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Performance Comparison of Several LPWAN Technologies for Energy Constrained IOT Network

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***Abstract*:** Energy efficiency is a contentious issue that may profit greatly from the adoption of the IoT paradigm, which provides the possibility to properly control a city's energy consumption. Furthermore, the Internet of Things may assist in identifying all entities that negatively impact urban energy usage and assisting authorities in developing measures to enhance their behaviours. Energy efficiency is of a very high interest if we talk about wireless sensor networks like LPWAN's to deal with the ongoing rise of energy-demanding applications in scenarios with limited energy resources, such as smart cities, etc. Thus to deploy an energy efficient smart city application has a great scope in urban or dense geographical areas and the study of the research will lead to the optimization of energy consumption. Here in this paper performance comparison of various LPWAN technologies are done and also it compares the path loss of each technology thus calculating the energy per bit.

Keywords: *LPWAN, LoRaWAN, Propagation Models, Energy per bit.*

1. Introduction

IoT & Smart City implementations are accelerating advances and study in wireless communication networks for long-range and low-power. Initially, Wireless Sensor Network (WSN) implementations were making use of customized hardware and protocols to enable connectivity. Developments in this region give birth to a new form of wireless networking network, the LPWANs [1]. As per the Ericson mobility report it was marked that by 2022, over 29 billion devices will be linked via wireless technology. There are several short range wireless technologies such as Zigbee, Bluetooth etc which were being used for IoT connectivity. These networks are being built competitively by various providers; in fact it is expected that around 31% of communications between IoT devices are expected to use LPWA wireless technologies by 2021[2].

LPWAN technologies recently launched are further explored by two parties, i.e. 3GPP [3rd generation partnership project group] which consists of NB-IoT and LTE (Long term evaluation) Cat-M1, and others implemented by non-3GPP which come under third parties consists of Sigfox and LoRaWAN, will be the primary IoT enablers.[3] .The global fame achieved by LPWAN is due to its low capacity, long distance and low communications costs. LPWAN are capable of providing high energy efficiency up to 10-15 Km in rural areas and 2-5 Km in urban areas [4][5].

This paper describes the comparison of all the three LPWAN technologies in terms of physical characteristics, technological variations and IoT performance factors (QoS), coverage, range, latency, battery life, scalability, payload length, distribution and cost. It includes the comparison of different propagation models in different scenarios for Sigfox, LoRa and NB-IoT.

Further the paper is organised as follows Section II considers the theoretical difference of all three LPWAN technologies. Section III consists of different propagation models in different scenarios. Section IV will give information regarding the LoRa energy calculations. Section V will be having the results and discussions followed by conclusion.

2. Overview of LPWAN Technologies

A brief description of the LPWAN technologies is mentioned in this section. LoRaWAN is an open standard that works in an ISM band, Sigfox gives the greatest coverage of Europe standards & NB-IoT operates in licensed spectrum. The summary of parameters of LPWAN technologies is presented in Table 1.

A.Sigfox

The bandwidth for this technology is 200 kHz in the ISM range and is dependent on the field with a central frequency of 868 or 915 MHz. This let Sigfox to have a distance of more than 10 km with capacity of 100 or 600bps as maximum depending on a bandwidth used for messaging [3].

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Sigfox runs on an operator model - consumers buy end-users and regional Sigfox-supported networks run by network operators and use a web portal or call-back to access info.

B.NB-IoT

NB-IoT (Narrow Band Internet of Things) is derived from the mainstream long term evolution LTE, which is substantially similar in numerology and infrastructure. NB-IoT has a strong combination success with current 3GPP technology, but is not completely backward compatible. In general, NB-IoT modifies LTE in return for relaxed latency, a faster data rate and lower spectrum performance to achieve improved coverage and decreased power usage [20][25-28]. The hardware supports 13 frequency ranges from 700 MHz to 2100 MHz, along with four and seven additional ranges. It relies on just half-duplex transmission with Frequency Duplex division (FDD). The following operating modes are possible with NB-IoT frequency band range,

1. Stand-alone operation: the use of GSM frequency bands commonly used may be a potential scenario.
2. Band of guard operations: usage of idle blocks of resources within the guard band of LTE carrier.
3. In-band operation: the use of LTE carrier resource blocks [19][36].

C.LoRaWAN

LoRa is developed by semtech and is termed as a technology which works in the physical layer, the modulation technique used in LoRaWAN is a type of Spread Spectrum known as CSS (chirp spread spectrum) with the facility of error correction (FEC). LoRaWAN is known for the well supported protocol in the top most layers [21][29-33] & is most commonly used technology. It is because firstly, LoRaWAN is an open standard that operates in the sub-GHz unlicensed ISM radio bands, secondly LoRa terminals and gateways are readily accessible on a commercial basis and lastly, it is practically possible to mount and manage LoRaWAN cells anywhere and everywhere [6][34][35].

Table 1. Summarised the different parameters of LPWAN technologies (Source: [1], [2],[3],[8],[12],[19])

Comparison Parameters	**Sigfox**	**LoRaWAN**	**NB-IoT**
Technique used for modulation	Binary Phase Shift Keying (BPSK)	Chirp Spread Spectrum (CSS)	Quadrature Phase Shift Keying (QPSK)
Coverage (MCL)	162 dB	157 dB	164 dB
Technology	Proprietary	Proprietary (Physical layer), Open (MAC layer)	Open LTE
Spectrum allotted	Unlicensed	Unlicensed	Licensed
Operating frequencies	868MHz , 915 MHz	433MHz, 868MHz, 915 MHz	700MHz - 2100 MHz
Band of operation (BW)	100Hz, 600 Hz	125KHz, 250KHz, 500 KHz	200 KHz
Max, ERP	14 dBm^2	14 dBm^2	23 dBm^2
Speed of downlink	0.61 kbps	0.3-50.0 kbps	0.5- 27.1 kbps
Speed of uplink	0.1kbps – 0.61 kbps	0.3kbps-50.0 kbps	0.3kbps-62.5 kbps
Uplink message size	12 Bytes	242 Bytes	1600 Bytes
downlink message size	8 Bytes	242 Bytes	1600 Bytes
Life time of Battery	More than 10	More than 10	More than 10
Cost of single module	3 $	6 $	12 $
Security	AES-128	AES-128	LTE security
Allow private network	No	Yes	No
Range (urban) Range (rural)	10km 40km	5 km 20km	1km 10km

From all different LPWAN technologies LoRaWAN is the one which achieves the low cost, long range & is power efficient and is always ready to give the finest possible performance. It uses star topology being an asymmetrical protocol, where all the computers are directly connected to the gateway that further communicates with the network server of LoRaWAN, which serves as a network controller. Owing to three separate computer capacities the devices can be of three types [6][7][37].

The base class Class A uses a random set of frequency channels for pure ALOHA channel control. After each uplink a computer is opened for downlink messages from the net server in two receiving windows. These are energy restricted devices with twofold connectivity but with much reduced power and are also meant for restricted devices. Class A consumes fewer resources than class B and class C. End devices here are controlled by batteries. Class B devices also synchronize with the net server via beacons and regularly open receiving windows. Class B specifies a scheduling system for machinery to get enhanced drop-down alerts, resulting in an extra expenditure of resources. End devices are normally controlled by batteries like in Class A. Class C devices are normally operated by the hand and receive the radio when they do not transmit. Finally, and though applications communicate, Class C permits the transmission windows to be open such that low-latency connectivity is accomplished. End devices are generally powered by mains (Electricity) [6][7][38][39].

LoRaWAN MAC uses two modes, dividing airtime between terminals for collision handling. The first mode is the ALOHA MAC that enables terminal devices to pass on as soon as they wake up and when crashes occur, they are exponentially back-off. The second mode is the TDMA scheduling system where each device will send its messages by setting a network server time-slot [8][40][41].

3. Propagation Models

The proposed multiple wireless technology propagation models come from three key sources: i) standards, ii) suppliers/operators and, iii) academies. Emphasis is on models of propagation that span the whole operational range of the three LPWAN standards employed in this study. It operates on the frequency band between 433 and 2100 MHz, Table 2 summarizes the five most often used propagation models and their fundamental parameters.3GPP Model [14] represents the standardization group. An example of a vendor category is the Ericsson propagation model [16']. Finally, two well recognized research attempts in this field have been established in the interim Okumura-Hata[10][47] and Stanford University (SUI) propagation models [12][42-46].

The Table 2 consists of following parameters where, h_b is considered as antenna height of Base Station, h_r is considered to be antenna height of End Devices, The distance between BS and ED is denoted by d, while the carrier frequency is denoted by f. Path Loss id denoted by L. The comparison is between four famous models namely, 3GPP, SUI, Okumara Hata and Ericsson. Here the antenna heights are in meters and distance between Base station and end device antenna is in kilometres and operating frequency range is dependent upon the technique used.

Table 2. Propagation Model and their basic parameters

<table>
<tr><th>Propagation Model</th><th>Operating Frequency</th><th>Base station Antenna Height</th><th>End Device Antenna Height</th><th>Base station to End device distance (d)</th><th>Path Loss (L)</th></tr>
<tr><td>3GPP</td><td><2600 MHz</td><td>0-50m</td><td>-</td><td><8km</td><td>$L = 40\left(1-(4\times h_b\times 10^{-3})\right)\log_{10} d - 18\log_{10} h_b + 21\log_{10} f + 80$</td></tr>
<tr><td>SUI</td><td><11000 MHz</td><td>15-40m</td><td>2-10m</td><td><10km</td><td>$L = A + 10\Upsilon\log_{10}(d/d_o) + \Delta L_{bf} + \Delta L_{bh}$
when $d > d_o'$
$d_o' = d_o * 10^{-\{X\}}$
$X = (\Delta L_{bf} + \Delta L_{bh}) / 10\,\Upsilon$
$\Upsilon = a - bh_b + c\,h_b$
$A = 20\log_{10}(4\pi d_o' / \lambda)$
<table>
<tr><th>Terrain Category</th><th>A</th><th>B</th><th>C</th></tr>
<tr><td>a</td><td>4.6</td><td>4.0</td><td>3.6</td></tr>
<tr><td>b</td><td>0.0075</td><td>0.0065</td><td>0.005</td></tr>
<tr><td>c</td><td>12.6</td><td>17.1</td><td>20</td></tr>
</table></td></tr>
<tr><td>Okumara-Hata</td><td>150-1900 MHz</td><td>30-200m</td><td>1-10m</td><td>1-20km</td><td>$L = 69.55 + 26.16\log_{10} f + (44.9 - 6.55\log_{10}(h_b)\log_{10} d) - 13.82\log_{10} h_b - a(h_m)$
$a(h_m) = 3.2\log_{10}(11.75h_r)^2 - 4.79$
$a(h_m)$ = correction factor of ED</td></tr>
<tr><td>Ericsson</td><td>150-1900 MHz</td><td>20-200m</td><td>1-5m</td><td>0.2-100km</td><td>$L = a_0 + a_1\log_{10} h_b + a_3\log_{10} h_b\log_{10} d - 3.2\log_{10}(11.75\times h_r)^2 + g(f)$
$g(f) = 44.9\log_{10} f - 4.78\log_{10} f^2$
<table>
<tr><th>Environment</th><th>a_0</th><th>a_1</th><th>a_2</th><th>a_3</th></tr>
<tr><td>Urban</td><td>36.2</td><td>30.2</td><td>-12</td><td>0.1</td></tr>
<tr><td>Sub Urban</td><td>46.2</td><td>68.93</td><td>-12</td><td>0.1</td></tr>
<tr><td>Rural</td><td>42.95</td><td>100.6</td><td>-12</td><td>0.1</td></tr>
</table></td></tr>
</table>

4. Energy Modelling for Lora

High energy efficiency is the main feature of LPWAN. The lifespan of devices is therefore a significant parameter. LoRa networks shall be running with limited maintenance for a longer span of 5-10 years. As a result, energy use for LoRa networking is becoming a big problem [8]. Devices are utilizing more resources than predicted because of some ineviTable conditions such as retransmissions, Obstacles to the channel etc, Thus Energy consumption has became a very important parameter for LoRaWAN Networks in dense populated areas and all applications of smart cities.

LPWAN uses the topology having simple network structure in order to achieve good energy efficiency; it offers large connectivity with low data rate.

These LoRa sensor nodes are commonly used in rough circumstances and conditions unavailable. Therefore, sensor nodes can run without human interference for long periods of time. For interacting sensors to track a particular target application, the energy model for finding out its usage is very important.

For most implementations, communications sensors can carry out the following tasks: sense the incoming events, Processing of detected events at the local level, and transfer of packets to the point of access. Therefore, the sensor node requires a specific model for energy consumption to predict the sensor lifetime [9].

We start calculating the payload symbol to measure air time (or packet length).

$$N_{payload} = 8 + max\left[ceil\left(\frac{8PL-4SF+44-20H}{4(SF-2DE)}\right)(CR+4), 0\right] \quad . \qquad (1)$$

Where H= Header value, H = 0 when header is present in the packet and H = 1 otherwise,

SF is the spreading factor

CR is the coding Rate which is between 1 to 4

PL is the Payload Number in bytes

DE is assumed to be 1 when optimizing low data speeds is allowed, or else DE = 0. Then the total airtime is given as following.

$$TOA = T_{preamble} + T_{payload} \qquad (2)$$

Where TOA is denoted as time on air, $T_{preamble}$ is time duration of preamble and $T_{payload}$ is time duration of payload and is represented in the equation (3),

$$T_{payload} = N_{payload} \times T_{sym} \qquad (3)$$

$T_{payload}$ is time duration of payload

$N_{Payload}$ is the number of devices in the payload

T_{sym} is the time required by the symbol

$$T_{preamble} = (N_p + 4.25) \times T_{sym} \qquad (4)$$

Where, $T_{preamble}$ is time duration of preamble

N_p is the symbol number of preamble and T_{sym} is the time required by the symbol

$$T_{sym} = \frac{2^{SF}}{BW} \qquad (5)$$

Here T_{sym} is the time required by the symbol, SF is the spreading factor and BW is the Bandwidth

From [9] we use an equation for calculating energy as per useful bit which is a significant metric for assessing the sensor node energy consumption.

$$E_{bit} = \frac{P_{cons(P_{Tr})} \times TOA}{8PL} \qquad (6)$$

E_{bit} is the energy used per bit, $P_{cond(PTr)}$ is the total consumed power, TOA is time on air and PL is payload size in bytes.

Taking values of $P_{cons(P_{Tr})}$, PL, from the datasheet of SX1278 transceiver (433MHz)[datasheet].

By using equation (6) we will be calculating the energy used per bit and for calculating the communication range path loss equation, from any of the selected propagation model from the five models mentioned above is used. With the help of the transmission path the link budget is calculated as,

$$L_{budget} = \frac{P_{cons(P_{Tr})}}{S_R(SF,BW)} \qquad (7)$$

Where Pcons(PTr) is the total power consumed dependent upon transmission power, S_R (SF, BW) is the receiver sensitivity depending upon spreading factor (SF) and bandwidth (BW). This sensitivity is calculated for SNR at its minimum (SNR_0),

$$SNR_0 = \frac{E_{bit}}{N_0} \qquad (8)$$

$$E_{bit} = SNR_0 \times N_0 \qquad (9)$$

N_0 = Noise power spectral density which is equivalent to product of NF.K.T i.e. Noise figure, Kelvin constant and temperature respectively,

Using data sheet of SX1278 transceiver the sensitivity can be written as,

$$S_R(SF,BW) = SNR(SF) \times N_0 \qquad (10)$$

$$SNR(SF) = \frac{SNR_0}{2^{SF}} \qquad (11)$$

Putting value of equation (11) in (10), we get,

$$S_R(SF,BW) = \frac{SNR_0}{2^{SF}} \times N_0 \qquad (12)$$

S_R (SF, BW) is the receiver sensitivity depending upon spreading factor (SF) and bandwidth (BW). SNR_o is signal to noise ration of output and N_o is noise power spectral density.

Putting value of equation (9) in (12), we get,

$$S_R(SF,BW) = \frac{E_{bit}}{2^{SF}} \qquad (13)$$

We presume the antenna gains to be equal to 0 and the L (path loss) = L_{Budget}.[9]

L_{budget} = Path Loss (L), from equation (7) we get

$$L = \frac{P_{cons(P_{Tr})}}{S_R(SF,BW)} \qquad (14)$$

Putting value of S_R (SF, BW) from equation (13) in equation (14)

$$L = \frac{(P_{Tr} \times 2^{SF})}{(E_{bit})} \qquad (15)$$

Where L is the path loss, P_{Tr} is the transmitted power, SF is the spreading factor and E_{bit} is the energy used per bit. Thus above equation estimates the relation between path loss and Energy consumption per bit.

5. Results & Discussions

From figure 1a to 1e the comparison of five different models of propagation is shown for LoRa(433MHz), Sigfox(868MHz) and NB-IoT(900MHz). The below graphs show that for all the Models LoRa is having best path loss relation due to its lower range of frequency when compared to Sigfox and NB-IoT.

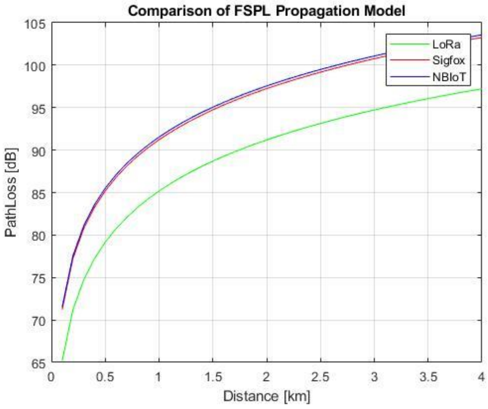

Fig. 1(a). FSPL Propagation Model for LPWAN technologies

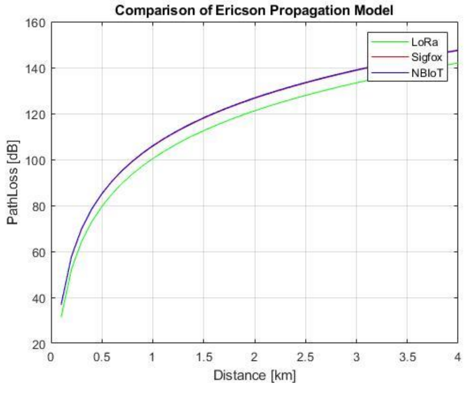

Fig. 1(b). Ericson Propagation Model for LPWAN technologies

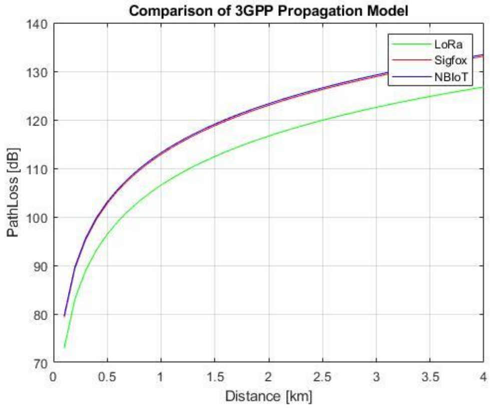

Fig. 1(c). 3GPP Propagation Model for LPWAN technologies

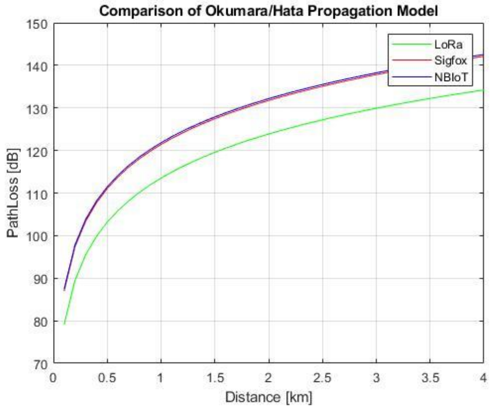

Fig. 1(d). Okumara/Hata Propagation Model for LPWAN technologies

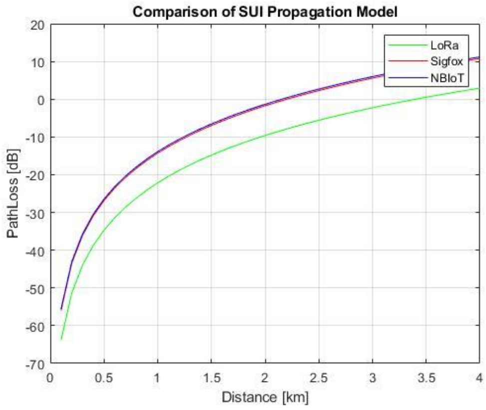

Fig. 1(e). SUI Propagation Model for LPWAN technologies

From figure 2a to 2c the graphs show the individual comparison of each technology. When all models of propagation with the identical input parameters are compared with each other, the diversity of their effects can be observed. At lower distances the maximum difference between Path Loss of different models is approx 45 dB and is gradually decreasing to 40 dB as the distance reaches 4kms. In the below graphs SUI model is not considered even after providing the optimistic values because the frequency range allowed in SUI lies in GHz and the frequency limits for LPWAN technologies considered are in MHz. For short distances between BS-EDs of few kms, the efficiency of two models named 3GPP & Hata model is quite comparable with each other. The 3GPP model predicts higher path loss values at greater distances. For Ericson model at lower distances the loss is very less but it increases very fast with respect to distance and reaches at the maximum value of Path loss when compared to other models and hence gives the most pessimistic results.

All these above models are empirical in nature and hence depend upon only the measurement campaigns values, because of which these models may result in inaccurate values at different geographical locations and morphology [3].

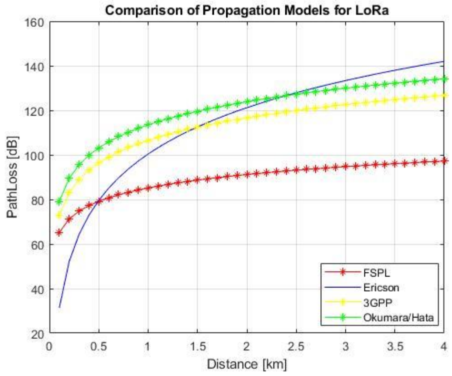

Fig.s 2(a). Comparison of propagation Models for LoRa

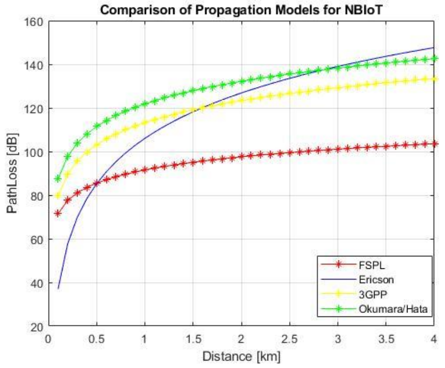

Fig. 2(b). Comparison of propagation Models for NB-IoT

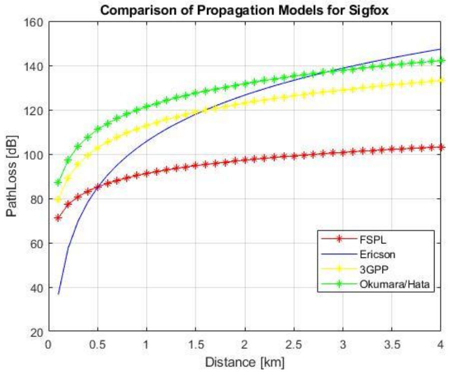

Fig. 2(c). Comparison of propagation Models for Sigfox

Now specifically discussing about LoRa and taking different SF values the equation 1 to 6 from section IV is used to calculate the Energy per bit and gives the following results. The figure 3(a) shows the TOA versus payload size with alternate values of SF. The bandwidth selected is set at 125 kHz. The air time rises when the SF is high. This means the sensor node uses more data transmission capacity. Figure 3(b) shows the influence of CR on air time. We note that an increase in the number of encoding bits increases the packet transmission, enabling the radio module to consume more energy.

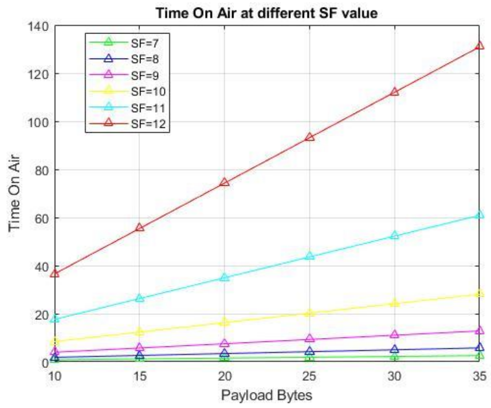

Fig. 3(a). TOA and Payload with increasing SF

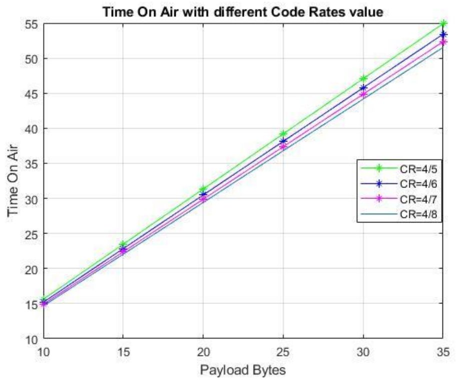

Fig. 3(b). TOA and Payload with increasing CR

Figure 4 shows the energy absorbed in different spread factor depending on the payload. Using Equation (6), this energy reduces as the number of useful bits increases except for SF value 12. The higher SF value, as mentioned previously, the more energy required to convey data, the more time it requires to send out a packet. Figure 4(b) depicts the energy per useable bit with SF feature for unchanged payload size (equal to 10 bits). As previously stated, the higher the value of SF, the more time it takes to deliver a packet and the more amount of energy is used in order to send data.

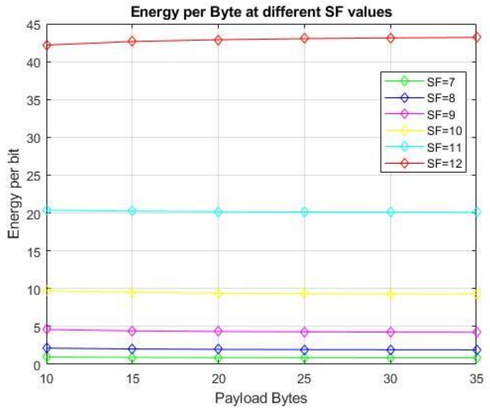

Fig. 4(a) Energy per useful bit and Payload with increasing SF

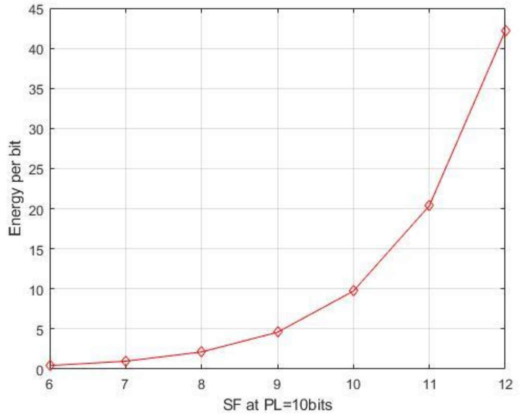

Fig. 4(b) Energy per useful bit and SF at PL= 10bits

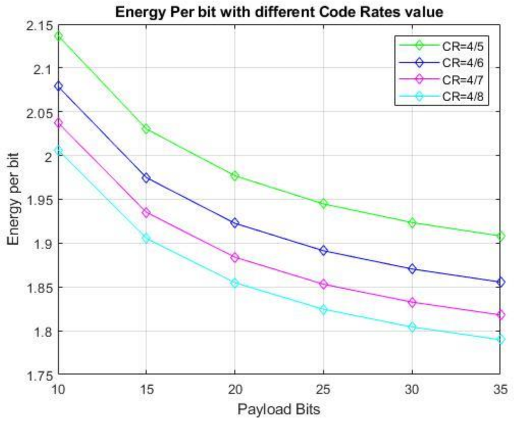

Fig. 5 Energy per useful bit and Payload with different CR

Figure 5 depicts the effect of coding rate (CR) on useful energy per bit. As the coding rate falls, so does the amount of time spent on the air and the amount of energy required. Figures 3-5 show that optimising LoRa parameters such as SF, CR, and payload size is a crucial influence in reducing the energy spent by the sensor node.

By using relation summarised in equation (15), figure 6 consists of four graphs between Energy used per bit and path loss for Ericson, FSPL, Hata and 3GPP propagation Models with respect to LoRa specifications respectively. All the above relation says that as the value of path loss increases the energy used per bit decreases. Thus as the communication range (d) increases the energy that can be used per bit will decrease.

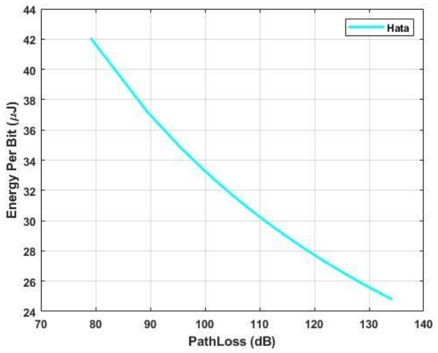

Fig. 6(a) Energy per useful bit and Path Loss at SF = 8 for Hata Model

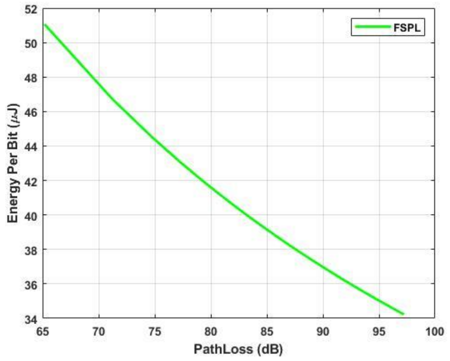

Fig. 6(b) Energy per useful bit and Path Loss at SF = 8 for FSPL

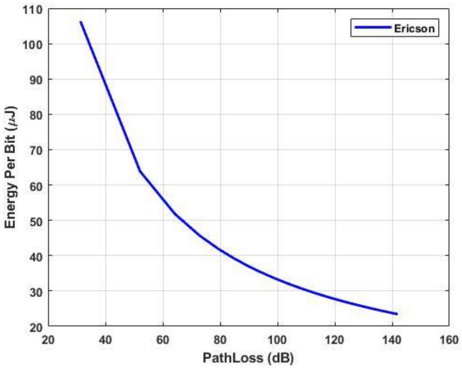

Fig.s 6(c) Energy per useful bit and Path Loss at SF = 8 for Ericson

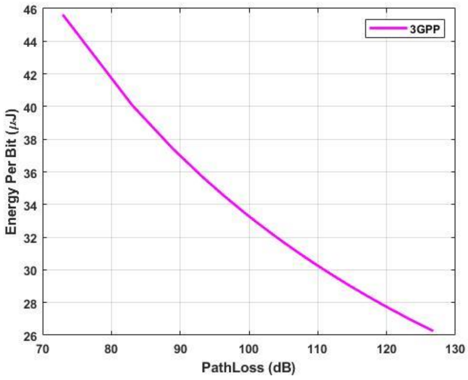

Fig. 6(d) Energy per useful bit and Path Loss at SF = 8 for 3GPP

6. Conclusion

To deploy an energy efficient smart city application which has a great scope in urban or dense geographical areas, this paper consists of the performance comparison of several LPWAN technologies and also compares the path loss of each technology thus calculating the energy per bit. We proposed a fitting and cross-validation strategy for building an appropriate model which is used in urban contexts for all important LPWAN technologies, including Sigfox, NB-IoT and LoRaWAN. Initially, we had examined the four major models of propagation used in LPWAN (SUI, 3GPP, Okumura-Hata and Ericsson) to find the optimum solutions depending on model parameters that have been fine-tuned for specific operating frequencies. According to study of Path loss the LoRaWAN technique out of all LPWAN technologies proves the best due to its low frequency and long range. Further varying the several parameters like CR (Coding rate) and Spreading factor (SF) Time on air also varies which in combination with different path loss techniques gives the output for Energy used per bit according to path loss. This study states that when using LoRa with Erricson model it can give the best results, as Ericson modelling offers the best relation with path loss and energy used per bit is decreased the most in Ericson modelling. Further we can test these results in real time test areas for urban environment and validate these results more.

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