A Comparative Study on Various LPWAN and Cellular Communication Technologies for IoT Based Smart Applications

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Sarath chandu Gaddam
Lovely Professional University

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Sarath Chandu Gaddam
ECE department
Lovely Professional University
Punjab, India
sarath.gaddam431@gmail.com

Mritunjay Kumar Rai
ECE department
Lovely Professional University
Punjab, India
raimritunjay@gmail.com

***Abstract*— The usage of Internet of Things (IoT) technology in device designing is increasing rapidly. Low Power Wide Area Networks (LPWAN) is popular and leading technology created for IoT networks. LPWAN is wireless based WAN technology that enables Low power consumption, long range, lower bandwidth with low bit rates. LoRa, sigfo x, NB-IoT, LTE-M are the leading low power, wide area network technologies useful for developing IoT networks. This paper presents a comprehensive study on various LPWAN technologies and comparative study between these technologies in terms of battery life time, cost, network coverage, latency, range and security. This paper e xpla ins all the merits and de-merits of the LPWAN technologies usage in real time scenarios and which technology fits best for each IoT s mart applications**.

***Keywords*— IoT, LPWAN, LoRa, Sigfox, NB-IoT**

I. INTRODUCTION

The difference between a device and the IoT device is its capability to connect with internet. One technology cannot solve all the requirements of IoT device applications. IoT device requires low power consumption or long battery life, Long range, good data rate, low latency and low cost. Fig. 1 shows considerable IoT parameters for IoT application. W i-Fi, ZigBee and Bluetooth are well established short range standards serves in all mobile related, personal devices and in-home applications. Cellular technologies like 2G, 3G, 4G, GPRS, and LTE are well- established technologies and these fit for applications that need long range and high data throughput. The IoT requires a communication technology which fit for both Long range and Low power consumption. Low Power Wide Area Network (LPWAN) offers very long battery life, can send the data to long ranges securely with low data rates. The most critical IoT factors involved in LPWAN are low power or long battery life time, robustness to interference, communication range, network architecture, network capacity, security and better communication link budget [1]. Fig. 2 describes about comparison between LAN, Cellular and LPWAN technologies.

LAN is short range communication with high data rate and not suitable for long range communications. Cellular is good for long range but it requires high power to transmit the data. LPWAN is fits for both long range and low power applications but it modulates low data rate.

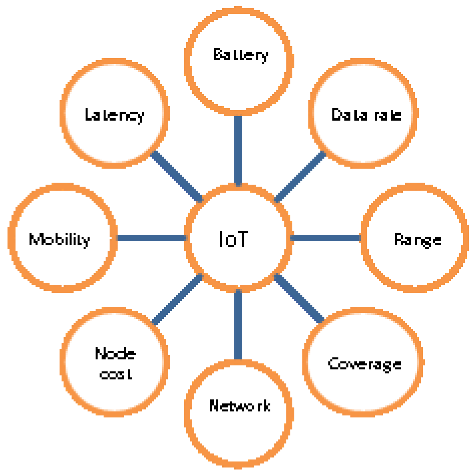

Fig: 1 IoT parameters considerations

Many existing wireless networks utilize frequency shift keying (FSK) as physical layer for effeiciant modulation and increasing battery life. LoRa uses chirp spread spectrum mudulation as physical layer to maintain low power consumption like FSK and in addition it increses the transmission range[2]. Lo Ra, sigfox are non- cellular technologies and Narrow band (NB-IoT) is cellular technology. Lo Ra Alliance association is formed by 400 member companies throughout the world. These 400 members includes Semtech, Microchip, Cisco, IBM, Swisscom and fastnet[3]. LoRaWAN is communication protocol governed by LoRa Alliance and it uses Lo Ra modulation as physical layer.

Modulation bit rate, Rb, is:

$$R_b = SF \times \frac{1}{2^{sf} / BW} bits/\sec \qquad (1)$$

BW = modulation Bandwidth in Hz.

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Lo Ra modulation as physical layer. Sigfox founded in 2009, simillar to LoRaWAN it uses very low data rate to transmit long ranges. NB-IoT standardized by 3rd generation partnership project (3GPP) and first specifications were released at release 13 of 3GPP in june 2016.

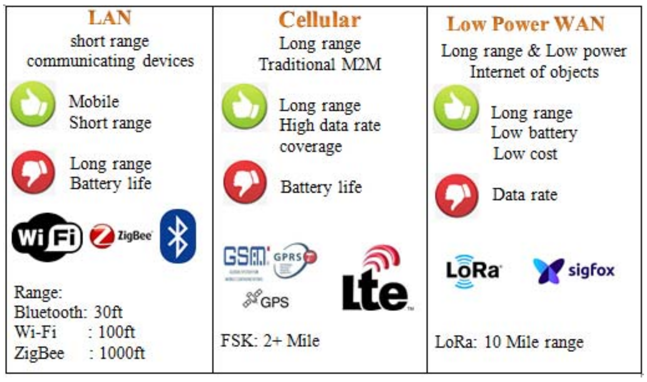

Fig: 2 Comparison of LAN, Cellular and LPWAN

This paper structured as 4 sections: Section II expla ins LoRa, Lo RaWAN, sigfox and NB-IoT technologies. Section III discusses about comparison between LoRa, Lo RaWAN, sigfox and NB-IoT based on IoT parameters. Section IV shows various applications and which technology is best fit for each application.

II. Technologies

A. LoRa

Lo Ra is Chirp spread spectrum modulation technique patented by Semtech and it varies data rate for the sensitivity by keeping fixed channel bandwidth. Lo Ra allows user or designer to trade the range, power by using variable data rate and orthogonal spread factors. The spread spectrum of LoRa modulation is obtained by developing a chirp signal which continuously changes in frequency, due to this timing and frequency offset of both transmitter and receiver are equivalent. The spectral bandwidth of the signal is equal to the frequency bandwidth of the chirp. To improve the robustness of the transmitting signal, Lo Ra modulation uses error correction scheme[4].

In Lo Ra modulation, the data bit rate, chip rate and symbol rate are e expressed as

$$Rs = \frac{1}{T\_s} = BW / 2^{sf} \quad \text{symbols/sec} \qquad (2)$$

Symbol rate, Rs = reciprocal of Symbol period, Ts

Chip rate, Rc expressed as:

$$Rc = Rs \times 2^{sf} \quad \text{Chips/Sec} \qquad (3)$$

From, equation (2) & equation (3)

$$Rc = BW \qquad (4)$$

From equation (4), one chip is sent per second per Hz of bandwidth.

Nominal bit rate, Rb, is defined as:

$$R_b = \frac{S_f \times \frac{4}{4+CR}}{\frac{2^{sf}}{BW}} \qquad (5)$$

CR= Code rate [1 to 4].

Lo Ra modulation depends on various parameters like Bandwidth, coding rate, spread factor (SF), t ime on air (ToA) and link budget[5] are explained below.

1 Modulation Parameters

a) Bandwidth

Bandwidth value shows the transmission speed and range of the transmission signal. Lo Ra operates in 3 types of bandwidths 125 kHz, 250 kHz & 500 kHz. 500 kHz fits for fast transmission and 125 kHz suits for long reach. Lower bandwidth leads to high time-on-air, high battery consumption, better sensitivity and better link budget.

b) Coding rate

Coding rate value has 4 options 4/5, 4/6, 4/7 and 4/8. Coding rate value defines that every 4 useful bits are encoded by 5, 6, 7 or 8 trans mission bits. Smaller coding rate employed to high time-on-air.

c) Spreading Factor

SF defines number of chips/symbol used in data before transmission. SF value is in between 6 to 12. High spreading factor value gives more capability the receiver to move the noise away from the signal. High SF takes more time to send a packet, high time-on-air.

d) Time-on-air

ToA defines the transmission signal time from transmitter to receiver. Higher time-on-air in a transmission takes high time to transmit a packet of data, task of receiver become easy to demodulate the packet with low receiving power. It leads to better sensitivity of receiver and better communication link budget.

e) Link budget

In wireless systems, link budget is measure of all gains and losses for transmitter, propagation channel and receiver[6].

Table 1 shows how the sensitivity, chip length and bit rate varies depend on spread factor[7].

TABLE 1: SF vs. other parameters

SF	Sensitivity (dBm)		Chip length	Bit rate (bps)	
	BW 500kHz	BW 125kHz		BW 500kHz	BW 125kHz
7	-114	-123	128	21875	5468
8	-117	-126	256	12500	3125
9	-120	-129	512	7031	1757
10	-123	-132	1024	3906	976
11	-125.5	-133	2048	2148	537
12	-128	-136	4096	1171	292

Fig. 3 & 4 shows that increase in SF value from 7 to 12 leads to increase in receiver sensitivity, chip length and decrease in bit rate at 125 kHz & 500 kHz bandwidths.

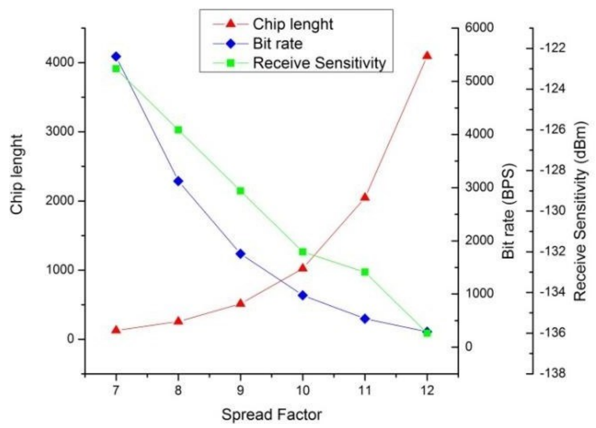

Fig: 3 Graph for SF vs. chip length, sensitivity and bit rate at 125 kHz band width

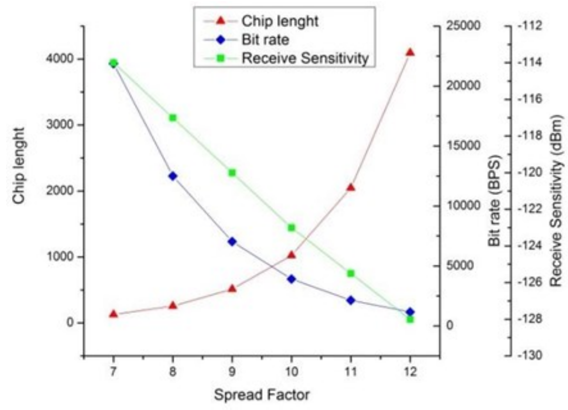

Fig: 4 Graph for SF vs. chip length, sensitivity and bit rate at 500 kHz band width

As already discussed Semtech Company patented the Lo Ra modulation and developed different LoRa products. Comparisons of these product specifications are described in table 2. Each device has built in bit synchronizer, ultrafast Channel Activity Detection (CAD) and excellent co-channel rejection[8].

TABLE 2 LoRa Modules and their specifications

Module name	**SX1261/62/68**	**SX1272/73**	**SX1276/ 77/78/79**
Modem	LoRa & FSK	LoRa	LoRa
link budget	170dB	157dB	168dB
Power amplifier	1261:+15dBm 62/68:+22dBm	+14 dBm	+14dBm
Rx current	4.6 mA	10 mA	9.9 mA
bit rate	62.5kbps-LoRa 300kbps-FSK	300 kbps	300 kbps
Sensitivity	-148 dBm	-137 dBm	-148 dBm
Blocking immunity	88 dB	89 dB	Excellent
Frequency	150MHz–960MHz	860MHz-1000MHz	137MHz-1020MHz
RSSI	---------	127 dB	127 dB

Lo RaWAN is a communication protocol defined by LoRa Alliance mapped to data link layer and network layer of the OSI model while Lo Ra modulation mapped to physical layer establishing long range communication link. Lo RaWAN uses Lo Ra as modulation technique and operates in unlicensed frequency bands[9]. The network architecture of LoRaWAN is shown in Fig. 5. LoRa nodes receive data from various sensors and transmit data to multiple gateways. Each gateway transmits the packet received from node to the cloud based network and application servers via IP connection[10].

End devices operate in three device classes (class A, class B and class C) to satisfy different requirements and different applications. Class A devices accepts bi-directional communication, sends uplink messages from end device to application randomly at any time is followed by two short downlink receive windows shown in Fig. 6. Server has to react in either first or second window, not both. Class A is most energy efficient because it supports downlink transmission at specific time intervals after uplink. Class B devices accepts extra receive windows for downlink messages depend on time synchronized beacons received by the gateway shown in Fig. 7. Class B devices are energy efficient and latency controlled devices. Class C devices opens receive windows continuously except if devices are transmitting. This device operates with high power consumption and low latency downlink[11].

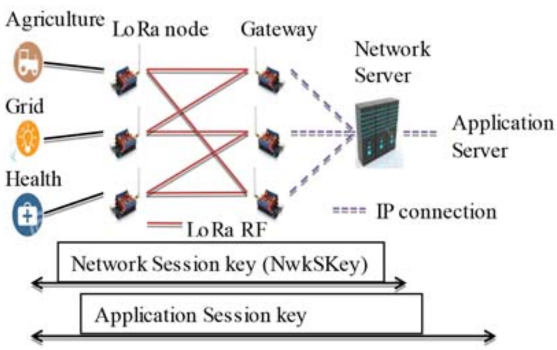

Fig: 5 LoRaWAN architecture

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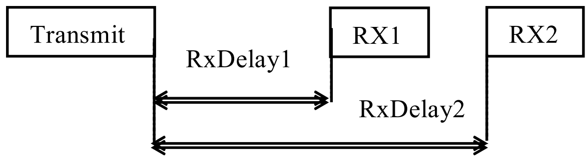

Fig: 6 LoRaWAN class A device receive windows

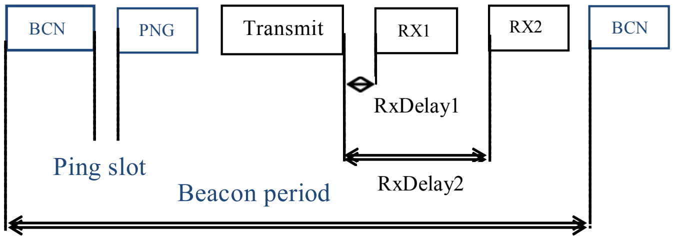

Fig: 7 LoRaWAN class B device receive windows

Lo RaWAN operates on three types of 128-bit security keys application key (AppKey), application session key (AppSKey) and a network session key (NwkSKey). End device and the application know only AppKey. When an end device starts the communication or joins in the network, an AppSKey and aNwkSKey are generated. NwkSKey is different for each device and used to validate message integrity between end device .

A. Sigfox

Sigfox protocol uses differential binary phase shift keying (D-BPSK) modulation to transmit the messages and operates in unlicensed ISM bands. Bit rate will be either 100 bps or 600 bps depends on the operation region. D-BPSK modulation takes only 1 Hz of the operation band to transmit 1bit/s. sigfox uses 100 Hz of operation band to transmit 100 bps. Sigfox operates on ultra- narrow band radio modulation to improve the robustness, capacity and range of the signal. D-BPSK modulates low bit rates, this leads to more time for demodulation, high base station receiver sensitivity and large link budget. Base station sensitivity changes depend on transmission bit rate like 100 bps bit rate has -142 dBm receiver sensitivity and 600 bps has -134 dBm receiver sensitivity. Sigfox supports light weight protocol for small messages. Protocol overhead is limited in sigfox to reduce the frame size. Sigfox t ransmits 12 bytes data payload of uplink data using 26 bytes of frame size in total. Light protocol frame size send less amount of data, it needs less energy results in long battery life and higher network capacity [14].

B. NB-IoT

NB-IoT is also called as LTE Cat NB1, connects many devices easily and efficiently by using well established mobile networks. It transmits data in both uplink and downlink directions securely[15]. As discussed in[16], it provides long battery life, great coverage area, low cost and network security. NB-IoT requires minimum180 kHz of bandwidth to operate, which is equal to smallest LTE Physical Resource Block (PRB). NB-IoT operates depend on spectrum availability in existing LTE network, it divided into 3 modes:

- Stand-alone operation: it deploys on its own or uses e xisting GSM low bands (700MHz, 800MHz and 900MHz).
- Gua rd band operation: operates in guard carries of already existing LTE spectrum.
- In-band operation: replacing PRBs in the existing LTE spectrum.

NB-IoT uses Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation for uplink data transmission and Orthogonal Frequency Division Multiplexing (OFDM) for downlink. Downlink contains 4 physical layer channels (Synchronization, broadcast, control and data channel). Uplink has two channels, namely, Narrowband Random Access Channel (NPRACH) and Narrowband uplink shared channel (NPUSCH).

Synchronization channel has narrowband primary synchronization sequence (NPSS) and Narrowband Secondary Synchronization Sequence (NSSS) signals. These two signals have bandwidth of 180 kHz. NPSS is for estimating symbol timing and carrier frequency and NSSS is for frame boundary and cell identity. Broadcast channel used to carry Master Information Block (MIB). Control channel carries downlink control data, size is 23 bits. Data channel is downlink shared channel works similar to the control channel, carries control information and system information. NPRACH used for establishing connection between user and base station. NPUSCH carries control information and data. The performance evolution of NB-IoT is based on transmit power, bandwidth, signal to noise ratio (SNR) and maximum coupling loss (MCL)[16][17].

In the present section the details of LoRa, Lo RaWAN, sigfox and NB-IoT technologies are exp lained. Ne xt section deals with comparisons between these technologies based on IoT parameters.

II. COMPARISION BETWEEN TECHNOLOGIES

As already stated Each IoT technology depends on various parameters as shown in Fig. 1. These all parameters have to be considered to select the best LPWAN technology for an IoT application.

A. Spectrum, Quality of Service and spectrum cost

Lo Ra and Sigfox use unlicensed frequency bands below 1GHz whereas NB-IoT and cellular technology works on licensed frequency bands below 1GHz. NB-IoT and cellular are based on time slotted and LTE synchronous protocols best for quality of service (QoS). Lo Ra and sigfox are asynchronous, designed for unique specifications and doesn't give best QoS than NB-IoT. Lo Ra and sigfox operates on free spectrum, reduces the cost of application whereas NB-IoT and cellular are licensed spectrums, which costs greater than 500 million dollars per MHz's[18]. QoS vs connective pricing per year ($/yr) comparison is shown in Fig 8.

B. Data rate, Range and payload

NB-IoT operates with high data rate of 200kbps and it suits for applications which need high throughput. The maximum data rate in LoRa is 50kbps. Sigfox offers 100bps data rate and it is much lower than NB-IoT and Lo Ra.

Fig: 8 QoS vs IoT pricing

Sigfox can transmit data up to 10kms in urban and 40kms in rural regions, ideal for long range applications with low data rate, low payload of 12 bytes. Lo Ra transmits data within 5kms range of urban regions and 20kms range in rural with 243 bytes payload. NB-IoT sends data to low ranges compared to LoRa and Sigfo x, 1km in urban and 10km in rural with payload of 1600 bytes. Throughput (Data rate) vs Range comparison is shown in Fig.9

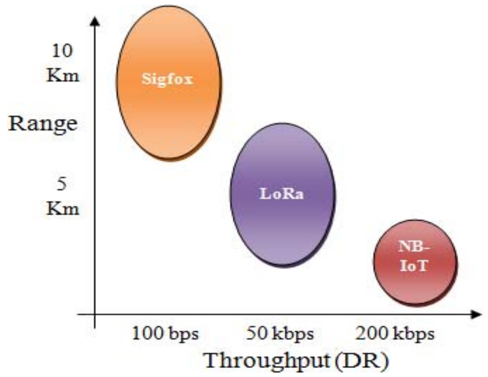

Fig: 9 Data rate vs Range

C. Battery li fe t ime, current consumption and energy

Every technology operates in different modes like transmission (TX), receive (RX), idle and sleep mode. LoRa and sigfox takes very less power compared to NB-IoT and cellular. Table 3 gives peak current consumption comparison between LoRaWAN, NB-IoT and cellular LTE cat-M 1. Lo RaWAN class A and sigfox has long battery life compared to Lo RaWAN class B & C, NB-IoT and cellular because of class A has high sleep time and low down link time.

A. Latency

Applications with low latency and frequent communication requirement, NB-IoT is good. Sigfox has high latency in communication and LoRaWAN class A devices has high latency in downlink communication. LoRaWAN class B & class C are designed to reduce downlink latency.

TABLE 3 Current comparison in TX, RX, Idle and sleep modes

	TX current	RX current	Idle current	Sleep current
Lo RaWAN[3][8]	24-44 mA	12 mA	1.4 mA	0.1 µA
NB-IoT[19]	74-220 mA	46 mA	6 mA	3 µA
Cellular LTE cat-M1[20]	100-490 mA	Not specified	9 mA	8 µA

Lo RaWAN works with less energy comparison compared to NB-IoT because of its lower energy consumption in sleep mode. Table 4 shows the energy consumption comparison between LoRaWAN and NB-IoT to transmit 50 byte payload.

TABLE 4 Energy of LoRaWAN and NB-IoT at different MCL/SF levels

MCL/SF	144 d B / SF7		154 d B / SF9		164d B/ SF12	
Energy (Joule)	/1 msg	Sleep energy/ day	/1 msg	Sleep energy/ day	/1 msg	Sleep energy / day
Lo RaWAN	0.03	0.03	0.07	0.03	0.42	0.03
NB-IoT	0.13	1.3	0.29	1.3	1.50	1.3

B. Device cost and deployment cost

Lo Ra and sigfox end devices are low cost because easy to made with available microcontrollers. Lo Ra end devices available in $4-$5 and sigfox devices available in $2-$3. NB-IoT devices are high in cost compared with Lo Ra and sigfo x, available in ≥ $20. Lo Ra base stations are cost effective compared to sigfox and NB-IoT. Lo Ra base stations deployment cost is >100€/ gateway and >1000€/base station. Sigfox deployment cost is >4000€/base station and NB-IoT cost is >15000€/base station.

TABLE 5 Airtime of LoRaWAN and NB-IoT at different MCL/SF levels

MCL/SF	144 d B/ SF 7			154 d B / SF 9			164d B/SF12		
	Tx (ms)	Rx (ms)	Idle (ms)	Tx (ms)	Rx (ms)	Idle (ms)	Tx (ms)	Rx (ms)	Idle (ms)
Lo RaWAN	118	65	1500	367	238	1500	2793	1725	1500
NB-IoT	49	388	22223	311	565	22451	2190	2672	23387

C. *Air Time*

NB-IoT has high air time because of its synchronous nature and protocol requirements. LoRaWAN spends less air time compared to NB-IoT. Table 5 gives the comparison of air t imes between transmit, receive and idle modes in LoRaWAN and NB-IoT.

In this section comparisons of technologies are expla ined with respect to IoT parameters. Coming section explains various applications and which technology fits best for each application.

III. Applications

As discussed in[21][22][23] , LPWAN technologies suitable for many smart applications. Any one technology can not satisfy all the requirements of applications. Each technology has their advantages and limitations.

A. *Smart Agriculture*

Smart Agriculture uses different types of low cost sensors to measure various parameters like Temperature, humidity, soil moisture, wind wane, wind speed, wind direction and rain gauge etc. it requires low power consumption communication technology to improve battery life. The sensors send the information few times per hour because the conditions will not change instantly. LoRa and Lo RaWAN are suitable for these requirements because of its long range and low power consumption. NB-IoT and LTE-M are not ideal because so many farms don't have cellular coverage.

B. *Smart Meter*

Smart meter continuously monitor the different loads and communicate the loads data with grid. In addition it works on fault detection or interrupts of loads and forecasting. Smart meter requires high data rate for frequent communication and low latency. NB-IoT is ideal for s mart meter because of its high data rate and low latency. Power sources available at each smart meter so, Power consumption for NB-IoT is not a problem.

Smart meters are placed at inside the city so NB-IoT has good cellular coverage. Lo RaWAN class C has low latency but low data rate not suit for metering. Sigfox and Lo Ra are not ideal for smart meter because of its low data rate and high latency.

C. *Smart Water*

Smart water mainly used for measuring water quality for drinking water and water quality used in fish ponds. Smart water for fish ponds measures pH level, dissolved oxygen, oxidation reduction potential, turbidity and temperature. These types of applications require long battery life t ime and signal coverage. Lo Ra and LoRaWAN is suitable for these requirements, sigfox gives long battery life but data rate is very poor and NB-IoT do not have signal coverage in some of the places . Smart water for drinking water measures pH and various water ions like chlorine, fluoride, calcium etc. it requires real time monitoring, high data rate and coverage. NB-IoT is ideal for these requirements and it is better for real time monitoring with high data rate.

D. *Smart City*

Smart city application measures environmental gases like CO_2, NO_2 etc, Dustbin management, temperature and humidity. Smart city uses various low cost sensors to measure the parameters and requires long battery life. It doesn't require frequent communication, high Qo S and high data rate so, LoRa is best suitable technology.

E. *Intelligent Building*

It monitors the temperature, water flow, security, electrical devices and electric plugs to prevent damage by providing alerts. The building manager can monitor these by using mobile device and get alerts directly to mobile for instance action. This application requires various sensors with low cost and long battery life is preferable. It is placed in underground to ensure 100 percent signal coverage. It doesn't require great QoS and frequent communication so, LoRa and LoRaWAN are ideal for this application.

Similarly smart parking displays the available parking slots in public places or other places. It requires long battery life and low cost sensors. LoRa is ideal for these requirements. Point of sale (POS) systems requires frequent communication, low latency and great QoS. NB-IoT meets these requirements so, NB-IoT best for POS systems.

IV. Conclusions

This paper e xpla ined about LoRa, Lo RaWAN, sigfox and NB-IoT technologies and compared these technologies in terms of IoT parameters. Each technology is good for limited parameters and suitable for few applications. Lo Ra, LoRaWAN class A & B suitable for Long battery life and low data rate applications like smart agriculture and intelligent building. Lo RaWAN class C ideal for low latency and low power applications like smart water. NB-IoT technology suitable for high data rate, low latency and guaranteed QoS applications like smart meter and point of sale systems.

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