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Determination Of Packet Transmission Energy Consumption For Lora-Based Sensor Node To Low Earth Orbit Satellite Communication Link

Miracle Aneke[1]
Department Of Electrical/Electronic And Computer Engineering,
University of Uyo, Akwa Ibom State Nigeria

Kufre M. Udofia[2]
Department of Electrical/Electronic and Computer Engineering,
University of Uyo, Nigeria
kmudofia@uniuyo.edu.ng

Philip M. Asuquo[3]
Department Of Electrical/Electronic And Computer Engineering,
University of Uyo, Akwa Ibom State Nigeria

Abstract— **In this paper, the determination of packet transmission energy consumption for LoRa-based sensor node to low earth orbit satellite communication link is presented. The analysis was conducted for Low Earth Orbit (LEO) satellites with altitude in the range of 400 km to 1525 km. Also, the data on SEMTECH SX1272/73 LoRa transceiver was used and the spreading factors SF 7, SF 8, SF 9, SF 10, SF 11 and SF 12 were considered with frequency of 868 MHz. Specifically, the LoRa transceiver parameters determined are the transmission time, the required transmitter power and the energy consumption for the earth-to-satellite communication link. The results show that for a given spreading factor, the packet transmission time increases with increase in the payload size, with a value of 48.86 ms at orbital altitude of 400 km with payload size of 10 bytes to a value of 105.18 ms at orbital altitude of 400 km with payload size of 50 bytes. There is also a marginal increase in the packet transmission time with the altitude. The results also show that for a given payload size and altitude of the satellite, the packet transmission time increases with increase in the spreading factor, with a value of 105.2 ms for the SF 7 at orbital altitude of 400 km to a value of 2309.6 ms for the SF 12 at the same orbital altitude of 400 km. Also, the required transmitter power decreases with increase in the spreading factor. On the other hand, the transmitter energy consumption decreases from the value of 400 mJ for SF 7 to a value of 2.04 mJ for SF 10 and then increases to 2.54 mJ for SF 11 and further to 2.80 mJ for SF 12. Hence, the energy consumption is least for the SF 10 configuration of the LoRa transceiver. The results will enable LoRa-based sensor network designers in selecting appropriate LoRa configurations that will ensure effective communications.**

Keywords — Time on Air, Required Transmitter Power, Transmission Energy Consumption for Lora-Based Sensor Node

1. Introduction

In the wireless sensor communication industry, sensors are used in monitoring and controlling systems [1,2,3,4,5,6, 7,8,9, 10,11,12,13,14,15,16]. Generally, the wireless sensors capabilities determine their applicability and durability in service. However, the wireless sensor nodes are usually considered to be resource constrained [17, 18, 19, 20, 21]. This means that the sensor nodes have limited resources like memory capacity, processing capability, power supply, sensor battery storage capacity and hence sensor battery lifespan. Accordingly, there is always need to estimate the energy demand for the operation of the sensor so as to determine the battery lifespan [22, 23, 24, 25, 26, 27,28]. The energy demand depends among other things on the path length, the various propagation losses and the total transmission time of the data packets [29,30, 31, 32,33, 34,35,36,37,38,39,40,41,42,43,45,46,47,48,49,50,51]. Consequently, in this paper, the focus is to determine the energy consumption of a battery-powered LoRa-based transceiver sensor node used for direct transmission of data packets from an earth station to a for Low Earth Orbit (LEO) satellite [52,53,54,55,56,57,58,59,60,61,62,63]. The study also determines the total packet transmission time which takes into account the propagation time and the transmission time [64, 65, 66, 67, 68]. The propagation loss is also determined. The study further compared the energy consumption, required power and energy for the transmission of data packets using the five different popularly implement spreading factors in LoRa transceiver. The idea presented in this paper will help in determining the sensor battery lifespan and energy efficiency for a LoRa transceiver based satellite communication link.

2. Methodology

The energy consumption (E_{ECt}) for transmitting a data packet on a satellite link can be determined from the knowledge of the required transmitter power $\left(P_{ET(dB)}\right)$ and the time spent in transmitting a data packet ($\mathbf{t_{packet}}$). Both parameters require the value of earth station to satellite path length (d_{ES}). When the earth station and satellite location coordinates and altitude are given, the path length (d_{ES}) and elevation angle (θ_{el}) can be computed. Hence, when the following parameters are given Satellite altitude(H_s), satellite orbit radius (R_s), satellite longitude (L_{LongS}), satellite latitude (L_{LatS}), earth radius (R_E), earth station longitude (L_{LongE}), earth station latitude (L_{LatE}) where R_E = 6378 Km, then ;

$$R_S = H_s + R_E \tag{1}$$

$$\Delta L_{on} = L_{ongE} - L_{ongS} \tag{2}$$

$$\cos(\theta_c) = \cos(L_{atE})\cos(L_{atS})\cos(\Delta L_{on}) + \sin(L_{atE})\sin(L_{atS}) \tag{3}$$

The earth station to satellite path length, d_{ES} is defined as;

$$d_{ES} = \sqrt{\left(R_s^2 + R_E^2 - 2(R_s)(R_E)\cos(\theta_c)\right)} \tag{4}$$

The earth station to satellite elevation angle (θ_{el}) is defined as;

$$\theta_{el} = cos^{-1}\left(\left(\frac{R_E + H_S}{d_{ES}}\right) sin(\theta_c)\right) \tag{5}$$

The time spent in transmitting a data packet (t_{packet}) in this paper is the sum of the transmission time (t_t) and propagation time (t_p), where;

$$t_{packet} = t_t + t_p \tag{6}$$

Where c is the speed of light ($c = 3 x 10^8$ m/s) and d_{ES} is in meters.

$$t_p = \frac{d_{ES}}{c} \tag{7}$$

The transmission time (t_t) is the time on air which for LoRa modulation is given as;

$$t_t = (n_{PL} + n_{PR} + 4.25)T_s \tag{8}$$

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

$$T_s = \frac{1}{R_s} = \frac{2^{SF}}{BW} \tag{10}$$

SF denotes the spreading factor

n_{PR} denotes number of bytes in the preamble and it is specified in the packet format

BW denotes the bandwidth, which can be 125 KHz, 250 KHz or 500 KHz

PL denotes number of bytes in the payload

H denotes header flag; H = 0 when enabled and H = 1 when disabled

DE denotes low data rate optimization; D= 1 enabled and DE = 0 when disabled,

CR denotes the coding rate where CR can be 1, 2, 3, or 4.

CRC = 1 for uplink and= 1 for down link

For a given required signal to noise ratio represented as SNR_{RQ}, transmitter antenna gain represented as $G_{Et(dB)}$, satellite antenna gain represented as $G_{SR(dB)}$, satellite receiver noise temperature represented as T_{sys}, and link noise bandwidth represented as B_u, the required earth station transmitter power represented as $P_{ET(dB)}$ is computed as follows;

$$P_{ET(dB)} = SNR_{RQ} - G_{Et(dB)} - \left(\frac{G_{SR(dB)}}{T_{sys}}\right) + L_{ESP} + 10(LOG(B_u)) - 228.6 \tag{11}$$

Where L_{ESP} represents the earth station-satellite path loss which is calculated using the free space propagation loss model as follows;

$$L_{ESP} = 32.45 + 20\,Log(f) + 20\,Log(d_{ES}) \tag{12}$$

Where f is in MHz and d_{ES} in km. Then, the energy consumption (E_{ECt}) for transmitting a data packet on a satellite link can be determined as;

$$E_{ECt} = (t_p)\left(10^{\left(\frac{P_{ET(dB)}}{10}\right)}\right) \tag{13}$$

3. Results and Discussion

The analysis was conducted for Low Earth Orbit (LEO) satellites with altitude in the range of 400 km to 1525 km. Also, the data on SEMTECH SX1272/73 LoRa transceiver was used and the spreading factors SF 7, SF 8, SF 9, SF 10, SF 11 and SF 12 were considered with frequency of 868 MHz and the data given in Table 1. The results of the packet transmission time for SF 7 with payload size of 10 bytes to 50 bytes are given in Table 2 and Figure 1. The results of the required transmission power for SF 7 with payload size of 10 bytes to 50 bytes are given in Table 3 and Figure 2 while the results of the required transmission power for SF 7 with payload size of 10 bytes to 50 bytes are given in Table 4 and Figure 3. The results show that for a given spreading factor, the packet transmission time increases with increase in the payload size, with a value of 48.86 ms at orbital altitude of 400 km with payload size of 10 bytes to a value of 105.18 ms at orbital altitude of 400 km with payload size of 50 bytes. There is also a marginal increase in the packet transmission time with the altitude, with a value of 48.86 ms at orbital altitude of 400 km with payload size of 10 bytes to a value of 56.77 ms at orbital altitude of 1465.37 km with payload size of 10 bytes. This is due to the propagation time component of the packet time. The results in Table 3 and Figure 2 show that required power for the transmission of the packet increases with increase in satellite altitude. The results in Table 4 and Figure 3 show that transmitter energy consumption increases with increase in satellite altitude. It also increases with increase in the payload size.

Table 1 The data on SEMTECH SX1272/73 LoRa transceiver for bandwidth of 125 KHz

SF	BW (kHz)	Sensitivity (dBm)	SNRrq (dB)
7	125	-124.0	-7.0
8	125	-127.0	-10.0
9	125	-130.0	-13.0
10	125	-133.0	-16.0
11	125	-135.0	-18.0
12	125	-137.0	-20.0

Table 2 The results of the packet transmission time for SF 7 with payload size of 10 bytes to 50 bytes

Altitude of Satellite Orbit, Hs (km)	Tpacket (ms) for spreading factor, SF7 with PL= 10 Bytes	Tpacket (ms) for spreading factor, SF7 with PL= 20 Bytes	Tpacket (ms) for spreading factor, SF7 with PL= 30 Bytes	Tpacket (ms) for spreading factor, SF7 with PL= 40 Bytes	Tpacket (ms) for spreading factor, SF7 with PL= 50 Bytes
400.00	48.86	64.22	79.58	89.82	105.18
459.19	49.43	64.79	80.15	90.39	105.75
518.37	49.96	65.32	80.68	90.92	106.28
577.56	50.47	65.83	81.19	91.43	106.79
636.75	50.95	66.31	81.67	91.91	107.27
695.94	51.42	66.78	82.14	92.38	107.74
755.12	51.86	67.22	82.58	92.82	108.18
814.31	52.30	67.66	83.02	93.26	108.62
873.50	52.72	68.08	83.44	93.68	109.04
932.68	53.13	68.49	83.85	94.09	109.45
991.87	53.53	68.89	84.25	94.49	109.85
1051.06	53.91	69.27	84.63	94.87	110.23
1110.24	54.29	69.65	85.01	95.25	110.61
1169.43	54.67	70.03	85.39	95.63	110.99
1228.62	55.03	70.39	85.75	95.99	111.35
1287.81	55.39	70.75	86.11	96.35	111.71
1346.99	55.74	71.10	86.46	96.70	112.06
1406.18	56.09	71.45	86.81	97.05	112.41
1465.37	56.43	71.79	87.15	97.39	112.75
1524.55	56.77	72.13	87.49	97.73	113.09

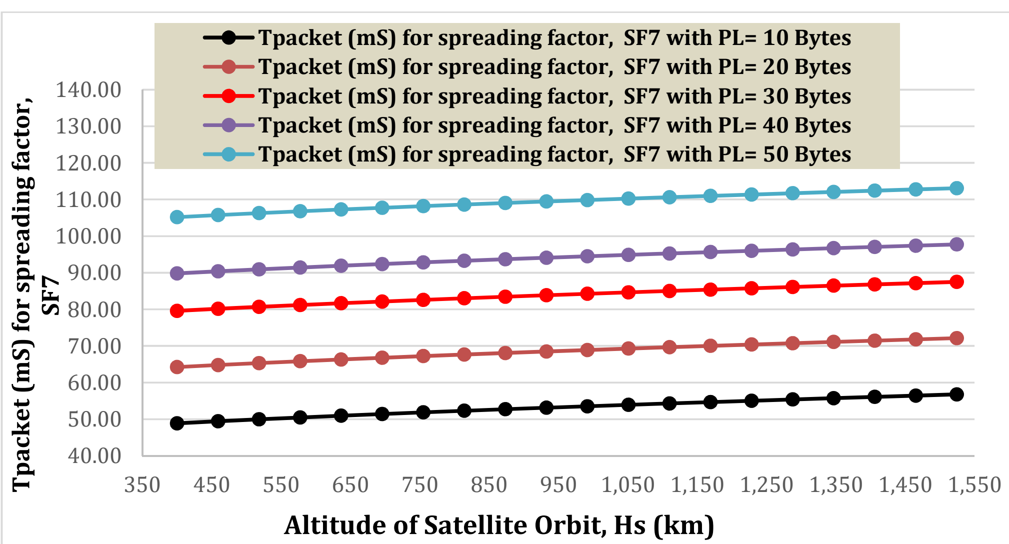

Figure 1 The graph of the packet transmission time versus altitude for SF 7 with payload size of 10 bytes to 50 bytes

Table 3 The results of the required transmission power for SF 7 with payload size of 10 bytes to 50 bytes

Altitude of Satellite Orbit, Hs (km)	Power (mW) for spreading factor, SF7 with PL= 10 Bytes	Power (mW) for spreading factor, SF7 with PL= 20 Bytes	Power (mW) for spreading factor, SF7 with PL= 30 Bytes	Power (mW) for spreading factor, SF7 with PL= 40 Bytes	Power (mW) for spreading factor, SF7 with PL= 50 Bytes
400.00	24.17	24.17	24.17	24.17	24.17
459.19	27.87	27.87	27.87	27.87	27.87
518.37	31.60	31.60	31.60	31.60	31.60
577.56	35.37	35.37	35.37	35.37	35.37
636.75	39.16	39.16	39.16	39.16	39.16
695.94	42.99	42.99	42.99	42.99	42.99
755.12	46.86	46.86	46.86	46.86	46.86
814.31	50.75	50.75	50.75	50.75	50.75
873.50	54.67	54.67	54.67	54.67	54.67
932.68	58.63	58.63	58.63	58.63	58.63
991.87	62.62	62.62	62.62	62.62	62.62
1051.06	66.65	66.65	66.65	66.65	66.65
1110.24	70.70	70.70	70.70	70.70	70.70
1169.43	74.79	74.79	74.79	74.79	74.79
1228.62	78.91	78.91	78.91	78.91	78.91
1287.81	83.06	83.06	83.06	83.06	83.06
1346.99	87.24	87.24	87.24	87.24	87.24
1406.18	91.46	91.46	91.46	91.46	91.46
1465.37	95.70	95.70	95.70	95.70	95.70
1524.55	100.00	100.00	100.00	100.00	100.00

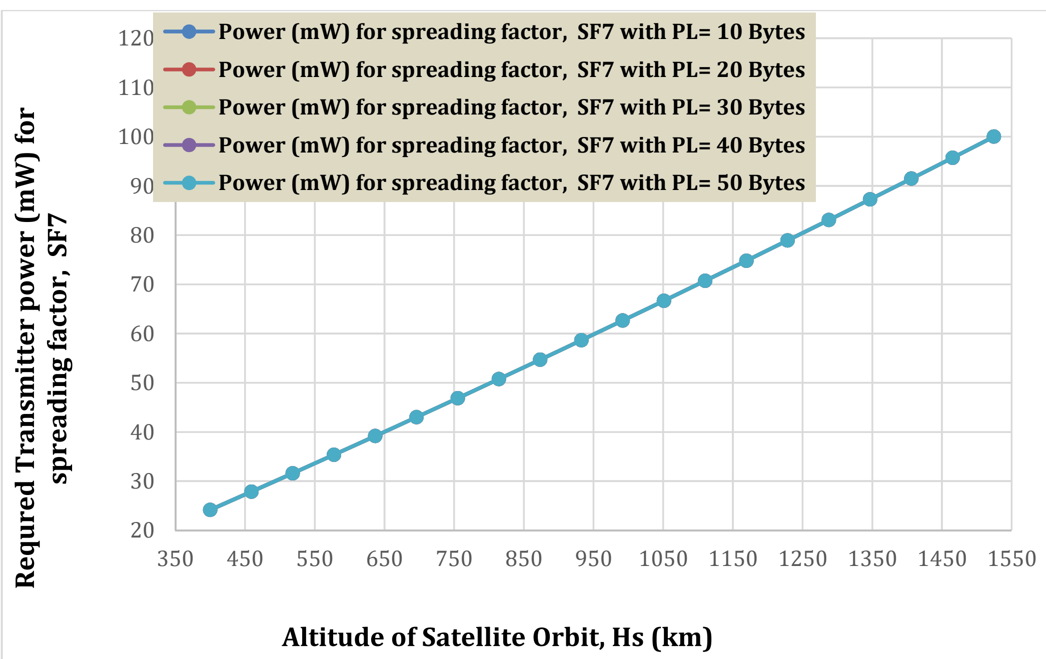

Figure 2 The graph of the required transmission power versus altitude for SF 7 with payload size of 10 bytes to 50 bytes

Table 4 The results of the transmitter energy consumption for SF 7 with payload size of 10 bytes to 50 bytes

Altitude of Satellite Orbit, Hs (km)	Energy (mJ) for spreading factor, SF7 with PL= 10 Bytes	Energy (mJ) for spreading factor, SF7 with PL= 20 Bytes	Energy (mJ) for spreading factor, SF7 with PL= 30 Bytes	Energy (mJ) for spreading factor, SF7 with PL= 40 Bytes	Energy (mJ) for spreading factor, SF7 with PL= 50 Bytes
400.00	1.18	1.55	1.92	2.17	2.54
459.19	1.38	1.81	2.23	2.52	2.95
518.37	1.58	2.06	2.55	2.87	3.36
577.56	1.78	2.33	2.87	3.23	3.78
636.75	2.00	2.60	3.20	3.60	4.20
695.94	2.21	2.87	3.53	3.97	4.63
755.12	2.43	3.15	3.87	4.35	5.07
814.31	2.65	3.43	4.21	4.73	5.51
873.50	2.88	3.72	4.56	5.12	5.96
932.68	3.11	4.02	4.92	5.52	6.42
991.87	3.35	4.31	5.28	5.92	6.88
1051.06	3.59	4.62	5.64	6.32	7.35
1110.24	3.84	4.92	6.01	6.73	7.82
1169.43	4.09	5.24	6.39	7.15	8.30
1228.62	4.34	5.55	6.77	7.57	8.79
1287.81	4.60	5.88	7.15	8.00	9.28
1346.99	4.86	6.20	7.54	8.44	9.78
1406.18	5.13	6.53	7.94	8.88	10.28
1465.37	5.40	6.87	8.34	9.32	10.79
1524.55	5.68	7.21	8.75	9.77	11.31

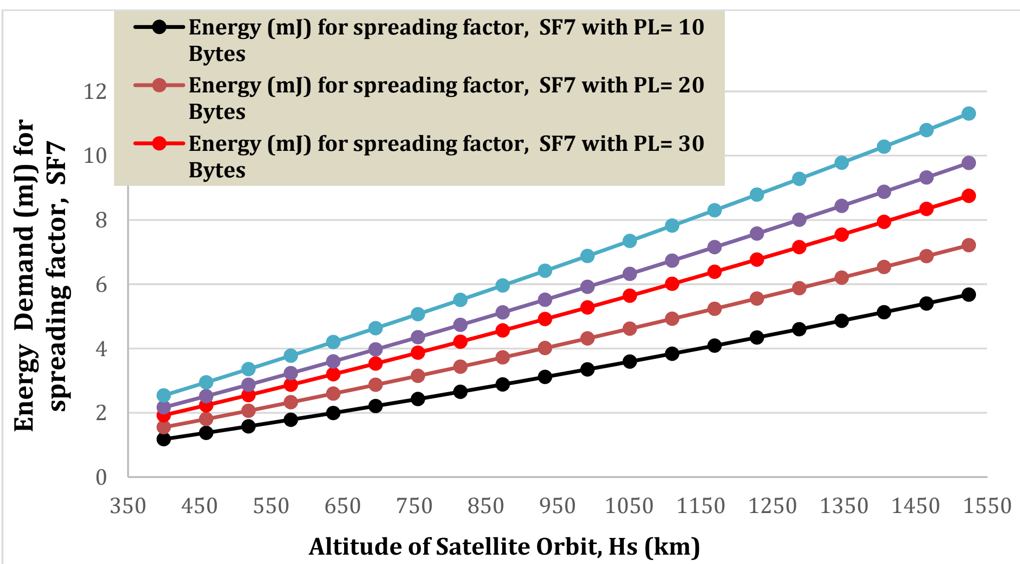

Figure 3 The graph of the transmitter energy consumption versus altitude for SF 7 with payload size of 10 bytes to 50 bytes

The results of the required packet transmission time for SF 7 to SF 12 with payload size of 50 bytes are given in Table 5 and Figure 4 while the results of the required transmission power for SF 7 to SF 12 with payload size of 50 bytes are given in Table 6 and Figure 5. Also, the results of the transmitter energy consumption for SF 7 to SF 12 with payload size of 50 bytes are given in Table 7 and Figure 6.

The results in Table 5 and Figure 4 show that for a given payload size and altitude of the satellite, the packet transmission time increases with increase in the spreading factor, with a value of 105.2 ms for the SF 7 at orbital altitude of 400 km to a value of 2309.6 ms for the SF 12 at the same orbital altitude of 400 km. Also, the results show that for a given payload size and altitude of the satellite, the required transmitter power decreases with increase in the spreading factor, with a value of 24.2 mW for the SF 7 at orbital altitude of 400 km to a value of 1.2 mW for the SF 12 at the same orbital altitude of 400 km. As such, the power required by the transceiver operating in the SF 12 is lower than the power required for SF 11. The SF7 has the highest power requirement for the given 50 bytes payload size. On the other hand, the results in Table 7 and Figure 6 show that for the given payload size of 50 bytes, the transmitter energy consumption was least for SF 10 .The transmitter energy consumption decreases from the value of 400 mJ for SF 7 to a value of 2.04 mJ for SF 10 and then increases to 2.54 mJ for SF 11 and further to 2.80 mJ for SF 12. Hence, the energy consumption is least for the SF 10 configuration of the LoRa transceiver.

Table 5 The results of the packet transmission time for SF 7 to SF 12 with payload size of 50 bytes

Altitude of Satellite Orbit, Hs (km)	Tpacket (ms) for spreading factor, SF7 with PL= 50 Bytes	Tpacket (ms) for spreading factor, SF8	Tpacket (ms) for spreading factor, SF9	Tpacket (ms) for spreading factor, SF10	Tpacket (ms) for spreading factor, SF11	Tpacket (ms) for spreading factor, SF12
400.0	105.2	182.2	336.4	624.1	1322.5	2309.6
459.2	105.7	182.8	336.9	624.7	1323.0	2310.2
518.4	106.3	183.3	337.4	625.2	1323.6	2310.7
577.6	106.8	183.8	338.0	625.7	1324.1	2311.2
636.7	107.3	184.3	338.4	626.2	1324.6	2311.7
695.9	107.7	184.8	338.9	626.6	1325.0	2312.2
755.1	108.2	185.2	339.4	627.1	1325.5	2312.6
814.3	108.6	185.7	339.8	627.5	1325.9	2313.0
873.5	109.0	186.1	340.2	627.9	1326.3	2313.5
932.7	109.4	186.5	340.6	628.4	1326.7	2313.9
991.9	109.8	186.9	341.0	628.8	1327.1	2314.3
1051.1	110.2	187.3	341.4	629.1	1327.5	2314.7
1110.2	110.6	187.7	341.8	629.5	1327.9	2315.0
1169.4	111.0	188.0	342.2	629.9	1328.3	2315.4
1228.6	111.4	188.4	342.5	630.3	1328.6	2315.8
1287.8	111.7	188.8	342.9	630.6	1329.0	2316.1
1347.0	112.1	189.1	343.2	631.0	1329.3	2316.5
1406.2	112.4	189.5	343.6	631.3	1329.7	2316.8
1465.4	112.8	189.8	343.9	631.7	1330.0	2317.2
1524.6	113.1	190.1	344.3	632.0	1330.4	2317.5

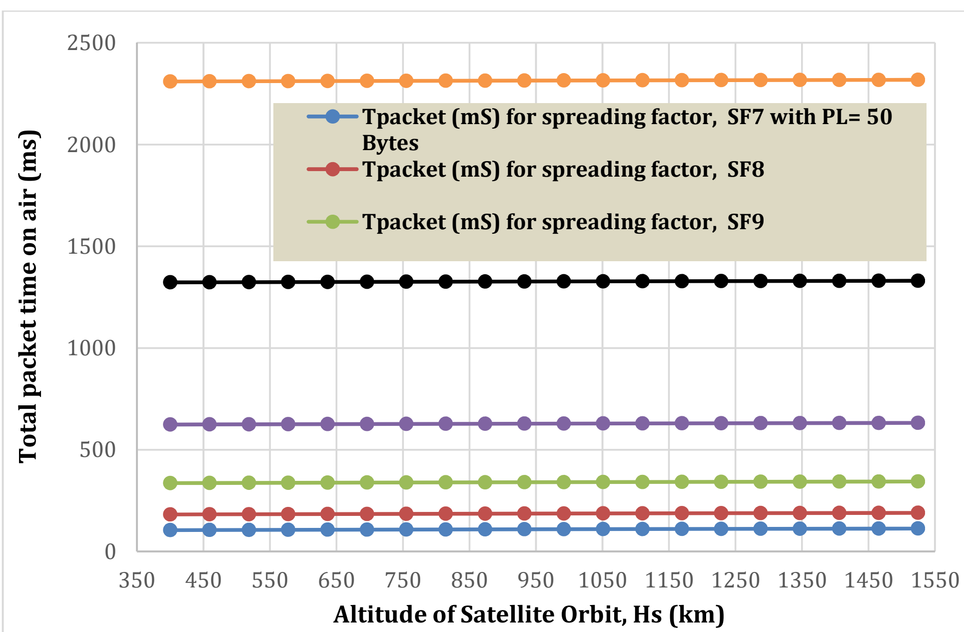

Figure 4 The graph of the packet transmission versus altitude for SF 7 to SF 12 with payload size of 50 bytes

Table 6 The results of the required transmission power for SF 7 to SF 12 with payload size of 50 bytes

Altitude of Satellite Orbit, Hs (km)	Power (mW) for spreading factor, SF7 with PL= 50 Bytes	Power (mW) for spreading factor, SF8	Power (mW) for spreading factor, SF9	Power (mW) for spreading factor, SF10	Power (mW) for spreading factor, SF11	Power (mW) for spreading factor, SF12
400.0	24.2	12.1	6.1	3.0	1.9	1.2
459.2	27.9	14.0	7.0	3.5	2.2	1.4
518.4	31.6	15.8	7.9	4.0	2.5	1.6
577.6	35.4	17.7	8.9	4.5	2.8	1.8
636.7	39.2	19.6	9.8	4.9	3.1	2.0
695.9	43.0	21.5	10.8	5.4	3.4	2.2
755.1	46.9	23.5	11.8	5.9	3.7	2.3
814.3	50.7	25.4	12.7	6.4	4.0	2.5
873.5	54.7	27.4	13.7	6.9	4.3	2.7
932.7	58.6	29.4	14.7	7.4	4.7	2.9
991.9	62.6	31.4	15.7	7.9	5.0	3.1
1051.1	66.6	33.4	16.7	8.4	5.3	3.3
1110.2	70.7	35.4	17.8	8.9	5.6	3.5
1169.4	74.8	37.5	18.8	9.4	5.9	3.7
1228.6	78.9	39.5	19.8	9.9	6.3	4.0
1287.8	83.1	41.6	20.9	10.5	6.6	4.2
1347.0	87.2	43.7	21.9	11.0	6.9	4.4
1406.2	91.5	45.8	23.0	11.5	7.3	4.6
1465.4	95.7	48.0	24.0	12.0	7.6	4.8
1524.6	100.0	50.1	25.1	12.6	7.9	5.0

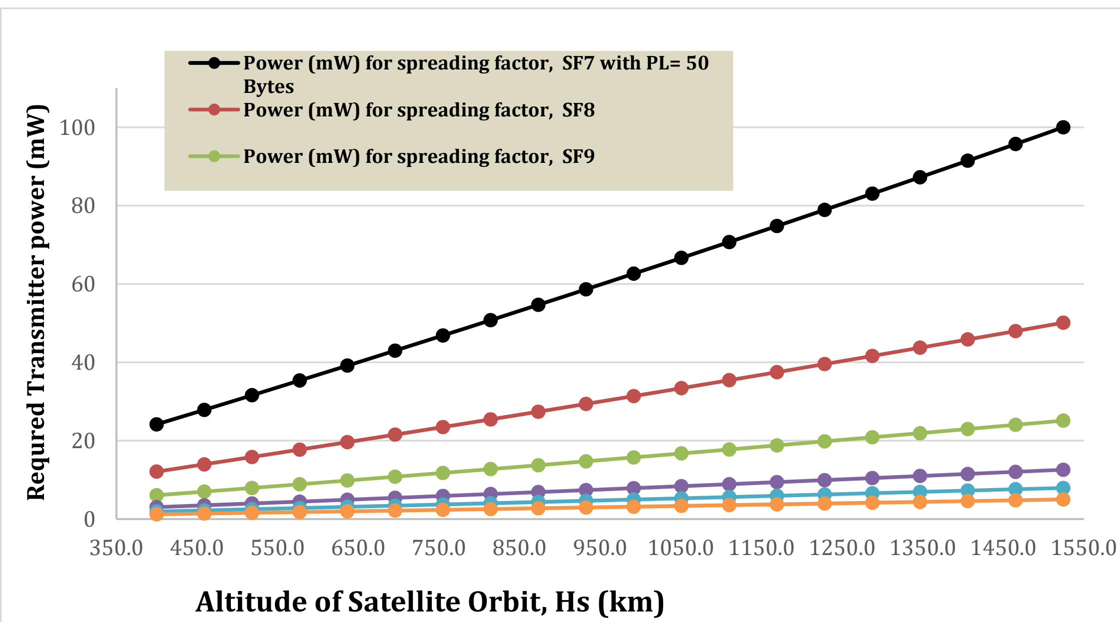

Figure 5 The graph of the required transmission power versus altitude for SF 7 to SF 12 with payload size of 50 bytes

Table 7 The results of the transmitter energy consumption for SF 7 to SF 12 with payload size of 50 bytes

Altitude of Satellite Orbit, Hs (km)	Energy (mJ) for spreading factor, SF7 with PL= 50 Bytes	Energy (mJ) for spreading factor, SF8	Energy (mJ) for spreading factor, SF9	Energy (mJ) for spreading factor, SF10	Energy (mJ) for spreading factor, SF11	Energy (mJ) for spreading factor, SF12
400.00	2.54	2.21	2.04	1.90	2.54	2.80
459.19	2.95	2.55	2.36	2.19	2.93	3.23
518.37	3.36	2.90	2.68	2.49	3.32	3.66
577.56	3.78	3.26	3.00	2.79	3.72	4.10
636.75	4.20	3.62	3.33	3.09	4.12	4.54
695.94	4.63	3.98	3.66	3.39	4.53	4.98
755.12	5.07	4.35	3.99	3.70	4.93	5.43
814.31	5.51	4.72	4.33	4.01	5.34	5.88
873.50	5.96	5.10	4.67	4.32	5.76	6.34
932.68	6.42	5.48	5.02	4.64	6.18	6.80
991.87	6.88	5.87	5.36	4.96	6.60	7.26
1051.06	7.35	6.26	5.72	5.28	7.03	7.73
1110.24	7.82	6.65	6.07	5.60	7.46	8.20
1169.43	8.30	7.05	6.43	5.93	7.89	8.68
1228.62	8.79	7.45	6.79	6.26	8.33	9.16
1287.81	9.28	7.86	7.15	6.59	8.77	9.64
1346.99	9.78	8.27	7.52	6.93	9.21	10.13
1406.18	10.28	8.68	7.89	7.27	9.66	10.62
1465.37	10.79	9.10	8.27	7.61	10.11	11.11
1524.55	11.31	9.53	8.65	7.96	10.57	11.61

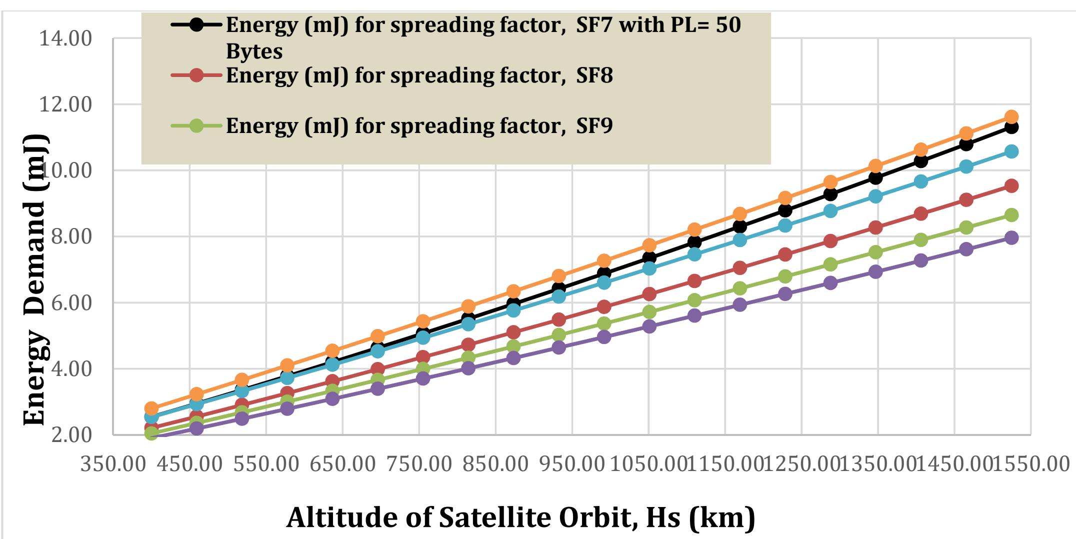

Figure 6 The graph of the transmitter energy consumption versus altitude for SF 7 to SF 12 with payload size of 50 bytes

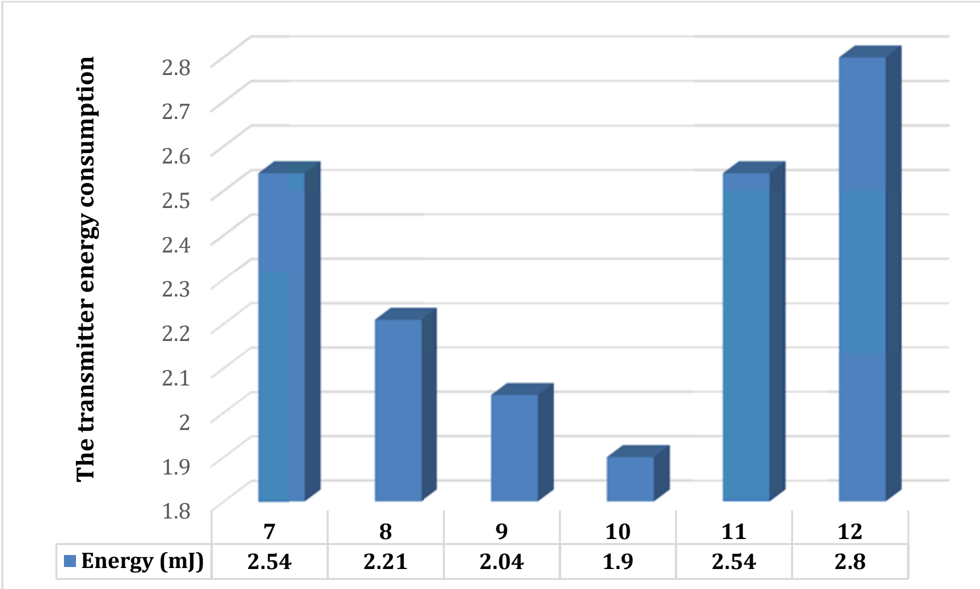

Figure 7 The bar chart of the transmitter energy consumption for satellite altitude of 400 km for SF 7 to SF 12 with payload size of 50 bytes

4. Conclusion

The approach for determination of the transmission time, the required transmitter power and the energy consumption of a LoRa transceiver used in earth to satellite communication link is presented. The analysis focused on the low earth orbit satellite and for small payload sizes of less about 50 bytes. The study compared the variations in the transmission time of packets, as well as the power and energy demand with the spreading factors of the LoRa transceiver. The results show that the transmission time increases with the spreading factor, the transmission power decreases with the spreading factor, while the transmission energy consumption is least at the middle SF of 10 and is highest at the lowest and the highest SF values of 7 and 12. The results will enable LoRa-based sensor network designers in selecting appropriate LoRa configurations that will ensure effective communications.

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