

## PAPER 143 – PARAMETERS CHARACTERIZATION OF WIRELESS TECHNOLOGIES: AN INDOOR LOCALIZATION PERSPECTIVE

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### ABSTRACT

The persistent rise in demand for affordable indoor localization systems and technologies capable of accurately predicting the real-time location of targets has been observed. While the Global Navigation Satellite System (GNSS) has proven its reliability in outdoor, it falls short of the required accuracy for indoor environments. In response, multiple wireless technologies have been proposed as potential alternatives to deliver location-based services in indoor settings with minimal errors. However, studies that comprehensively analyze and evaluate the parameter characteristics of these evolving technologies in indoor applications remain rare. In this regard, this paper assesses and characterizes different wireless technologies based on six parameters. Our study examines four short-range including WiFi, BLE, Zigbee and UWB, and the two long-range wireless technologies such as LoRa and WiFi Halow. The selected technologies are characterized using available information and distance-dependent models in terms of frequency band, data rate, coverage area, power consumption, signal-to-interference-plus-noise ratio, smartphone availability and deployment cost, and application. Result indicates that UWB is suitable for small indoor environment because of wide frequency band, this is followed by WiFi, BLE and Zigbee while LoRa is ideal for large indoor environment. LoRa has the least energy consumption followed by BLE. The energy consumed by Zigbee and UWB are considerably low while WiFi consumes the most energy. WiFi, BLE and UWB are smartphone accessible, hence they have the lowest cost while other technologies need extra hardware for deployment. These findings can be used as a guideline in selecting a wireless technology for an indoor localization system based on application requirements.

**KEYWORDS:** Indoor localization, WiFi, BLE, Zigbee, UWB, LoRa and WiFi Halow

### 36. INTRODUCTION

Location-based services (LBSs) have grown in popularity due to technological advancements and increase in the number of Internet of Things (IoT) devices. An IoT is a collection of interconnected end devices, including sensors and software, that are embedded in a specific environment with the capacity to sense, communicate, process, and store data without the need for human interaction. However, the collected environmental data remains insignificant until the precise location of its acquisition is determined. Thus, localization is a key step towards developing smart and IoT applications. Localization is the process of using available information and algorithms to determine the location of a target (Sadowski & Spachos, 2018a). Localization can be in outdoor or indoor scenarios. Outdoor localization has been achieved successfully using various types of regional-based Global Navigation Satellite System (GNSS). However, using GNSS in indoor scenario is accompanied by a lot of environmental and economic challenges. Furthermore, people tend to spend about 87-90% of their time indoors (Klepeis et al., 2001; Sarigiannis, Gotti, & Karakitsios, 2019; Wang, Shang, & Wu, 2023). Therefore, alternative solutions to locating people and objects in indoor environments need to be explored.

The use of wireless technologies has increased in the last decades in our daily lives. Wireless Access points (WAPs) have been deployed in a multitude of indoor environments for provision of internet connection. Although these technologies were designed for communication, the transmitted signal can be used to estimate the location of a target in the satellite denied environments (Asaad & Maghdid, 2022). However, the environmental constraints need to be overcome with proper analysis of the signal propagation to achieve accurate and robust indoor localization services. During signal propagation in a medium, there is signal degradation as the signal travels from the transmitter to the receiver. This signal loss increases exponentially as the distance between the transmitter and receiver increases. Besides the medium loss, presence of obstacles such as walls, stationary and moving objects also pose a challenge to accurate signal-to-distance estimation. The presence of obstacles along the signal propagation direction causes signal impairments such as reflection, refraction, absorption, and scattering (Farahsari, Farahzadi, Rezazadeh, & Bagheri, 2022). Various wireless technologies commonly used for communication have been employed in the design of indoor localization models.

The study in this paper is structured as follows: Section II reviews the relevant work, followed by an extensive overview of wireless technology in Section III. Section IV presents the system distance-dependent model, and Section V addresses the wireless technology's appropriateness. Section VI brings the study to a conclusion.

### **37. RELATED WORK**

The task of indoor localization presents more difficulties compared to its outdoor counterpart due to the presence of environmental obstacles. Numerous studies have been conducted to determine the parameter characterization of various wireless technologies (Sadowski & Spachos, 2018a, 2018b, 2019) (Khan, Awais, Rasheed, Masood, & Ghadi, 2021; Sadowski, Spachos, & Plataniotis, 2020; Simka & Polak, 2022; Tabaa & Hachimi, 2022). Nevertheless, each of these technologies exhibits its unique strengths and limitations in the context of localization. The study in (Sadowski & Spachos, 2018a) compared the accuracy and power consumption of Zigbee, BLE, and WiFi for the development of an indoor positioning system. WiFi was the most accurate system, followed by BLE. BLE was discovered to use the least amount of power. When Line of Sight (LoS) is available, Zigbee transmit up to 100 m. Similarly, the study in (Sadowski & Spachos, 2018b) evaluates the accuracy and power consumption of WiFi, BLE, Zigbee, and LoRa. The tests were carried out using a trilateration technique in two different environments. WiFi proved to be the most accurate also, followed by BLE. BLE was discovered to consume the least amount of power. When operating at maximum transmission power, LoRa has the longest range.

The study presented by Sadowski and Spachos (2019) verify the maximum number of beacons required in indoor localization to optimize accuracy. The result showed that placing six beacons and using nonlinear least algorithm with three closest references and a moving average filter yields the optimal result. Sadowski et al. (2020), performance of two memoryless localization techniques with trilateration on three technologies using RSSI was described. Results established that k-Nearest Neighbours (k-NN) with  $k = 4$  was the most accurate. Khan et al. (2021), evaluation of WiFi, BLE and LoRa for suitability in a particular indoor localization domain was carried out with Pycom's LoPy. WiFi exhibited the highest level of accuracy, followed by LoRa, while BLE had the lowest accuracy.

Simka and Polak (2022), present the evaluation of different configuration modes of LoRa at 2.4 GHz in three different environments. Trilateration was setup to determine the location of an object using RSSI. The results indicate that the performance of LoRa was influenced by factors such as signal configuration, node positioning, and the characteristics of the indoor environment. The performance of LoRa was also evaluated under both LOS and NLOS indoor environments in the study conducted by Tabaa and Hachimi (2022). Results show improved performance of LoRa as the spreading factor increases from 7 to 12.

In this paper, detailed parameter characteristic of these wireless technologies from indoor localization perspective was analysed. Additionally, wireless technology recently incorporated into smartphone was compared with the existing ones. The comparison was based on using available information and distance-dependent models.

### **38. WIRELESS TECHNOLOGIES**

Indoor localization schemes require wireless communication technology for the transmission and reception of data from one device to another. The most popular short and long-range technologies are WiFi, BLE, Zigbee, UWB, WiFi Halow and LoRa. This section focuses on their suitability in the development of indoor localization models and presents a comparison of these technologies.

#### **3.1 WiFi (IEEE 802.11)**

WiFi is one of the most used wireless technologies because it is compatible with a lot of portable devices from laptops to smartphones and smartwatches. It was first released in 1997 and later clarified in 1999. It works in the industrial scientific and medical (ISM) band of 2.4 or 5 GHz. It is commonly used to create a Wireless Local Area Network (WLAN) and largely used to link various devices to the internet in private and public settings. Due to the advancement in smart applications, there has been an exponential growth in the number of WiFi-enabled devices. This growth has inspired several researchers to use this technology for the development of affordable indoor localization services in recent years (Grgić, Balić, Križanović, & Žagar, 2022; Kargar-Barzi, Farahmand, Mahani, & Shafique, 2023; Zhou, Meng, Zhou, & Teng, 2022). WiFi networks are primarily designed for communication purposes, and thus, efficient algorithms are required to enhance their accuracy for localization purposes (Martin-Escalona & Zola, 2020).

The IEEE 802.11 standard has undergone continuous improvements, starting from its initial release as IEEE 802.11b in 1999, which operated at a frequency of 2.4 GHz, to IEEE 802.11g (2003) and IEEE 802.11n (2008), operating at 2.4 or 5 GHz, offering improved data rates, bandwidth, and coverage area. The IEEE 802.11ah standard (2017), also known as WiFi low power or WiFi Halow, was developed specifically for IoT device connectivity at sub-1-GHz frequency, providing an extended transmission range of approximately 1 km. The advent of IEEE 802.11ac (2014) and its more recent successor, IEEE 802.11ax (2020), which operate at the 6

GHz frequency band, have led to improved throughput, particularly in high-density environments. Furthermore, the forthcoming IEEE 802.11be (2024), which is slated to operate at 2.4/5/6 GHz frequency bands, will be specially designed to cater for WLAN indoor and outdoor localization operations. Table 1 presents an overview of the various generations of WiFi technologies, along with their distinctive key characteristics.

TABLE 1: Generation of WiFi (IEEE 802.11) Wireless Technology Standards

WiFi Generation	IEEE Standard	Release Date	Frequency Band (GHz)	Data Rate	Coverage Range (m)	Max. Transmission Power (mW)
WiFi	802.11	1997	2.4	1 - 2 Mbps	20-100	100
WiFi-1	802.11b	1999	2.4	1 - 11 Mbps	35-140	100
WiFi-2	802.11a	1999	5	6 - 54 Mbps	35-120	100
WiFi-3	802.11g	2003	2.4	6 - 54 Mbps	38-140	100
WiFi-4	802.11n	2008	2.4/5	72 - 600 Mbps	70-250	100
WiFi-Gig	802.11ad	2012	60	Up to 6.7 Gbps	1-10	10
WiFi-5	802.11ac	2014	5	433 - 6.933 Gbps	35-70	160
WiFi-Halow	802.11ah	2017	0.9	Up to 347 Mbps	100-1,000	100
WiFi-6/6E	802.11ax	2019/2020	2.4/5/6	574 - 9.608 Gbps	30-120	100
WiFi-EDMG	802.11ay	2021	60	Up to 20 Gbps	10-100	10,000
WiFi-7	802.11be	2024	2.4/5/6	1.376-46.120 Gbps	30-120	Not yet defined

### 3.2 BLE (IEEE 802.15.1)

Bluetooth Low Energy (BLE) is a Wireless Personal Area Network (WPAN) technology for low-power and short-range communication. It was intended for energy-constrained devices, and it operates at 2.4000 – 2.4835 GHz frequency bands. BLE was introduced by Bluetooth Special Interest Group (SIG) in 2010. Compared to older versions, BLE offers higher energy efficiency, an improved data rate of 24 Mbps, and a coverage range of 30-60 meters (Martin-Escalona & Zola, 2020). However, the most recent Bluetooth version (5.3) launched in 2021 has a transmission rate and range of about 2-50 Mbps and 240 meters, respectively.

There has been a drastic improvement from Bluetooth classic and BLE. The former refers to versions 1.0 in 1999 to 3.0 in 2009, while the latter includes versions 4.0 in 2009 to the most recent versions 5.3 launched in 2021 with two-fold increase in transmission range and rate. Classic Bluetooth suffers from short battery lifetime, making it impractical for IoT applications while BLE was introduced to meet the demand for wireless connectivity of small devices. Due to low power usage of BLE, it's ideal for IoT devices (Andy 2023). Table 2 summarizes the various improvements in BLE versions from Bluetooth classic to BLE.

TABLE 2: Improvement in Bluetooth Technology

Versions Factors	Bluetooth v1	Bluetooth v2	Bluetooth v3	Bluetooth v4	Bluetooth v5
Data Rate	732.2 kbps to 1 Mbps	2.1 Mbps Enhanced Data Rate	800 kbps - 24 Mbps (via WiFi) (EDR)	1 Mbps (LE), 25 Mbps (EDR)	2 Mbps (LE), 50 Mbps (EDR)
Range	10 m	30 m	30 m and 10 m indoors	60 m and 40m indoors	240 m
Compatibility	N/A	Ok for any mobile phone, little sound sync issues	Ok for any mobile phone	Best for models with the same version	Best for newer phone models
Power	High	High	High	Mid-high	Low
Reliability	Low	Low	Low	Mid-high	High

#### a. Zigbee (IEEE 802.15.4)

Zigbee is a popular wireless technology designed to enable low-cost, low-power machine-to-machine (M2M) communication in sensor networks. It operates at 868 MHz band in Europe, 915 MHz band in the US and Australia, and 2.4 GHz in other regions (Obeidat, Shuaieb, Obeidat, & Abd-Alhameed, 2021). Zigbee is used for long-distance communication between devices in wireless sensor network. Although Zigbee is cost-effective, energy-efficient, and suitable for sensor localization in Wireless Sensor Networks (WSNs), it is not commonly found on most user devices, making it unsuitable for indoor localization of targets. Additionally, since it operates without a license in ISM bands, it is susceptible to interference from other signals operating in the same spectrum, such as WiFi and BLE.

**b. UWB (IEEE 802.15.4a)**

Ultra-Wideband (UWB) is a promising low energy, short-range radio-based technology that enables quick and reliable transmission of pulses at the speed of light (0.3m/ns) and larger bandwidth (<500MHz) in the frequency range of 3.1 to 10.6 GHz. This technology is particularly well-suited for the development of advanced micro-location-based systems that require secure and real-time positioning information, regardless of whether they are used indoors or outdoors (Kinexon, 2022). The standard was designed to be both low-power and low-cost while also being capable of supporting many connected devices.

Although UWB has been incorporated into some new smartphones from Apple, Samsung, Google, and Xiaomi like WiFi and BLE, it differs because it operates at a very high frequency and thus uses a wide spectrum of several GHz. Wireless technologies are often limited to narrow bands to avoid interference with each other. However, UWB technology addresses this issue by using extremely low power levels that fall within the noise floor of other wireless applications. Essentially, the UWB spectrum is wide enough to be easily detectable, but low-powered enough to prevent interference with other signals. Fig. 1 shows the spectrum of common wireless technologies. UWB technology is becoming increasingly popular, with the Apple AirTag being one of its most common applications. Its ability to track the location of objects makes it useful in various scenarios, and it holds promise for secure car unlocking and smart homes in the future (Viot, Bizational, & Seegars, 2021). In contrast to WiFi and BLE, which rely on RSSI for distance estimation, this technology utilizes time of flight (ToF) multiplied by the speed of light in air to determine both distance and direction from the transmitter. The pulse-based nature of UWB technology enables this significant advantage.

Technologies that rely on RSSI can yield misleading distance and location measurements in indoor environments. The multipath effects can be ignored in UWB because the technology uses the shortest distance to calculate the ToF even if the direct signal is weaker than the obstructed signals. In addition, it only requires a single measurement to determine position accurately and reliably, while other technologies may require multiple samples with filtering to determine location (Viot et al., 2021).

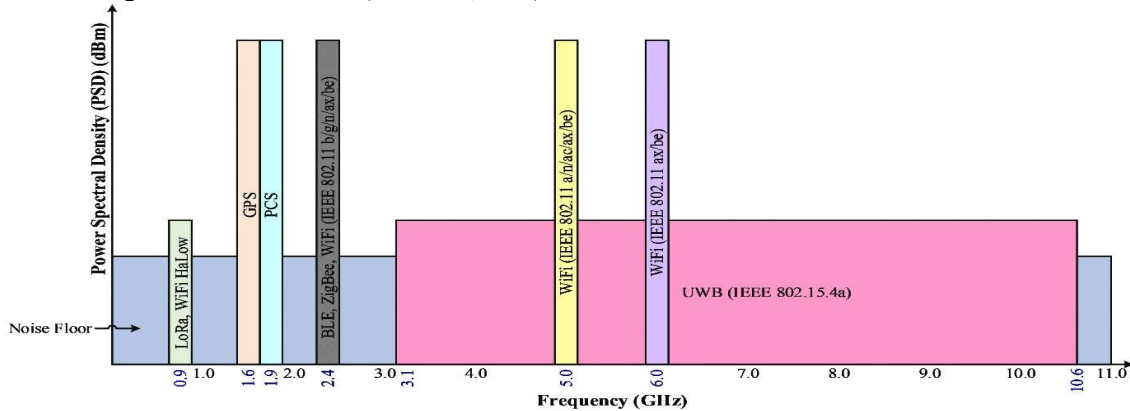


Fig 1: Spectrum used by common Wireless Technologies.

**c. LoRa (Long Range)**

LoRa is a wireless technology that has emerged as one of the most frequently utilised long range and Low-Power Wide-Area Network (LPWAN) technology in a variety of IoT applications. LoRa operates at frequencies of 868 MHz and 915 MHz in the unlicensed ISM bands in Europe and America, respectively, providing a range of around 5 km in urban areas and up to 15 km in rural areas (Al Khattat, Anas, & Saif, 2022). The low power, low data rate and long range makes it the ideal technology for IoT and smart applications, unlike other technologies transmitting more data and hence consumes more power. LoRa uses a Chirp Spread Spectrum (CSS) modulation to improve robustness against noise and bandwidth of 125, 250 or 500 kHz to transmit small data packet (0.3-50 kbps) on the sub-1 GHz bands.

The important parameters of LoRa are Bandwidth (BW), Spreading Factor (SF) and Code Rate (CR). These parameters influence its bit rate, resistance to interference and receiver or decoder sensitivity (Tabaa & Hachimi, 2022). An increase in BW lowers the receiver sensitivity, increases the data rate, whereas an increase in SF increases the receiver sensitivity, increases power consumption, lower data rate and its resistance to interference.

**39. SYSTEM DISTANCE-DEPENDENT MODEL**

Considering an indoor environment where there is LOS between a transmitter and a receiver at a distance of  $d = 100\text{ m}$  apart, the carrier frequency  $f_c$ , and the path loss exponent  $n$ . Path loss of any wireless technology can be defined in (Ghosh et al., 2022):

$$PL_{wt}[dB] = 2n \log_{10} \left[ \frac{4\pi d}{f_c} \right] + 10 \log_{10} \left[ \frac{4\pi}{\lambda} \right]^2 \tag{1}$$

Where  $w_t$  is refers to any of the wireless technology,  $\lambda$  is the wavelength and is related to frequency and speed of light  $c$  by

$$\lambda = \frac{c}{f_c} \quad (2)$$

The received power is related to the transmitted power  $P_{t_{wt}}$ , transmitter and receiver gains ( $G_{t_{wt}}$  and  $G_{r_{wt}}$ ) and system loss  $L_{wt}$  by:

$$P_{r_{wt}}[dBm] = P_{t_{wt}} + G_{t_{wt}} + G_{r_{wt}} - PL_{wt} - L_{wt} \quad (3)$$

The noise spectral density is given as:

$$N_{0-wt} = -174 + 10 \log_{10} BW_{wt} \quad (4)$$

Signal-to-interference-plus-noise ratio (SINR) is related to the received power  $P_{r_{wt}}$ , Bandwidth  $BW_{wt}$  and noise spectral density  $N_{0-wt}$  by:

$$SINR_{wt}[dB] = P_{r_{wt}} - N_{0-wt} - 10 \log_{10} BW_{wt} \quad (5)$$

Data rate of the wireless technology is related to the bandwidth and SINR by Shannon Hartley equation (Ghosh et al., 2022) as:

$$R_{b-wt}[bps] = BW_{wt} \times \log_2(1 + 10^{\frac{SINR_{wt}}{10}}) \quad (6)$$

Coverage range is also related to gains, receiver sensitivity by Friis equation (Augustin, Yi, Clausen, & Townsley, 2016) as:

$$Range_{wt}[m] = \frac{\lambda}{4\pi} \sqrt{\frac{P_{t_{wt}} \times G_{t_{wt}} \times P_{r_{wt}}}{P_{min-wt} \times G_{r_{wt}}}} \quad (7)$$

#### 40. RESULTS AND DISCUSSION

Some underlying factors need to be considered for a wide-scale adoption of any of these technologies in indoor localization systems. The factors are frequency band, coverage range, Signal-to-Interference-plus-Noise Ratio, power consumption, deployment cost and smartphone accessibility and applications. Table 3 summarizes these factors. The parameters in Table 3 assumed the devices are transmitting with maximum power and LOS is maintained between the devices.

Table 3: Parameter characteristics of different Wireless Technologies in Indoor Environment

Technology Metrics	WiFi	BLE	Zigbee	UWB	WiFi Low Energy	LoRa
Frequency (GHz)	2.4/5/6	2.4-2.48	2.4	3.1-10.6	0.9	0.915
Coverage (m)	~100	30-60	10-30	10-30	100-1,000	2,000-5,000
Data rate (Mbps)	2-600	1-2	0.25-1	53.3-480	8.67-347	0.3-50 kbps
Consumption	Medium	Very low	Low	Low	Low	Extreme low
Smartphone availability	Yes	Yes	No	Partial	No	No
Applications	Smart cities	IoTs	WSN	LBS, Smart Car Access	IIoTs	IoTs, Smart farming
Advantages	Widely available, low cost and portable	Widely available, low cost and portable	Low-cost and power consumption	Accurate, reliable, and low power consumption	Wide range, low power consumption	Wide range, low power, and low-cost
Disadvantages	Prone to noise, signal blockage	Prone to noise, signal blockage	Limited range and data rate	Limited adoption and range, Require LOS	Prone to noise, Extra HW, not suitable for higher BW applications	Limited data rate and BW, Require Extra HW

Frequency band and coverage area: the frequency of the wireless technology can affect the coverage of the system. Lower frequency signals tend to have a longer range and are better suited for large indoor spaces such as LoRa and WiFi Halow, while higher frequency signals tend to have a shorter range and are better suited for smaller indoor spaces. Data Rate: Higher data rate improves system capacity but at the expense of energy consumption. Most indoor LBSs does not need to transfer large amount of data. UWB, WiFi and BLE uses tens of Mbps while the data rate of LoRa, WiFi Halow and Zigbee is in the order of tens of kbps as shown in Fig. 2. SINR: A higher SINR means that the received signal is stronger relative to the interference and noise, which reduces the probability of errors and increases the capacity of the network as seen in Fig. 3. Power Consumption: The consumption should be low to support battery-operated devices and enable long lifetime. LoRa, BLE and WiFi

Bluetooth Low Power (BLE) is the most appropriate technology with least power consumption. Zigbee and UWB are suitable for devices that may need to work for few months with medium power consumption. WiFi technology has the highest energy consumption, but common WiFi-based APs are usually powered from the main supply. Smartphone accessibility and deployment cost: Both parameters are interwoven. Lower deployment cost can make indoor localization systems more accessible and affordable for a wider range of applications and users. WiFi and BLE tend to have lowest cost because they are readily available on smartphones. Recently, UWB technology is also available on smartphones from vendors like Apple, Samsung, Google Pixel and Xiaomi Mix. LoRa, Zigbee and WiFi all require special hardware (HW), but the range of LoRa can be compensated with the cost of the HW. Applications: Wireless technology-based indoor localization is a cost-effective and precise solution for a variety of satellite-denied applications such as healthcare, industries, logistics, context-aware marketing, and emergency response.

Based on Equations (1-7), the estimated data rate and quality of the received signal can be measured by SINR for the wireless technologies as illustrated in Figures 2 and 3. The results in Figure 3 indicate that UWB and WiFi have significantly higher data rates compared to BLE and Zigbee which have relatively low data rates, and LoRa has the lowest achievable data rate. UWB and WiFi are suitable for real-time applications. SINR is a metric used to determine the signal quality relative to noise and interference in the environment. UWB provides the best signal quality, followed by WiFi, while LoRa exhibits the least signal quality. Zigbee and BLE have relatively good signal quality. It is important to note that the actual signal strength may vary greatly depending on the environment, such as the presence of walls, humans, other wireless devices, interference, and other factors.

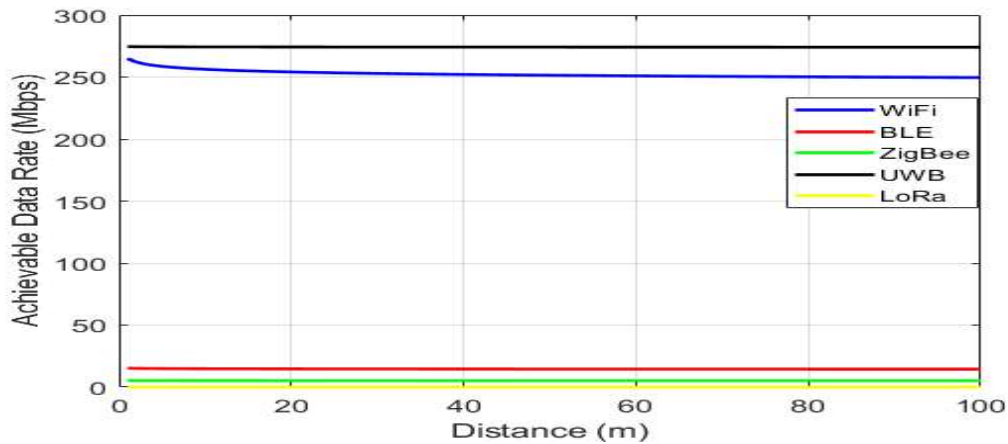


Fig 2: Data Rate of the Wireless technologies

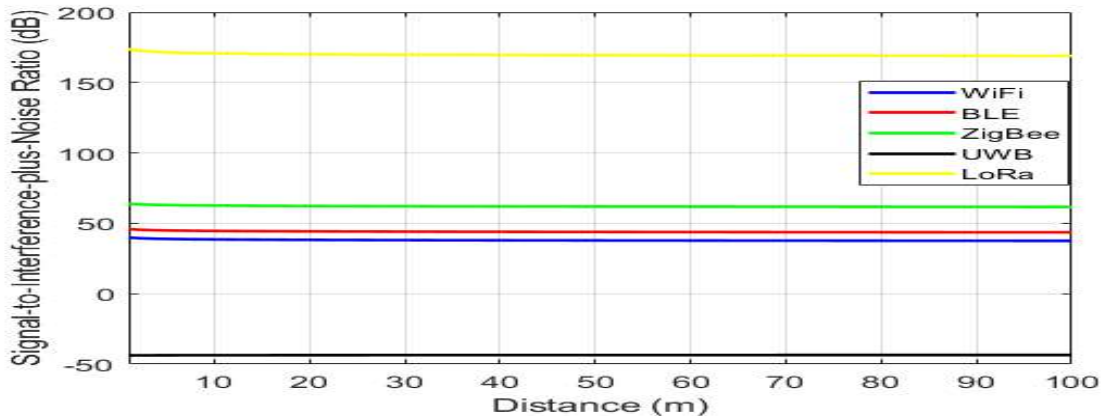


Fig 3: SINR of the Wireless technologies

#### 41. CONCLUSION

In this study, we characterize and analyse the performance of several wireless communication technologies in terms of frequency band, data rate, SINR, energy consumption, smartphone availability, deployment cost and application areas. The essence of the characterization is to help us to decide the appropriate wireless technology for a specific indoor localization application. In the analysis, UWB is found to be suitable for small indoor environment because of the wide frequency band, followed by WiFi, BLE and Zigbee while LoRa and WiFi

Halow are suitable for large indoor environment. LoRa has the least energy consumption followed by BLE and WiFi Halow. The energy consumed by Zigbee and UWB are relatively low while WiFi consumes the most energy. WiFi, BLE and recently UWB are smartphone accessible, hence they have the lowest cost while others wireless technologies need extra hardware for deployment.

However, it is important to note that the accuracy of this analysis can be affected by a variety of factors, including environmental conditions and device heterogeneity. Future study should consider experimental evaluation of the wireless technologies in different environments with different interference level using robust indoor localization techniques.

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