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Survey of Wireless Technologies for Battery Operated Devices and Their use in IoT Applications

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ABSTRACT: The Internet of Things (IoT) has enabled connection of “things”, such as everyday objects, to the internet. Wireless technologies play a vital role in getting these devices connected and enable communication over the internet. Due to the compact and usually mobile nature of these things connecting devices using wireless technologies is the best option. This compactness requires the batteries to be small which reduces the total capacity of battery. Devices such as sensor nodes are designed to last for many years without the need to change or recharge the battery. This kind of designs require low power wireless technologies to be implemented. This paper aims to analyse four such wireless technologies namely Zigbee, Bluetooth Low Energy, Long Range Wide Area Network (LoRaWAN) and Narrow Band IoT (NB-IoT). A comparative analysis is presented using metrics that are major factors affecting battery life. We have considered various application domains and few popular IoT based applications in each domain and explain which technology fits for each application

KEYWORDS: Zigbee, BLE, LoRaWAN, NB-IoT, IoT Applications.

I. INTRODUCTION

The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it. Mark Weiser wrote this in a seminal paper in Scientific American [1]. Traditionally, for many years wired connectivity has been used, but with the advancement and diversity of wireless technology, its adoption in various industries has increased. With advent of IoT in various industries use of wireless technology has even replaced wired technology in many cases.

In the past decade, many wireless standards have come on the market. Some have been created and some have evolved to serve the IoT market, but one fact many experts in the industry agree upon is that one wireless standard cannot fulfil all the IoT applications. This is because of the diverse nature of IoT applications. Therefore, a particular wireless standard is designed to serve a particular set of use cases.

Many IoT applications require sending a small amount of data infrequently for many years. The wireless technologies considered in this paper are specifically optimized for battery operated devices. Therefore, the main feature of wireless technologies considered is low power consumption that allow for multi-year battery life. Each layer of protocol along with hardware is optimized to achieve the goal of low power consumption. The most common method used by nearly all wireless technologies to optimize battery life is to turn off the radio when not required. Processor in the wireless nodes goes into sleep mode; where the processing and communication is turned off thus consuming low-current (order of micro-Amperes). Therefore, average current consumption by the node reduces allowing longer battery life.

We have chosen four such wireless standards that have emerged as dominant standards in the industry. Namely Zigbee, BLE (Bluetooth mesh), LoRaWAN and NB-IoT. We have also provided the trade-offs that are associated with each metric. In section 3, we have provided details which enables these standards to be used in various application domains along with their limitations. In section 4, we analyse various IoT application domains along with some applications from these domains and provide recommendations on use of wireless communication technology suitable for respective applications. In section 5, we conclude the paper.

II. RELATED WORK

A significant amount of research has been done comparing low power wireless technologies for various applications. Since NB-IoT and Bluetooth mesh are relatively new technologies, empirical research in terms of practical implementation is less due to non-availability of modules or operators that do not support NB-IoT.

In [2], several mesh networking standards are analysed such as Bluetooth mesh, IEEE 802.15.4 based mesh networking standard (e.g., Zigbee) and LoRa for IoT based applications. Authors also provide two reference use cases involving mesh technologies discussed in paper. In reference [3], different wireless technologies for IoT applications are compared in terms of power consumption along with the empirical results on power consumption of wireless modules of each wireless technology under consideration. Reference [4] compares the performance of six wireless protocols qualitatively using various parameters. Reference [5] reviews some of the enabling wireless technologies in IoT. Various metrics are used to compare wireless technologies under consideration along with implementation issues. Reference [6] provides review on major applications of Wireless Body Area Network (WBAN) and highlights their Quality of Service (QoS) requirements. Various technologies are presented and an appropriate WBAN was chosen based on WBAN application. Paper also discusses the requirements of each application and suggests appropriate WBAN technology. The trade-offs have been considered for choosing an appropriate industrial wireless network in [7]. As per the requirements and challenges in industrial wireless networks various wireless technologies are evaluated.

Details on wireless technologies for IoT are provided in [8] and open challenges in IoT are discussed. Summary of technical differences of Low Power Wide Area Network (LPWAN) technologies is given in [9] and their advantages in terms of various factors along with major issues are discussed. Authors also suggest wireless technologies for different IoT applications. Reference [10] has compared various LPWAN technologies with GPRS. Authors provide theoretical and practical analysis on these technologies and provide recommendations on which technology fits for a particular IoT application. White paper [11] and series of articles [12] provide comparison between various wireless technologies. Comparison is based on their effect on battery life. In [13] authors explain how narrow band improves spectral efficiency, long range and improved battery life in LPWAN technologies. They also introduce a concept called effective bandwidth which represents a bandwidth providing optimal trade-off between system spectral efficiency, battery efficiency and coverage area.

III. WIRELESS TECHNOLOGIES

Ideal communication technology would consume very low power, have wide range and have high bandwidth. In the real world such technology does not exist, there is always a trade-off between range, Power Consumption and Bandwidth. Therefore, wireless technologies can be categorized as [14]

- High Power Consumption, High Range, High Bandwidth (e.g., Cellular or Satellite)
- Low Power Consumption, Low Range, Low Bandwidth (e.g., RFID, NFC, Thread, BLE, Zigbee)
- Low Power Consumption, High Range, Low Bandwidth (e.g., NB-IoT, LoRa, Sigfox, IEEE 802.11 ah)

We will be focusing on category 2 and 3 as power consumption is low. In category 2, we have chosen Zigbee and BLE. Technologies in this category are also known as Low Power Wireless Personal Area Networks (LPWPAN). The wireless technologies in category 3 are also known as Low Power Wide Area Networks (LPWAN). These wireless technologies were designed to enable low data rate communication with long coverage areas. This enables star topology with simple network deployment. From this category we have chosen LoRa and NB-IoT. While the former works in ISM band, the latter works in cellular licensed band.

A. Zigbee

Zigbee is an open, low-power self-healing mesh networking protocol stack developed and maintained by Zigbee Alliance. The Physical (PHY) and Media Access Control (MAC) layers are IEEE 802.15.4-2011 standard. On top of that Zigbee protocol stack implements Networking (NWK), Application (APP) layer and security layer. Zigbee uses ISM 2.4GHz (16 channels) worldwide, 915MHz (10 channels) in North America and 868MHz (1 channel) in Europe. It provides the raw data rate of 250 kbps (2.4 GHz), 40 kbps (915 MHz) and 20kbps (868 MHz). Zigbee has a range of 300 m (LoS) and 100 m (indoor) and has a theoretical network capacity of 65,535 nodes. Zigbee employs 128-bit Advanced Encryption Standard (AES) on the network and application layer. To improve coexistence with other wireless technologies, Zigbee employs Direct Sequence Spread Spectrum (DSSS) to mitigate interference. Zigbee also implements frequency agility, where if a Zigbee device detects a high amount of interference, it can report this to Zigbee Coordinator (ZC) and ZC will move the network to the channel with least interference. IEEE 802.15.4 employs Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). Acknowledgements and retries are

employed at various levels of stack [15]. Since Zigbee is short range technology transmission power is low, which limits the range. To achieve long distance communications, routers are used to relay the packets. This increases the power consumption and complexity of the network along with latency in communication. Communication in the 2.4 GHz spectrum is significantly affected by objects, walls, water and humans. Being a global ISM band, many other technologies operate in this band which may interfere with Zigbee communication.

B. Bluetooth Low Energy (BLE)

BLE is developed, maintained and released by Bluetooth Special Interest Group (SIG). BLE was created to address communication requirements of battery operated IoT devices which require long battery life. Presence of BLE chips in personal devices such as mobiles, tablets and laptops make them ubiquitous and allow BLE devices to access the internet. BLE operates in 2.4 GHz ISM band and uses 40-2 MHz channels, out of which 3 are advertising channels and 37 are data channels. BLE provides range from 50m (LoS) to 10m (indoor with obstacles). In Bluetooth 5.0, range up to 800m can be achieved. Raw data rates in Bluetooth 5.0 are 1, 2 Mbps and 500, 125 kbps. Only 8 nodes are supported in piconet although, number can be increased to 2-billion theoretically [16]. BLE employs 5 security features. Pairing, the process of creating one or more shared secret keys. Bonding, act of storing keys created during pairing for use in subsequent connections with trusted devices. Device authentication, verification of two devices that have the same keys. Encryption, this provides message confidentiality using AES-CCM cryptography. Message Integrity, this protects against message tempering [17]. For robustness BLE uses 24-bit CRC on all packets along with 2/3 rate forward error correction (FEC). BLE uses Frequency Hopping Spread Spectrum (FHSS) for robust communication. In Bluetooth 5, improved Channel Selection Algorithm (CSA #2) is used to improve pseudo-randomness of next hop [12]. BLE also employs programmable timed acknowledgement [18]. Since BLE operates in global 2.4 GHz it is prone to interference from other wireless technologies operating in the same band. Also, objects, walls, water and humans affect communication. Range of BLE might be a major limiting factor with the fact that there is no relay feature in BLE star topology (but it is present in Bluetooth mesh). This can affect the scaling of the network.

III.B.1 Bluetooth Mesh

Bluetooth mesh is developed, maintained and released by Bluetooth SIG. It provides mesh functionality to BLE devices which was previously absent in BLE. However, this standard is not part of Core Bluetooth standard rather it is defined in its own specification. Bluetooth mesh builds on top of BLE stack, which means it must be engineered upon either BLE 4 or BLE 5. Specification allows 32767 provisioned nodes in a network [19]. Bluetooth mesh uses only the advertising/scanning states of BLE devices [20]. Managed flooding is used to exchange messages in Bluetooth mesh.

C. Long Range Wide Area Network (LoRaWAN)

LoRaWAN is a popular open MAC layer communication protocol developed and managed by LoRa Alliance which uses LoRa as its PHY layer that provides the long-range communication link [21]. It was developed by Cycleo (French start up later acquired by Semtech). LoRaWAN is deployed as star-of-star topology [22] in which all the end-devices only communicate with gateway nodes. Gateway has IP backhaul (e.g., Ethernet, Cellular) to the network server. The communication between end-nodes and gateway is bi-directional, although uplink communication is favoured. In LoRaWAN network nodes are not associated with specific gateway. Instead, data transmitted by a node is received by multiple gateways. Each gateway will forward the received packet to the network server (via IP backhaul). Network server has the intelligence and complexity to manage the network, which will discard the redundant packets, perform security checks, schedule acknowledgements through optimal gateway [21]. LoRa is proprietary technology owned by Semtech. It is a modulation technique which uses (Compressed High Intensity Radar Pulse) CHIRP Spread Spectrum (CSS). This provides great resistance against multipath and Doppler-effect. LoRa modulation has three main parameters spreading factor (SF), code rate (CR) and bandwidth (BW). LoRa operates in the sub-GHz ISM bands. The band of frequencies used changes as per region or country regulation e.g., LoRa operates on EU 863-870 MHz in Europe, US 902-928 MHz in North America, CN 779-787 MHz in China, IN 865-867 MHz in India etc. [23]. The LoRa supports 125 kHz, 250 kHz and 500 kHz bandwidth in HF ISM 868 and ISM 915 band. Frequency hopping is exploited in order to mitigate external interference.

Communication between end-devices and gateway uses multiple frequencies and multiple data-rates based on spreading factor. Selection of a spreading factor is a trade-off between range and data rate, link robustness or energy consumption. Higher the SF (i.e., lower is the data rate) longer the communication range. There are 6 spreading factors (SF6-SF12). The codes used in different SFs are orthogonal, this means multiple frames can be exchanged in the network at the same time as long as the SF used is different for each frame. Some countries or regions impose



duty cycle restriction on transmit time for the wireless technologies that operate in sub-GHz spectrum. LoRaWAN uses Forward Error Correction (FEC) technique for error correction. CR can be chosen as 4/5, 4/6, 4/7 or 4/8. Depending on the SF payload size varies from 51 bytes to 242 bytes. Raw data rate varies from 250 bps (125 kHz SF12) to 11 kbps (125 kHz SF7) (22 bps (7.8 kHz SF12) to 27 kbps (500 kHz SF12) considering all cases [24]) with LoRa modulation. LoRaWAN implements end-to-end encryption with 128-bit AES keys on NWK and APP layer [25].

Many IoT applications have static nodes which makes them vulnerable to obstructions such as buildings. Buildings and other obstacles which are present, or might appear as time passes, will cause obstruction to signal propagation. This might not allow communication to occur in some regions. Fixing this issue will require installation of more gateways. According to [24] data rate, duty-cycle regulation etc. affect the LoRaWAN scale. Network size is limited by duty cycle. The duty cycle also affects the throughput. Firmware-Over-the-Air (FOTA) in LoRaWAN is difficult to achieve although LoRa Alliance does state the possibility of FOTA in class B and Class C devices. As stated in [26], gateway transmissions are uncoordinated, therefore time spent by gateway transmitting firmware downlink messages, it is not listening to the network. Nodes, unaware that gateway is not listening, send messages which are lost.

D. Narrow Band-IoT (NB-IoT)

The 3rd Generation Partnership Project is a well-known partnership project focused on cellular technology which develops and maintains NB-IoT. NB-IoT is a new system built from existing LTE functionalities. Already deployed LTE networks provide ubiquity needed for IoT applications. Reuse of LTE design has maximized the backward compatibility, minimized the development effort and time to market. NB-IoT is not a minimal architecture of LTE. When User Equipment [UE] connects to the network it searches for an NB-IoT channel assigned by the network operator [27]. The performance in urban areas is better due to availability of LTE base stations.

NB-IoT provides 180 kHz (1 resource block of LTE channel, with 12 sub carriers and each subcarrier separated by 15 kHz) of downlink and 200 kHz uplink bandwidth, this allows coexistence with legacy LTE UEs. Frequency band used depends on MNO. NB-IoT enables bidirectional communication using Single Carrier-Frequency Division Multiple Access (SC-FDMA) for uplink and Orthogonal Frequency Division Multiplexing (OFDM) for downlink. A single BS can handle 55k devices [10]. Downlink data rate ranges from 0.5 to 200 kbps and uplink data rates range from 0.3 to 180 kbps. Maximum transmit power is 23 dBm (200 mW). Higher throughput also enables Firmware-Over-the-Air (FOTA) updates. NB-IoT reuses the basic features of LTE such as robust authentication and encryption which makes it very secure.

Nodes that do not receive an adequate level of power from a base station are out of infrastructure-management. Therefore, 100 percent target coverage cannot be reached. Buildings and other obstacles which are present, or might appear as time passes, will cause obstruction to signal propagation. MNO might have to install a new base station, which can be costly. MNOs can charge a monthly subscription fee for service and network usage. The economic savings achieved by application is reduced. Also, the cost might increase over time.

The comparison between four wireless technologies discussed above is presented in Table 1.

Table 1: COMPARISON OF WIRELESS TECHNOLOGIES

Metrics	Zigbee	BLE	LoRaWAN	NB-IoT
Frequency Band	2.4 GHz, 915 MHz (North America), 868 MHz(Europe)	2.4 GHz	Region Specific Sub-1 GHz e.g., 915 MHz (North America), 868 MHz(Europe)	Licensed LTE band (region and operator specific)
Bandwidth	2 MHz	2 MHz	125 kHz, 250 kHz, 500 kHz ¹	180 kHz (DL), 200 kHz (UL)
Data Rate ²	20 kbps to 250 kbps	125 kbps to 3 Mbps	250 bps to 50kbps	0.5 to 200 kbps (DL), 0.3 to 180 kbps (UL)
Latency	~16 ms	~3 ms	500 ms to 10s	1 to 10s
Range	300m (LoS), 100m (indoors)	100 m in BLE, 800 m in Bluetooth 5.0	2-3 km in urban and 5-7 km in rural	8 - 35 km
Robustness	32-bit MIC ³ , DSSS	FHSS, 24-bit CRC, ARQ	CSS modulation, FEC	HARQ
Security	128-bit AES, CCMmode ⁴	128-bit AES-CCM	128-bit AES-CMAC ⁵	EPS Encryption Algorithm ⁶ (EEA),

¹ Bandwidth of 500 kHz cannot be used in Europe
²Data rate depends on various set of configurations
³ MIC = Message Integrity Code
⁴CCM = Counter with CBC-MAC, CBC-MAC = Cipher Block Chaining-Message Authentication Code
⁵AES-CMAC = Advanced Encryption Standard-Cipher-based Message Authentication Code



				DTLS, VPNs
Number of Nodes (Theoretical)	65,535	Depends on configuration	~4000 ⁷	~55,000
Max. Payload Size	102 ⁸	244	242 ⁹	1600
Max. Tx. Power	+20 dBm in 2.4 GHz, region specific in other band	+20 dBm in 2.4 GHz, region specific in other band	+14 dBm (UL) and +27 dBm (DL) ¹⁰	+23 dBm

IV. APPLICATIONS

In this section various IoT application domains are discussed along with some applications from these domains. We also suggest appropriate wireless technology best suited for each application based on the requirements of application. Multiple wireless technologies can be used to fulfil the requirements of a particular application. Applications considered require battery operated sensor nodes that must provide multi-year battery life.

A. Smart City

According to Wikipedia [28] smart city is an urban area that uses different types of electronic IoT sensors to collect data and then use insights gained from that data to manage assets, resources and services efficiently. Some of the most popular smart city projects are smart street lighting, smart waste management, air quality and pollution monitoring and smart parking. In case of Smart Street lighting applications street lights on roadways, public space and parking areas are attached with a mote which communicates with central control for dimming, turning on or off of LED lamps. This reduces total energy consumption of street lights. Smart waste management sensors are placed on or in waste bins which provide information on the level of garbage in bins. This information is used by the municipality or concerned private contractor to increase efficiency of the whole garbage collection process. Air quality and pollution is monitored using cheap sensors that detect levels of various pollutants, in the air, around different sectors of the city. These sensors generate spatial and temporal data. Sensors placed can be static (e.g., on street lights or signals) or mobile (e.g., on public transportations). IoT based solutions can provide real time occupancy status of spots in the parking lot to lot operators (private lots) or the municipality (public lots) and drivers. Each sensor is battery powered that detects the occupancy, arrival, presence and departure of the vehicle on the parking spot. The data acquired from these sensors can be sent wirelessly to a concentrator which will relay this data to central control for analytics.

The number of nodes is $\llbracket 10 \rrbracket^2$ to $\llbracket 10 \rrbracket^4$ within a square kilometre of area. The environment around mote keeps changing with possibility of high interference and noise. Latency is in order of tens of seconds. Therefore, we suggest use of the LoRa network as it gives private company or municipality control over the network setup and maintenance with no operating cost. LoRa also provides GPS free location service using Time Difference of Arrival (TDoA). Also, using a common wireless technology brings all applications under one infrastructure. Many literatures have been published analysing use of LoRaWAN along with Zigbee and NB-IoT in smart city environment [29, 30, 31, 32, 33, 34, and 35].

B. Smart Farming

Smart farming is the application of Information and Communication Technology to agriculture [36]. The crop yield and animal produce can be enhanced using the data analytics techniques used on data acquired from sensors placed all over the farm. From a farmer’s perspective, smart farming should allow farmers to make better management decisions, save resources and increase production [37]. Applications such as cattle tracking require coverage of large areas, high capacity to form a network with thousands of nodes and tracking of cattle. Soil moisture, pH and temperature probes are deployed all over the field to monitor properties of soil so that plants remain healthy. These sensors require long range and their location must be known. In greenhouses, environmental parameters such as humidity, ventilation, pH and temperature are controlled to optimize plant growth. Here, distance between nodes is less compared to other applications. Local on farm weather stations are being used by farmers to better predict weather and farm needs. There are many components of weather station such as Anemometer (wind direction and speed), Thermometer (atmospheric temperature), Barometer (atmospheric pressure to predict precipitation), Hygrometer (relative humidity using percentage of water vapour in the air), Rain Gauge (measures liquid precipitation using an open container),

⁶EAA = EPS Encryption Algorithm, EPS = Evolved Packet System

⁷value can be increased with different configuration and number of gateways

⁸IEEE 802.15.4 MAC max. payload size

⁹Changes with data rates

¹⁰Regulation for Europe

Pyranometer (solar radiation levels in watts per square meter), UV sensor, Leaf Wetness Sensor (surface moisture of plants), Soil moisture sensor, Soil temperature sensor [38]. These stations can be installed along with gateways across the farm.

Absence of LTE coverage in rural areas makes LoRa a preferred choice of communication technology. Farmers will prefer a lower price of LoRa over NB-IoT [39]. Since sensors can have clear LoS to gateway most of the time, sensors can be deployed on long-range using few gateways. GPS free tracking is an added benefit in LoRaWAN networks. However, use of mesh technology (BLE mesh or Zigbee mesh) is feasible in small areas such as vegetable garden or greenhouse where it is easy to install mains supply for nodes that prefer to run on mains supply [2]. Although with increase in number of node mesh network complexity and power consumption increases. These literatures have used Zigbee and LoRaWAN in smart agriculture applications [40, 41, 42, 43, 44, and 2].

C. Smart Healthcare

Smart health care provides accuracy, efficiency and availability of medical treatment enabled by advances in wireless technology and smaller electronic sensors placed in, on or around the human body [6]. The network of such sensors is called Wireless Body Area Network (WBAN). Sensors need to sample at high-frequency, have small size (thus small battery capacity) and need reliable and real-time communication. Telemedicine and remote patient monitoring enable the remote delivery of health services using health information systems and several healthcare systems and telecommunication technologies [6]. Common medical devices are electrocardiography (ECG) and blood pressure sensor to monitor heart condition, electroencephalogram (EEG) to monitor cognitive abilities, respiration and skin sensors to track infection, accelerometers and gyroscope to track mobility [45]. In rehabilitation and therapy, patients with mobility problems, such as those recovering from stroke or brain injury or major accident use gyroscope, accelerometer, and magnetometer for gait analysis. In biofeedback, data from the thermometer, blood pressure sensor, ECG, EEG etc. are fed back to the user so they can track and modify their physiological activity to improve their health. Environmental lighting and music can be personalized based on the user's emotional state to relax the user [45]. In ambient assisted living, people with disability and elderly can improve the quality of life using home automation. Acoustic, vibration, location and vision-based sensors placed around the house to monitor activity and lifestyle of residents. Another interesting and rapidly growing application is motion and gesture tracking for fitness. Performance and fitness monitoring tools allow athletes and military personnel to optimize training protocols to improve endurance. Several sensors can be found in fitness trackers such as magnetometer, GPS, accelerometer, heart rate monitor, barometer etc.

Data generated by the sensors from can be sent to the central server for intelligent analysis. Most important metric of wireless technology used in WBAN application is latency, which is of the order of a few milliseconds (real time). Therefore, LoRa and NB-IoT are not preferred. Many literatures suggest use of BLE, as BAN was one of the application focus of creating this technology [6]. Presence of BLE chips in smartphones, tablets and laptops has made the presence of BLE chips ubiquitous, they can also act as an internet gateway. Another benefit of using BLE is the availability of an open-source stack and large developer community.

D. Smart Factory

Industrial automation is the use of control systems for automating different processes and machineries. Wireless technologies have been used as serial cable replacement, Ethernet cable replacement, seamless roaming for Automated Guided Vehicles, Fieldbus cable replacement, wireless sensors and actuators etc. These networks are hundreds of meters wide and contain dense networks of hundreds of thousands of nodes. Wireless networks have to operate in an environment with unpredictable changes in humidity, pressure, temperature, vibration, presence of highly reflective surfaces and constant presence of electromagnetic noise [7]. Wireless technology must be reliable, robust, fault-tolerant, secure and deterministic. Application such leak detection requires placement of sensors to detect leakages in fluids (gases and liquids) such as water, natural gas and chemicals. These sensors carry critical information, QoS offered by wireless sensors must be high. Also, there is a need of localization and tracking of these motes to locate the source of leak. Warehouse monitoring is the process by which inventory is received, tracked, organized, sent out, analysed, and forecasted throughout a warehouse [46]. Sensors such as position tracker can be used to track pallets, boxes or units. Temperature, vibration and current sensors can be used for predictive maintenance. Actionable and real time data is gathered from these sensors. This data is then analysed to predict possible breakdowns and schedule proactive maintenance. Usually sensors are stationary, small, battery powered, require bidirectional communication and FOTA. Traditionally Bluetooth and 802.15.4 (Zigbee) networks have been used. BLE and Zigbee may be used in applications where sensors and actuators are used and require real time communication. BLE and LoRaWAN can be used for indoor tracking as indoor GPS performance is poor [46]. NB-IoT is also a better choice due to the high level of QoS requirements of industrial applications [39]. LoRa, NB-IoT, BLE and Zigbee can provide site-wide network coverage if



configured and deployed considering different trade-offs [7]. Literature provides analysis on use of Zigbee and LoRaWAN in smart factory environments [47], [48].

E. Smart Grid

Smart grid is a self-sufficient electricity network system based on digital automation for monitoring, control and analysis within the supply chain [49]. Various grid elements from generation to end user are connected to the internet. Smart grid applications have bandwidth requirements from bps to Mbps, latency requirements from milliseconds to seconds, uptime from 90 percent to 99.9999 percent, network needs to be scalable to a large number of devices, and range requirements are from meters to kilometres. There are several challenges when WSN is deployed in smart grid applications [50]. Wireless sensor nodes are subjected to harsh environmental conditions, high noise levels, security of wireless sensor network is important from physical tampering (also known as node capture) standpoint to hacking of wireless network and the QoS must be maintained at all the times due to mission critical nature of some applications. In case of smart power transmission and distribution, various components such as overhead transmission lines, underground cable network, substations and distribution transformers are monitored using sensors and Supervisory Control and Data Acquisition (SCADA). Advanced Metering Infrastructure (AMI) is an integrated system of smart meters, communication networks and meter data management system (MDMS) that enables two-way communication between utility and customers [51]. Data from meters is received by the AMI host system which is sent to MDMS. Similar infrastructure can be used with gas and water meters. Energy requirements in electric meters are not much of concern as mains supply can be used to power the RF chip on meters, but in case of gas or water meters, which are typically operated using batteries, power constraints must be taken into consideration.

Use of NB-IoT and LoRaWAN in WAN application and use of Zigbee and BLE in Home Area Network (HAN) has become popular [52]. HAN is used for home automation where consumer electronics appliances and wireless sensors are used, which communicate with a central regulator or smart meter. For reliable communication use of Zigbee and when monitoring non-critical parameters LoRaWAN can be used. Traditionally mesh networking technology has been used in smart metering applications [52, 53, and 54]. Many LoRaWAN devices have come into the market serving smart metering applications. Since most electric meters won't be dependent on batteries and also will be in a dense city environment NB-IoT can be used for better QoS and security at expense of monthly subscription that the utility company has to pay.

F. Connected Living

IoT enabled connected living offers improvement in the quality of life of the people living in a smart home or people working in smart buildings. Sensors such as temperature, humidity, light intensity, motion detection, shock detection, leakage detection, occupancy sensors, smart meters, smart indoor parking sensors etc. providing data enables smart automated decisions which provide cost efficient and environment friendly solutions. Other services such as smart grid, smart city and smart waste management can use services of smart homes or smart buildings to improve their own services. Requirements of the smart home network are as follows [55, 56]. The node density may be on the order of hundreds. Wireless technology must be robust as there may be presence of reflective surfaces, other wireless technologies operating in the same band and electromagnetic noise from home appliances. Wireless technology must also support some degree of mobility. In critical applications such as security, remote control and fire safety low latency is necessary. In a smart home, embedded sensors and actuators communicate with each other and home control unit. A smart home may contain smart appliances such as smart TV, home security system, smart refrigerators, smart air conditioner, smart washing machine, fire detection, lighting and temperature control etc. Building automation is an automated system that converges, integrates and connects many different facility technologies through information flow to a monitoring point [57]. Sensors such as temperature, humidity, light intensity, motion detection, shock detection, leakage detection, occupancy sensors etc. are being used to optimize the resource usage of the commercial buildings. Controlling Heating, Ventilation and Air Conditioning (HVAC), lighting and occupancy can reduce electricity cost substantially.

Bluetooth mesh, Zigbee, NB-IoT and LoRa have potential to be used in a connected living environment. Bluetooth mesh is expected to rise in the building automation market [58]. Article [59] provides benefits of using LoRaWAN in smart building scenarios. NB-IoT is also seen as potential wireless technology used with sensors that are placed deep inside the building. NB-IoT also provides good QoS and security. Although much of the research uses Zigbee [55, 56, 60, and 61] as one of the wireless technologies for evaluation, the research itself is conducted before LPWAN technologies came into existence. Literature such as [55, 60, and 62] provide technical analysis using Zigbee for home automation application. Bluetooth mesh has been developed with building automation as one of the target applications [63] although technology is new and issues must be resolved.



Various IoT applications and suggested suitable wireless technology are presented in Table 2.

Table 2: IOT APPLICATIONS AND SUGGESTED WIRELESS TECHNOLOGY

Application		Zigbee	BLE	LoRaWAN	NB-IoT
Smart City	Smart Street Lighting	*		*	*
	Smart Waste Management			*	
	Air Quality and Pollution Monitoring			*	
	Smart Parking	*		*	
Smart Farming	Cattle Tracking			*	
	Soil Monitoring			*	
	Greenhouses			*	
	Meteorological Station Network			*	
Smart Health Care	Telemedicine		*		
	Rehabilitation and Therapy		*		
	Biofeedback		*		
	Ambient Assisted Living	*	*		
	Motion and Gesture Tracking for Fitness		*		
Smart Factory	Leak Detection	*		*	*
	Warehouse Monitoring		*	*	
	Predictive Maintenance	*			*
Smart Grid	Smart Power Transmission and Distribution	*		*	
	Advance Metering Infrastructure	*		*	*
Connected Living	Smart Home	*	*		
	Building Automation	*			*

V. CONCLUSION AND FUTURE WORK

In this paper, we looked at metrics that are commonly used to compare wireless technologies along with trade-offs with other metrics. We briefly looked at features of four wireless technologies namely Zigbee, BLE (Bluetooth Mesh), LoRaWAN and NB-IoT. We also discussed different IoT application domains and suggested appropriate wireless technology best suited based on application requirements. We can see that every application has its own set of challenges and requirements that only a particular type of wireless technology can solve. Therefore, one wireless technology cannot fulfil the requirements of all IoT applications. The metrics on which battery life depends are interrelated, therefore, change in one metric will affect the other. Each wireless technology uses different methods to optimize battery life, thus serving unique application domains and solving a set of challenges from that domain.

Wireless standards Zigbee and BLE are effective at low ranges up to 100m. LoRaWAN and NB-IoT are effective at 1-2 km in urban environments and 10-15 km in rural environments. In future, when NB-IoT is supported by MNOs in



India, one can perform range and current consumption tests. Over the years, Zigbee and BLE have proven reliable in real time applications and LoRaWAN and NB-IoT will serve applications that have relaxed latency requirements. At time of writing the paper, NB-IoT was in the development phase and few real-life implementations took place as opposed to LoRaWAN which has made strong market presence as leading LPWAN technology. In future, when NB-IoT matures, it would be interesting to see the business model that competes with other LPWAN technologies.

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