

PAPER 141 – COMMUNICATION RANGE ASSESSMENT OF LORA-BASED IOT SENSOR NODE FOR SMART CITY APPLICATIONS

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ABSTRACT

In this paper, communication range assessment of LoRa-based IoT sensor node for smart city application is presented. Specifically, the effect of Degree of Urbanisation (DoU), payload size and bit error probability (BEP) on the sensor node communication range are considered. Semtech SX1272 LoRa transceiver operating in the EU868 (863–870/873 MHz) frequency band with spreading factor of 12 and transmitter power of 13 dBm, was used for numerical computations using Visual Basic for Applications (VBA) as implementation tool. The results show that for rural area with building coverage of 3 %, the communication range are 16.854 km and 16.338 km while BEP are 5.186×10^{-04} and 1.307×10^{-04} at payload size of 5 bytes and 51 bytes respectively. Similarly, DoU corresponding to urban area with building coverage of 16 %, gave communication range of 4.994 km and 4.841 km with BEP of 5.186×10^{-04} and 1.307×10^{-04} at payload size of 5 bytes and 51 bytes respectively. Specifically, based on the results, a minimum payload size of 26 bytes was selected and it has transmission range of 16.519 km for PB of 3 %, 8.100 km for PB of 8 % and 4.895 km for PB of 16 %. In any case, although the lower payload size gives higher communication range, small payload size requires higher percentage of overhead bits and also has higher bit error rate which leads to lower data delivery success ratio. As such, in practice, careful compromise is required between payload size and communication range.

KEYWORDS: Bit Error Probability, Communication Range, LoRa, Sensor node, Internet of Things, Smart City Application

1. INTRODUCTION

Nowadays, advancements in embedded systems, sensors, communication and Internet technologies have given rise to proliferation of smart systems for diverse applications such as smart agriculture, smart homes, smart transportation system and smart city applications [1,2]. Particularly, smart city applications require deployment of sensor nodes with requisite wireless communication capabilities that will enable data collection from various locations within the area of interest. Such wireless sensor network coverage is dependent on several factors and mostly propagation loss models are used to estimate the communication range [3,4].

Notably, in wireless sensor communication applications, long range (LoRa) transceiver technologies are popular because of their low power consumption and long range communication capability [5,6]. Also, for LoRa transceivers, apart from the environmental factors which are captured in the propagation model, the communication range is also affected by the payload size. As such, determination of the achievable communication range for a LoRa-based sensor node requires careful selection of the payload size for any give set of LoRa sensor node parameter configuration. Accordingly, this paper presents the requisite analytical models and algorithm that can be used to determine the communication range of LoRa-based IoT sensor node for smart city applications. Particularly, the paper presented approaches to select the minimum payload size that can be used to achieve a given communication range while satisfying the required sensor data capacity and duty cycle requirements. Sample numerical computations are implemented using Visual Basic for Applications (VBA).

2. METHODOLOGY

In this section, analytical expressions for computing the sensor node bit error rate and transmission range based on expected data delivery success ratio and Comit'e International des Radio-Communication (CCIR) path loss model are presented. According to [7] energy per useful (payload) bit or energy efficiency, EC_{ppldb} for a sensor node is given as;

$$EC_{ppldb} = \frac{(I_{avg})(V)(t_{cycl})}{B_{pldb}} \quad (1)$$

where I_{avg} is the average current drawn per cycle, V is the operating voltage and t_{cycl} is the cycle time of the sensor node. Also, according to [7], B_{pldb} is the fraction of the payload data that is successfully delivered and it is given as;

$$B_{pldb} = (B_{pavl}) \left((1 - BER) \left(\left(\frac{E}{4} \right)^{(B_{dataL} - B_{headL})} \right) \right) (1 - P_{coll}) \quad (2)$$

where B_{payL} is the actual payload data size; B_{pldb} is the portion of the payload data that is successfully delivered, B_{dataL} is the total size of the data packet including the payload and the header bits, B_{headL} is the packet header which is 20-bits and R_{succ} is the data delivery success ratio, where R_{succ} is given as,

$$R_{succ} = \frac{B_{pldb}}{B_{payL}} = \left((1 - BER) \left(\left(\frac{5}{4} \right)^{(B_{dataL} - B_{headL})} \right) \right) (1 - P_{coll}) \quad (3)$$

where P_{coll} is the probability of packet collision at the media access control layer. Notably, the concept of data delivery success ratio, R_{succ} is used to sum up the impact of packet collision probability (P_{coll}) that occurs due to the media access control protocol and the packet loss that occur due to error which is captured using the bit error probability (BER, also referred to as bit error rate, BER), where;

$$BER = 1 - \left(\left[\frac{R_{succ}}{(1 - P_{coll})} \right] \left(\left(\frac{5}{4} \right)^{(B_{dataL} - B_{headL})} \right)^{-1} \right) \quad (4)$$

For LoRa transceiver with spreading factor, SF and bit error rate, BER, the operating energy per bit to noise power spectral density, E_b/N_o is computed as follows;

$$E_b/N_o = \frac{erf^{-1}(1 - 2(BER))}{\left(\frac{\log_{12}(SF)}{\sqrt{2}} \right)} \quad (5)$$

The value of E_b/N_o expressed in dB is denoted as $\left. \frac{E_b}{N_o} \right|_{dB}$, where;

$$\left. \frac{E_b}{N_o} \right|_{dB} = 10 \log \left(\frac{E_b}{N_o} \right) \quad (6)$$

In order to determine the LoRa transceiver Operating Link Margin, OLM, the required signal to noise ratio, SNR_{rq} is needed and it is given as;

$$SNR_{rq} = S_{sensitivity} + 174 - 10 \log_{10}(BW) - NF \quad (7)$$

where $S_{sensitivity}$ the LoRa receiver sensitivity, BW is the bandwidth and NF is the noise figure. The operating signal to noise ratio, SNR_{op} is given as;

$$SNR_{op} = \left. \frac{E_b}{N_o} \right|_{dB} + 10 \log_{10}(SF) + 10 \log_{10} \left(\frac{4}{4 + CR} \right) - 10 \log_{10}(2^{SF}) \quad (8)$$

where CR is the coding rate. The Operating Link Margin, OLM is equal to $SNR_{op} - NR_{rq}$. The achievable transmission range (d) for a LoRa transceiver based on Comit'e International des Radio-Communication (CCIR) path loss model is defined as follows;

$$d = 10^{\left(\frac{P_t - S_{sensitivity} - (SNR_{op} - SNR_{rq}) - A + DoU}{B} \right)} \quad (9)$$

where

$$A = 69.55 + 26.16 * \log_{10}(f) - 13.82 * \log_{10}(h_b) - a(h_m) \quad (10)$$

$$a(h_m) = [1.1 * \log_{10}(f) - 0.7] * h_m - [1.56 * \log_{10}(f) - 0.8] \quad (11)$$

$$B = 44.9 - 6.55 * \log_{10}(h_b) \quad (12)$$

$$DoU = 30 - 25(\log_{10}(PB)) \quad (13)$$

where P_t represents the transmitter power in dBm, DoU represents the degree of urbanization and PB represents the percentage of the signal propagation area that is covered by building (note, PB is the degree of urbanization determining factor). The value of PB is such that $PB \geq 16\%$ for urban area, $PB < 16\%$ for sub-urban area (with typical value of $PB = 8\%$) and $PB < 8\%$ for rural area (with typical value of $PB = 3\%$). Also, d is the communication distance in km and f is the frequency in MHz, where $150 \text{ MHz} \leq f \leq 1000 \text{ MHz}$; $40 \text{ m} \leq h_b \leq 200 \text{ m}$; $1 \text{ m} \leq h_m \leq 10 \text{ m}$ and $1 \text{ km} \leq d \leq 20 \text{ km}$.

3. SIMULATION PROCEDURE AND INPUT DATASET

The algorithm for computing the sensor node bit error rate (BER), and transmission range (d) based on expected data delivery success ratio (R_{succ}) is presented in Procedure 1. The use case multisensor node adopted for the simulation has four sensors comprising of MQ-4 natural gas and methane (CH4) sensor, MQ-7 carbon monoxide (CO) sensor, DS 18S20 temperature sensor and Sensirion DS 18S20 relative humidity sensor. As regards the transceiver and microcontroller, the WM-SG-SM-42 LoRa module [8,9] which consist of Semtech SX1272 LoRa transceiver and STMicro STM32L0 series 32 bit microcontroller unit (MCU) was used. Specifically, the Semtech SX1272 LoRa transceiver operating in the EU868 (863–870/873 MHz) frequency band with spreading factor of 12 was used for the numerical computations implemented using Visual Basic for Applications (VBA). Other data input for the simulation includes: the bandwidth, $BW=125 \text{ KHz}$; the Code Rate, $CR=1$; the transmitter power (P_t) = 13 dBm; the signal frequency, $f = 863 \text{ MHz}$; the payload size, $B_{payL} = 5 \text{ bytes to } 51 \text{ bytes}$; packet collision probability, $P_{coll} = 0$; the total data frame header size, $B_{headL} = 20 \text{ bits}$; the degree of urbanization determining factor, PB, 3% for rural area, 8% for sub-urban area and 16% for urban area; LoRa transceiver sensitivity,

$S_{sensitivity} = -137$ dBm; data delivery success ratio, $R_{Succ} = 0.99$ and the Noise Figure, $NF = 6$. For every payload, B_{payL} in bytes the overhead size is 13 bytes, hence, the total size of the data packet including the payload and the header, B_{dataL} is given as;

$$B_{dataL} = B_{payL} + 13 \quad (14)$$

PROCEDURE 1: The algorithm for computing the sensor node bit error rate (BER), packet loss probability (Ploss), operating link margin (OLM) and transmission range (d) based on expected data delivery success ratio (R_{Succ})

Step 1: Input the following LoRa-based sensor node parameters values:

- | | |
|--|--|
| i. The Bandwidth, BW | ii. The total data frame header size, B_{headL} |
| iii. The Code Rate, CR | iv. The degree of urbanization determining factor, PB |
| v. The transmitter power (P_t) | vi. The total data frame size, $B_{dataL} = B_{payL} + 13$ |
| vii. The signal frequency, f | viii. Lora Transceiver Sensitivity, $S_{sensitivity}$ |
| ix. The total payload size, B_{payL} | x. Data delivery success ratio, R_{Succ} |
| xi. Packet collision probability, P_{coll} | xii. The Noise Figure, NF (Note, $NF = 6$) |

Step 2: Set LoRa modulation spreading factor, SF =12

Step 3: Compute the successfully delivered payload data, $B_{pldb} = (R_{Succ})B_{payL}$

Step 4: Compute the Packet Loss Probability (P_{Loss}): $P_{loss} = 1 - \left(\frac{R_{Succ}}{1-P_{coll}}\right)$

Step 5: Compute the sensor node bit error rate (BER):

$$\text{Step 6 BER} = 1 - \left(\left[\frac{R_{Succ}}{1-P_{coll}} \right] \left(\frac{5}{4} \right)^{(B_{dataL}-B_{headL})} \right)^{-1}$$

Step 7 $SNR_{rq} = S_{sensitivity} + 174 - 10 \log_{10}(BW) - NF$

$$\text{Step 8: } \frac{E_b}{N_o} = \frac{\text{erftnv}(1-2(BER))}{\left(\frac{\log_{12}(SF)}{\sqrt{2}}\right)}$$

$$\text{Step 9: } \frac{E_b}{N_o} \Big|_{dB} = 10 \text{Log} \left(\frac{E_b}{N_o} \right)$$

$$\text{Step 10: } SNR_{op} = \frac{E_b}{N_o} \Big|_{dB} + 10 \log_{10}(SF) + 10 \log_{10} \left(\frac{4}{4+CR} \right) - 10 \log_{10}(2^{SF})$$

Step 11: OLM = $SNR_{op} - SNR_{rq}$

Step 12: $A = 69.55 + 26.16 * \log_{10}(f) - 13.82 * \log_{10}(h_b) - a(h_m)$

Step 13: $a(h_m) = [1.1 * \log_{10}(f) - 0.7] * h_m - [1.56 * \log_{10}(f) - 0.8]$

Step 14: $B = 44.9 - 6.55 * \log_{10}(h_b)$

Step 15: DoU = $30 - 25(\log_{10}(PB))$

$$\text{Step 16: } d = 10^{\left(\frac{P_t - S_{sensitivity} - OLM - A + DoU}{B} \right)}$$

Step 17: Output B_{payL} , R_{Succ} , B_{pldb} , P_{loss} , BER, OLM, d

Step 18: Stop

Furthermore, based on the selected parameter settings of the four sensors in the multisensor node used in the simulation, the multisensor node generates 206 bytes per cycle with cycle time of 30 minutes or 1800 seconds (1,800,000 ms). The simulation is conducted for the following payload sizes 5, 11, 21, 31, 41 and 51 bytes and the corresponding packet time on air for each payload size is determined. Also, for each payload size, the number of transmission required per cycle to effectively transmit all the 206 data bytes generated per cycle by the multisensor is determined. Notably, the transmission repeat time is selected based on the packet time on air for the given payload size, the number of required transmission per cycle for delivering the 206 bytes in 1800 seconds and the 1 % duty cycle restriction imposed on LoRa transceiver technologies. The essence of the simulation is to determine the bit error rate (BER) and transmission range (d) for a given expected data delivery success ratio (R_{Succ}) and payload size, as well as the number of payload transmissions required per sensor node cycle time of 1800 seconds and the percentage of overhead bits per payload size. The results are required to make informed decision on the selection of the minimum payload size for any desired communication range.

Let PToA(k) denote the packet time on air for payload size k. The PToA for each of the payload size is computed using an online tool located at <https://avbentem.github.io/airtime-calculator/ttn/eu868>. Again, let ntrx_TTLPLD be the required number of transmissions to deliver all the 206 bytes generated by the sensor node per cycle and let trxcycle_TTLPLD in seconds be the required transmission cycle time if ntrx_TTLPLD transmissions are to be carried out in the 1800 seconds sensor node cycle time. Then;

$$ntrx_TTLPLD = 206 \text{ bytes} / \text{Payload size in bytes} \quad (15)$$

$$trxcycle_TTLPLD \text{ in seconds} = 1800 \text{ s} / (206 \text{ bytes} / \text{Payload size in bytes}) \quad (16)$$

Also, let $trxcycle_PToA \ \&DC$ in seconds be the required transmission cycle time if the payload size with packet time on air ($PToA$ in seconds) is used for the transmission and let $ntrx_PToA \ \&DC$ be the required number of transmissions to deliver all the 206 bytes if the $trxcycle_PToA \ \&DC$ in seconds transmission cycle time is used. Then;

$$trxcycle_PToA \ \&DC \text{ in seconds} = 100 * PToA \text{ in seconds} \quad (17)$$

$$ntrx_PToA \ \&DC = 1800 \text{ seconds} / (100 * PToA \text{ in seconds}) \quad (18)$$

Any payload size for which $trxcycle_PToA \ \&DC \leq trxcycle_TTLPLD$ is appropriate for the sensor node.

Likewise, any payload size for which $ntrx_TTLPLD \ \& \leq ntrx_PToA \ \&DC$ is also considered appropriate for the sensor node.

4. RESULTS AND DISCUSSION

The simulation results for the transmission cycle time and number of required transmissions per sensor node cycle time of 1800 seconds and payload size are shown in Figure 1 and Figure 2. Notably, in Figure 2, payload sizes that have transmission cycle time based on total payload per cycle ($trxcycle_TTLPLD$) greater or equal to the transmission cycle time based on packet time on air and duty cycle ($trxcycle_PToA \ \&DC$) are selected as those that can be used for the use case multisensor node. Those are the payload sizes that can deliver the total of 206 bytes generated by multisensor node in each sensor node cycle time of 1800 seconds and also satisfy the 1% duty cycle restriction. Accordingly, payload size of 26 and above can be used for the use case multisensor node since such payload sizes will satisfy both the duty cycle requirement and the total number of payload data required to be transmitted in the given multisensor cycle time.

Again, the simulation results for the transmission range, d and bit error probability, BER , versus payload size in byte are shown in Figure 3. The results showed that the transmission range decreases as the payload size increases. Particularly, the highest transmission range of 16.854 km occurred for payload size of 5 bytes operated in the rural area with urbanisation determining factor of 3 % whereas the same payload size has transmission range of 16.338 km in the same rural area for a payload size of 51 bytes. Also, the transmission range decreases as the degree of urbanization determining factor, PB increases from 3% for the rural area to 16 % for the urban area. Specifically, the maximum transmission range for $PB = 8 \%$ is 8.264 km while that of $PB = 16 \%$ is 4.994 km for payload size of 5 bytes.

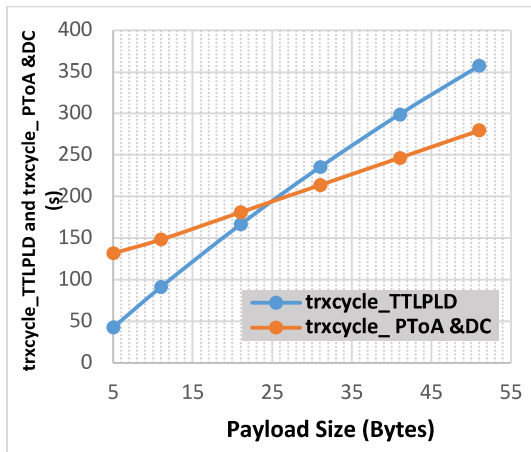


Fig 1: Transmission cycle time based on total payload per cycle ($trxcycle_TTLPLD$) and transmission cycle time based on packet time on air and duty cycle ($trxcycle_PToA \ \&DC$) versus payload size

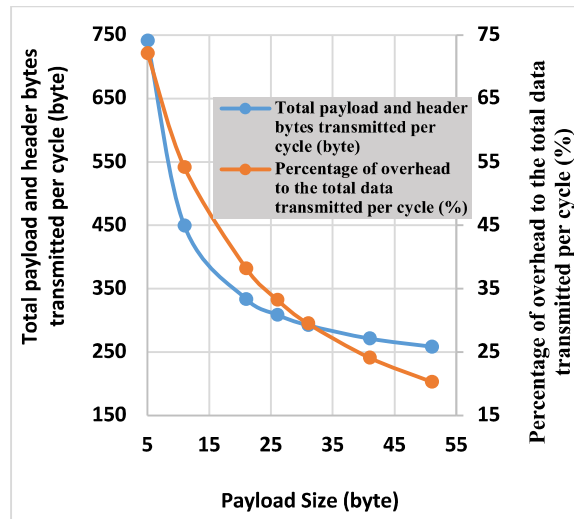


Fig 2: Total payload and header bytes transmitted per cycle and Percentage of overhead to the total data transmitted per cycle

Furthermore, based on the results in Figure 2, the minimum payload size that can be applied in the use case multisensor node is 26 and this gives a transmission range of 16.519 km for $PB = 3 \%$, 8.100 km for $PB = 8 \%$, and 4.895 km for $PB = 16 \%$. In any case, while the smaller payload size has higher transmission range, the bit error probability (BER), as shown in Figure 3 and the percentage of overhead bits, as shown in Figure 2 are highest for the smallest payload size. In essence, while small payload size can give longer transmission range, it also has very high bit error rate or bit error probability which will lead to higher probability of packet loss due to error and

hence the need to retransmit the packet. Such retransmission of packet will required additional time and energy consumption in the sensor node. In addition, the total number of data bytes (including the payload and overhead bits) transmitted per cycle is highest (741.6 bytes) for the smallest payload size of 5 bytes and the percentage overhead bit is 72.2 % whereas the total data bytes transmitted for payload size of 51 bytes is 258.5 bytes and the percentage overhead bit is 20.3 %.

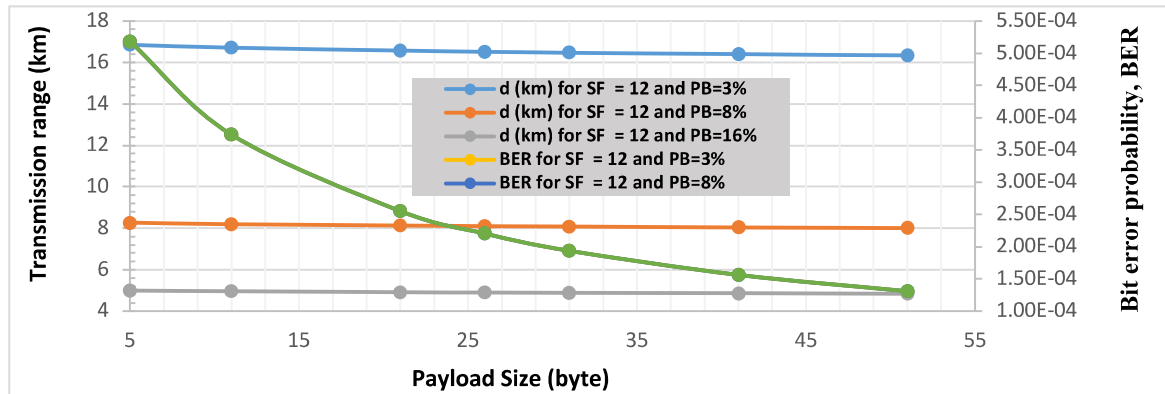


Fig 3: Transmission range (km) and bit error probability, BER, versus payload size in byte

5. CONCLUSION

Analytical expressions and algorithm for computing LoRa-based Internet of Things (IoT) sensor node bit error rate and transmission range based on expected data delivery success ratio and Comité International des Radio-Communication (CCIR) path loss model are presented. Also, presented are analytical expressions for determining the number of transmissions required per sensor node cycle and the transmission cycle time required for the LoRa transceiver, as well as the percentage of overhead bits for any given payload size. In all, the results show that the transmission range is inversely related to the payload size; the transmission range decreases as the payload size increases. Similarly, the bit error probability and percentage of overhead bits to the total transmitted data packets per cycle decrease with increase in payload size. Essentially, small payload size can be used to achieve higher transmission range, but its downside is that it is more susceptible to bit error and also more overhead bits are transmitted which will require higher energy consumption in the sensor node. As such, in practice, careful compromise is required between the payload size and desired transmission range.

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