D2D-LoRa Latency Analysis: An Indoor Application Perspective

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***Abstract*—LoRaWAN is one of the popular Internet of Things (IoT) wireless technologies due to its versatility, long transmission range, and low power communication capabilities. In LoRaWAN, the data from the source to the destination is routed through the gateways, increasing the communication latency. The higher latency being a barrier in real-time applications has prompted researchers to employ the physical (PHY) layer of the LoRaWAN protocol -commonly termed as LoRa, which utilizes the Device-to-Device (D2D) based communication techniques to minimize the communication latency. However, an extensive analysis of the D2D-LoRa is needed for optimizing and better designing the network, which is missing in the current literature. To address the void, this paper analyzes the latency performance of the D2D based LoRa by varying Spreading Factors (SF) and bandwidths and explores the trade-offs with experimental deployment in a 110 m long indoor environment. The evaluation shows that with SF 7 and bandwidth 500 kHz, the communication latency is minimum which is 33.67 ms at 0 m and 53 ms at 110 m for the data packet of 13 bytes for each of the cases.**

Keywords*—*LoRa, D2D-LoRa, Latency analysis, Round trip latency, Spreading Factor, Bandwidth.

I. Introduction

The recent development of wireless communication has prompted the Internet of Things (IoT) to grow multi-fold in the last few years. The applications of IoT have also been expanding in various fields, including industry, home applications, medical diagnosis, traffic monitoring, agriculture, smart grids, and smart energy systems [1] [2] [3]. The performance of these IoT systems greatly relies on various wireless technologies such as Zigbee, LoRa, NB-IoT, Sigfox, and Bluetooth Low Energy (BLE) which are employed to maintain the interconnection of the system components. LoRaWAN is one of the most popular IoT wireless technologies based on Wide Area Network (WAN) and supported by LoRa Alliance. LoRa is the physical layer protocol of the LoRaWAN, which enables the Device-to-Device (D2D) based communication.

LoRa and LoRaWAN are being extensively used in various indoor and outdoor applications due to their long communication range and energy efficiency. It is one of the versatile wireless technologies which operates across multiple frequency ranges- 915 MHz, and 433 MHz (North America and Australia), 868 MHz (Europe), and 923 MHz (Asia). LoRa can transmit up to 2-5 km in urban areas, which is extended to a distance of 15 km in suburban areas [4]. On the contrary, the LoRa transmission is restricted by its low data rate of 27 Kbps [5]. There are three classes of end devices in this protocol- class A, class B, and class C. Their

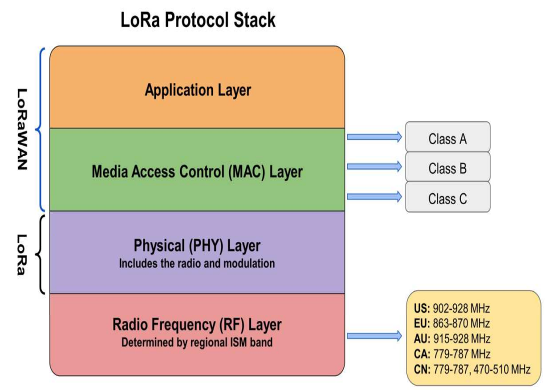

Figure 1. LoRa networking stack

communication ranges and transmission capabilities vary according to their classes. LoRa protocol, thus the wireless modulation is defined in the physical layer. In contrast, the network topology, LoRaWAN capabilities, different types of devices, and the security aspects are represented by LoRaWAN in MAC layer [6]. Figure 1 illustrates the networking stack of the LoRaWAN. The physical (PHY) layer of LoRaWAN deals with the radio and the modulation techniques. LoRa is based on Chirp Spread Spectrum (CSS) modulation, which can trade the throughput for link sensitivity in a fixed bandwidth channel [7]. Thus, LoRa offers the flexibility to design and optimize the system according to the demand, i.e., achieve a higher transmission range with a lower data rate or vice versa. Several parameters such as spreading factors, channel bandwidth, modulation techniques, and transmission power can be tuned to design or optimize the system according to the user demand. Extensive research is going on to improve the LoRa performance by optimizing these parameters. However, most of this research is focused on enhancing the communication latency, data rates, and energy efficiency of a LoRaWAN network rather than Device-to-Device (D2D) based LoRa communication. D2D based LoRa communication is very efficient in real-time applications such as vehicular communication where communication latency and data rates are given utmost importance. D2D based LoRa minimizes the latency and data overheads as it enables direct communication rather than routing the data via gateways. However, this mode of LoRa communication still needs further studies and evaluation with above mentioned LoRa parameters to provide a clearer idea for better network designing. Thus, this work aims to do a real-time latency analysis to provide an approximate trend of the round-trip latency for SF7-SF12 with the bandwidths of 500 kHz, 125 kHz, and 75 kHz for D2D communication in an indoor environment. Extensive tests have been carried out in an indoor hallway of 110 m long with usual public movement. This research is going to fill the void in the literature with different parameters studies for D2D communication mode.

The rest part of the paper is structured into three sections. Section two shows the extensive analysis on background and the different parameters of LoRa. Section three shows the description and evaluation of experimental setups. Finally conclusion is drawn in section four.

II. Background and LoRa Parameters

LoRa can be configured with six different Spreading Factors (SFs) ranging from SF7-SF12. Spreading Factors determine how much time a chirp takes to be transmitted, which is approximately 2^{SF}. Thus, the transmission time of a single chirp increases with the increase of the SF, resulting in an overall increase in the latency. The energy consumption of the transceiver also increases with the increase of the SFs. On the contrary, a higher transmission range is achieved with the higher values of SFs. This is one of the trade-offs that one has to consider while designing a LoRa network. It plays an important role in developing long-range real-time applications with LoRa. It is needed to define a unique trajectory in the chirp intervals for each 2^{SF} symbol state. An offset of k chips is applied for each of the states by encoding the state's value on a frequency scale of $f_0 - f_{BW}$ (f_0 is the initial frequency and f_{BW} is the bandwidth frequency). For any frequency f_k, the modulation of the state k is presented by equation 1 where the initial frequency is shifted by k times of Δf [8] . Therefore, the encoded chirps are the periodically shifted reference signal starting from the initial frequency. Because of this, there is an abrupt frequency change in k^{th} chip, which allows LoRa to have multistate chirp modulation in the range – 2^7-2^{12}. The instantaneous frequency is depicted by f_i in equation 2 where f_c is the carrier frequency and T_s is the chirp signal duration [8].

$$f_k = f_0 + k.\Delta f = f_0 + k.\frac{BW}{2^{SF}} \quad (1)$$

$$f_i(t) = \begin{cases} f_c + \frac{BW}{T_s}\left(t - \frac{k}{T_s}\right) + BW \;\; dla \; -\frac{T_s}{2} \le t < \frac{k}{BW} \\ f_c + \frac{BW}{T_s}\left(t - \frac{k}{T_s}\right) \;\; dla \; \frac{k}{BW} \le t \le \frac{T_s}{2} \end{cases} \quad (2)$$

Bandwidth is another important factor in LoRa modulation. The most popular and commonly used LoRa bandwidths are 75 kHz, 125 kHz, and 500 kHz. At any particular spreading factor, the data rates and communication latency highly depend on the bandwidths, the higher bandwidth results in better data rates and less time on air or latency. On the other hand, setting up a lower bandwidth at the same SF will result in comparatively lower data rates and higher latency. The coding rate or coding efficiency is defined by R, and it maintains the proportion of bits that carries information. The bit rate R_b and symbol rate R_s are given equation 3 and 4, which lead to the equation for chip rate R_c in equation 5 [8]. It suggests that LoRa transmits the spread data stream with the chip rate the same as the allocated bandwidth.

$$R_b = SF.T_s.R = SF.\frac{2^{SF}}{BW}.R \quad (3)$$

$$R_s = \frac{1}{T_s} = \frac{BW}{2^{SF}} \quad (4)$$

$$R_c = \frac{BW}{2^{SF}}.2^{SF} = BW \quad (5)$$

Latency or delay is another vital aspect of LoRa transmission. Latency or transmission delay is another crucial aspect of LoRa transmission. Especially for real-time applications, for instance, vehicular communication as in [1], latency plays an important role. The communication latency of the LoRa network can be optimized by fine-tuning the spreading factor and bandwidth. On the other hand, latency increases with the increase of the SF, resulting in the highest latency with SF 12 and the lowest latency at SF7, provided every other parameter in the network remains the same. However, with the decrease of the SF, the transmission range and the sensitivity also decrease. Therefore, an extensive evaluation of the latency is necessary concerning bandwidth and SF, optimizing any wireless system with the above-defined trade-off.

Thus, substantial research has been going on with the latency and overall performance analysis of LoRaWAN. Sanchez-Ibora et al. have done the performance evaluation of LoRaWAN in three different urban, suburban, and rural scenarios. This study considers both the static and dynamic scenarios on the assessment, and it also includes a theoretical analysis of the coverage area with a radio planning tool. This study uses a class A LoRaWAN device at the end node based on the RN2483 module and a Semtech SX1301 based board at the base station [9]. Faber et al. conduct an extensive theoretical and experimental evaluation of LoRa to study its communication capabilities in negative Signal-to-Noise Ratio (SNR) [10]. Myagmardulam et al. have done a study on the 920 MHz bands of LoRa in Takakuma forest region to elucidate its performance in the hilly forest region under the tree canopy openness affect the propagation. This group has analyzed with SF12 and found a positive relationship between the Sky View Factor (SVF) and Received Signal Strength Indicator (RSSI) values [11]. Tovar-Soto et al. evaluated the performance of LoRa protocol in the rural areas between Sibate and Granada, Colombia, to find the best setup for correct data reception. The results suggest that D2D based LoRa with SF9 and bandwidth 125 kHz perform with minimum packet error with an average air time of 0.2 s [12]. Guo et al. have done the experimental evaluation with the packet reception performance of LoRa with negative SNR and illustrated the relationship between the packet reception performance with PHY parameters. This study also concluded that the larger packet sizes give better performances in large data transmission [13]. Furtado et al. analyzed the LoRa uplink communication considering both PHY and MAC layer with class A devices [14]. Miles et al. conducted a performance analysis for LoRaWAN in an agricultural farming scenario with Network Simulator 3 [15]. A simulation-based two-step method is adopted in [16] for the performance evaluation of LoRaWAN in smart irrigation scenarios considering the sensor density, SFs, and gateway distance. It is clear from the above discussion that most of the performance analysis of LoRa technology is concerned with LoRAWAN and with parameters, energy efficiency, link quality, energy efficiency, sensitivity, and transmission distance. However, D2D based LoRa or PHY layer LoRa pro-tocol has an excellent potential for time-critical applications, which has not been extensively explored under practical scenarios for latency analysis. Thus, this work aims to elucidate the latency or the delay performance of D2D based LoRa with varying bandwidths and SFs.

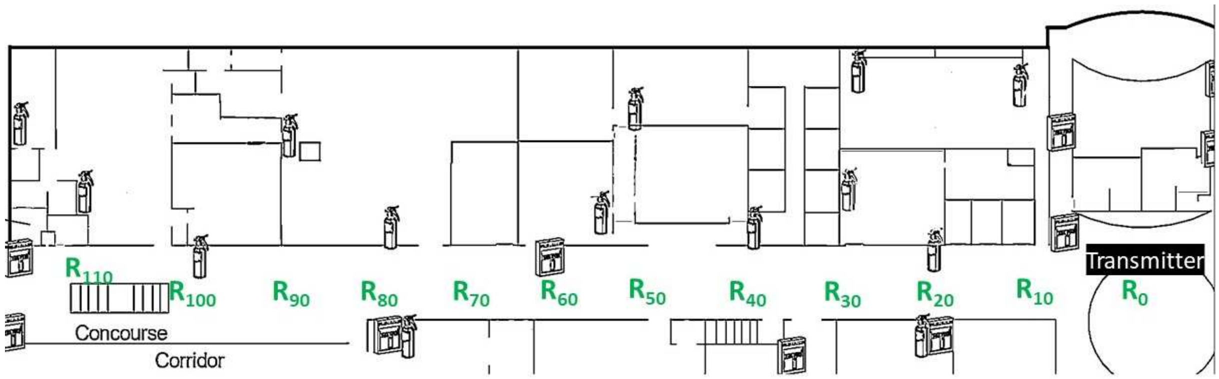

Figure 2. Different transmitter and receiver location of the experimental setup

III. Experimental setup and evaluation

A. Experimental setup

For latency analysis, the round trip delay is taken into consideration. Round Trip Delay (RTD) can be illustrated as the time required for a packet of data to be transmitted, received by the transceiver at the other end, and looped back to be received by the transmitter. In another way, it is the sum of the transmission time and reception time. RFM95W transceiver module based on SX1276 LoRa module is used in designing both the LoRa transmitter and receiver. The evaluation is carried out with the American ISM of 915 MHz variants, a line-of-sight range of 2 km. The average current consumption of this module during active radio reception is 30 mA that can reach up to a peak of 100 mA [17]. The test has been carried out in an indoor hallway of 110 m long by placing the transmitter at one end of it and the receiver at variable distances from the transmitter to analyze the varying distance performances. The receiver is placed at a distance ranging from 0 m -110 m with 10 m of interval at R_0, R_{10}, R_{20}……. R_{110} as indicated by Figure 2. The transmitter is kept fixed at one end of the hallway as shown in the Figure 2 and the receivers were placed at different distances from the transmitter. R_0, R_{10}, R_{20}, R_{30}, R_{40}, R_{50}, R_{60}, R_{70}, R_{80}, R_{90}, R_{100}, R_{110} represent different location of the receiver at a distance of 0 m, 10 m, 20 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m, 100 m, and 110 m respectively from the transmitter. This experimental scenario helped to evaluate the indoor latency performance of LoRa with varying distances. The round-trip latency is measured for SF7-SF12 with 30 trials for each location in R_0………R_{110}. And this test is carried out recursively with three different bandwidths of 500 kHz, 125 kHz, and 75 kHz.

The experimental results obtained from the evaluation explain how the variation of distances, SFs, and bandwidths play a role in latency performances. This would greatly facilitate to design of an optimized network with the demanded latency tolerance. Tests have also been carried out to evaluate the link quality in SNR and Kalman filtered RSSI in the experimental scenario [1]. The next part of the section considers and discusses these experimental results.

B. Experimental Result Analysis

Round Trip Delay (RTD) has been taken with an RFM95W transceiver. The receiver is placed with 10 m of interval at a distance ranging from 0 m -110 m where the transceiver is placed at one end in an indoor hallway of 110m. The project is carried out with all the supported spreading factors supported by LoRa for three different bandwidths of 75 kHz, 125 kHz, and 500 kHz. The experimental setup has been shown in Figure 3.

Round Trip Delay (RTD) varies from 37.67 ms to 100.33 ms by changing the receiver distance from 0m-110m for Bandwidth (BW) of 75 kHz. For a fixed BW, an increase in SF results in higher latency due to increased airtime in LoRa transmission. For BW 75 KHz, the latency is measured for SF7-SF12, which is depicted in Figure 4. The results show that the latency at any particular location is least for SF 7 and highest for SF 12 -the latency increases as the SF increases. The evaluation with BW 125 KHz and BW 500 KHz shows the same latency trend as illustrated in Figure 5 and Figure 6. But then again, with the decrease of the SF, the transmission range of LoRa decreases, and that trade-offs one must consider in designing an indoor D2D-LoRa network.

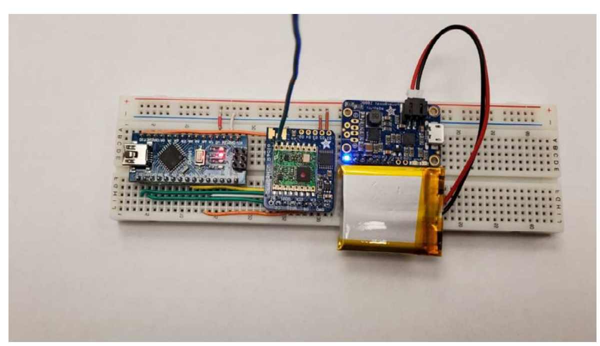

Figure 3. Experimental setup

At 0 m with SF 7, the least latency is 33.67 ms with BW 500 kHz, and the highest latency is 36 ms with BW 75 kHz.

Table I. Percent increase of on-air time variation from starting point to ending point

Supported Spreading Factor By LoRa	BW 75 kHz			BW 125 kHz			BW 500 kHz		
	Latency (ms) at 0 m	Latency (ms) at 110 m	% increase (0-110) m	Latency (ms) at 0 m	Latency (ms) at 110 m	% increase (0-110) m	Latency (ms) at 0 m	Latency (ms) at 110 m	% increase (0-110) m
SF **7**	36	74.67	51.78	34	55	38.18	33.67	53	36.47
SF **8**	36.67	76.33	51.95	35	58	39.66	34	54.2	37.27
SF **9**	37.33	78.5	52.45	36	60	40	35	56	37.5
SF **10**	38	84.5	55.03	36.5	60.5	39.67	35.37	56.67	37.59
SF **11**	38.5	89.33	56.9	37.5	64	41.4	36.5	59	38.13
SF **12**	37.67	100.33	62.4	40	73.67	45.7	37.3	67.67	44.87

At 0 m, with constant SF 7, the latency improves by 5.55% and 6.47% with BW 125 kHz and BW 500 kHz, respectively. Similarly, at 110 m, the minimum latency of 53 ms is achieved with BW 500 kHz and latency increases to the highest value of 74.67 ms with BW 75 kHz. At 100 m with SF 7, the latency improves by 3.77% and 40.88% with BW 125 kHz and BW 500 kHz. Therefore, for any stable position and SF, the minimum latency is achieved by the highest BW. Therefore, in the real-time network where transmission range cannot be compromised either, lower latency can be achieved by setting up the highest possible BW- 500 kHz in this case.

The transmission distance also plays an important role in the communication latency of the real-time applications. A substantial percentage increases the round-trip delay or latency with the increase of distances as depicted in Table I. It also presents the latency at 0 m and 110 m with SF 7- SF 12 at BW 75 kHz, 125 kHz, and 500 kHz. It also indicates that the maximum latency has been found on SF 12 at 110 m

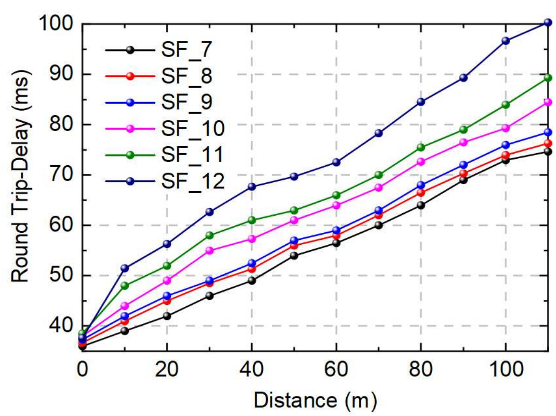

Figure 4. Latency analysis for 75 kHz

which is 100.33 ms for BW 75 kHz and 37.3 ms for BW 500 kHz, and it shows the minimum latency at 0 m on SF 7, which is 36 ms for BW 75 kHz and 33 ms for BW 500 kHz. The

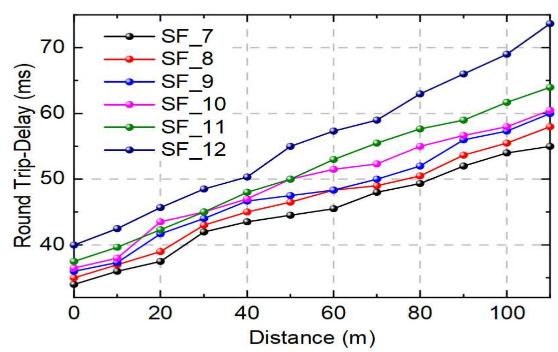

Figure 5. Latency analysis for 125 kHz

best scenario (least latency scenario) is marked with green color, and the worst-case scenario (highest latency scenario) has been marked with orange color. The increase in latency from 0 m to 100m varies by 51.78% - 62.4% at 75 kHz of 500

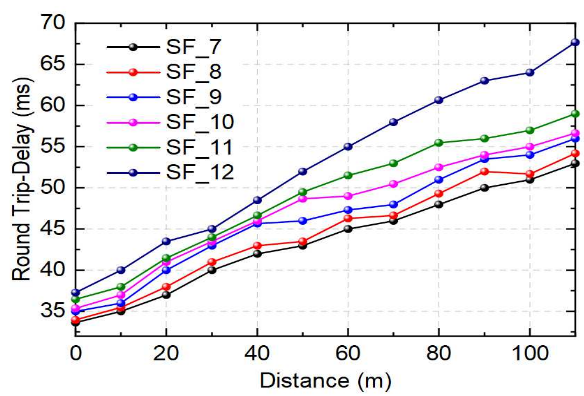

Figure 6. Latency analysis for 500 kHz

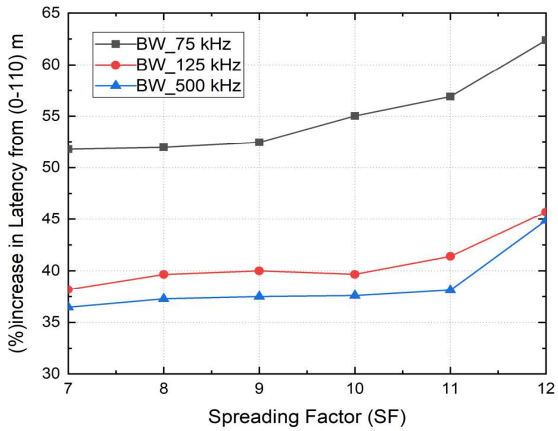

Figure 7. (%) Increase in latency for different SF (7-12)

kHz, this variation with different SFs 38.18% -45.7% and 36.47% - 44.87% respectively. It shows an interesting trend that this percent increase in latency for 0 m -110 m increases with SFs. The percent increase of the latency (from 0 m -100 m) for different BW and SF is illustrated in Figure 7. It shows that the percent change of latency is higher with the lower BW and it gradually decreases with the higher BWs. The experiment was conducted in a 110 m indoor hallway within the good range of line-of-sight. For the distance of 0 m -110 m, the RSSI value decreases from -47 to -89 and the SNR value ranges from 5 to 6 for all the experimental setups. So, there is no considerable variation in the SNR and RSSI values which indicates the good link quality for indoor environment. Those results have been shown in Figure 8.

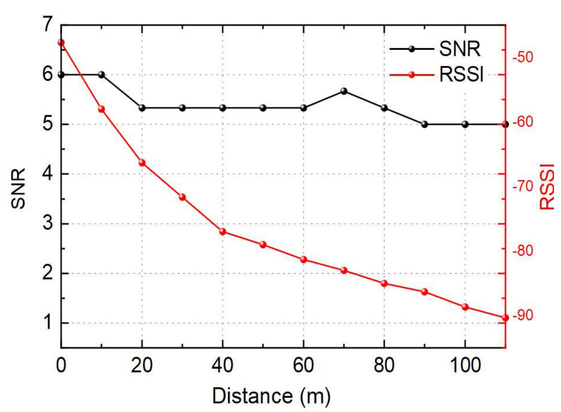

Figure 8. SNR and RSSI outline for different SF 7-12

As the project focused on D2D based LoRa communication in an indoor application, a highlight has been given on round trip delay. Hence, it is obvious that where transmission range is an essential, a higher spreading factor will be needed, and when latency gets the predominance, a lower spreading factor is desired.

IV. CONCLUSION

D2D based communication plays a very crucial and vital part in real time applications as it does not need any gateway. Suitably, to reduce the latency, for sure D2D based LoRa communication performs significantly better than LoRaWAN network. Henceforth, an actual time D2D-LoRa latency experiment has been performed in this project at a 110 m long indoor lobby with normal free movement of the public. Our project viewed that the link quality remains stable as there are slight variations in the SNR values with changing the distance of the receiver module across the hallway. Round-Trip-Latency with three different bandwidths (BWs) of 75 kHz, 125 kHz, and 500 kHz has been investigated with all the supported spreading factors (SFs) of the RFM95W LoRa transceiver. For 75 kHz with different SFs, the increase in latency from (0-100) m varies by 51.78% - 62.4% whereas, with BW 125 kHz and BW 500 kHz, these variations with different SFs are (38.18 - 45.7)%, and (36.47 - 44.87)% correspondingly which implies that latency will increase with the higher value of SFs owing to the increase of the airtime in LoRa transmission for a constant BW. Alongside, as the BW increases, the round-trip delay or the latency decreases as higher BW means better data rates. At 110 m (highest distance point), the lowest latency value has been observed on BW 500 kHz with SF 7, 53 ms, and maximum latency values have been noted on BW 75 kHz SF 12, which is 100.33 ms. However, though minimum latency has been found on lower SF, the higher values of SFs provide a higher transmission range. In short, lower SF is needful in those places where on-air time is imperative.

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