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Comparative Study of Short-Range Wireless Protocols Across Different Wireless Network

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Abstract

Wireless communication has become indispensable to modern data transmission, replacing cable-based links across personal, local, metropolitan, and wide-area settings. This paper presents a condensed comparative study of the four dominant short-range wireless protocols — Bluetooth (IEEE 802.15.1), Ultra-Wide Band or UWB (IEEE 802.15.3), ZigBee (IEEE 802.15.4), and Wi-Fi (IEEE 802.11a/b/g) — alongside the broader classification of wireless networks into Personal, Local, Metropolitan, and Wide Area categories (WPAN, WLAN, WMAN, and WWAN). Each protocol and network category is reviewed in terms of frequency band, data rate, range, topology, security, and coexistence mechanism, drawing on the underlying M.Phil. dissertation. A quantitative evaluation further compares transmission time, data coding efficiency, protocol complexity, and power consumption across the four short-range protocols using standard reference chipsets. Results show that ZigBee and Bluetooth are efficient for small, low-power payloads such as sensor data, while UWB and Wi-Fi are preferable for high-data-rate, energy-efficient transmission such as audio and video. No single protocol is found to be universally superior; suitability ultimately depends on the target application and its constraints.

Keywords: Bluetooth, UWB, ZigBee and Wi-Fi, Wireless Communication Protocols, Wireless Network Performance, Power-Efficient Data Transmission

INTRODUCTION

Data transmission from one location to another is a central requirement of modern communication, and an increasing share of that traffic now moves over wireless rather than wired links. Wireless Sensor Networks (WSNs) in particular emphasise communication with minimal energy consumption; each sensor node carries a limited battery and expends power on sensing, processing, receiving, and transmitting data. WSNs are deployed in military, area-monitoring, transportation, environmental, structural, industrial, and agricultural applications, with every node built around four basic units — a sensor unit, a transceiver unit, a power unit, and a processing unit [1-3].

The shift away from cabled connections was driven by the practical inconvenience of wired links for mobile users — for example, a traveller who needs to transmit data immediately but has no physical network connection available. To address this, the IEEE introduced a succession of wireless standards, each designed to overcome the limitations of the one before it [4]. Bluetooth was introduced first, followed by Wi-Fi, and then ZigBee. Bluetooth and ZigBee are short-distance protocols, while Wi-Fi supports a considerably wider range. Wi-Fi itself has a drawback in that it is not fully reliable when bandwidth is constrained, which motivated the development of ZigBee — a lower-power, more reliable protocol for short-range transmission. ZigBee evolved from a star topology, to a mesh topology, and finally to a cluster-tree topology that allows a transmitting node to borrow bandwidth from its parent node when required, using an Adaptive Parent-Based Framework and a Pull-Push-Reliable protocol.

Most wireless local networks are built on the IEEE 802.11 family of standards, operating in the 2.4 GHz or 5 GHz ISM bands, and organised either in infrastructure mode — where an access point (AP) mediates all communication in a Basic Service Set (BSS) — or in ad-hoc mode, where stations communicate directly without a master. Security has evolved alongside these standards, from the original, easily broken Wired Equivalent Privacy (WEP) scheme to the more robust IEEE 802.11i (WPA2) specification.

Several prior studies inform this comparative review. Lee et al compared Bluetooth, UWB, ZigBee, and Wi-Fi in terms of transmission time, data coding efficiency, complexity, and power consumption [3]. Priyadarshini et al examined energy-harvesting and clustering techniques to extend WSN lifetime [4]. Separate studies by Rani et al, Bhut et al, and Sharma et al explored Li-Fi as a visible-light alternative to RF-based transmission, reporting bandwidth, efficiency, and security advantages over Wi-Fi [5-7]. Chakkor et al compared Wi-Fi, Wi-MAX, UWB, Bluetooth, ZigBee, and GSM/GPRS on utilisation efficiency, energy consumption, and implementation cost, while Ferro and Potorti surveyed Bluetooth and Wi-Fi in terms of capacity, topology, security, and quality of service [8], [9].

Wireless Protocols

The short-range wireless landscape is currently dominated by four protocols — Bluetooth, UWB, ZigBee, and Wi-Fi — corresponding respectively to the IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11a/b/g standards. The IEEE defines the physical (PHY) and MAC layers for wireless communication over an effective range of roughly 10–100 metres. This section reviews each protocol in turn [12], [13].

Bluetooth

Bluetooth is a low-cost, low-power, short-range technology developed by Ericsson in 1994 to replace cable connections between handheld devices, PDAs, and computer peripherals. It operates in the unlicensed 2.4–2.485 GHz ISM band using adaptive frequency hopping at roughly 1600 hops per second, forming ad-hoc networks called piconets — collections of two or more Bluetooth devices sharing the same hopping sequence, with one device acting as master and up to seven as slaves. Two or more piconets can combine into a larger scatternet. Its principal benefits include cable replacement, easy file distribution, wireless synchronisation, and shared Internet connectivity [14], [15]. Devices are grouped into three power classes by range, summarised in Table 1.

Table 1: Bluetooth Device Classes

Class	Power (nW)	Power (dbM)	Distance (m)	Sample Devices
1	100	20	-100	BT Access Point, dongles
2	2.5	4	-10	Keyboards, mice
3	1	0	-1	Mobile Phone headset

Bluetooth security operates at both service and device level through authorisation, authentication, and key management (link key, PIN, and encrypted key), and is implemented in three modes ranging from fully open (Mode 1) to link-level enforced security using a shared secret key derived during pairing (Mode 3). Despite this, Bluetooth's broad service support and peer-to-peer design expose it to vulnerabilities such as identity detection, location tracking, denial of service, and unauthorised device or data access.

UWB (Ultra-Wide Band)

Ultra-Wide Band was developed to replace fast wired connections over short distances with data rates in the hundreds of Mbit/s. As defined by the U.S. Federal Communications Commission (FCC), a UWB system occupies more than 25% of its centre frequency or more than 1.5 GHz of bandwidth — far greater than conventional narrowband or wideband systems — and is typically implemented without a carrier, directly modulating very short pulses to occupy several GHz of spectrum. The FCC permitted UWB operation in the United States in 2004 within the 3.1–10.6 GHz band at a power spectral density of −41.3 dBm/MHz; the European Commission followed in February 2007 with a 4.8–6 GHz allocation [16], [17].

UWB systems are attractive because their large occupied bandwidth, per the Shannon channel-capacity theorem ($C = B \cdot \log_2(1 + S/N)$), gives them greater capacity headroom than more spectrum-constrained systems, and they exhibit inherent robustness to multipath fading [18]. Trade-offs between pulse bandwidth and pulse repetition frequency allow range to be extended for a fixed average transmit power, though at the cost of increased peak power. UWB has found application in fast home networks for audio/video transport, and as a wireless replacement for high-speed serial buses such as USB 2.0 and IEEE 1394.

ZigBee

ZigBee, based on IEEE 802.15.4, targets low-power wireless sensor networking and automation applications where Bluetooth and Wi-Fi are too complex or power-hungry [19-21]. It operates in the ISM bands — 868 MHz

(Europe), 915 MHz (USA/Australia), and 2.4 GHz (worldwide) — with data rates from 20 to 900 kbit/s, and uses O-QPSK modulation with Direct Sequence Spread Spectrum. Established by the ZigBee Alliance in 2001, the specification (ZigBee 2007) supports full mesh networking for more than 64,000 devices on a single network, through the ZigBee and ZigBee PRO feature sets, and secures data using AES-128 encryption [21], [22].

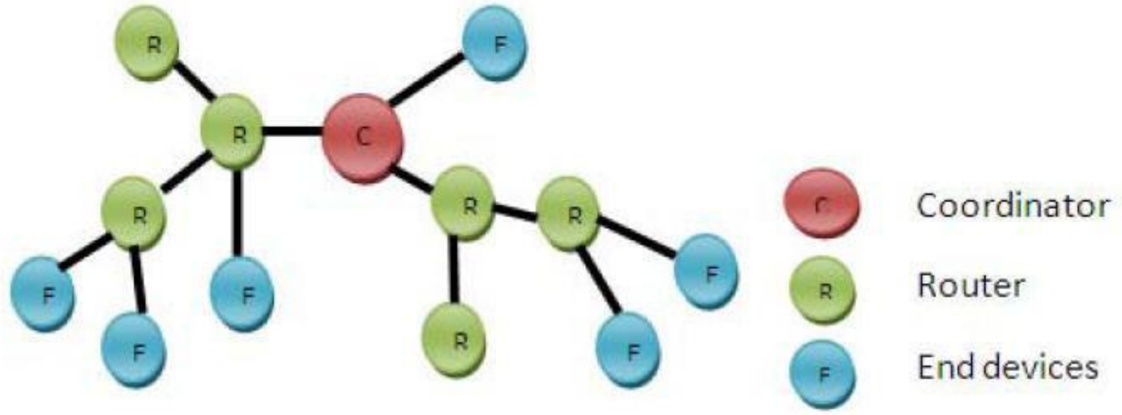


Figure 1: ZigBee Network

ZigBee devices combine an application layer (e.g., a light sensor or controller), a logical role (coordinator, router, or end device), and a physical device type — Full Function Device (FFD) or Reduced Function Device (RFD). Its key advantages are reliability, self-healing mesh operation, very long battery life, low cost, global operation, and remotely upgradeable firmware, making it well suited to industrial monitoring, home automation, and other applications with small, infrequent data payloads [19].

Wi-Fi (Wireless Fidelity)

Wi-Fi, based on the IEEE 802.11 family (802.11a/b/g/n), provides wireless local-area connectivity with a normal access-point coverage of about 20 m indoors and 100 m outdoors, extending to several hundred metres with the MIMO-OFDM techniques introduced in 802.11n (theoretical rates of 400–600 Mbit/s) [23], [24]. A basic deployment connects laptops, tablets, and smartphones to an access point that bridges the wireless segment to a wired backbone, as illustrated in Figure 2.

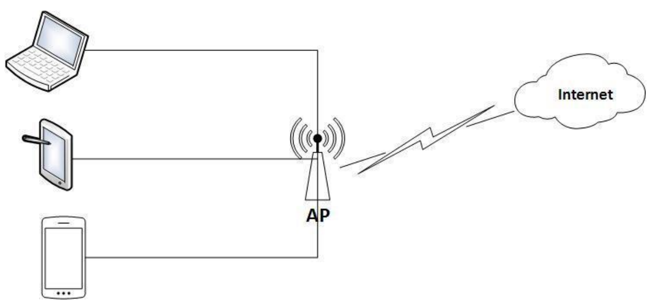


Figure 2: Deployment of a Wi-Fi Network

Wi-Fi is complemented at metropolitan scale by Wi-MAX (IEEE 802.16), a broadband wireless access standard with coverage of up to 50 km, intended for the 'last mile' where wired infrastructure is costly [25], [26]. Table 2 summarises the key differences between the two.

Table 2: Comparison of Wi-Fi and Wi-MAX

Feature	Wi-Fi	Wi-MAX
Standard	802.11a/b/g/n	802.16d/e
Data rate (MAX)	300 Mbps	70 Mbps
Transmission distance (MAX)	300m	50Km
Operating Frequency	2.4 GHz and 5GHz	2-11 GHz
Channel Bandwidth	20 to 25 MHz	Ranging From 1.25 to 20 MHz
Encryption	RC4 and Advanced Encryption Standard(AES)	Triple Data Encryption Algorithm (3DES) and Advanced Encryption Standard (AES)

Wi-Fi's principal limitations at scale are channel interference between neighbouring access points, the 'network island' effect created by its short range, and poor support for high-speed mobility (e.g., on trains or buses). Wi-MAX and Wi-Fi are therefore best viewed as complementary: multi-mode devices combining both technologies extend hotspot roaming while retaining Wi-Fi's high local throughput [27-32].

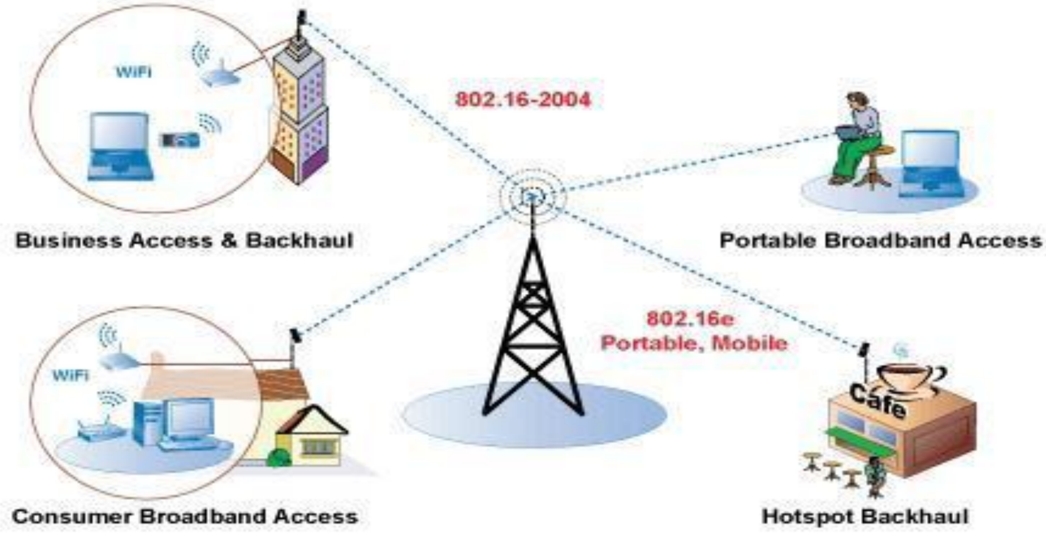


Figure 3: A Wi-MAX Network

Wireless Networks

Wireless networks are conventionally divided into four groups based on signal range and application: Wireless Personal Area Network (WPAN, up to ~10 m), Wireless Local Area Network (WLAN, ~30 m indoors / ~100 m outdoors), Wireless Metropolitan Area Network (WMAN, ~5 km, commonly branded Wi-MAX), and Wireless Wide Area Network (WWAN, built on mobile-operator infrastructure and covering the widest area). This classification is illustrated in Figure 4.

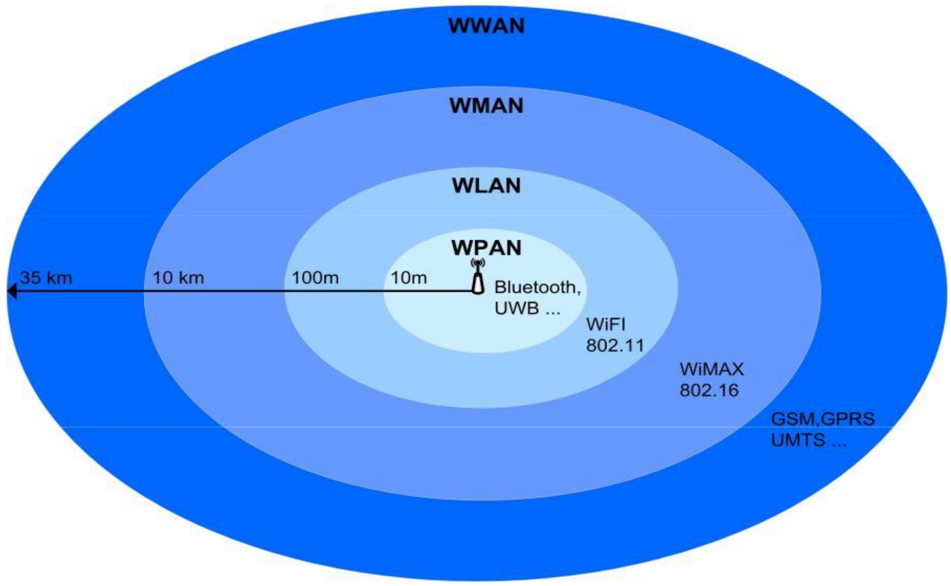


Figure 4: Classification of Wireless Networks by Range

Each network type is characterised by frequency band, bitrate, signal range, and bandwidth efficiency (the ratio of achievable bitrate to occupied channel bandwidth, expressed in bit·s^{-1}/Hz).

WPAN (Wireless Personal Area Network)

WPANs are short-range wireless networks designed for communication among personal and low-power devices, generally within a range of about 10 m. They provide low power consumption, moderate data rates, and support ad-hoc communication without requiring a central access point. Major WPAN technologies include Bluetooth (IEEE 802.15.1), UWB (IEEE 802.15.3a), and ZigBee (IEEE 802.15.4) [33].

i. **Bluetooth – IEEE 802.15.1:** Bluetooth operates in the 2.4 GHz ISM band and uses Frequency Hopping Spread Spectrum (FHSS). It was developed primarily for short-range, low-power device connectivity. Bluetooth 1.2 provides a data rate of approximately 723 kb/s, while Bluetooth 2.0 with Enhanced Data Rate (EDR) can reach 2.1 Mbit/s. Its transmission range varies according to device class, from approximately 1 m to 100 m. The use of π/4-DQPSK in Bluetooth 2.0 improves data and bandwidth efficiency [34].

ii. **UWB – IEEE 802.15.3a:** Ultra-Wideband (UWB) was developed to provide high-speed wireless communication over short distances. It operates across a wide frequency spectrum and can support data rates of hundreds of Mbit/s. Its low transmission power and resistance to interference make it suitable for high-speed multimedia and short-range data-transfer applications. UWB also provides comparatively strong resistance to signal interception [35].

iii. **ZigBee – IEEE 802.15.4:** ZigBee is designed for low-power, low-data-rate wireless communication. It supports multi-hop ad-hoc networking, allowing communication over extended distances without direct line of sight. Its major advantages include low power consumption, reliability, low cost, and easy implementation. Depending on the operating frequency, data rates range from 20 kb/s to 250 kb/s, with 250 kb/s available at 2.4 GHz. ZigBee is particularly suitable for large networks of energy-constrained devices [36].

NAME	ORIGIN DATE	b [GHz]	Vp [Mbit/s]	sr [m]	be [bps/Hz]
Bluetooth v 2.0	2004	2,4-2,4835	2,1	10	2,1
UWB	2007 (Eur)	4.8-10	480	10	0.96
Zigbee	2004	2,4-2,484	250	10	0.125

WLAN (Wireless Local Area Network)

WLANs are based primarily on the IEEE 802.11 family of standards and are intended for wireless connectivity within buildings and local areas. They provide higher data rates than WPANs but generally consume more power. WLANs commonly use CSMA/CA for medium access. The major standards considered include 802.11a, 802.11b, 802.11g, and 802.11n [37].

i. **IEEE 802.11a:** IEEE 802.11a operates in the 5 GHz band and uses OFDM, providing a theoretical maximum data rate of 54 Mbit/s. The 5 GHz band offers more non-overlapping channels and generally experiences less interference than the 2.4 GHz band. Its bandwidth efficiency is approximately 2.7 bits/s/Hz. However, it is not backward-compatible with 802.11b/g (Table 3) [37], [38].

ii. **IEEE 802.11b:** IEEE 802.11b operates at 2.4 GHz using DSSS and CCK modulation, with a maximum theoretical data rate of 11 Mbit/s. Only three non-overlapping channels are commonly used. Although widely adopted, its limitations include relatively low data rate, interference from other 2.4 GHz devices, and limitations in quality of service and security [37], [38].

iii. **IEEE 802.11g:** IEEE 802.11g also operates at 2.4 GHz but employs OFDM to achieve a theoretical maximum data rate of 54 Mbit/s. It maintains backward compatibility with 802.11b, although this may reduce network performance when older devices are present. It provides higher performance than 802.11b while retaining operation in the widely used 2.4 GHz band. The Table 4 shows the modulation schemes used for different bitrate values [37], [38].

iv. **IEEE 802.11n:** IEEE 802.11n introduced Multiple Input Multiple Output (MIMO) technology and supports operation in both the 2.4 GHz and 5 GHz bands. Its theoretical data rate can reach approximately 540 Mbit/s, supported by wider 40 MHz channels and multiple antennas. Backward compatibility can reduce the available data rate when older 802.11 devices are connected [37], [38].

Name	Origin Date	b [GHz]	Vp [Mbit/s]	sr [m]	be [bps/Hz]
IEEE 802.11a	1999	5	54	30/100	2,7
IEEE 802.11b	1999	2,4-2,484	11	35/110	0.55
IEEE 802.11g	2003	2,4-2,484	54	35/110	2.7
IEEE 802.11n	2006	2,4/5	150	35/110	3.7

Table 3: The 802.11a – Modulation table with the bitrate and signal range values.

bitrate [Mbit/s]	6,9	12,18	24,36	48,54
Modulation	BPSK	QPSK	16-QAM	64-QAM
Signal range [m]	70	50	30	10

Table 4: The 802.11g modulation schemes

bitrate [Mbit/s]	1,2	5,5 and 11	6,9,12,18,24,36,48, 54
modulation	(DBPSK/DQPSK)	DSSS -CCK	OFDM

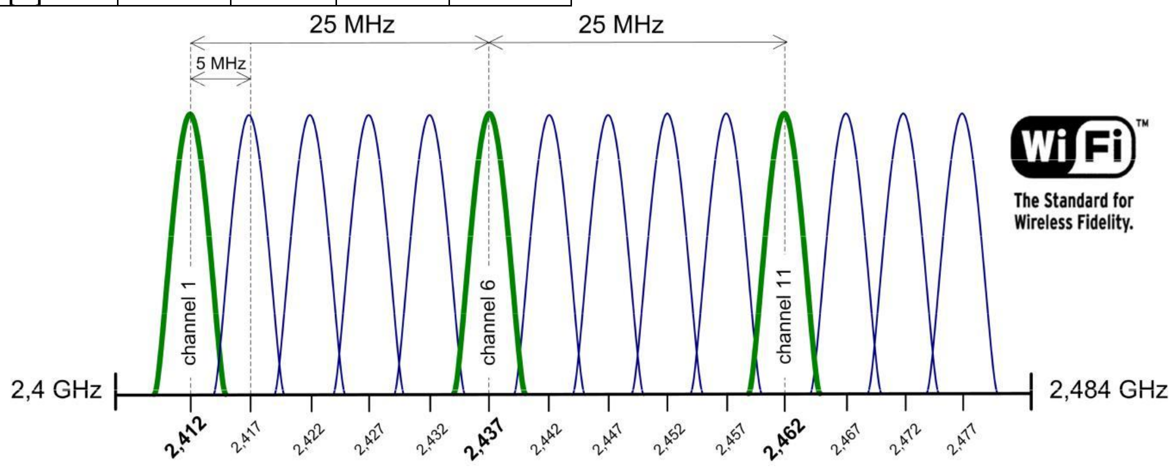


Figure 5: The 802.11b channels

WMAN (Wireless Metropolitan Area Network)

WMAN technologies provide broadband wireless connectivity over metropolitan-scale areas and are primarily associated with the IEEE 802.16 family (WiMAX). They are designed to provide wireless broadband access over distances greater than WLANs and support applications such as data transmission, videoconferencing, and quality-of-service (QoS) services [39].

i. **WiMAX QoS:** WiMAX provides different QoS classes according to application requirements: UGS provides a fixed reserved data rate, rtPS supports variable-rate real-time applications, nrtPS guarantees a minimum data rate, and BE (Best Effort) provides transmission without a guaranteed rate.

ii. **IEEE 802.16:** The original IEEE 802.16 standard operates in the 10–66 GHz band, requires line-of-sight (LOS) communication, and provides data rates of approximately 32–134 Mbit/s. Its LOS requirement and high operating frequency limited its practical deployment.

iii. **IEEE 802.16a:** IEEE 802.16a extended operation to the 2–11 GHz range and introduced support for non-line-of-sight (NLOS) communication. OFDM and OFDMA technologies improved coverage and enabled more practical broadband wireless deployment.

iv. **IEEE 802.16c:** IEEE 802.16c primarily addressed detailed implementation specifications, interoperability, and testing procedures for WiMAX systems.

v. **IEEE 802.16d–2004:** IEEE 802.16d, commonly known as fixed WiMAX, operates in the 2–11 GHz band and supports NLOS communication. It can provide data rates up to approximately 75 Mbit/s with bandwidth efficiency of about 3 bits/s/Hz. Unlike mobile WiMAX, it is designed for fixed users.

vi. **IEEE 802.16e–2005:** IEEE 802.16e introduced mobile WiMAX, supporting user mobility and handover between cells. It operates mainly in the 2–6 GHz range and can support mobility up to approximately 150 km/h, although higher mobility reduces data rates. Practical data rates are lower than the theoretical maximum because of mobility and protocol overhead.

vii. **WiMAX Advantages:** WiMAX provides wide-area coverage, broadband data transmission, QoS support, and reduced dependence on wired infrastructure. These characteristics make it suitable for metropolitan broadband access and applications requiring wider coverage than WLANs [40].

viii. **WiBRO (Wireless Broadband):** WiBRO is a wireless broadband technology developed in South Korea and closely related to mobile WiMAX. It operates around 2.3–2.4 GHz, supports mobility, and provides data rates of approximately 30–50 Mbit/s per user over ranges of about 1–5 km. It can support voice, data, and multimedia services.

Name	Origin Date	b [GHz]	Vp [Mbit/s]	sr [m]	be [bps/Hz]
IEEE 802.16	2001	10-66	134	5	4.5
IEEE 802.16a	2003	2-11	70	10	3.7
IEEE 802.16d	2004	2-11	75	8	3
IEEE 802.16e	2005	2-6	30	5	1.1

WWAN (Wireless Wide Area Network)

WWAN technologies provide wireless connectivity over large geographic areas using mobile network infrastructure. They support communication beyond the coverage of WPAN, WLAN, and WMAN technologies. Major technologies include GSM, GPRS, EDGE, UMTS, HSDPA, HSUPA, and MBWA (IEEE 802.20).

i. **GSM (Global System for Mobile communication):** GSM is a second-generation (2G) mobile communication technology providing voice and basic data services. It commonly operates at 900 MHz and 1800 MHz and supports roaming, handover, and security functions. Its maximum data rate is approximately 9.6 kb/s, making it limited for modern data-intensive applications [41].

ii. **GPRS (General Packet Radio Service):** GPRS introduced packet-switched data transmission to GSM networks and is classified as a 2.5G technology. Its data rate depends on the coding scheme, signal quality, and number of available timeslots. It improved mobile data services by enabling users to share network resources and pay according to data usage [42].

iii. **EDGE (Enhanced data rates for Global Evolution):** EDGE is a 2.75G enhancement of GSM/GPRS that uses 8-PSK modulation to increase data rates and spectral efficiency. It supports both enhanced packet-switched and circuit-switched services, with practical data rates substantially higher than conventional GPRS [43].

iv. **UMTS (Universal Mobile Telecommunication System):** UMTS represents third-generation (3G) mobile communication and uses Wideband CDMA (WCDMA) for access. It operates around the 2 GHz band and provides significantly higher data rates than GSM/GPRS. However, packet delay and jitter were important limitations, leading to subsequent enhancements [44].

v. **HSDPA (High speeds Downlink Packet Access):** HSDPA is a 3.5G technology designed to increase downlink data rates in UMTS networks. It supports theoretical rates up to 14.4 Mbit/s, although practical rates are considerably lower. QPSK and 16-QAM modulation are used to improve high-speed packet data transmission [45].

vi. **HSUPA (High speeds Uplink Packet Access):** HSUPA extends UMTS by improving uplink performance, reducing jitter, and increasing data transmission rates. It can provide uplink data rates of approximately 1.45 Mbit/s, supporting improved mobile broadband services.

vii. **MBWA – IEEE 802.20:** IEEE 802.20 was proposed for mobile broadband wireless access and aimed to support high-speed mobile users. It was designed for operation below 3 GHz, with NLOS capability and support for mobility up to approximately 250 km/h. OFDM-based transmission and TDD/FDD techniques were considered for broadband mobile communication [46].

Name	Origin Date	b [GHz]	Vp [Mbit/s]	sr [m]	be [bps/Hz]
GSM	1992	900/1800	9,6	35	0,05
GPRS	1997	900/1800	80	35	0,4
EDGE	2003	900/1800	200/100	30	1,2
UMTS	2000	1,8-2,2	2.048	2	0,4
HSDPA	2004	873/1900	14,4	6	2,8
HSUPA	2005	873/1900	1,45	5	0,4
MBWA 802.20	2002	<3	1/0,3	12	1,0

The technologies reviewed demonstrate a clear trade-off between coverage, data rate, power consumption, mobility, complexity, and application requirements. WPAN technologies are appropriate for short-range, low-power applications; WLANs provide higher data rates within local areas; WMAN technologies extend broadband connectivity across metropolitan regions; and WWAN technologies provide wide-area mobile communication. Table 5 summarizes the principal characteristics of the individual wireless technologies and provides a comparative reference for selecting an appropriate standard according to specific application requirements.

Table 5: Summary of wireless networks

Name	Origin date	Frequency band	Bandwidth	Bitrate	Signal range	Bandwidth efficiency	modulation
Bluetooth	2004	2,4 GHz	1GHz	2,1 Mbit/s	10m	2,1 bps/ Hz	GMSK
UWB	2007	4,8-10 GHz	500MHz	480Mbit/s	10m	0,96 bps/Hz	OFDM
ZigBee	2004	2,4 GHz	2MHz	250kbit/s	10m	0,125 bps/Hz	O-QPSK
Outdoor /indoor							
IEEE 802.11a	1999	5 GHz	20GHz	54Mbits/s	100/30 m	2,7 bps/Hz	OFDM, BPSK, QPSK 16QAM, 64QAM
IEEE 802.11b	1999	5 GHz	20 MHz	11Mbit/s	110/35m	0,55bps/Hz	BPSK, QPSK, CCK
IEEE 802.11g	2003	2,4 GHz	20MHz	54 Mbit/s	110/35 m	2,7 bps/Hz	OFDM, BPSK, QPSK, 16QAM, 64QAM
IEEE 802.11n	2006	2,4/5 GHz	40 MHz	150 Mbit/s	160/70 m	3,7 bps/Hz	MIMO
IEEE 802.16	2001	10-66 GHz	28 MHz	134 Mbit/s	5km	4,5 bps/Hz	QPSK, 16QAM, 64QAM
IEEE 802.16a	2003	2-11 GHz	20 MHz	75 Mbit/s	10 km	3,7 bps/Hz	BPSK, 16QAM, 64QAM
IEEE 802.16d	2004	2-11 GHz	25 MHz	75 Mbit/s	8 km	3 bps/Hz	BPSK, QPSK, 16QAM, 64QAM
IEEE 802.16e	2005	2-6 GHz	20 MHz	30 Mbit/s	5 km	1,1 bps/Hz	BPSK, QPSK, 16QAM, 64QAM
Downlink/uplink							
GSM	1992	900/1800 MHz	200 KHz	9,6 Kbit/s	35 km	0,05 bps/Hz	GMSK
GPRS	1997	900/1800 MHz	200 KHz	80 Kbit/s	30 km	0,4 bps/Hz	GMSK
EDGE	2004	900/1800 MHz	200 KHz	200/100 Kbit/s	30 km	1,2 bps/Hz	8-PSK
UMTS	2000	1885-2200 MHz	5 MHz	2048 Kbit/s	2 km	0,4 bps/Hz	QPSK
HSDPA	2004	873/1900 MHz	5 MHz	14,4 Mbit/s	6 km	2,8 bps/Hz	QPSK, 16-QAM
HSUPA	2005	873/1900 MHz	5 MHz	1,4 Mbit/s	5 km	0,4 bps/Hz	QPSK, 16-QAM
IEEE 802.20	2002	<3,5GHz	1,25 MHz	1024/300 Kbit/s	12 km	1,0 bps/Hz	OFDM

RESULT AND DISCUSSION

Factory automation has become an important research area by integrating communication, information, computing, control, sensors, and actuators to improve industrial performance and system efficiency [47]. Industrial communication networks play a key role in connecting sensors, controllers, and heterogeneous machines through common communication standards. Various wired networks, including CAN, Profibus, Modbus, Ethernet, ControlNet, and DeviceNet, have been developed for shop-floor applications; however, selecting the most suitable network depends on application requirements [48].

Wireless communication has gained importance because it provides flexibility, mobility, reduced cabling, lower deployment costs, and dynamic network formation. Four major short-range wireless technologies are Bluetooth, UWB, ZigBee, and Wi-Fi, corresponding to IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11 standards, respectively [49]. Previous studies have compared these technologies based on throughput, network topology, security, quality of service, and power consumption. Results indicate that Bluetooth and Wi-Fi offer competitive performance, while ZigBee provides advantages for industrial applications through low power consumption, extended battery life, flexible networking, and reliable mesh communication [50], [51].

Accordingly, this study comparatively evaluates Bluetooth, UWB, ZigBee, and Wi-Fi with respect to transmission time, data-coding efficiency, protocol complexity, and power consumption, providing a basis for selecting appropriate wireless communication technologies for factory automation applications.

Bluetooth over IEEE 802.15.1 - Bluetooth, also known as the IEEE 802.15.1 standard is based on a wireless radio system designed for short-range and cheap devices to replace cables for computer peripherals, such as mice, keyboards, joysticks, and printers. This range of applications is known as wireless personal area network (WPAN). Two connectivity topologies are defined in Bluetooth; the piconet and scatternet. A piconet is a WPAN formed by a Bluetooth device serving as a master in the piconet and one or more Bluetooth devices serving as slaves. A frequency-hopping channel based on the address of the master defines each piconet. All devices participating in communications in a given piconet are synchronized using the clock of the master. Slaves communicate only with their master in a point-to-point fashion under the control of the master. The master's transmissions may be either point-to-point or point-to-multipoint. Also, besides in an active mode, a slave device can be in the parked or standby modes so as to reduce power consumptions. A scatternet is a collection of operational Bluetooth piconets overlapping in time and space. Two piconets can be connected to form a scatternet. A Bluetooth device may participate in several piconets at the same time, thus allowing for the possibility that information could flow beyond the coverage area of the single piconet. A device in a scatternet could be a slave in several piconets, but master in only one of them.

UWB over IEEE 802.15.3 - UWB has recently attracted much attention as an indoor short-range high-speed wireless communication [52]. One of the most exciting characteristics of UWB is that its bandwidth is over 110 Mbps (up to 480 Mbps) which can satisfy most of the multimedia applications such as audio and video delivery in home networking and it can also act as a wireless cable replacement of high-speed serial bus such as USB 2.0 and IEEE 1394. Following the United States and the Federal Communications Commission (FCC) frequency allocation for UWB in February 2002, the Electronic Communications Committee (ECC TG3) is progressing in the elaboration of a regulation for the UWB technology in Europe. From an implementation point of view, several solutions have been developed in order to use the UWB technology in compliance with the FCC's regulatory requirements. Among the existing PHY solutions, in IEEE 802.15 Task Group 3a (TG3a), multi-band orthogonal frequency-division multiplexing (MB-OFDM), a carrier-based system dividing UWB bandwidth to sub-bands, and direct-sequence UWB (DS-UWB), an impulse-based system that multiplies an input bit with the spreading code and transmits the data by modulating the element of the symbol with a short pulse have been proposed by the WiMedia Alliance and the UWB Forum, respectively. The TG3a was established in January 2003 to define an alternative PHY layer of 802.15.3. However, after three years of a jammed process in IEEE 802.15.3a, supporters of both proposals, MB-OFDM and DS-UWB, supported the shutdown of the IEEE 802.15.3a task group without conclusion in January 2006. On the other hand, IEEE 802.15.3b, the amendment to the 802.15.3 MAC sublayer has been approved and released in March 2006.

ZigBee over IEEE 802.15.4 - ZigBee over IEEE 802.15.4 defines specifications for low-rate WPAN (LR-WPAN) for supporting simple devices that consume minimal power and typically operate in the personal operating space (POS) of 10m. ZigBee provides self-organized, multi-hop, and reliable mesh networking with long battery lifetime [53], [54]. Two different device types can participate in an LR-WPAN network: a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in three modes serving as a PAN coordinator, a coordinator, or a device. An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor. They do not have the need to send large amounts of data and may only associate with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. After an FFD is activated for the first time, it may establish its own network and become the PAN coordinator. All-star networks operate independently from all other star networks currently in operation. This is achieved by choosing a PAN identifier, which is not currently used by any other network within the radio sphere of influence. Once the PAN identifier is chosen, the PAN coordinator can allow other devices to join its network. An RFD may connect to a cluster tree network as a leave node at the end of a branch, because it may only associate with one FFD at a time. Any of the FFDs may act as a coordinator and provide synchronization services to other devices or other coordinators. Only one of these coordinators can be the overall PAN coordinator, which may have greater computational resources than any other device in the PAN.

Wi-Fi over IEEE 802.11a/b/g - Wireless fidelity (Wi-Fi) includes IEEE 802.11a/b/g standards for wireless local area networks (WLAN). It allows users to surf the Internet at broadband speeds when connected to an access point (AP) or in ad hoc mode. The IEEE 802.11 architecture consists of several components that interact to provide a wireless LAN that supports station mobility transparently to upper layers. The basic cell of an IEEE 802.11 LAN is called a basic service set (BSS), which is a set of mobile or fixed stations. If a station moves out of its BSS, it can no longer directly communicate with other members of the BSS. Based on the BSS, IEEE 802.11 employs the independent basic service set (IBSS) and extended service set (ESS) network configurations. As shown in Fig. 6(a), the IBSS operation is possible when IEEE 802.11 stations are able to communicate directly without any AP. Because this type of IEEE 802.11 LAN is often formed without pre-planning, for only as long as the LAN is needed, this type of operation is often referred to as an ad hoc network. Instead of existing independently, a BSS may also form a component of an extended form of network that is built with multiple BSSs. The architectural component used to interconnect BSSs is the distribution system (DS). The DS with APs allow IEEE 802.11 to create an ESS network of arbitrary size and complexity. This type of operation is often referred to as an infrastructure network.

In general, the Bluetooth, UWB, and ZigBee are intended for WPAN communication (about 10m), while Wi-Fi is oriented to WLAN (about 100m). However, ZigBee can also reach 100m in some applications. Table 6 summarizes the main differences among the four protocols. Each protocol is based on an IEEE standard. Obviously, UWB and Wi-Fi provide a higher data rate, while Bluetooth and ZigBee give a lower one.

Radio Channels - Bluetooth, ZigBee and Wi-Fi protocols have spread spectrum techniques in the 2.4 GHz band, which is unlicensed in most countries and known as the industrial, scientific, and medical (ISM) band. Bluetooth uses frequency hopping (FHSS) with 79 channels and 1 MHz bandwidth, while ZigBee uses direct sequence spread spectrum (DSSS) with 16 channels and 2 MHz bandwidth. Wi-Fi uses DSSS (802.11), complementary code keying (CCK, 802.11b), or OFDM modulation (802.11a/g) with 14 RF channels (11 available in US, 13 in Europe, and just 1 in Japan) and 22 MHz bandwidth. UWB uses the 3.1-10.6 GHz, with an unapproved and jammed 802.15.3a standard, of which two spreading techniques, DS-UWB and MB-OFDM, are available.

Coexistence Mechanism - Since Bluetooth, ZigBee and Wi-Fi use the 2.4 GHz band, the coexistence issue must be dealt with. Basically, Bluetooth and UWB provide adaptive frequency hopping to avoid channel collision, while ZigBee and Wi-Fi use dynamic frequency selection and transmission power control. IEEE 802.15.2 discussed the interference problem of Bluetooth and Wi-Fi. Also, Sikora and Groza [10] provided quantitative measurements of the coexistence issue for ZigBee, Bluetooth, Wi-Fi, and microwave ovens. Shuaib et al. [55] focused on quantifying potential interferences between Zigbee and IEEE 802.11g by examining the impact on the throughput performance of IEEE 802.11g and Zigbee devices when co-existing within a particular environment. Moreover, Neelakanta and Dighe [56] presented a performance evaluation of Bluetooth and ZigBee collocated on an industrial floor for factory wireless communications.

Network Size - The maximum number of devices belonging to the network's building cell is 8 (7 slaves plus one master) for a Bluetooth and UWB piconet, over 65000 for a ZigBee star network, and 2007 for a structured Wi-Fi

BSS. All the protocols have a provision for more complex network structures built from the respective basic cells: the scatternet for Bluetooth, peer-to-peer for UWB, cluster tree or mesh networks for ZigBee, and the ESS for Wi-Fi.

Security - All the four protocols have the encryption and authentication mechanisms. Bluetooth uses the E0 stream cipher and shared secret with 16-bit cyclic redundancy check (CRC), while UWB and ZigBee adopt the advanced encryption standard (AES) block cipher with counter mode (CTR) and cipher block chaining message authentication code (CBC-MAC), also known as CTR with CBC-MAC (CCM), with 32-bit and 16-bit CRC, respectively. In 802.11, Wi-Fi uses the RC4 stream cipher for encryption and the CRC-32 checksum for integrity. However, several serious weaknesses were identified by cryptanalysts, any wired equivalent privacy (WEP) key can be cracked with readily available software in two minutes or less, and thus WEP was superseded by Wi-Fi protected access 2 (WPA2), i.e. IEEE 802.11i standard, of which the AES block cipher and CCM are also employed.

Transmission Time - The transmission time depends on the data rate, the message size, and the distance between two nodes. The formula for transmission time (μs) can be described as

$$\mathrm{Ttx} = \left(N_{\mathrm{data}} + \left(\frac{N_{\mathrm{data}}}{N_{\mathrm{maxPld}}} \times N_{\mathrm{ovhd}}\right)\right) \times T_{\mathrm{bit}} + T_{\mathrm{prop}}$$

Where N_{data} is the data size, N_{maxPld} is the maximum payload size, N_{ovhd} is the overhead size, T_{bit} is the bit time, and T_{prop} is the propagation time between any two devices. For simplicity, the propagation time is negligible in this paper. The typical parameters of the four wireless protocols used for transmission time evaluation are listed in Table 7 Note that the maximum data rate 110 Mbit/s of UWB is adopted from an unapproved 802.15.3a standard. As shown in Fig. 6(b), the transmission time for the ZigBee is longer than the others because of the lower data rate (250 Kbit/s), while UWB requires less transmission time compared with the others. Obviously, the result also shows the required transmission time is proportional to the data payload size and disproportional to the maximum data rate.

Data Coding Efficiency - The data coding efficiency is defined by the ratio of the data size and the message size (i.e. the total number of bytes used to transmit the data). The formula for data coding efficiency (%) can be described as:

$$\mathrm{P}_{\mathrm{codEff}} = \frac{\mathrm{N}_{\mathrm{data}}}{\left(\frac{\mathrm{N}_{\mathrm{data}}}{\mathrm{N}_{\mathrm{maxPld}}} \times \mathrm{N}_{\mathrm{ovhd}}\right)}$$

The parameters listed in Table 7 are also used for the coding efficiency comparison. Fig. 6(b) shows the data coding efficiency of the four wireless networks versus the data size. For small data sizes (around smaller than 339 bytes), Bluetooth is the best solution. Also, ZigBee have a good efficiency for data size smaller than 102 bytes. For large data sizes, Bluetooth, UWB, and Wi-Fi have much better efficiency of over 94%, as compared to the 76.52% of ZigBee (where the data is 10K bytes as listed in Table 7). The discontinuities in Fig. 6(a) and 6(b) are caused by data fragmentation, i.e. the maximum data payload, which is 339, 2044, 102, and 2312 bytes for Bluetooth, UWB, ZigBee, and Wi-Fi, respectively. In a Wi-Fi infrastructure mode, note that most APs connect to existing networks with Ethernet, and therefore limit the payload size to the maximum Ethernet payload size as 1500 bytes. However, for a general comparison, an ad-hoc mode is assumed and the 2312 bytes.

For a wireless sensor network in factory automation systems, since most data size of industrial monitoring and control are generally small, (e.g. the temperature data in an environmental monitoring may require less than 4 bytes only), Bluetooth and ZigBee protocols may be a good selection (from a data coding efficiency point of view) in spite of their slow data rate. An evaluation of the Bluetooth, UWB, ZigBee, and Wi-Fi on different aspects is provided. It is important to notice that several slight differences exist in the available sources. For example, in the IEEE 802.15.4 standard, the action range is about 10m, while it is 70-300m in the released documents from ZigBee Alliance. Thus, this work intends to provide information only, since other factors, such as receiver sensitivity and interference, play a major role in affecting the performance in realistic implementations.

Protocol Complexity – In this work, the complexity of each protocol is compared based on the numbers of primitives and events, which is shown in Table 8.

Power Consumption - Bluetooth and ZigBee are intended for portable products, short ranges, and limited battery power. Consequently, it offers very low power consumption and, in some cases, will not measurably affect battery life. UWB is proposed for short-range and high data rate applications. On the other hand, Wi-Fi is designed for a longer connection and supports devices with a substantial power supply. In order to practically compare the power consumption, four wireless products for which detailed characteristics are publicly available are briefly presented as an example, including BlueCore2 [57] from Cambridge Silicon Radio (CSR), XS110 [58] from Freescale, CC2430 [59] from Chipcon of Texas Instruments (TI), and CX53111 [60] from Conexant. The current consumptions of the transmit (TX) and receive (RX) conditions for each protocol are shown in Table 9. The data shown are for particular products, although are broadly representative for examples of the same type. Fig.6(d) indicates the power consumption in mW unit for each protocol. Obviously, the Bluetooth and ZigBee protocols consume less power as compared with UWB and Wi-Fi. Based on the bit rate, a comparison of normalized energy consumption is provided in Fig. 6(e). From the mJ/Mb unit point of view, the UWB and Wi-Fi have better efficiency in energy consumption.

The Bluetooth and ZigBee are suitable for low data rate applications with limited battery power (such as mobile devices and battery-operated sensor networks), due to their low power consumption leading to a long lifetime. On the other hand, for high data rate implementations (such as audio/video surveillance systems), UWB and Wi-Fi would be better solutions because of their low normalized energy consumption.

In This dissertation work we have presented a broad overview of the four most popular wireless standards, Bluetooth, UWB, ZigBee, and Wi-Fi with a quantitative evaluation in terms of the transmission time, data coding efficiency, protocol complexity, and power consumption. Furthermore, the radio channels, coexistence mechanism, network size, and security are also preliminary compared. This work is not to draw any conclusion regarding which one is superior since the suitability of network protocols is greatly influenced by practical applications, of which many other factors such as the network reliability, roaming capability, recovery mechanism, chipset price, and installation cost need to be considered in the future.

Table 6: Comparison of the Bluetooth UWB, ZigBee and Wi-Fi Protocols

Standard	Bluetooth	UWB	ZigBee	Wi-Fi
IEEE spec.	802.15.1	802.15.3a	802.15.4	802.11a/b/g
Frequency band	2.4 GHz	3.1-10.6 GHz	868/915 MHz,2.4 MHz	2.4 GHz, 5 GHz
Max signal rate	1 Mb/s	110 Mb/s	250 Kb/s	54 Mb/s
Nominal range	10 m	10 m	10-100 m	100 m
Nominal TX Power	0-10 dBm	-41.3 dBm/MHz	(-25) – 0 dBm	15-20 dBm
Number of RF channels	79	(1-15)	1/10; 16	14 (2.4 GHz)
Channel Bandwidth	1 MHz	500 MHz – 7.5 GHz	0.3/0.6 MHz; 2 MHz	22 MHz
Modulation Type	GFSK	BPSK, QPSK	BPSK(ASK), O-QPSK	BPSK, QPSK, COFDMM CCK, M-QAM
Spreading	FHSS	DS-UWB, MB-OFDM	DSSS	DSSS, CCK, OFDM
Coexistence Mechanism	Adaptive freq. hopping	Adaptive freq. hopping	Dynamic freq. selection	Dynamic freq. selection, transmit power control (802.11h)
Basic cell	Piconet	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Peer-to-Peer	Cluster tree, Mesh	ESS
Max number of cell nodes	8	8	>65000	2007
Encryption	Eos tram cipher	AES Block cipher (CTR, counter mode)	AES Block cipher (CTR, counter mode)	RC4 stream cipher (WEP), AES block cipher
Authentication	Shared secret	CBC-MAC(CCM)	CBC-MAC (Ext. of CCM)	WPA2 (802.11i)
Data protection	16-bit CRC	32-bit CRC	16-bit CRC	32-bit CRC

Where, ASK - amplitude shift keying, GFSK - Gaussian frequency SK, BPSK/QPSK - binary/quadrature phase SK, O-QPSK - offset-QPSK, OFDM - orthogonal frequency division multiplexing, COFDM - coded OFDM, MB-OFDM - multiband OFDM, M-QAM - M-ary quadrature amplitude modulation, CCK - complementary code keying, FHSS/DSSS - frequency hopping/direct sequence spread spectrum, BSS/ESS - basic/extended service set, AES - advanced encryption standard, WEP - wired equivalent privacy, WPA - Wi-Fi protected access, CBC-MAC - cipher block chaining message authentication code, CCM - CTR with CBC-MAC, CRC - cyclic redundancy check.

Table 7: Typical System Parameters of the Wireless Protocols

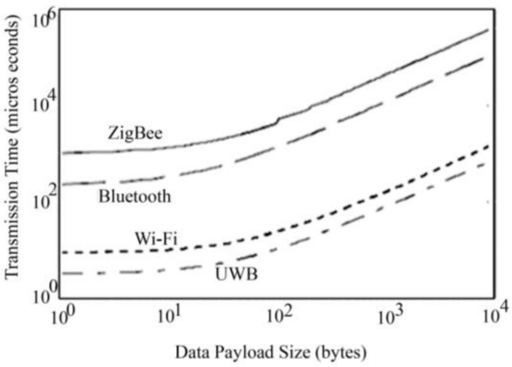
Standard	Bluetooth	UWB	ZigBee	Wi-Fi
IEEE Spec.	802.15.1	802.15.3	802.15.4	802.11a/b/g
Max data rate (Mbit/s)	0.72	110	0.25	54
Bit time (µ S)	1.39	0.009	4	0.0185
Max data payload (bytes)	339 (DH5)	2044	102	2312
Max overhead (bytes)	158/8	42	31	58
Coding efficiency (%)	94.41	97.94	76.52	97.18

Table 8: Number of Primitives and Events for Each Protocol

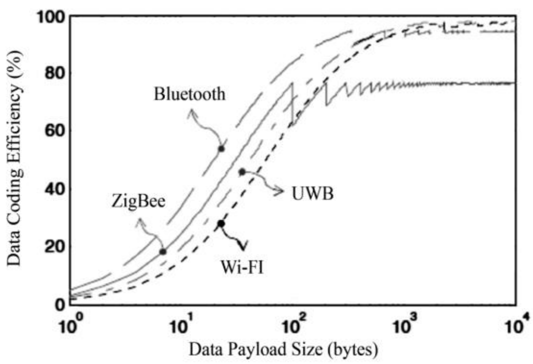
Standard	Bluetooth	UWB	ZigBee	Wi-Fi	Standard
IEEE Spec.	802.15.1	802.15.3	802.15.4	802.11a/b/g	IEEE Spec.
Premitives	151	77	35	32	MAC primitives
HCI events	37	23	13	43	PHY primitives

Table 9: Current Consumption of Chipsets for Each Protocol

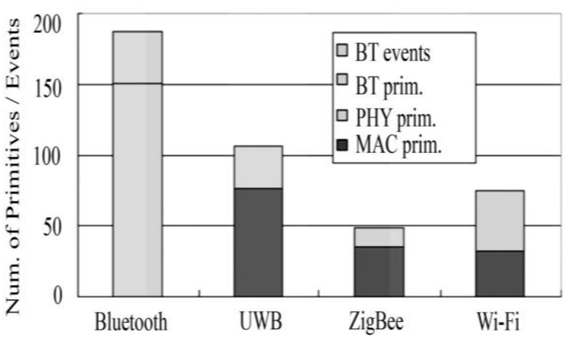
Standard	Bluetooth	UWB	ZigBee	Wi-Fi
Chipset	BlueCore2	XS110	CC2430	CX53111
VDD (volt)	1.8	3.3	3.0	3.3
TX (mA)	57	~227.3	24.7	219
RX (mA)	47	~227.3	27	215
Bit rate (Mb/s)	0.72	114	0.25	54



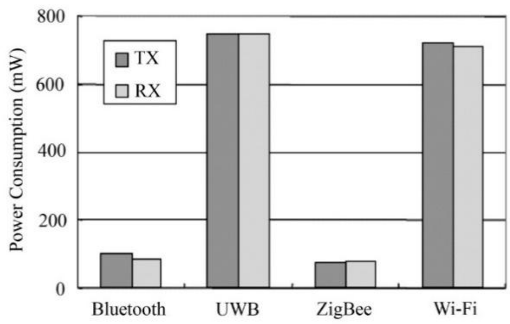
(a)



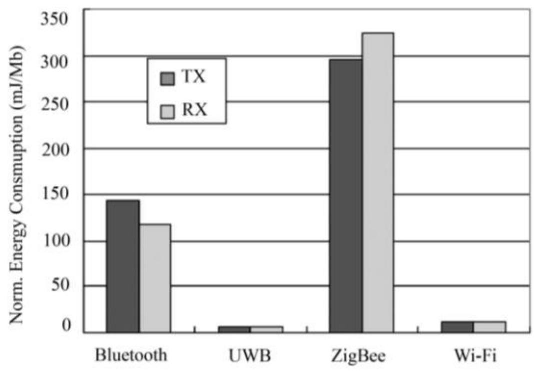
(b)



(c)



(d)



(e)

Figure 6: Comparison of (a) the transmission time versus the data size; (b) the data coding efficiency versus the data size; (c) the complexity for each protocol; (d) the Power consumption for each protocol; (e) the normalized energy consumption for each protocol.

CONCLUSION

This paper has presented a comparative review of the leading short-range wireless protocols — Bluetooth, UWB, ZigBee, and Wi-Fi — together with the wider classification of wireless networks into WPAN, WLAN, WMAN, and WWAN. Each protocol was examined for its radio characteristics, topology, security mechanism, and coexistence behaviour, while each network category was reviewed for its representative standards, frequency bands, and achievable data rates. The four short-range protocols were further compared quantitatively on transmission time, data coding efficiency, protocol complexity, and power consumption. The results show that ZigBee and Bluetooth are best suited to low-power, small-payload applications such as sensor networks and industrial monitoring, while UWB and Wi-Fi offer superior throughput and normalised energy efficiency for high-data-rate applications such as audio and video transmission. No single protocol is universally optimal; the appropriate choice depends on the application's requirements for range, data rate, power budget, network size, and cost. Future comparative work should extend this analysis to include network reliability, roaming capability, recovery mechanisms, chipset pricing, and installation cost under real deployment conditions.

REFRENCES

[1]. A. M. Gonasai, N. N. Soni, and N. Goswmi, "Emerging Wireless Technologies for Fast Data Transmission on Library Network," *International Journal of Information Services and Technology*, vol. 1, no. 1, pp. 16–20, 2004.

[2]. C. N. Verdouw, J. Wolfert, A. J. M. Beulens, and A. Rialland, "Virtualization of Food Supply Chains with the Internet of Things," *Journal of Food Engineering*, vol. 176, pp. 128–136, 2016, doi: 10.1016/j.jfoodeng.2015.11.009.

[3]. J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Taipei, Taiwan, 2007, pp. 46–51.

[4]. N. P. Mohapatra, J. Jena, and S. K. Sahu, "Improving the Life of the Wireless Sensor Network Using Energy Harvesting Clustering," *International Journal of Computer Applications*, vol. 114, no. 10, 2015.

[5]. J. Rani, P. Chauhan, and R. Tripathi, "Li-Fi (Light Fidelity)—The Future Technology in Wireless Communication," *International Journal of Applied Engineering Research*, vol. 7, no. 11, 2012.

[6]. J. H. Bhut, D. N. Parmar, and K. V. Mehta, "Li-Fi Technology—A Visible Light Communication," *International Journal of Engineering Development and Research*, vol. 2, 2014, pp. 25–28.

[7]. R. R. Sharma, Raunak, and A. Sanganal, "Li-Fi Technology: Transmission of Data Through Light," *International Journal of Computer Technology and Applications*, vol. 5, no. 1, pp. 150–154, 2014.

[8]. S. Chakkor, B. Mostafa, E. A. Cheikh, and A. Hajraoui, "Comparative Performance Analysis of Wireless Communication Protocols for Intelligent Sensor and Their Applications," *International Journal of Advanced Computer Science and Applications*, vol. 5, no. 4, 2014.

[9]. E. Ferro and F. Potortì, "Bluetooth and Wi-Fi Wireless Protocols: A Survey and a Comparison," *IEEE Wireless Communications*, vol. 12, no. 1, pp. 12–26, 2005.

[10]. V. K. Sharma, "Exploring Visible Spectrum: A Study of Light Fidelity System and Its Application," *International Journal of Enhanced Research in Science Technology & Engineering*, vol. 3, no. 5, pp. 349–353, 2014.

[11]. A. M. Gonasai, N. N. Soni, and N. Goswmi, "Emerging Wireless Technologies for Fast Data Transmission on Library Network," *International Journal of Information Services and Technology*, vol. 1, no. 1, pp. 16–20, 2004.

[12]. J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Taipei, Taiwan, 2007, pp. 46–51.

[13]. N. P. Mohapatra, J. Jena, and S. K. Sahu, "Improving the Life of the Wireless Sensor Network Using Energy Harvesting Clustering," *International Journal of Computer Applications*, vol. 114, no. 10, 2015.

[14]. U. L. M. Rijah, S. Mosharani, S. Amuthapriya, M. M. M. Mufthas, M. Hezretov, and D. Dhammearatchi, "Bluetooth Security Analysis and Solution," *International Journal of Scientific and Research Publications*, vol. 6, no. 4, pp. 333–338, 2016.

[15]. P. Singh, D. Sharma, and S. Agrawal, "A Modern Study of Bluetooth Wireless Technology," *International Journal of Computer Science, Engineering and Information Technology*, vol. 1, no. 3, pp. 55–63, 2011.

[16]. F. Cuorno, C. Martello, F. Caprioth, IEEE, 20(9), 1722(2002).

[17]. P. Baldi, L. De Nardis, and M. G. Di Benedetto, "Modeling and Optimization of UWB Communication Networks Through a Flexible Cost Function," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 9, pp. 1733–1744, 2002.

[18]. Y. Fang and Y. Zhang, "Call Admission Control Schemes and Performance Analysis in Wireless Mobile Networks," *IEEE Transactions on Vehicular Technology*, vol. 51, no. 2, pp. 371–382, 2002, doi: 10.1109/25.994812.

[19]. B. Frouzan, Tata McGraw Hill, 2, 19(2004).

[20]. D. Peng, S. Wan, OPJ, 3(2), 277(2013).

[21]. Z. Jianjun,W. Xiu, Z. Wei & C. Jichen, ICCSEE, 2, 2361(2013).

[22]. A. Sayeeraman, P. Ramesh, 37(2), 199(2012).

[23]. S. Banerji ,R.S. Chowdhury, IJE, 2(5), 21(2013).

[24]. J. V. Shiral, "A Comparative Study on Cellular, Sensor and Adhoc Networks," *International Journal of Advanced Smart Sensor Network Systems*, vol. 2, no. 3, pp. 43–?, 2012, doi: 10.5121/ijassn.2012.2305.

[25]. Z. Alisa, IJCA, 62(13), 22(2013).

[26]. D. Akbas,H .Gumuskaya, Science Direct, 3, 1039(2011).

[27]. B. Kamali, R. Bennett, D.C. Cox, IEEE, 31(5), 23(2012).

[28]. Sargun, S. Maan, S. Rana, IJARCCE, 3(1), 369(2015).

[29]. S. Khan, B. Aziz, S. Najeeb, A. Ahmed, M. Usman, and S. Ullah, "Reliability of Network Simulators and Simulation Based Research," in *2013 IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2013.

[30]. R. Cramer, R.Scholtz ,M. Win, IEEE, 50(5), 561(2002).

[31]. D. Akbaş and H. Gümüşkaya, "Real and OPNET Modeling and Analysis of an Enterprise Network and Its Security Structures," *Procedia Computer Science*, vol. 3, pp. 1038–1042, 2011.

[32]. S. Dhanalakshmi,M.Sathiya, IJCSMC, 4(1), 85(2015).

[33]. S. Banerji, R. Chowdhury, IJMNCT, 3(4), 17(2013).

[34]. R.B. Marks, IEEE Comm. Mag., 1, 98(2002).

[35]. R. Cramer, R. A. Scholtz, and M. Z. Win, "Evaluation of an Ultra-Wide-Band Propagation Channel," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 5, pp. 561–570, 2002.

[36]. K. Poranki, Y. Perwey, A. Perwey, RJSITM, 4(3), 29(2015).

[37]. S. Dhanalakshmi and M. Sathiya, "An Overview of IEEE 802.11 Wireless LAN Technologies," *International Journal of Computer Science and Mobile Computing*, vol. 4, no. 1, pp. 85–93, 2015.

[38]. L. Hongwei, L. Dongxiao, D. Yuanshun, IEEE, 3(1), 127(2015).

[39]. C. Eklund, R. B. Marks, K. Stanwood, and S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN Air Interface for Broadband

Wireless Access," *IEEE Communications Magazine*, vol. 40, no. 6, pp. 98–107, 2002.

[40]. T.Lui, V. Sethuraman,P. Subrahmanya, IEEE, 10(2), 474(2011).

[41]. A. Greenspan, IEEE, 46(7), 84(2008).

[42]. R. Zurawski, IEEE ,49(6), 1189(2002).

[43]. F. L. Lian, J .R. Moyne, D. M. Tilbury, IEEE,22(1), 66(2001).

[44]. D. Miorani, S. Vitturi, IJCA, 3(4), 479(2005).

[45]. E. Ferro, F. Potorti , IEEE,12(1), 12(2005).

[46]. K. Pothuganti , A. Chitneni, AEEE, 4(6), 655(2014).

[47]. D. Porcino,W. Hirt, IEEE,41(7), 66(2003).

[48]. K. Pothuganti and A. Chitneni, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," *Advances in Electronic and Electrical Engineering*, vol. 4, no. 6, pp. 655–662, 2014.

[49]. J. S. Lee, Y. C. Huang,IEEE, 14, 1467(2006).

[50]. F.-L. Lian, J. R. Moyne, and D. M. Tilbury, "Networked Control Systems Toolkit: A Simulation Package for Analysis and Design of Control Systems with Network Communications," Technical Report UM-ME-01-04, University of Michigan, 2001.

[51]. E. Ferro and F. Potortì, "Bluetooth and Wi-Fi Wireless Protocols: A Survey and a Comparison," *IEEE Wireless Communications*, vol. 12, no. 1, pp. 12–26, 2005.

[52]. K. Pothuganti and A. Chitneni, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," *Advances in Electronic and Electrical Engineering*, vol. 4, no. 6, pp. 655–662, 2014.

[53]. D. Porcino and W. Hirt, "Ultra-Wideband Radio Technology: Potential and Challenges Ahead," *IEEE Communications Magazine*, vol. 41, no. 7, pp. 66–74, 2003.

[54]. J. S. Lee, Y. W. Su, and C. C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Taipei, Taiwan, 2007, pp. 46–51.

[55]. S.Chakkor, M. Baghouri, H. Abderrahmane, IJACSA, 4(5), 76(2014).