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Adjacent Interference of LoRa for Large-scale Livestock Monitoring

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Abstract

Recently, ad hoc networks have been widely used because of the progress of the Internet of Things (IoT). A long-range wide-area network (LoRaWAN) is one of a number of low-cost wide-area networking technologies and has been drawing attention because of its outstanding performance in long-range low-power communication. LoRa is an implementation of LoRaWAN that is now used in many applications, including grazing management for livestock monitoring. LoRa uses carrier-sense multiple access with collision avoidance (CSMA/CA) to improve resilience against interference. However, in our personal experience implementing livestock-monitoring networks using LoRa, we have encountered performance degradation issues due to collisions among channels. In this paper, we first explain the problems that we encountered. Then, we explain the experiments undertaken herein to investigate these problems. Finally, we propose a solution and evaluate its effectiveness based on a simulation, which simulated real-world conditions. In the preliminary experiment, we used two transmitters to measure interference at different channel distances, bandwidths (BWs), and spreading factors (SFs) and found that a closer channel, smaller BW, and/or larger SF led to a higher carrier sense rate and greater interference distance. Thus, we proposed a cellular communication network for channel allocation to reduce adjacent-channel interference and a duration division mode to solve the insufficient channel issue. The calculations demonstrated that the proposed solution can monitor approximately 3,000 cows in a pasture with an area of 4×4 km^2.

Keywords: LoRa, carrier sense, adjacent-channel interference, channel allocation, cellular communication, livestock monitoring

1 Introduction

Recently, ad hoc networks have been widely used due to the progress of the Internet of Things (IoT). A long-range wide-area network (LoRaWAN) is one of a number of low-cost wide-area networking technologies, and it is drawing attention because of its outstanding performance in long-range low-power communication [1]. LoRaWAN is widely used in a variety of areas, especially in agriculture, due to its low cost, low power consumption, long-distance communication ability, good device connection capability, and strong noise-resistance based on the chirp spread spectrum technology [2]. In particular, it has been used in the design of livestock monitoring systems for grazing management [3] and environment monitoring systems for farm management [4].

A sub-GHz wireless communication technology, LoRa uses carrier-sense multiple access with collision avoidance (CSMA/CA), which is a network multiple access method that uses carrier sense. According to CSMA/CA, nodes attempt to avoid collisions by beginning transmission only after a channel is sensed to be idle, thus improving resilience against interference [5]. Fig. 1 shows the method by which communication is performed between two radio stations with carrier sense. LoRa first receives sending instructions and then begins to execute carrier sense (clear channel assessment [CCA]) approximately 5 ms after a backoff (a random wait time of several ms). If the CS level is under a threshold value, LoRa begins to send the data packet. If the CS level is above the threshold, LoRa begins to execute carrier sense again.

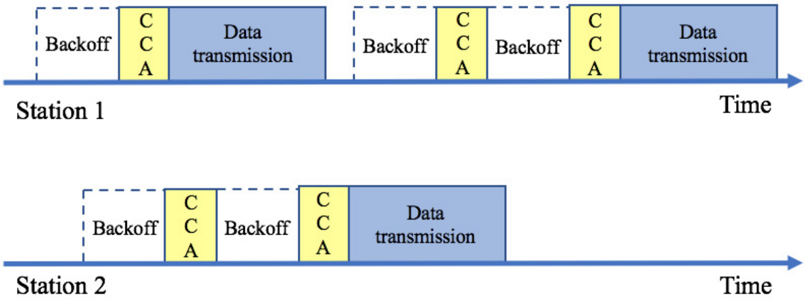

Figure 1: Carrier sense between two stations

In our implementation of a livestock-monitoring system, we intended to collect cow movement data in real time to determine cow location in case a cow lost its way, and we calculated the amount of grass eaten during grazing to determine the amount of additional food necessary after grazing. We used LoRa to transmit the data payload because it has excellent radio-wave wraparound characteristics and a communication distance of up to 4.2 km, which is necessary when it comes to Japanese farms that are located between forests and mountains. In addition, the merits of low power consumption and high connection capabilities make it possible to use LoRa for large-scale grazing.

However, we encountered two problems while using LoRa: First, we experienced reduced performance due to adjacent-channel interference, which had a serious negative impact on communication efficiency; second, when hundreds of transmitters were being employed, we had an insufficient number of available channels. It is crucial to ensure that data transmission is free from inter-network interference, especially in some fields including an intensive implementation of endpoints. As an emerging technology, there is relatively little research on LoRa, and the relationships between the interference and adjacent channels, bandwidth (BW), and spreading factor (SF) is not clear.

Therefore, this study aims to measure the degree of interference under different conditions and determine solutions to reduce interference and increase the number of available channels for large-scale monitoring in a pasture. We used carrier sense rate (CSR) as an interference indicator of LoRa and explain the relationship between interference degree and various other parameters based on variation in CSR. Based on the results, we then propose a three-channel allocation scheme and a duration division mode for practical application, and the performance of the proposed method is measured under real grazing conditions.

The remainder of this paper is structured as follows. Section 2 introduces a variety of related research. In Section 3, we explain the preliminary experiment details, data processing method, and analysis results on the relationship between CSR and various conditions. In Section 4, we outline the simulation experiment conducted under real grazing conditions and present the obtained results. In Section 5, we propose a solution to reduce adjacent interference for large-scale livestock monitoring and perform a calculation to determine the number of livestock it is possible to monitor. Finally, we present our conclusions in Section 6.

2 Related works

2.1 Related works on adjacent interference in LoRa

There have been a number of studies regarding interference in LoRa. Adjacent-channel interference issues between long-term evolution and LoRa systems in the 2.4 GHz band were discussed in [6], though no adjacent-channel interference within LoRa systems was mentioned. In [7], an interference measurement setup for LoRa, Sigfox, Z-Wave, and io-homecontrol revealed a payload loss in sub-1-GHz technologies, though it did not determine the relationship between payload loss caused by interference and other communication parameters.

An algorithm based on an interference-aware SF assignment to counteract interference caused by the same or different SFs was proposed in [8]. In [9], an analysis of bit-error rate and the coverage performance of LoRa modulation under the same SF interference with signal-to-noise ratio and signal-to-interference-plus noise ratio was presented. However, these studies focusing on SF did not comprehensively analyze the relationship between interference and other parameters, such as BW and channel distances.

2.2 Related works on livestock monitoring using LoRa

Several studies have discussed livestock monitoring systems based on LoRaWAN. For example, [10] proposed a system based on a LoRa wide-area network that included nodes, gateways, and servers to achieve long communication distances and low power consumption. However, no simulations were conducted to evaluate its performance. A livestock monitoring system using a mobile LoRa gateway with one and multiple static gateways to resolve the crowded spectrum issue in a narrow livestock area was presented in [11]. However, there was no self-interference in this small-scale deployment of a LoRa inter-network. In [12], interference modeling based on packet loss for large-scale implementation was discussed to investigate scalability in terms of the number of end devices under specific conditions. However, no specific communication parameters affecting the degree of interference were discussed.

3 Preliminary experiment

To measure the degree of interference under different conditions and determine how it changes with varying parameters to provide experimental support for solutions under real circumstances, we used two LoRa transmitters to simulate the communication between stations.

3.1 Experiment design

A. Conditions

We set two conditions for the experiment, which are as follows:

Condition 1—No interference from other sub-GHz communication signals.

Condition 2—The same beginning time and duration of communication for both the transmitters.

To meet the aforementioned conditions, we conducted our experiment in the following manner. First, we chose a playground (shown in Fig. 2) as the experimental site because the surrounding trees could effectively isolate external sub-GHz interference. Second, as shown in Fig. 3, Raspberry Pi Zero was used in the two transmitters to ensure the LoRa started and stopped simultaneously.

B. Experiment details

As shown in Fig. 3, both the transmitters consisted of a LoRa module, a Raspberry Pi and a battery. Antenna height was about 1 m and antenna gain was 0 dBi. We set transmission power as 13 dBm which is in common use.

The LoRa chirp signal spectrum varies in BW and SF. At first, we tested various combinations of BWs and SFs. The results revealed that there was slight interference when SF was 7, 8, or 9 and severe interference when using a BW of 3 with an SF of 11 or 12. This pattern did not reveal the variation trend of the interference. Therefore, to obtain a consistent interference trend based on

Figure 2: Experimental site

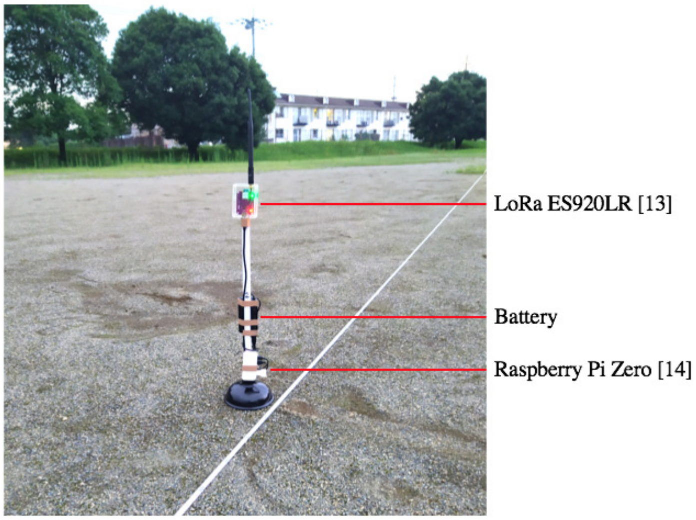

Figure 3: Composition of the two transmitters

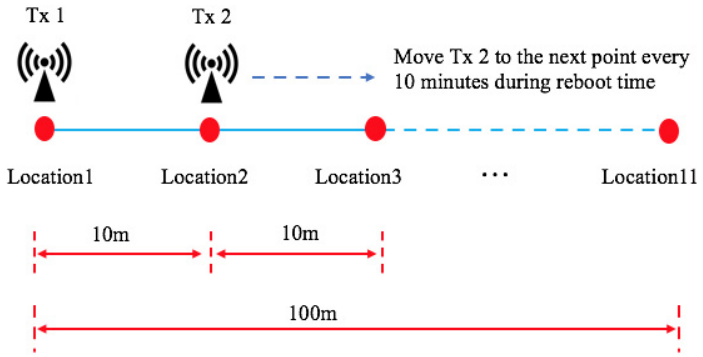

Figure 4: Experiment at different distances

Table 1: Parameters tested in experiment (time on air for 8-byte payload; ms)

BW(kHz)	SF					
	7	8	9	10	11	12
62.5(3)	133.6	246.8	411.6	823.3	1482.8	2637.9
125(4)	66.8	123.4	205.8	**411.6**	**741.4**	**1318.9**
250(5)	33.4	61.7	102.9	**205.8**	**370.7**	**659.5**
500(6)	16.7	30.8	51.5	**102.9**	**185.3**	**329.7**

BW and SF, we conducted experiments with SF varying from 10 to 12 and BW varying from 125 to 500 kHz, as shown in Table 1 (nine set parameters, marked in bold).

To measure the interference degree of adjacent channels with different intervals, we tested five sets of channels ((CH1,CH1), (CH1,CH2), (CH1,CH3), (CH1,CH4), and (CH1,CH5)) with two transmitters in each set of selected BW/SF combinations.

We also altered the distance between the two transmitters (in 10 m intervals within a distance of 100 meters) to determine the maximum interference distance of the adjacent channel. The two transmitters were set to start and stop simultaneously. As shown in Fig. 4, we fixed transmitter 1 at location 1 and moved transmitter 2 to the next point during the reboot time after 10 minutes of transmission.

3.2 Data processing

The two transmitters continuously sent data packets consisting of random 8-byte numbers (which were convenient for comparing and analyzing logs due to the low probability of repetition) for over 10 minutes with each parameter setting, and they logged records regarding the success or failure of transmission. Let the numbers of attempted packets sent be N_{pck1} and N_{pck2}, and let the numbers of "NG 102" errors returned by the LoRa when the carrier sense was detected be Err_1 and Err_2; we can then calculate the CSR as follows:

$$CSR = \frac{Err_1 + Err_2}{N_{pck1} + N_{pck2}}$$

3.3 Analysis results

A. Relations between CSR, BW, and SF

We calculated the CSR at a variety of BWs (125, 250, and 500 kHz) and SFs (10, 11, and 12). We found that a smaller BW or larger SF led to a higher CSR (Fig. 5), meaning the degree of interference was negatively related to the BW and positively related to the SF.

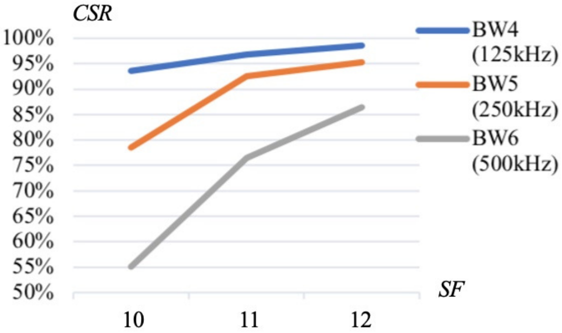

Figure 5: CSR at different BW/SF settings

B. Relation between CSR and channel distance

Considering that the same distances between different channels (such as between CH1-2 and CH3-4) can be inconsistent regarding the degree of interference, we first measured the CSR of the same distances in different channels. As shown in Table 2, four sets of channels (CH-s1, CH-s2, CH-s3, CH-s4) at each BW (CH1-2, CH5-6, CH10-11, and CH14-15 at BW4; CH1-2, CH2-3, CH4-5, and CH6-7 at BW5; and CH1-2, CH2-3, CH3-4, CH4-5 at BW6) were selected, and the relative standard deviation (RSD) under 1% demonstrated that there was a consistent degree of interference at each distance [15].

Table 2: CSR at the same distance with different channels

	CH-s1	CH-s2	CH-s3	CH-s4	*RSD*
BW4	95.73%	95.72%	95.72%	95.70%	0.01%
BW5	90.66%	90.52%	90.50%	90.62%	0.09%
BW6	67.10%	67.18%	66.95%	67.01%	0.15%

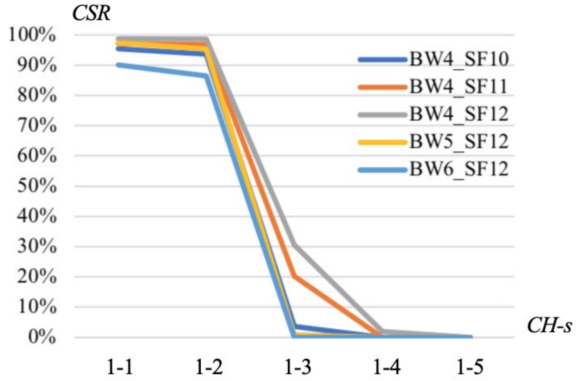

Figure 6: CSR at different channel distances

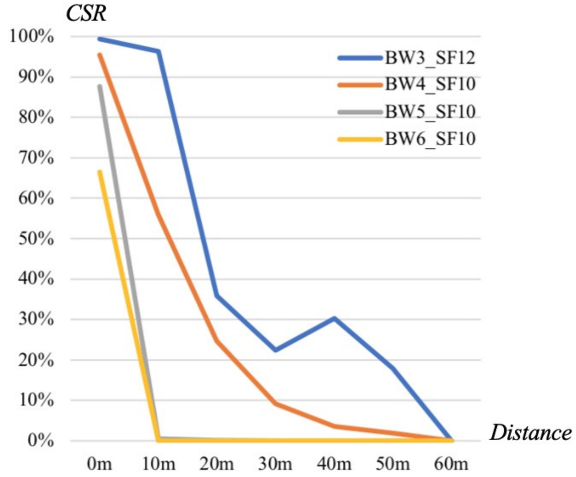

Figure 7: Interference distances of adjacent channels with different BW/SF settings

To reveal the impact of channel distance on interference, we selected five sets of channels (CH1-1, CH1-2, CH1-3, CH1-4, and CH1-5) for each BW/SF setting at a short distance. Fig. 6 shows some of the experimental results, which included the following findings:

- The interference degree decreased with an increasing channel distance and dropped significantly when varying from an adjacent channel to a separate channel.
- The CSR decreased slightly from CH1-1 to CH1-2 for each set of parameters, meaning the adjacent-channel interference was as significant as the co-channel collision at a short distance.
- When the distance varied from CH1-1 to CH1-4 in BW4, there was still a small CSR when the SF was set at 12 but not at 10 or 11. At the same SF (12), CSR dropped down to 0 on CH1-5 at BW4, on CH1-4 at BW5, and on CH1-3 at BW6 with an increasing distance. Therefore, we can infer that LoRa is more sensitive to interference with a smaller BW and/or larger SF.

C. Interference distance with different parameters

We also calculated the CSR of different distances (within 100 m) and found that a smaller BW or larger SF led to a greater interference distance (Fig. 7). The results also revealed that the CSR dropped dramatically to 0 when the distance was over 50 m, even with the smallest BW (3) and the largest SF (12). It should be noted that there was an exceptional value when the distance was 30 m with BW3/SF12, with no interference being detected after the wind blew down one of the transmitters (the CSR should have been somewhere between 35.88% and 30.33%).

4 Simulation experiment

In the preliminary experiment, the relationship between interference degree and BW and that between SF and channel distance were determined using two LoRa transmitters. However, in actual grazing environments there are thousands of transmitters, which is likely to make the communication conditions more complex. According to the results in Section 3, we can infer that there will be a maximum interference distance even when using the same channel, meaning it will be possible to repeatedly allocate the same channels to respective grazing areas. Therefore, we undertook an experiment to simulate the interference environment present in actual grazing conditions and determine the maximum interference distances at different channel distances.

In our previous experiment, we confirmed that the parameter combination of BW = 62.5 kHz and SF = 12 was optimal for long-distance communication in a pasture. We thus used this setting for each LoRa transmitter. To make full use of the transmission payload, we set a maximum size for each data packet (50 bytes), which took approximately 6 seconds to transmit. Accordingly, we increased the duration for each measurement to one hour to ensure the validity of the test results. We performed the following two experiments using the outlined parameters:

Experiment 1: Examine the maximum interference distances of different channel distances.

Experiment 2: Measure the interference degree under real grazing conditions.

4.1 Experiment 1: Examining the maximum interference distance of different channel distances

In this experiment, we determined the maximum interference distances when the channel distances were 0, 1, and 2. Similar to the preliminary experiment, we used two transmitters to send data packets simultaneously for 1 hour in every location. The results revealed that no co-channel interference was detected when the distance between the transmitters exceeded 120 m. We also found that the maximum interference distance was 50 m when using adjacent channels (channel distance = 1). When the channel distance was 2, all the data packets could be transmitted successfully at all distances over approximately 2 m (shown in Fig. 8). Therefore, it is expected that the number of LoRa transmitters can be significantly increased by allocating channels into divided sections.

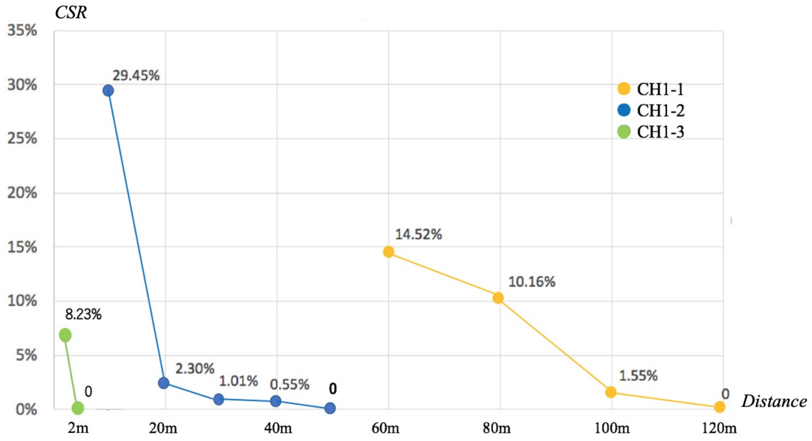

Figure 8: Maximum interference distances of different channel distances

4.2 Experiment 2: Measuring the interference degree under real grazing conditions

In experiment 1, we determined that the maximum co-channel interference distance was 120 m and that using separate channels was within 2 m. According to our direct observations, we found that the distance between grazing cows varies from tens to hundreds of meters. Taking the body shapes of cows and the attached positions of the transmitter into account, we can assume that in actual grazing conditions the minimum distance between the transmitters will be approximately 2 m (as shown in Fig. 9).

As shown in Fig. 10, we first measured the interference degree using separate channels in cases in which three or five grazing cows were gathered together. Since the transmitter in the middle (Tx. 1) suffered from a high possibility of communication interference, we calculated its CSR under two scenarios. The results revealed that all the data packets were successfully transmitted, meaning it is helpful to use separate channels (channel distance = 2) for cows grazing in a single area to avoid channel interference.

Further, an experiment using multiple co-channels was conducted to confirm the possibility of using channels repeatedly in different grazing areas (Fig. 11). According to the results, no interference was detected, demonstrating that the same channels can be used in different grazing areas separated by a distance over 120 m to increase LoRa nodes.

5 Solution for large-scale livestock monitoring

Adjacent-channel interference has a serious negative impact on communication efficiency. It causes large-scale communication congestion when applied to a network with a large number of endpoints and a dense deployment, such as livestock monitoring systems for grazing management. In such systems, adjacent-channel interference leads to undesirable communication interference when thousands of domestic animals meander randomly over a pasture.

We conducted our experiments with the intention of designing a livestock-monitoring system that uses LoRa to track cow movements, including exercise and eating, on a pasture with approximately 300 cows [16]. Under the assumption that one channel will be allocated individually to each cow, the number of available channels would not be sufficient, even if all the BW/SF settings were used. In addition, considering the random movement of cows, this would cause serious carrier sense, and transmitters would not be able to send data.

A pasture is usually divided into several sections based on topography. According to related research, it is often beneficial to divide livestock into different groups based on the nutritional requirements for desired performance levels to make the most out of the pasture and prevent injuries

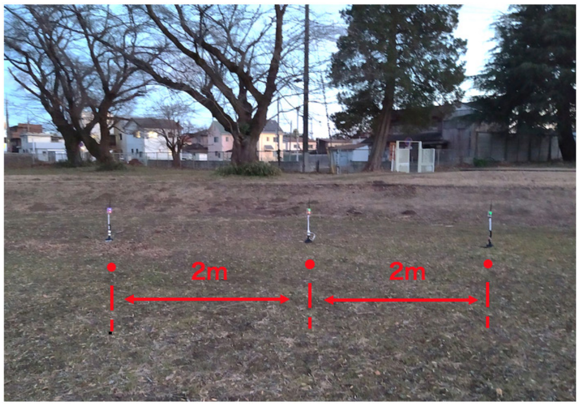

Figure 9: Simulation experiment with three transmitters

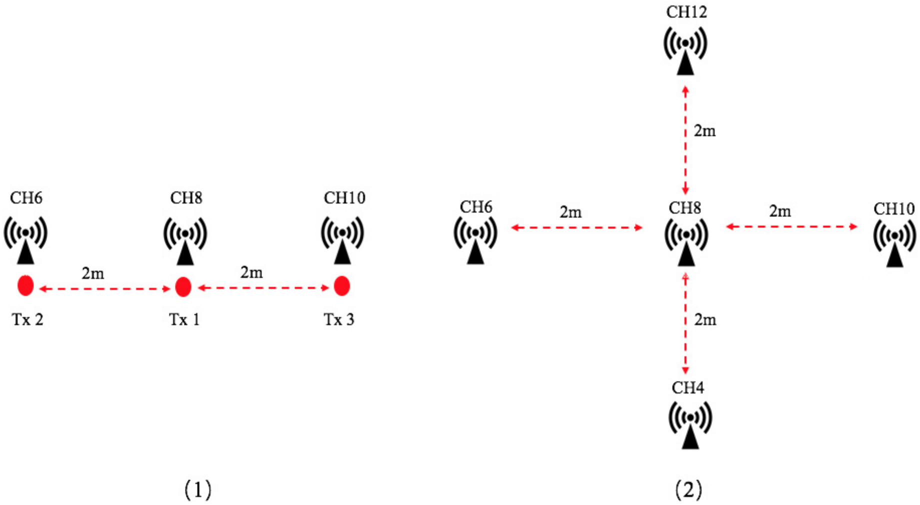

Figure 10: Simulation of situations in which grazing cows are gathered together

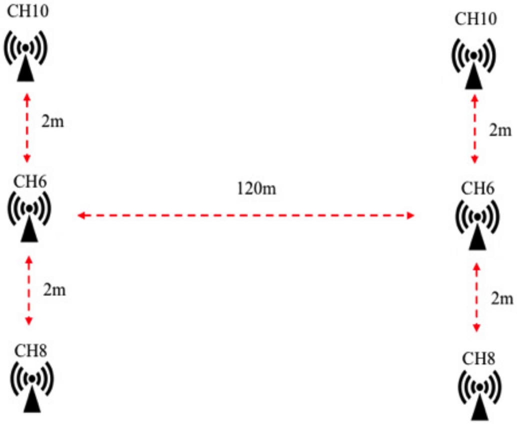

Figure 11: Simulation of multiple co-channel use

caused by fighting [17]. Therefore, it is feasible to group livestock into separate grazing areas and allocate different channels to avoid interference (ex. Figure 12 shows a kind of channel allocation). Further, considering that the eating and movement of livestock take place at a slow pace, it is possible to divide durations and send payloads every few minutes for each transmitter. Accordingly, we here present our solution for large-scale monitoring using LoRa as follows.

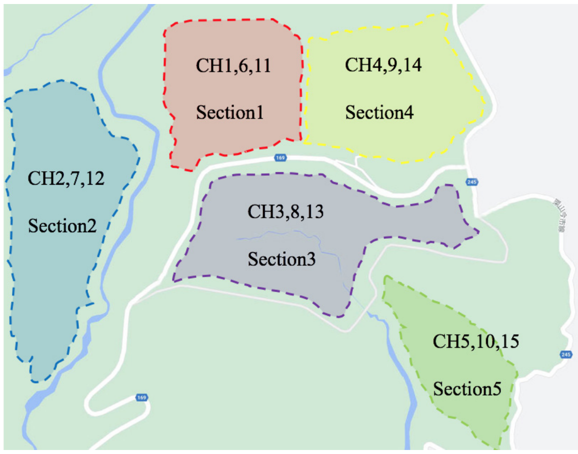

Figure 12: Channel allocation based on pasture topography

5.1 Cellular communication network for channel allocation

Since the maximum interference distance is 120 m when using co-channels, 50 m when using adjacent channels, and 2 m when using separate channels, it is expected that a cellular network with three-cell repetition can be constructed [18]. To achieve this, 15 channels were divided into three sets (set 1: (1, 4, 7, 10, 13), set 2: (2, 5, 8, 11, 14), set 3: (3, 6, 9, 12, 15)). As shown in Fig. 13, the pasture was divided into three-cell repetition sections with edge areas, and the grazing area was located in the middle of each section to avoid contact between the areas. We allocated the channel sets to according to sections (set 1 for Section 1, set 2 for Section 2, and set 3 for Section 3). If the edge width was 25 m and the side length was above 50 m, the distance between any two grazing areas using adjacent channels would be 50 m, and it would be over 120 m for those using the same channels. Therefore, the data transmission of each section should not be affected by co-channel or adjacent-channel interference.

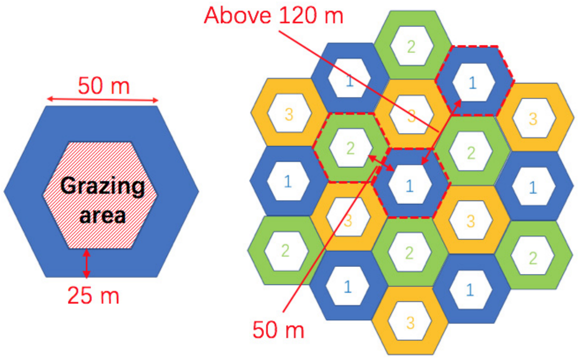

Figure 13: Three-channel allocation scheme

5.2 Duration division mode

BW 3 (62.5 kHz) of LoRa was allocated to 15 channels, and the maximum interference interval was 1 at a distance of 2 m when the SF was 12. In the case without grouping, any two transmitters had a chance of transmitting data at a close distance due to the random movements of the cows. Thus, when all 15 channels were used, only eight of them worked due to adjacent-channel interference.

It takes 6 sec to send a 50-byte data packet by LoRa, and if the guard time is 2 sec, the transmission time will be 8 sec for each payload. Taking the slow eating and movement of livestock into account and assuming the LoRa transmitters send a payload every X minutes, these X minutes were divided into 60X/8 time segments (Fig. 14), meaning the number of cows we were able to monitor could be increased by 37.5 times when we set the transmitters to send a payload every 5 min.

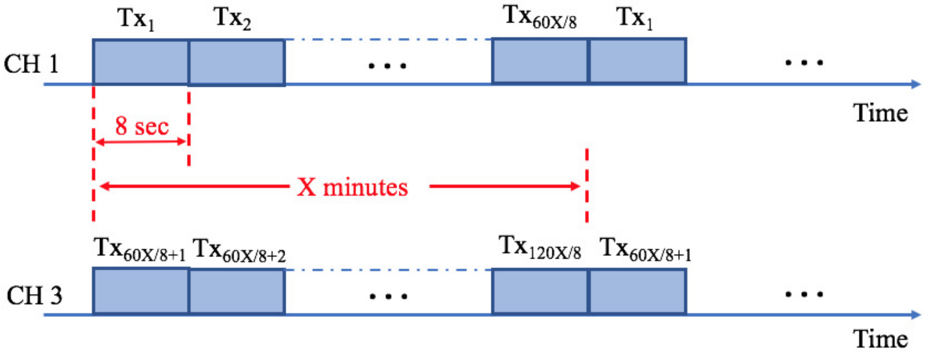

Figure 14: Duration division mode

5.3 Application to real grazing conditions

Based on the solution we have put forward, we talk about its application to real grazing conditions as follows.

As shown in Fig. 15, when we set transmitters to send payload every 5 min (300 s), it is divided into 60 segments when transmission time is 5 s according to our duration division mode. Every duration segment is allocated to one transmitter and each of those transmitters using the same channel operates to send payload during its segment. Thus, there is always only one transmitter sending data in each channel during each grazing area.

Therefore, there are only several transmitters sending data by using the same channel during a certain time on the whole pasture. Besides, it is also possible to expand the duration time and allocate different duration segments to transmitters of different sections to decrease the possibility of interference. For example, we can set transmitters to send payload every 10 min and divide it into two segments for adjacent sections using the same channel. As shown in Fig. 16, transmitters of section 1 are set to send payload during 00:01 $\sim$ 05:00 and transmitters of section 2 are set to send payload during 05:01 $\sim$ 10:00. Although the number of transmitters increases to several thousand, it is available to apply our solution to monitoring system with a low possibility of interference.

5.4 Calculation of the maximum cows we can monitor

To confirm the validity of our solution, we calculated the maximum number of cows that could be monitored on a pasture with an area of 4×4 km^2 using our three-channel allocation scheme and duration division mode. The hypothetical parameters of the calculation are shown in Table 3. We assumed that the transmitters send payload every X min, and the radius of grazing area is R m (Fig. 17).

In the case that grazing density (the radius of the section varies with the number of grazing cows inside it) is not taken into consideration, the relationship between the number of cows that can be

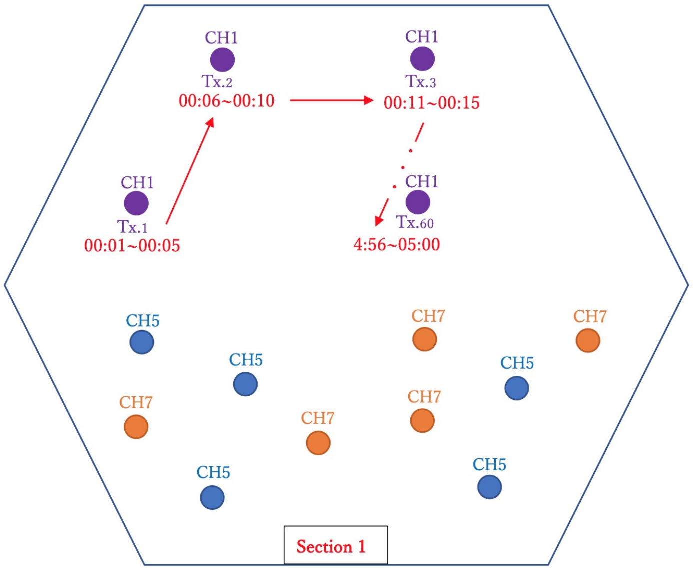

Figure 15: Duration division mode in a grazing area

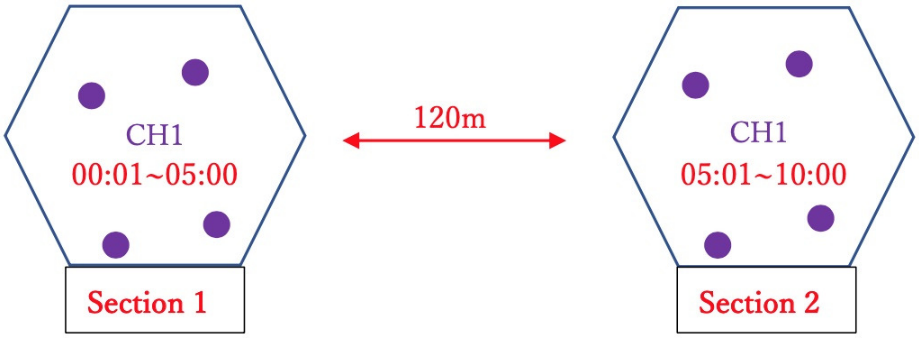

Figure 16: Duration division for adjacent sections using the same channel

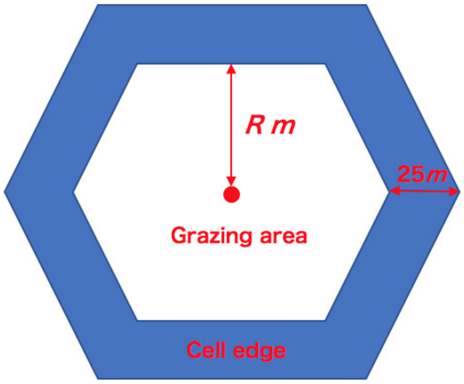

Figure 17: Cell section

Table 3: Hypothetical parameters for calculation

Bandwidth	62.5 kHz
Spreading factor	12
Number of available channels	15
Duration	X minutes
Radius of grazing area	R meters
Size of the pasture	4×4 km^2

monitored (N), the radius of the section (R), and duration (X) is expressed as follows:

$$N = \frac{\sqrt{3}X}{(R+25)^2} \cdot 10^8 \tag{1}$$

However, the number of cows that can graze in a certain area is limited, and a grazing area of approximate 0.5 ha (5,000 m^2) is generally required for each cow [19]. The relationship between the radius of the grazing area (R) and the number of cows can be determined by the following equation:

$$N = \frac{\sqrt{3}R^2}{2500} \tag{2}$$

We illustrated Eq. (2) by Fig. 18, and it shows that the number of cows that can graze increases sharply as the radius of grazing area expands.

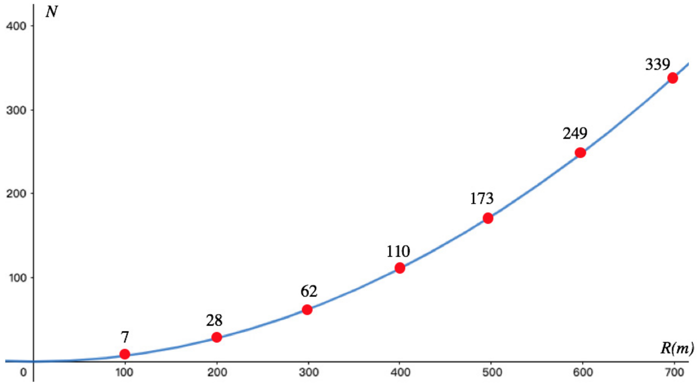

Figure 18: Relation between grazing area radius and number of cows

According to our duration division mode, the number of cows that can be monitored in each grazing area is $(60X/8) \times 5$. Thus, substituting this into Eq. (2), we can calculate the minimum radius of the grazing area using the following equation:

$$R_{min} = 125\sqrt{2\sqrt{3}X} \tag{3}$$

The relation between the minimum grazing area radius and the duration described by Eq. (3) is shown in Fig. 19. It indicates that a larger grazing area is necessary when we set transmitters to send payload with a longer duration.

Further, substituting Eq. (3) into Eq. (1), the relation between the maximum number of dairy cows that can be monitored and the duration (X) under hypothetical conditions can be determined as follows:

$$N_{max} = \frac{\sqrt{3}X}{(125\sqrt{2\sqrt{3}X}+25)^2} \cdot 10^8 \tag{4}$$

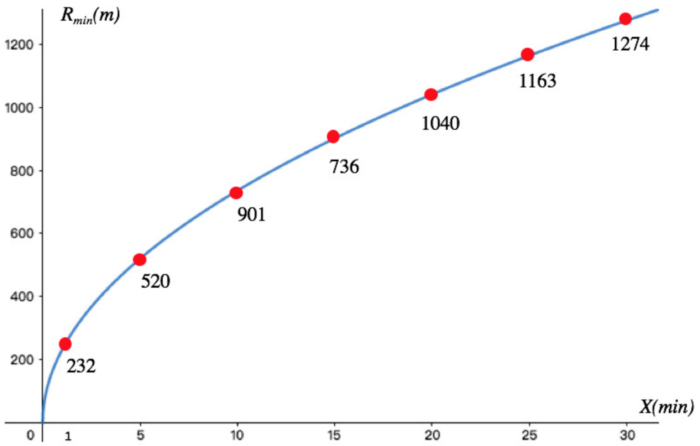

Figure 19: Relation between minimum grazing area radius and duration

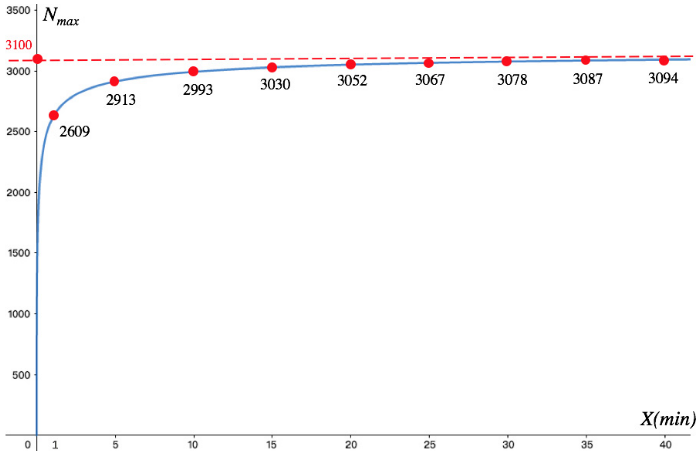

Figure 20: Relation between maximum number of cows and duration
(the maximum number of cows we can monitor is 3100)

The relation between the maximum number of cows and the duration described by Eq. (4) is shown in Fig. 20. It shows that when the duration increases from 0 to 5 minutes, the maximum number of cows we can monitor increases dramatically to about 3,000, and when the duration exceeds 5 minutes, it increases slowly and reaches a limit value gradually. This implies that if the transmitters send a payload every 5 min, we can monitor approximately 3,000 grazing cows in a pasture with an area of 4×4 km^2 when implementing our solution.

6 Conclusion

In this study, we performed experiments on LoRa adjacent-channel interference in different circumstances and analyzed the results. The results indicate that smaller BWs, larger SFs, and/or closer channel distances lead to more serious interference and a greater interference distance. The maximum interference distance was found to be 120 m when using co-channels, 50 m when using adjacent channels, and within 2 m when using separate channels outdoors with LoRa transmission. While this certainly explains the LoRa interference, it is also possible that it will help illuminate the interference of other sub-GHz technologies, such as Sigfox [20].

We then presented our solution for large-scale livestock monitoring. In particular, we introduced a three-cell repetition channel allocation scheme and a duration division mode to avoid interference from the internal network and increase the number of available channels. The calculation results demonstrated that our solution is effective for grazing management and can be used to monitor approximately 3,000 cows on a pasture with an area of 4 × 4 km^2. This solution could also provide assistance for solving interference problems of LoRa in other scenarios.

In our next study, we will apply the construction of a cellular network in cellular mobile communication systems to LoRaWAN for large-scale monitoring and measure its performance in a practical implementation.

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