is set to 10, u_1 is set to 0.5, d_1 is set to 1, and d_2 is set to 1.25.

Chapter 6

Evaluation

In this chapter, we analyze the performance of the existing ADR mechanisms [4, 5], server side ADR mechanism using EoE, NbADR, NbADR using the SNR information. The existing ADR mechanism is expressed ADR. Also, NbADR using actual SNR information of the 10 recently transmitted uplinks instead of predicted SNR is expressed as NbADR (SNR). This ADR mechanism is used to show the possibility of performance improvement when NbADR predict SNR more accurately. Also, server side mechanism using EoE is expressed as Server (EoE). Server (EoE) is a method to allocate the transmission parameters based on EoE using the minimum SNR of 10 recently transmitted uplinks. This mechanism is the comparison mechanism to show the advantages of EoE when using EoE on the server side. Simulator extends LoRaSim [16], a discrete-event simulator utilizing SimPy, including the ability to allocate the transmission parameters according to channel condition. Also, we assume that there is no loss for downlink transmission because there is little difference in performance analysis of the experiments. We evaluate the scalability of the ADR mechanisms through delivery ratio, energy consumption,

and energy efficiency and additionally analyzed the robustness and fairness of nodes.

6.1 Simulation Settings

In simulation, there are only Class A nodes operating in confirmed mode. Also, the nodes are distributed randomly within a radius of 200m based on a gateway. Each node transmits about 1000 frames in one experiment. This is to reduce the effect of the initial transmission parameter settings on the overall performance and focus on the performance analysis of the ADR mechanisms.

Table 6.1.1 Transmission parameters

Transmission Parameters	Values
BW	125kHz
CR	$\frac{4}{5}$
CF	922MHz
SF	7,8,9,10,11,12
TP	2dBm ~ 14dBm
Payload	20Bytes
Path loss model value	$\overline{L_{pl}}(d_0) = 127.41 \text{ dB}, \gamma = 2.08,$ $\sigma = 1, 1.5, 2, 2.5, 3$

In each experiment, the transmission parameters are used as shown in Table 6.1.1. The results of the experiments mean the average value of the results obtained by repeating the same experiment 10 times.

6.2 Simulation Results

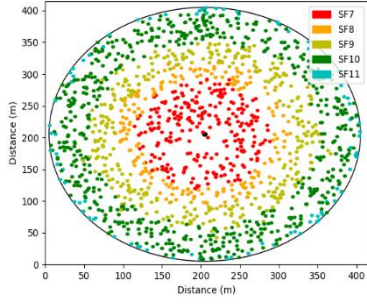
We evaluate the scalability of the ADR mechanisms through analysis of delivery ratio, energy consumption, and energy efficiency. The experiment was conducted by changing the number of nodes or arrival rate. First, the performance of three experiments was measured by increasing the number of nodes from 100 to 1500 in 200 intervals. Each node transmits a frame every 25 minutes. Figure 6.2.1 shows the distribution of SF after each node transmits about 1000 frames. In Figure 6.2.1 (a), it can be seen that many nodes use relatively high SF. Because relatively high SF is selected due to the margin of SNR used in the ADR mechanism of TTN. However, the three mechanisms based on EoE increase the ratio of SF7 that consumes low energy by using the small air time for energy efficiency. Figure 6.2.2, Figure 6.2.3, and Figure 6.2.4 are performances for delivery ratio, energy consumption of all nodes, and energy efficiency. In Figure 6.2.2, ADR showed better delivery ratio overall than the EoE based mechanisms due to the margin of SNR. On the contrary, EoE based mechanisms use the approach to reduce energy consumption while slightly reducing delivery ratio performance to improve energy efficiency. In

addition, it can be seen that the delivery ratio of NbADR (SNR) and Server (EoE), which can use the SNR information close to the actual SNR, is higher in all cases than NbADR, which estimates SNR through downlink pattern. From the delivery ratio perspective, it seems that ADR, which shows consistently high performance even when the number of nodes increase, is a better mechanism. However, NbADR and the ADR mechanisms using EoE are better in energy efficiency. In addition, we use a new performance evaluation index, because it is difficult to evaluate energy efficiency simply using total energy consumption. Therefore, we define Energy Consumption Efficiency (ECE) as a performance evaluation for energy efficiency. ECE is expressed as:

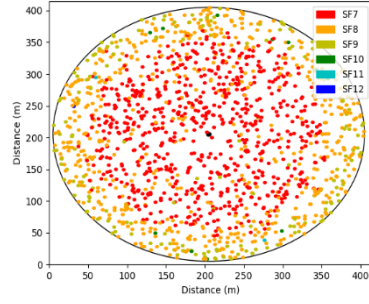
$$ECE = \frac{\text{Number of successfully transmitted frames}}{\text{Total energy consumption}}.$$

In Figure 6.2.3, all mechanisms generally increase energy consumption in proportion to the number of nodes. In particular, the energy consumption of ADR is significantly higher than other mechanisms. In addition, when ECE of NbADR, NbADR (SNR), and Server (EoE) is seen as Figure 6.2.4, it seems that these mechanisms can transmit three times more frames at the same energy compared to the existing ADR mechanism. These results show weakness of the existing ADR mechanism in terms of energy efficiency and the nodes operated by batteries are greatly affected. So far, we have evaluated the performance in

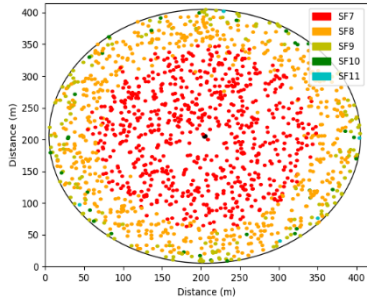
congested situations due to an increase in the number of nodes. Additionally, we analyze the performance for arrival rate changes in 1800 randomly distributed nodes. Arrival rate was increased from 0.5 to 2.5 in 0.5 intervals, and nodes were configured to transmit frames by fitting corresponding arrival rate. Through this experiments, it shows the extended results of the previous results. Figure 6.2.5 shows delivery ratio for arrival rate. In this figure, it can be seen that the delivery ratio reduction of NbADR (SNR) and Server (EoE) decreases rapidly compared to other ADR mechanisms. As shown in Figure 6.2.6 and Figure 6.2.7, NbADR (SNR) and Server (EoE) reduce a certain level of delivery ratio to improve energy efficiency. In addition, NbADR decreases delivery ratio as arrival rate increases, but does not shows a significant decrease, and improves the performance in terms of energy efficiency. Because NbADR is sensitive to failure in the process of predicting SNR, predicts SNR lower than actual SNR, and prepares for performance degradation due to the congestion. Through this results, it can be seen that NbADR is the ADR mechanism for energy efficiency on the node side. Also, energy efficiency can be significantly improved when using EoE compared to existing ADR mechanisms.



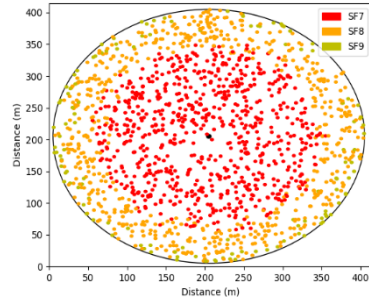
(a) ADR



(b) NbADR



(c) NbADR (SNR)



(d) Server (EoE)

Figure 6.2.1 SF allocation when using (a) ADR, (b) NbADR, (c) NbADR (SNR), and (d) Server (EoE) for 1,500 nodes

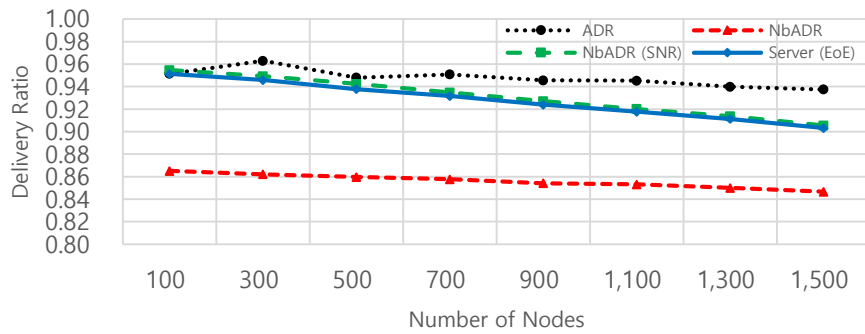


Figure 6.2.2 Delivery ratio for number of nodes

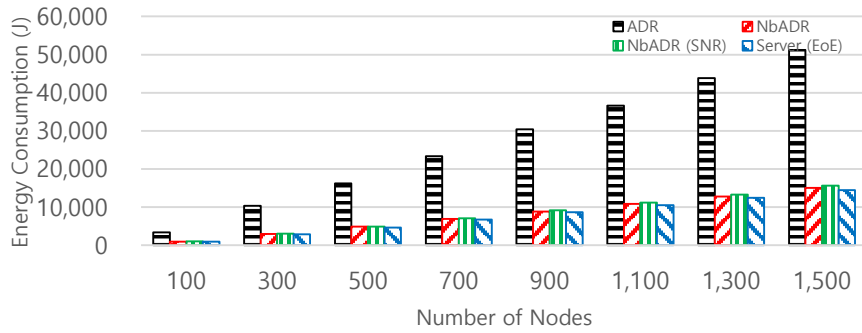


Figure 6.2.3 Total energy consumption for number of nodes

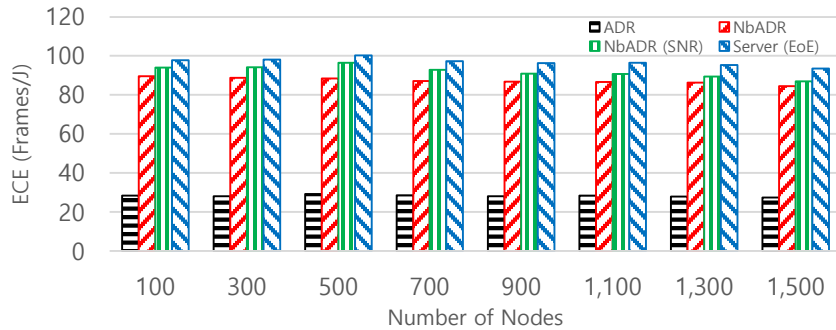


Figure 6.2.4 Energy efficiency for number of nodes

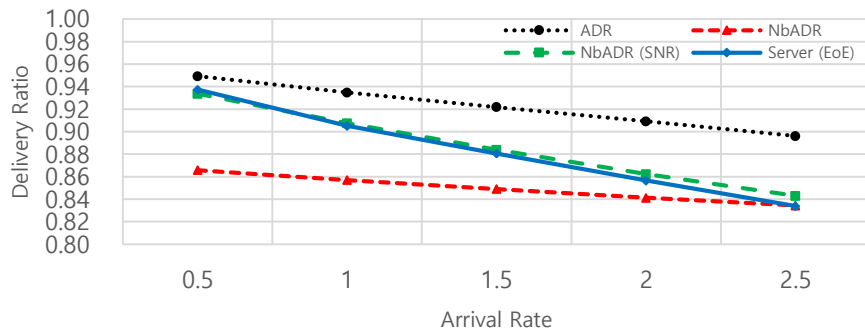


Figure 6.2.5 Delivery ratio of 1,800 nodes for arrival rate

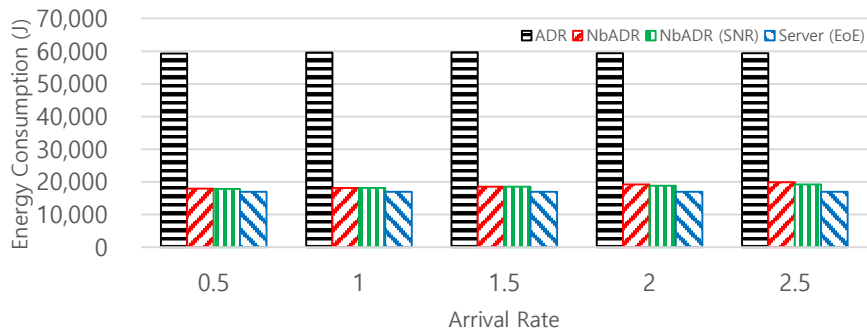


Figure 6.2.6 Total energy consumption of 1,800 nodes for arrival rate

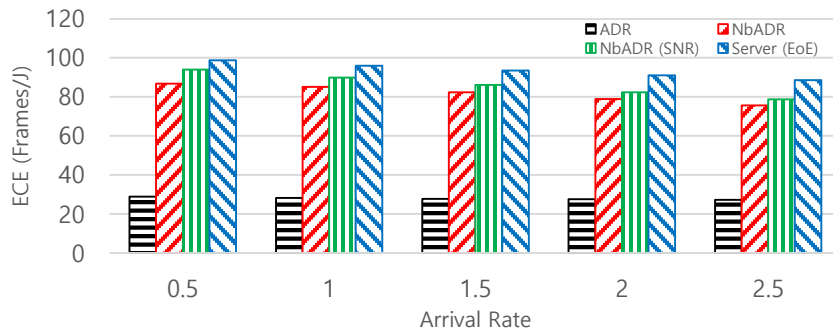


Figure 6.2.7 Energy efficiency of 1,800 nodes for arrival rate

The dynamic change of noise in the network directly affects the performance. LoRa network is affected by noise. We measured the performance of the ADR mechanisms for noise. In the experiments, 500 nodes were randomly distributed. The standard deviation of path loss that we used when modeling with respect to network noise was increased from 1 to 3 in 0.5 intervals. Figure 6.2.8 and Figure 6.2.9 are the results according to noise. In the existing ADR mechanism, delivery ratio decreases drastically and energy efficiency increases as the change of the noise increases. This result shows characteristics of TTN based ADR mechanism. As the noise change of the network increases, the probability of selecting a higher SNR increases. As a result, delivery ratio drastically decreases by selecting lower SF or TP. On the contrary, the energy efficiency of ADR is improved by using the transmission parameters that consume less energy. The EoE based mechanisms have no significant changes in delivery ratio and energy efficiency even with large noise change. The reason is that these mechanisms prepare the change of the noise by predicting SNR lower than the actual SNR. Through these results, we can confirm that EoE based mechanisms are robust to noise changes.

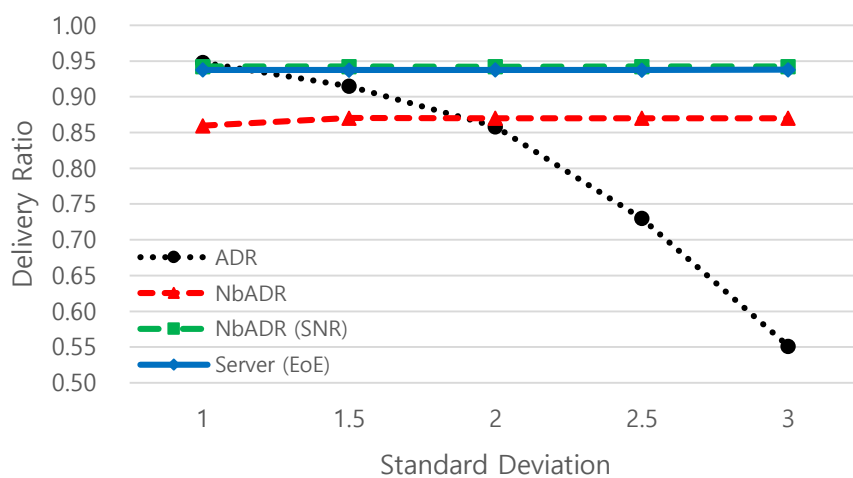


Figure 6.2.8 Delivery ratio of 500 nodes for standard deviation of path loss

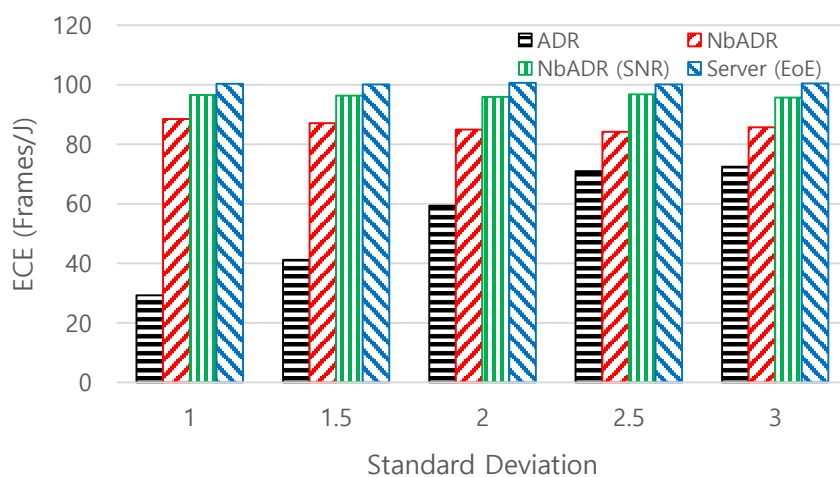


Figure 6.2.9 Energy efficiency of 500 nodes for standard deviation of path

Additionally, we analyze fairness of nodes in LoRa network. This experiment was conducted on 1800 randomly distributed nodes. Also, we use the Jain's fairness index to confirm fairness of nodes. Jain's fairness is expressed as:

$$f = \frac{(\sum_{i=1}^N DR_i)^2}{N \cdot \sum_{i=1}^N DR_i^2}.$$

f means fairness of N nodes in the network and DR_i is delivery ratio of i -th node. In Figure 6.2.10, NbADR and EoE based mechanisms have fairness close to 1, whereas the existing ADR mechanism has about 0.97 fairness in all arrival rate. This is because, some nodes among total nodes using the existing ADR mechanism show a relatively low delivery ratio. When using the existing ADR mechanism, many nodes are distributed for high SF as shown in Figure 6.2.1 (a). In the case of nodes using high SF, the air time of the frames becomes longer, so the probability of collision between the frames increases. Therefore, delivery ratio of nodes using low TP among nodes using high SF is reduced. We can confirm that NbADR and EoE based mechanisms perform well in terms of fairness.

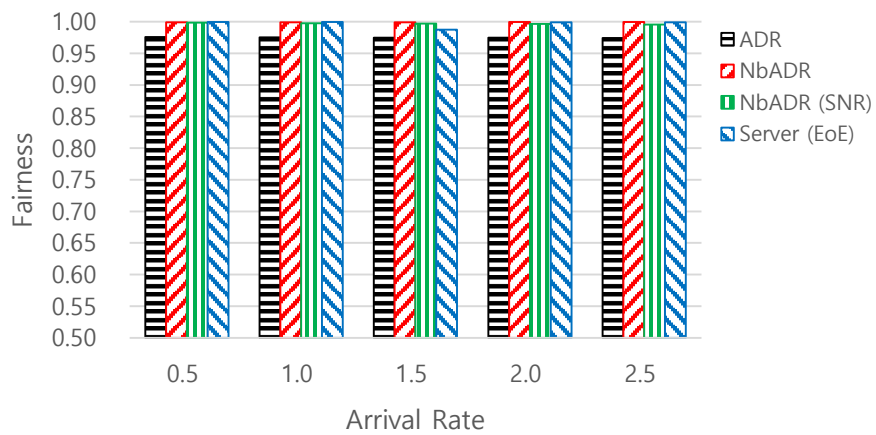


Figure 6.2.10 Fairness for delivery ratio of 1,800 nodes in the network for arrival rate

Chapter 7

Conclusion

In this paper, we propose a node-based ADR mechanism for Class A nodes operating in confirmed mode to improve energy efficiency. NbADR allocates the transmission parameters using EoE by predicting the SNR information. This ADR mechanism performs better than the existing ADR mechanisms even when there are many nodes in LoRa network or when the channel condition changes dynamically. NbADR improves performance of energy efficiency. In addition, performance improvement in fairness can be expected. We defined EoE metric that is used in NbADR and can be used in other ADR mechanisms, and confirmed that EoE shows a great effect on energy efficiency through the performance analysis of the ADR mechanisms using EoE. Also, we modeled the channel for performance evaluation and constructed the simulation environments. Through this simulation environments, we conduct extensive experiments with the existing ADR mechanisms, proposed mechanism, and EoE based mechanisms. We confirmed that NbADR can not only improve energy efficiency, but also keep throughput in situations where the channel state changes dynamically. As a result, NbADR allocates the transmission

parameters on the node side, reduces the overhead of the server, and improves performance simply by adjusting the transmission parameters without changing the existing protocol or additional devices. Through this features, it can also improve the scalability of LoRa networks and extends applications using LoRa technology.

Bibliography

- [1] Semtech, “LoRa,” <https://www.semtech.com/lora/what-is-lora> (accessed Jun. 26, 2020).
- [2] Weightless, “Weightless,” <http://www.weightless.org> (accessed Jun. 26, 2020).
- [3] Sigfox, “Sigfox,” <https://www.sigfox.com/en> (accessed Jun. 26, 2020).
- [4] LoRa Alliance, “Lorawan™ 1.1 specification,” LoRa Alliance, 2017.
- [5] The Things Network, “The Thing Network Wiki: Adaptive Data Rate,” <https://www.thethingsnetwork.org/docs/lorawan/adaptive-data-rate.html>, (accessed Jun. 26, 2020).
- [6] F. Cuomo, M. Campo, A. Caponi, G. Bianchi, G. Rossini, and P. Pisani, “Explora: Extending the performance of lora by suitable spreading factor allocations,” in 2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp. 1–8, IEEE, 2017.
- [7] M. Slabicki, G. Premsankar, and M. Di Francesco, “Adaptive configuration of lora networks for dense iot deployments,” in NOMS 2018-2018 IEEE/IFIP Network Operations and Management Symposium, pp. 1–9, IEEE, 2018.

- [8] F. Cuomo, J. C. C. G´amez, A. Maurizio, L. Scipione, M. Campo, A. Caponi, G. Bianchi, G. Rossini, and P. Pisani, “Towards traffic-oriented spreading factor allocations in lorawan systems,” in 2018 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), pp. 1–8, IEEE, 2018.
- [9] J.-T. Lim and Y. Han, “Spreading factor allocation for massive connectivity in lora systems,” *IEEE Communications Letters*, vol. 22, no. 4, pp. 800–803, 2018.
- [10] L. Amichi, M. Kaneko, N. El Rachkidy, and A. Guitton, “Spreading factor allocation strategy for lora networks under imperfect orthogonality,” in *ICC 2019-2019 IEEE International Conference on Communications (ICC)*, pp. 1–7, IEEE, 2019.
- [11] N. BENKAHLA, H. TOUNSI, S. Ye-Qiong, and M. FRIKHA, “Enhanced adr for lorawan networks with mobility,” in *2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC)*, pp. 1–6, IEEE, 2019.
- [12] B. Su, Z. Qin, and Q. Ni, “Energy efficient resource allocation for uplink lora networks,” in *2018 IEEE Global Communications Conference (GLOBECOM)*, pp. 1–7, IEEE, 2018.
- [13] K. Q. Abdelfadeel, V. Cionca, and D. Pesch, “Fair adaptive data rate allocation and power control in lorawan,” in *2018 IEEE 19th International Symposium on” A World of Wireless, Mobile and Multimedia Networks” (WoWMoM)*, pp. 14–15, IEEE, 2018.

- [14] W. Gao, W. Du, Z. Zhao, G. Min, and M. Singhal, "Towards energy-fairness in lora networks," in 2019 IEEE 39th International Conference on Distributed Computing Systems (ICDCS), pp. 788–798, IEEE, 2019.
- [15] M. Bor, J. Vidler, and U. Roedig, "Lora for the internet of things," in Proceedings of the 2016 International Conference on Embedded Wireless Systems and Networks (EWSN), pp. 361-366, 2016.
- [16] M. Bor, U. Roedig, T. Voigt, and J. M. Alonso, "Do lora low-power wide-area networks scale?," in Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, pp. 59–67, 2016.
- [17] M. Bor and U. Roedig, "Lora transmission parameter selection," in 2017 13th International Conference on Distributed Computing in Sensor Systems (DCOSS), pp. 27–34, IEEE, 2017.
- [18] D. Bankov, E. Khorov, and A. Lyakhov, "On the limits of lorawan channel access," in 2016 International Conference on Engineering and Telecommunication (EnT), pp. 10–14, IEEE, 2016.
- [19] D. Bankov, E. Khorov, and A. Lyakhov, "Mathematical model of lorawan channel access with capture effect," in 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1–5, IEEE, 2017.

- [20] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the limits of lorawan," *IEEE Communications magazine*, vol. 55, no. 9, pp. 34–40, 2017.
- [21] T. Voigt, M. Bor, U. Roedig, and J. Alonso, "Mitigating inter-network interference in lora networks," in *Proceedings of the 2017 International Conference on Embedded Wireless Systems and Networks (EWSN)*, pp. 323–328, 2017.
- [22] F. Van den Abeele, J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Scalability analysis of large-scale lorawan networks in ns-3," *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 2186–2198, 2017.
- [23] O. Georgiou and U. Raza, "Low power wide area network analysis: Can lora scale?," *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, 2017.
- [24] A. Mahmood, E. Sisinni, L. Guntupalli, R. Rondón, S. A. Hassan, and M. Gidlund, "Scalability analysis of a lora network under imperfect orthogonality," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 3, pp. 1425–1436, 2018.
- [25] B. Ousat and M. Ghaderi, "Lora network planning: Gateway placement and device configuration," in *2019 IEEE International Congress on Internet of Things (ICIOT)*, pp. 25–32, IEEE, 2019.

[26] B. Reynders, W. Meert, and S. Pollin, “Power and spreading factor control in low power wide area networks,” in 2017 IEEE International Conference on Communications (ICC), pp. 1–6, IEEE, 2017.

[27] U. Coutaud and B. Tourancheau, “Channel coding for better qos in lora net-works,” in 2018 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp. 1–9, IEEE, 2018.

[28] Semtech, “Semtech,” <https://www.semtech.com> (accessed Jun. 26, 2020)

[29] T. S. Rappaport et al., Wireless communications: principles and practice, vol. 2. prentice hall PTR New Jersey, 1996.

[30] B. Reynders, W. Meert, and S. Pollin, “Range and coexistence analysis of long range unlicensed communication,” in 2016 23rd International Conference on Telecommunications (ICT), pp. 1–6, IEEE, 2016.

[31] A. Kamerman and L. Monteban, “Wavelan®-ii: a high-performance wireless lan for the unlicensed band,” Bell Labs technical journal, vol. 2, no. 3, pp. 118–133, 1997.

국 문 초 록

최근 IoT 시스템이 증가하고 무선 센서 네트워크가 넓어지면서 이와 관련된 연구가 증가하고 있다. 그 중에서도 장거리 통신 기술에 대한 관심이 증가하고 있다. 이와 관련하여 LoRa, Weightless, Sigfox 와 같은 LPWA 네트워크 기술들이 등장하고 있다. 또한, ISM 밴드에서 사용 가능한 LoRa 와 LoRaWAN 관련 다양한 연구가 진행되고 있다. LoRa 네트워크에서 노드들은 스타 토폴로지를 구성하기 위하여 게이트웨이와 1 홉으로 연결되어 있다. LoRa 노드들은 프레임을 전송하기 위하여 SF, TP, BW, CR, CF 와 같은 전송 파라미터를 사용한다. 이 과정에서 채널 상태와 전송 타이밍으로 인한 프레임 손실과 프레임 간 충돌이 발생할 수 있다. 이러한 문제를 완화하기 위하여 LoRaWAN 에서는 노드 측에서 네트워크 상황을 고려하여 적절한 전송 파라미터를 선택하기 위한 ADR 메커니즘을 사용한다. 게다가 서버 측에서 전송 파라미터를 할당하는 ADR 메커니즘이 존재한다. ADR 메커니즘들은 서버와 노드의 연결을 유지하고 적절한 전송 파라미터를 설정한다. 하지만 기존의 ADR 메커니즘들은 일부 한계점을 가지고 있다. 첫 번째, 서버 측 ADR 메커니즘은 전송하는 프레임에 비례하여 서버의 부하를 증가시킨다. 두 번째, 동적인 채널에서 빠르고 효율적으로 대처하기 어렵다. 세 번째, 이러한 ADR 메커니즘들에서 선택된 전송 파라미터들이 에너지 효율성을 위한 최적의 전송 파라미터가 아닐 수 있다. 이러한 문제점들은 배터리로 동작하는 노드들의 큰 에너지 소모를 야기하고 LoRa 네트워크의 채널이 동적으로 변경되는 환경에서 성능을 감소시킨다. 본 논문에서 우리는 서버의

부하를 최소화하며 에너지 효율성을 최대화하는 노드 기반의 ADR 메커니즘인 NbADR 을 제안한다. 제안하는 메커니즘은 노드 측에서 전송 받은 다운링크 패킷을 기반으로 채널 상황에 빠르게 대응하고, Efficiency of Energy (EoE) 메트릭을 활용하여 효율적인 에너지 소모를 위한 전송 파라미터를 선택한다. 우리는 EoE 기반으로 선택한 전송 파라미터의 효율성을 분석하고, 광범위한 실험을 진행한다. 결론적으로, NbADR 은 기존의 ADR 메커니즘들과 비교하여 에너지 효율성 측면에서 효과적이다. 추가적으로, NbADR 은 급격하게 변화하는 채널 환경에서 LoRa 네트워크의 처리량을 보장하고 노드 간 공평성을 향상시킨다.

주요어 : 사물 인터넷, 무선 센서 네트워크, 저전력 장거리 네트워크, LoRa, LoRaWAN, ADR 메커니즘, 자원 할당

학 번 : 2018-26264