Parametric Analysis Of LoRa Sensor Network Data Rate And Packet Time On Air

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***Abstract* - In this paper, parametric analysis of LoRa sensor network data rate and packet time on air is presented. Notably, LoRa transceivers use Chirp Spread Spectrum (CSS) modulation and Forward Error Correction (FEC) technique that depends on chirp spreading factor, code rate and bandwidth. These parameters, among others significantly affect the operating data rate and packet transmission time, otherwise known as packet time on air. The focus in this paper is to evaluate the impact of the key parameters on the LoRa sensor network data rate and packet time on air. The parametric analysis was done by keeping other parameters constant and varying one specific parameter and then computing the desired parameter value. For the bit rate, the results show that for code rate, CR = 1, the bit rate for SF of 7 is 5468.8 bps whereas that for SF of 12 is 293.3 bps. Also, the bit rate decreases with increase in CR; notably, for SF of 7 at CR =1 the bit rate is 5468.8 bps whereas at CR =4 the bit rare is 3418.0 bps. In addition, the bit rate increases with the bandwidth. For the time on air ,TOA, with payload, PL size of 10 bytes, the results show that for SF of 7 the TOA is 41.216 ms while the TOA is 991.232 ms for SF of 12. Also, the TOA increases exponentially with SF. Remarkably, the data rate and TOA together determine how much energy is required to transmit a given amount of data over a given communication range. Hence, knowing how the other parameters affect the data rate and packet transmission time can help LoRa sensor network designers to select appropriate parameter values to suit their applications.**

***Keywords* — Parametric Analysis, Packet Time On Air, LoRa, Sensor Node, Data Rate, Sensor Network**

1. Introduction

In recent years, wireless communication technologies have attracted the attention of researchers and network designers as it is the driver for the emerging Internet of Things (IoT) and smart applications [1,2,3,4,5,6,7,8,9,10]. More so, the growing demand for applications that rely on autonomous sensors that are installed in remote areas has also added to the growing research on wireless communication networks [11,12, 13,14, 15,16, 17,18, 19,20,21,22]. Accordingly, today there are different kinds of wireless technologies that are developed for wireless sensor applications. In particular, long range (LoRa) technology is one of the most popular wireless networking technology targeted at machine to machine (M2) and Internet of Things (IoT) networks [23,24, 25,26, 27,28, 29,30, 31,32]. LoRa technologies are widely applied in sensor networks as they offer long range wireless communication with very low power consumption [33, 34, 35, 36, 37, 38, 39, 40].

Generally, wireless networks designers aim is to satisfy a certain performance specifications in the face of some known setbacks that tend to degrade the signal strength and quality. Notable setbacks includes diffraction loss, propagation loss, atmospheric losses, multipath loss and some losses that occur due to some fade mechanisms [41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62]. These setbacks can affect the attainable communication range, the achievable data rate and bit error performance [63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75] . In the case of LoRa technology, the extent of the impact of the setbacks depends on the spreading factor and other parameter settings for the LoRa network.

In this paper, the focus is on the LoRa network data rate and packet time on air (TOA) which together determine how much energy is required to transmit a given amount of data over a given communication range [76,77,78,79,80,81]. Particularly, in this paper evaluation of the impact of key network parameters on the LoRa sensor network data rate and packet time on air is studied. The key parameters considered are chirp spreading factor, code rate and bandwidth. This is because, knowing how these parameters affect the data rate and packet transmission time can help LoRa sensor network designers to select appropriate parameter values to suit their applications. The detailed analytical expressions for the computation are presented along with some sample numerical computations.

2 Methodology

The LoRa sensor bandwidth, denoted as BW represents the range of frequencies of the LoRa transceiver. LoRa provides three scalable BW settings of 125 kHz, 250 kHz and 500 kHz. LoRa transmitters sends data at a chip rate equal to the system bandwidth in chips per-second, meaning that LoRa's Chip-Rate, denoted as □□ is computed as:

□□=□□ [□□□□□/□] (1)

The Chirp Spread Spectrum (CSS) modulation used in LoRa transceivers is performed by representing each bit of pay-load information by multiple chips of information. In LoRa, each symbol is spread by a spreading code of length 2^{SF} chips where SF denotes the Spreading Factor and the chip length in chips/symbol is given as 2^{SF}. The Symbol Rate, denoted as R_s can be computed as:

$$R_s = \frac{RC}{2^{SF}} = \frac{BW}{2^{SF}} (2)$$

The duration of a LoRa symbol (□□) can be determined as;

$$T_s = \frac{1}{R_s} = \frac{2^{SF}}{BW} (3)$$

The Forward Error Correction (FEC) technique supported by LoRa uses CR (code rate) redundant bits, where CR can be 1, 2, 3, or 4. Hence, $Rate\ Code\ (RC)$ in terms of CR is given as;

$$Rate\ Code\ (RC) = \left(\frac{4}{4+CR}\right) (4)$$

2.1 The LoRa sensor network bit rate (R_b)

The LoRa sensor network bit rate, denoted as R_b in bps is defined as;

$$R_b = SF\left(\frac{BW}{2^{SF}}\right)(RC) (5)$$

2.2 LoRa Packet Time on Air

The total transmission time, often called Time on air, denoted as TOA of a Lora packet is defined as:

$$\text{ToA} = T_{\text{preamble}} + T_{\text{payload}} (6)$$

$$T_{\text{preamble}} = (n_{\text{preamble}} + 4.25)T_s (7)$$

$$T_{\text{payload}} = (n_{\text{payload}})T_s (8)$$

$$n_{\text{payload}} = 8 + max\left(\left(ceil\left[\frac{8PL-4SE+28+16\,CRC-20H}{4(SF-2DE)}\right](CR+4)\right), 0\right) T_s (9)$$

$$\text{ToA} = (n_{\text{preamble}} + n_{\text{payload}} + 4.25)T_s (10)$$

Where PL is the number of payload bytes, H = 0 when the header is enabled and H = 1 when no header is present, DE = 1 when the low data rate optimization is enabled and DE = 0 when it is disabled, CR is the coding rate from 1 to 4 (FEC codes 4/(CR+4)), CRC = 1 for uplink and 0 for down link packet.

3. Results and discussion

The parametric analysis examines how variations of one parameter affect another parameter. It is done by keeping other parameters constant and varying one specific parameter and then computing the desired parameter value. In this wise, the variation of the data rate with respect to the spreading factor, bandwidth and code rate are examined separately. Similar approach is adopted to examine the variation of other parameters on LoRa packet time on air.

3.1 Results on parametric analysis of LoRa Sensor Network bit rate

Bit rate is computed for various SF ranging from 7 to 12 and the results are presented in Table 1 and Figure 1. The results show that for Code Rate, CR = 1, the bit rate for SF of 7 is 5468.8 bps whereas that for SF of 12 is 293.3 bps. Also, the bit rate decreases as SF increases. In addition, the results for Code Rate, CR = 1, 2, 3 and 4 (in Table 1 and Figure 1) show that the bit rate decreases with increase in CR; notably, for SF of 7 at CR =1 the bit rate is 5468.8 bps whereas at CR =4 the bit rare is 3418.0 bps.

The results of the Bit rate , Rb (bps) for CR =1 and BW of 125 KHz , 250 KHz and 500 KHz for various spreading factor, SF ranging from 7 to 12 is shown in Table 2 and Figure 2. The results show that the bit rate increases with the bandwidth; it has a value of 21875 bps for the 500 KHz, 10938 bps for the 250 KHz, and 5469 bps for the 125 KHz.

Table 1 The results of the Bit rate , Rb (bps) for BW of 125 KHz for various spreading factor, SF ranging from 7 to 12 and Code Rate, CR ranging from 1 to 4.

Spreading Factor, SF	Data rate , Rb (bps) for CR =1	Data rate , Rb (bps) for CR =2	Data rate , Rb (bps) for CR =3	Data rate , Rb (bps) for CR =4
7	5468.8	4557.3	3906.3	3418.0
8	3125.0	2604.2	2232.1	1953.1
9	1757.8	1464.8	1255.6	1098.6
10	976.6	813.8	697.5	610.4
11	537.1	447.6	383.6	335.7
12	293.0	244.1	209.3	183.1

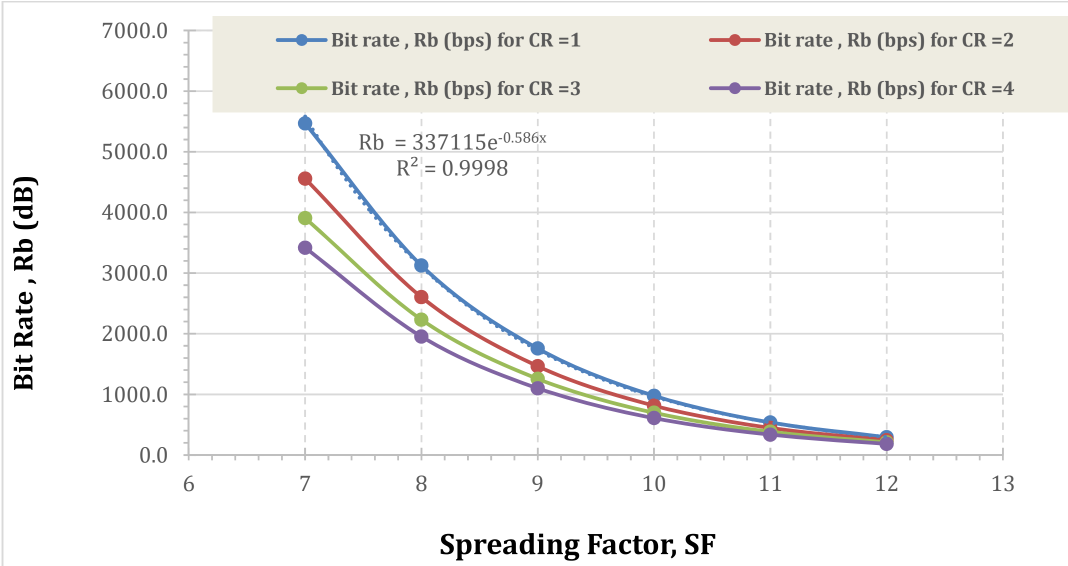

Figure 1 Graph of the results of the Bit rate , Rb (bps) for BW of 125 KHz for various spreading factor, SF ranging from 7 to 12 and Code Rate, CR ranging from 1 to 4.

Table 2 The results of the Bit rate , Rb (bps) for CR =1 and BW of 125 KHz , 250 KHz and 500 KHz for various spreading factor, SF ranging from 7 to 12

Spreading Factor, SF	Bit rate , Rb (bps) for CR =1, BW = 125 KHz	Bit rate , Rb (bps) for CR =1, BW = 250 KHz	Bit rate , Rb (bps) for CR =1, BW = 500 KHz
7	**5469**	10938	21875
8	**3125.0**	6250	12500
9	**1757.8**	3515.625	7031.25
10	**976.6**	1953.125	3906.25
11	**537.1**	1074.219	2148.4375
12	**293.0**	585.9375	1171.875

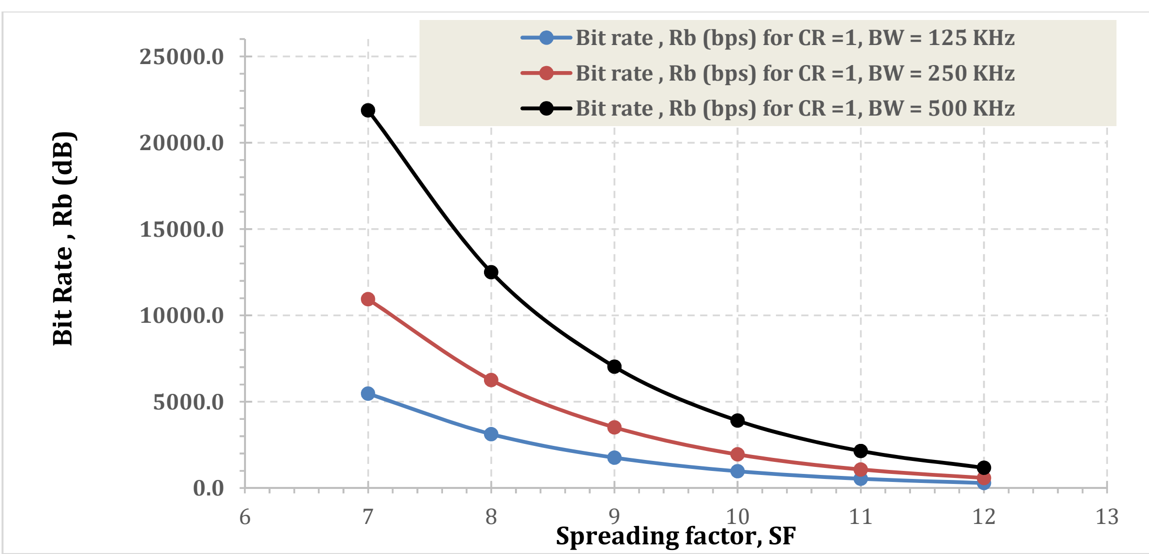

Figure 2 Graph of the results of the Bit rate , Rb (bps) for CR =1 and BW of 125 KHz , 250 KHz and 500 KHz for various spreading factor, SF ranging from 7 to 12

3.2 Results on parametric analysis of LoRa packet time on air

The results of the packet time on air, TOA for BW =125 KHz is shown in Table 3 and Figure 3. The computation was conducted with payload, PL size of 10 bytes and the results show that for SF of 7 the TOA is 41.216 ms while the TOA is 991.232 ms for SF of 12. Also, the graph show that the TOA increases exponentially with SF.

The results of the packet time on air, TOA for BW =250 KHz is shown in Table 4 and Figure 4. The computation was conducted with payload, PL size of 10 bytes and the results show that for SF of 7 the TOA is 20.608 ms while the TOA is 495.616 ms for SF of 12. Also, the graph show that the TOA increases exponentially with SF.

The results of the packet time on air, TOA for BW =500 KHz is shown in Table 5 and Figure 5. The computation was conducted with payload, PL size of 10 bytes and the results show that for SF of 7 the TOA is 10.304 ms while the TOA is 247.808 ms for SF of 12. Also, the graph show that the TOA increases exponentially with SF.

Comparison of the time on air for the three bandwidths is shown in Figure 6. The results show that the TOA decreases as the bandwidth increases. Accordingly, TOA for the bandwidth of 125 KHz is the highest for all the spreading factors considered. On the other hand, the bandwidth of 500 KHz has the lowest TOA for all the SF considered.

Table 3 The results of the packet time on air for BW =125 KHz

SF	BW (KHz)	CR	npreamb	PL	H	DE	Tsymb	Tpreamb	Tpayload	LoRa Packet Time on Air, ToA, (ms)
7	250	1	8	10	0	0	0.512	6.272	14.336	20.608
8	250	1	8	10	0	0	1.024	12.544	23.552	36.096
9	250	1	8	10	0	0	2.048	25.088	47.104	72.192
10	250	1	8	10	0	0	4.096	50.176	94.208	144.384
11	250	1	8	10	0	0	8.192	100.352	147.456	247.808
12	250	1	8	10	0	0	16.384	200.704	294.912	495.616

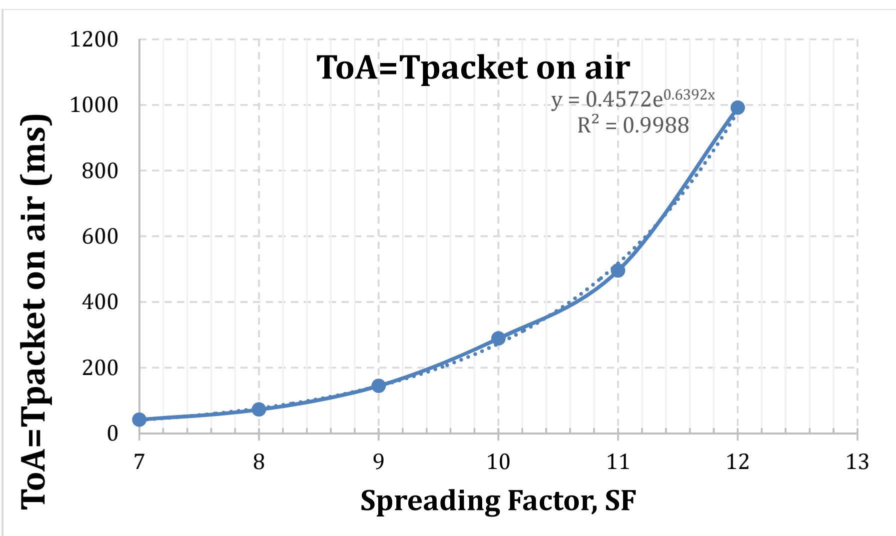

Figure 3 The graph of packet time on air versus spreading factor, SF for BW =125 KHz

Table 4 The results of the packet time on air for BW =250 KHz

SF	BW (KHz)	CR	npreamb	PL	H	DE	Tsymb	Tpreamb	Tpayload	LoRa Packet Time on Air, ToA, (ms)
7	500	1	8	10	0	0	0.256	3.136	7.168	10.304
8	500	1	8	10	0	0	0.512	6.272	11.776	18.048
9	500	1	8	10	0	0	1.024	12.544	23.552	36.096
10	500	1	8	10	0	0	2.048	25.088	47.104	72.192
11	500	1	8	10	0	0	4.096	50.176	73.728	123.904
12	500	1	8	10	0	0	8.192	100.352	147.456	247.808

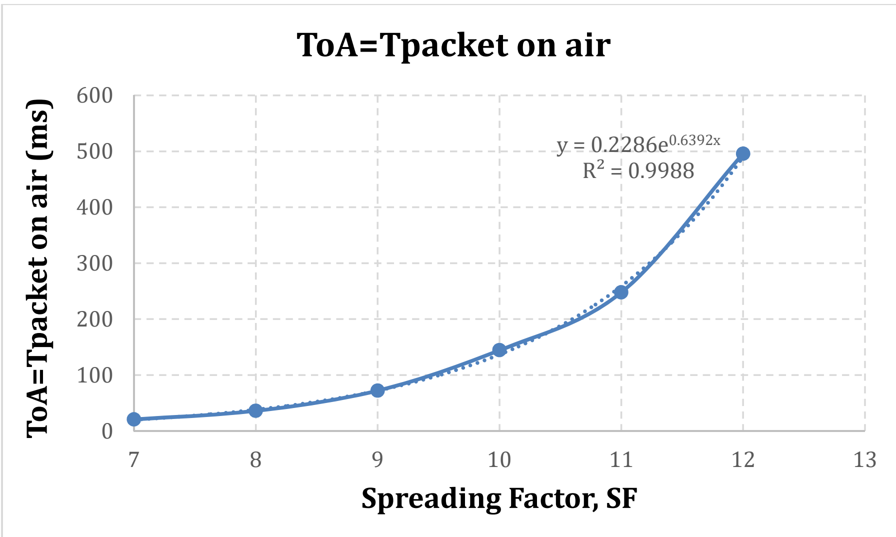

Figure 4 The graph of packet time on air versus spreading factor, SF for BW =250 KHz

Table 5 The results of the packet time on air for BW =500 KHz

SF	BW (KHz)	CR	npreamb	PL	H	DE	Tsymb	Tpreamb	Tpayload	LoRa Packet Time on Air, □□□, (ms)
7	500	1	8	10	0	0	0.256	3.136	7.168	10.304
8	500	1	8	10	0	0	0.512	6.272	11.776	18.048
9	500	1	8	10	0	0	1.024	12.544	23.552	36.096
10	500	1	8	10	0	0	2.048	25.088	47.104	72.192
11	500	1	8	10	0	0	4.096	50.176	73.728	123.904
12	500	1	8	10	0	0	8.192	100.352	147.456	247.808

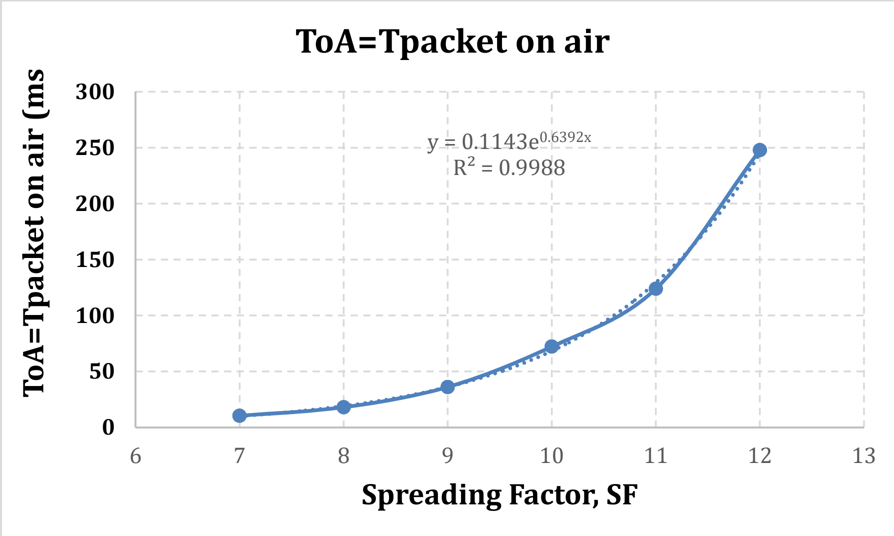

Figure 5 The graph of packet time on air versus spreading factor, SF for BW =500 KHz

Table 6 The packet time on air versus spreading factor, SF for BW =125 KHz, 250 KHz and 500 KHz

SF	LoRa Packet Time on Air, *ToA*, (ms) for CR =1 and BW = 125 KHz	LoRa Packet Time on Air, *ToA*, (ms) for CR =1 and BW = 250 KHz	LoRa Packet Time on Air, *ToA*, (ms) for CR =1 and BW = 500 khZ
7	41.216	20.608	10.304
8	72.192	36.096	18.048
9	144.384	72.192	36.096
10	288.768	144.384	72.192
11	495.616	247.808	123.904
12	991.232	495.616	247.808

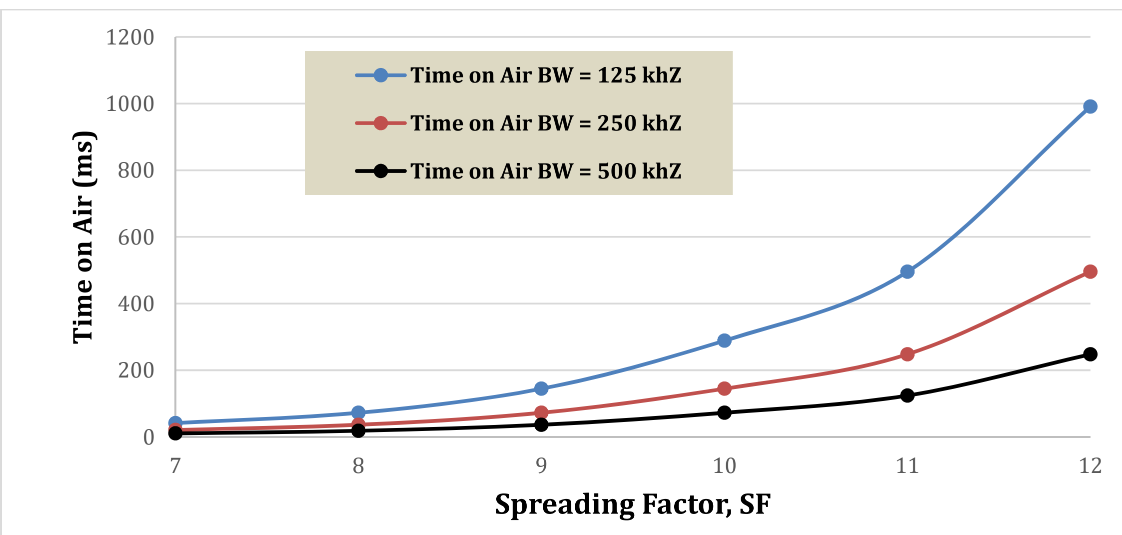

Figure 6 The graph of packet time on air versus spreading factor, SF for BW =125 KHz, 250 KHz and 500 KHz

The TOA for bandwidth of 125 KHz is examined for the two values of DE (the low data rate optimization parameter). The TOA was computed for PL = 10 bytes and for the case of DE = 1 (enabled low data rate optimization) and for the case of DE = 0 (disabled low data rate optimization). The results showed that enabling DE increases the TOA whereas disabling DE reduces the TOA, as shown in Table 7 and Figure 7.

The TOA for bandwidth of 125 KHz is examined for the two values of H (the extended header parameter). The TOA was computed for PL = 10 bytes and for the case of H = 0 (enabled extended header) and for the case of H = 1 (disabled extended header). The results showed that enabling the extended header (that is H =0) increases the TOA whereas disabling the extended header (that is H =1) reduces the TOA, as shown in Table 8 and Figure 8. However, the increase in the TOA based on the value of H does not affect the values of TOA for SF = 7 and also for SF =8. The variation in the value of TOA due to the H is noticeable for SF >8.

The TOA for bandwidth of 125 KHz is examined for the two values of PL (the number of payload bytes). The TOA was computed for PL = 10 bytes and for PL = 50 were examined. The results showed that increasing the value of PL increases the TOA, as shown in Table 9 and Figure 9. Hence, for all the spreading factors, SF =7 to 12, the TOA for PL =50 is higher than the TOA for PL =10.

Table 7 LoRa Packet Time on Air, TOA (ms) for DE =0 and DE =1 and BW = 125 KHz

SF	**LoRa Packet Time on Air, TOA (ms) for DE =1 and** BW = 125 KHz	**LoRa Packet Time on Air, TOA (ms) for DE =0 and** BW = 125 KHz
7	128.256	97.536
8	225.792	174.592
9	390.144	328.704
10	698.368	616.448
11	1314.816	1150.976
12	2301.952	2138.112

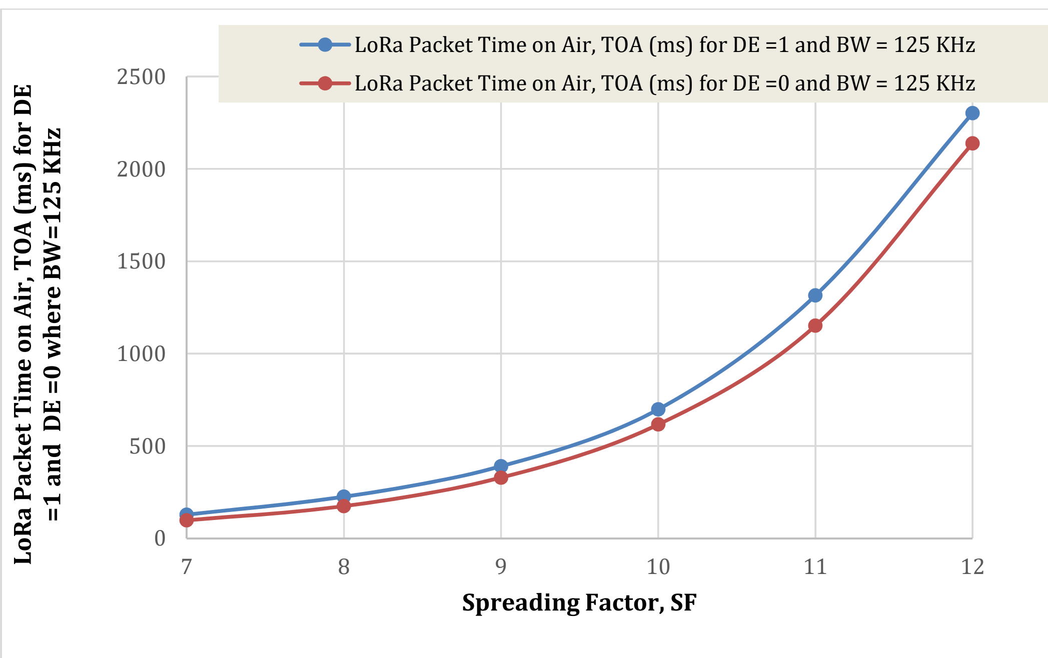

Figure 7 LoRa Packet Time on Air, TOA (ms) for DE =0 and DE =1 and BW = 125 KHz

Table 8 LoRa Packet Time on Air, TOA (ms) for H=0 and H =1 and BW = 125 KHz

SF	LoRa Packet Time on Air, TOA (ms) for H =0 and BW = 125 KHz	LoRa Packet Time on Air, TOA (ms) for H =1 and BW = 125 KHz
7	97.536	97.536
8	174.592	174.592
9	328.704	308.224
10	616.448	575.488
11	1150.976	1069.056
12	2138.112	1974.272

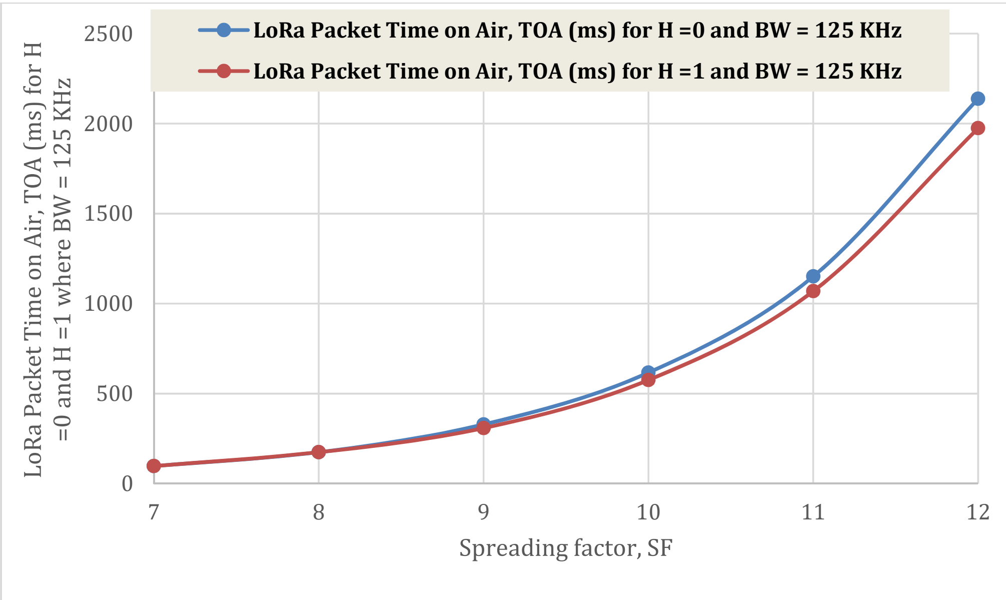

Figure 8 LoRa Packet Time on Air, TOA (ms) for H=0 and H =1 and BW = 125 KHz

Table 9 LoRa Packet Time on Air, TOA (ms) for bandwidth of 125 KHz PL =10 and PL=50

SF	LoRa Packet Time on Air, TOA (ms) for PL =10 and BW = 125 KHz	LoRa Packet Time on Air, TOA (ms) for PL =50 and BW = 125 KHz
7	36.096	97.536
8	72.192	174.592
9	123.904	308.224
10	247.808	575.488
11	495.616	1069.056
12	991.232	1974.272

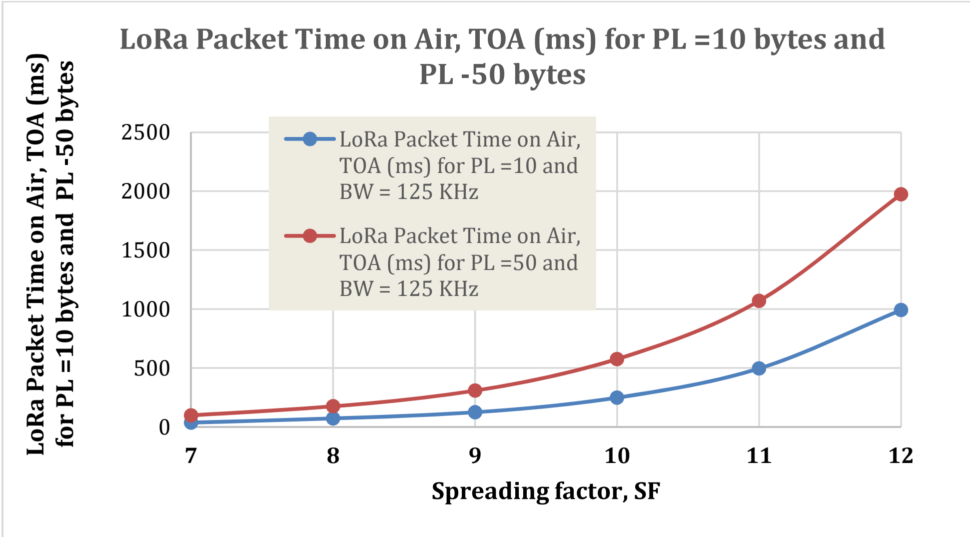

Figure 9 LoRa Packet Time on Air, TOA (ms) for bandwidth of 125 KHz PL =10 and PL=50

4. Conclusion

The data rate and packet transmission time of LoRa-based sensor network are studied. The Chirp Spread Spectrum (CSS) modulation used in LoRa transceivers is built upon chirp spreading factor (SF) and few other key parameters like code rate and bandwidth. In this paper, the impact of these key LoRa CSS modulation parameters on the data rate and packet time on air (TOA) is presented. The results showed that the time on air increases with increase in spreading factor but it decreases as the bandwidth increases. On the other hand, the data rate decreases with increase in spreading factor but it increases as the bandwidth increases. Notably, the data rate and TOA together determine how much energy is required to transmit a given amount of data over a given communication range. Hence, knowing how the other parameters affect the data rate and packet transmission time can help LoRa sensor network designers to select appropriate parameter values to suit their applications.

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