A Survey on Interference Avoiding Methods for Wireless Sensor Networks Working in the 2.4 GHz Frequency Band

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Abstract

Wireless sensor networks (WSN) are a very important and relevant field of research for modern control and monitoring applications in today’s communications and information networks. The increased use of wireless devices across a variety of settings, from smart buildings to smart homes, energy consumption monitoring, healthcare applications, plus a myriad of mobile devices’ applications worldwide have multiplied the already crowded radio spectrum anywhere causing problems. Hence, interference among concurrent transmissions causes severe performance degradation due to the coexistence of different wireless networks working on the very same frequency band, something which has an impact on the different applications’ performance. The WSN working on the 2.4GHz frequency band experience interference from competing networks like Bluetooth, Wi-Fi (IEEE 802.11b/g) and also gets negatively influenced by applications like microwave oven and cordless phone. Because of said interference, the performance of the WSN is getting degraded. Furthermore, the operation of low power WSN is extremely vulnerable and unpredictable under interference conditions. Hence there is an increasing need for research on interference avoiding methods and on improving the coexistence mechanisms among different wireless devices operating on the same frequency band. This paper presents a comprehensive review on the important aspects of experimental analysis, estimation, modeling, and avoiding of interference for WSN and offers some insight in dealing with aforementioned problem.

Keywords: Wireless sensor networks, Bluetooth, Data Communication, Interference, 2.4 GHz Frequency and, Wi-Fi, ZigBee.

1. Introduction

Progress on advanced research in wireless data communications and embedded micro-sensing applications like MEMS (Micro-Electro-Mechanical Systems), IoT (Internet of Things) technologies has made WSNs prominent [1]. Wireless sensor networks (WSNs) are widely used in industry today since they are able to efficiently sense various parameters in a myriad of industrial and service processes with high accuracy and low power consumption. The development of a multiplicity of sensors and networks everywhere based on sensor nodes have impacted our work environments and our everyday life. A WSN normally comprises of many low-cost wireless nodes, each proficient for collecting various types of information, processing, and communicating data with adjacent nodes in the network [2]. Numerous WSN applications found appropriate for applications such as surveillance, smart homes, automation, precision agriculture, vehicular traffic supervision, environment monitoring, and disaster recognition [3]. Modern industrial, scientific, and medical (ISM) applications based wireless devices operate in 2.4 GHz unlicensed frequency band. The WSN has become ubiquitous particularly in office, campus and residential buildings [4]. Likewise, the 2.4GHz frequency-based technologies like ZigBee, Wi-Fi or WLAN, and Bluetooth are working in the common frequency band often causing some degree of interference. The domestic applications like micro-wave oven and cordless phone are also radiating in 2.4GHz band. Thus applications working on 2.4GHz frequency band are influencing one another’s performance. Particularly, the performance of ZigBee based WSN is highly influential because of other technologies and therefore is getting degraded in terms of high packet drop, and increased frame error rate (FER) because of data collisions and increased energy consumption. The coexistence of various wireless technologies operating in 2.4GHz is shown in Fig.1 pictorially. The efficient packet delivery makes WSN reliable. The data generated at source must be propagated to the destination in a proficient way without any influence of other variables causing the distortion of the data [5]. On the other hand, the variables affecting the interference in the 2.4GHz frequency band include the distance between source and destination, inefficient routing, obstacle causing the fading and shadowing. To this we must add the environmental conditions (temperature), and node behavior [6]. The important factor to be considered in coexistence environments is interference. The interference is considered as a serious issue particularly for the low power wireless networks like WSN. The interference shows impact on the link quality. The devices operating in the same frequency band, same location and transmitting signals or data with high energy (Wi-Fi) will cause substantial degradation in low-power network (WSN) performance [7-8].
The main consequence of the interference is increased packet error rate (PER), packet loss ratio (PLR), and increased data congestion. The network traffic is increased significantly due to the packet retransmissions that increase the overhead and in turn increase the network load. Interference results in the inaccessibility to the channels, increased delay and depletion of battery levels of the node [9]. The interference leads to the contention delay and increased latencies. The interference can be classified in to two types, internal interference and external interference. The internal interference occurs because of the disturbances experienced from the nodes of the same network. It can be minimized by selecting an organized network configuration, node placement, network topology, routing and systematic channel access algorithms design etc. Also in today’s world of wireless communications, the presence of different wireless systems is a potential for interference. Wireless systems can interfere with each other at distances of 2000 feet (600 meters) or more. The external interference is occurring because of different technologies or applications (Microwave-oven) operating in the common frequency band [10]. The external interference avoidance is a very complex and very few works have been reported on this area. Hence there is a requirement of high research on this area.

A systematic research on the various techniques for avoiding interference may lead to the deployment of a safer, more efficient operating WSN, which is not simple task [11]. Interference is complex because, firstly, the interference is intermittent and dynamic, hence designing solutions for avoiding interference is very complex. Secondly, it is extremely difficult to predict the sources of external interference and their behavior at a given location and time [12]. There are 3 major pointers for assessing network performance (i.e., latency, throughput and packet loss). The time taken to transmit a packet across a network is generally defined as Latency. Throughput is expressed as the amount of data being transmitted/received by unit of time. Packet loss is assessed based on the number of packets lost per 100 packets of data transmitted by a host [13]. Figure 1 shows different technologies like ZigBee, Bluetooth, Wi-Fi, and Cordless phone all of which share unlicensed 2.4GHz frequency band. The microwave oven also radiates in the same frequency band, hence the distortion caused by this appliance has to be also considered and dealt with accordingly.

ZigBee has secured the prominent place and is considered for technologies, like IoT (Internet of Things) communication. The ZigBee Alliance has improved a two-way wireless communication standard allowing products with little price, and low power consumption. The ZigBee device can be easily embedded into consumer electronics aimed with sensor and actuator based controlling applications and building automation [14]. ZigBee is built on the top of IEEE 802.15.4 standard and strengthens the interoperability among different technologies in terms of automation and control. The performance of ZigBee can be optimized by adjusting the parameters relative to physical (PHY) layer, medium access control (MAC) layer, and network (NWK) layers [15]. The adjustment of network layer parameters also improves the network life time. The initial two layers, PHY layer and MAC sub-layer specifications were defined by IEEE 802.15.4. The ZigBee alliance defined the operation and working specifications in both NWK layer and application sub-layer (APS) [16].

Wireless LAN (WLAN) is designed for fast and reliable information transmission system to provide local self-regulating network communication between computing systems by means of wireless instead of a cable structure [17]. WLANs specification is based on IEEE 802.11 standard. WLANs use high-frequency electromagnetic transmission, either by employing radio frequency (RF) or infrared (IR), to communicate information from one point to another with low mobility range [18]. Bluetooth on the other hand is based on IEEE 802.15.1 standard, and it is intended for very small-range, low-budget wireless communications suitable to replace the cables. The devices linked using Bluetooth can function either as a master node or a slave node [19]. An overview of different parameters and technical specifications of wireless technologies like Zigbee, Bluetooth and WLAN or Wi-Fi and technologies are discussed in Tab. 1 as following.

![Fig. 1. The modern wireless technology based applications operating in 2.4GHz frequency band.](image)

**Table 1. Comparison of Zigbee, WiFi and Bluetooth parameters working in the 2.4 GHz frequency Band.** [21-25]

| Parameters              | ZigBee          | Wi-Fi           | Bluetooth       |
|-------------------------|-----------------|-----------------|-----------------|
| Physical Layer Standard | IEEE 802.15.4   | IEEE 802.11     | IEEE 802.15.1   |
| Maximum Data Rate       | 20, 40 & 250 Kbps | 11 Mbps         | 1 Mbps          |
| Power Consumption       | Years           | Hours           | Days            |
| Modulation              | DSSS/QPSK       | OFDM            | FHSS/BPSK       |
| MAC                     | CSMA/CA         | TDMA/TDD        | TDMA/TDD        |
| Number of channels      | 26              | 11-14           | 79              |
| Networking topology     | Star, Mesh and Cluster-tree | Star | Star |
| Frequency operating band| 868 MHz, 900-928 MHz and 2.4GHz | 2.4 GHz and 5 GHz | 2.4 GHz |
| Coverage                | 10-300 M        | 76 M (for low speed) | 10M |
There is a need for improved solutions for effective interference management. Something which requires continuous monitoring, identification of the sources causing interference, and consequently initiating the steps to avoid the identified interference [20-22]. Figure 2 shows a modern smart home considering ZigBee for automation, Wi-Fi for accessing internet and Smart meter (Home Gate Way) for Smart grid based energy management. Figure 2 consists of 4 ZigBee coordinators, connected through wireless connection to about 17 ZigBee nodes. Where, each ZigBee coordinator is connected to about 4 to 5 ZigBee nodes. There are 4 WiFi access points (AP) and about 5 WiFi clients, each AP is connected to 1 to 2 WiFi clients. The position of all the nodes is assumed and placed such that they fall under each other’s influence. The ZigBee coordinator and WiFi access points are connected to Home Gate-Way (HGW) through wired network as shown in the figure. The HGW can be considered as Smart Meter that is very important for Smart grid applications.

In this paper we present a detailed survey on existing interference avoiding techniques for ZigBee based WSN. We have studied the sources of the interference and classified them in detail. Firstly, we have presented the methodologies for analyzing, estimating and avoiding the interference for the effective operation of WSN coexisting with other technologies like Wi-Fi and Bluetooth technologies working in same 2.4GHz frequency band. Secondly, we have presented methodologies for avoiding interference from the nodes of same ZigBee network (internal interference). Thirdly we have presented the survey of various works on measurement and modelling of the interference in 2.4 ISM band. Fourthly various ways of experimenting, analyzing interference using hardware and software solutions were studied. In the fifth section, various modern applications of coexisting systems were presented and
finally a discussion based on the study performed were presented.

This paper is organized as follows. Section 2 presents the classification of interference for WSN. The interference measurement and modeling are described in section 3. The details of experimenting with interference using simulators, emulators and testbeds are discussed in section 4. In the Section 5 presents the application for WSN that works under the influence of WiFi. The discussion and insights are presented in section 6. Section 7 discusses the open research issues and finally, section 8 concludes the paper.

2. Interference

The 2.4GHz ISM band is jointly shared by multiple technologies for data communication aimed at different applications. In general ZigBee nodes have 27 channels, of them only channel ‘0’ works in 868 MHz band, in 915MHz band consists of channels ‘1-10’, and the channels ‘11-26’ will operate in 2.4GHz frequency band. WLAN (Wi-Fi) technology has ‘11-14’ channels varying geographically (11 channels are available in the USA, 13 channels in Europe, 14 channels are available only in Japan) operating in 2.4GHz ISM band [23]. In case of WLANs among the available 11-14 channels operating in 2.4GHz only 3 channels i.e., 1, 6 and 11 are available for data communication [24]. Bluetooth has ‘80’ channels working in 2.4GHz ISM band. The channel distribution and overlapping of the wireless technologies working in the 2.4GHz frequency band is as shown in the following Figure 3. From Figure 3 the following points can be observed: channel ‘1’ of Wi-Fi is influencing channels 11th to 14th of ZigBee. Channel 6 of Wi-Fi is influencing 16th channel to 20th channel of ZigBee and channel 11 of Wi-Fi is overlapping with 20th channel to 24th channel of ZigBee. Though the Bluetooth channels are distributed across 2.4GHz band, based on the literature, it can be inferred that the effects of interference from other technologies on Bluetooth are very less influential.

Table 2 below shows the technical specifications comparison for Wi-Fi, Bluetooth and ZigBee technologies [12] [13] [25]. In this section, two types of interferences, external interference and internal interference are discussed in detail.

![Fig. 3. Channel specifications of the wireless technologies operating in 2.4GHz Frequency Band.](image)

| Data Rate | Number of Channels | Minimum Quiet Bandwidth Required | Interference Avoidance Method |
|-----------|--------------------|----------------------------------|-----------------------------|
| Wi-Fi     | 11Mbps             | 13                               | Fixed Channel Collision Avoidance |
| Bluetooth | 723Kbps            | 79                               | Adaptive Frequency Hopping   |
| ZigBee    | 128Kbps            | 16                               | Fixed Channel Collision Avoidance |

A. Interference from other coexisting technologies working on same frequency band

WSN (ZigBee network based on IEEE 802.15.4 standard) operating in the 2.4GHz frequency band is coexisting with other technologies like Wi-Fi (IEEE 802.11) and Bluetooth. Microwave oven used domestically and cordless phone for wired communication both also emanate electromagnetic noise in the 2.4GHz ISM band. All of the above serve as examples for external interference (WSN experiencing interference from other coexisting technologies) and has a strong impact on the performance of WSN. The effects of the interference on WSN is a reduction of the packet delivery ratio and decreases the network lifetime because of increased listening and reduced node sleeping schedules. Because of the external interference, the latency and packet retransmissions of the network are also increased [26] [27]. The effects of external interference on WSN from the other technologies like Wi-Fi, Bluetooth, and micro wave oven are discussed in detail in the following sections.

a. The coexistence of WSN and Wi-Fi based networks in the common area.

N. CihanTa et al. [28] have presented the analytical frame work on the issues of the coexistence between WSN and Wi-Fi networks. Based on the experimentation it was inferred that the network parameters in a Wi-Fi network can be dynamically adjusted to optimize channel/bandwidth utilization of the WSN while minimizing the effects of interference. They have also...
presented the MATLAB simulation results of their theoretical framework proposed. Beata K et al. [29] have described the effects of Wi-Fi standard on the transmission of WSN. A measurement-based verification is presented to evaluate the influence of Wi-Fi on WSN. This type of measurement can be useful for designing WSN, because they are often located near to the wireless networks which may cause distortions or loss of data transmission. Yanchao Mao et al. [30] have investigated the interference between 802.11b/g and 802.15.4 networks. They have carried out different experiments for analyzing the influence of interference in terms of link quality and measured performance of WSN under the influence of 802.11b/g, and vice-versa. The following points were observed: (1) The 802.11b interferes with WSN in a higher frequency range but with less interference strength, compared to 802.11g. (2) WSN also has a considerable impact on the working of 802.11b/g. (3) Finally it was understood that different modulation methods of 802.11b/g show different impact on the link quality of WSN.

Ioannis Giaropoulos et al. [31] have used an analytical model and a hardware setup for analyzing the coexistence of ZigBee, and WLAN. The proposed system concentrates on two features, namely energy& timing. The results obtained show that the power levels and timing parameters jointly have an influence on the functioning of WSN. James Hou et al. [32] have proposed the methodology to prove that ZigBee is vulnerable to interference and have proposed potential solutions analytically, to resolve interference problem for improving the ZigBee performance. M. Danilo Abrignani et al. [33] have investigated the interference created by IEEE 802.11 upon ZigBee network. The investigations were made on different parameters and understood that effect of interference from Wi-Fi is severely affecting the performance of ZigBee based point-to-point network. Performance is evaluated in terms of PLR, average round trip time and overhead. Tests were conducted on the European Laboratory of Wireless Communications for the Future Internet (EuWin) testbed at the University of Bologna. Furthermore, environmental conditions were taken into consideration during experiments so as to account for this factor as well. Srinivasan et al. [34] have done extensive practical experiments on the coexistence of 802.11b and WSN and have observed the following: (i) 802.11b is avoiding clear channel assessment (CCA) of WSN, which has an effect on increased delays. (ii) 802.11b has very high power and acts as the high source of noise for WSN nodes, which leads to high packet losses. (iii) It is also observed that the presence of WSN nodes does not have any effect on the 802.11b nodes.

Authors in [35] have proposed an approach for analyzing the performance of ZigBee technology under the influence of Wi-Fi. It is inferred that the influence of Wi-Fi on the ZigBee performance increases as it moves nearer and, on the contrary, the effect decreases as the distance is increased. The authors have analyzed the advantages of adjusting the offset values for improving the performance of both ZigBee and Wi-Fi. Daniele Croce et al. [36] have proposed a mathematical model for characterizing the Wi-Fi receivers in presence of controlled interference sources (training phase) using hidden Markov chains. The above process identifies the sources for the cause of error patterns. Based on the experimental results obtained the effect of ZigBee interference was clearly understood. Kunho Hong et al. [37] have presented a framework to regulate the WLAN data traffic when there exist ongoing ZigBee data transmissions. Because of WLAN interference, the MAC delay exceeded the maximum tolerable delay (threshold) of ZigBee. They aimed to ensure that the delay experienced by ZigBee sensors (especially for alarm signals) did not exceed the threshold delay, while upholding the throughput of WLAN’s as high as possible.

An adaptive interference avoidance algorithm was proposed in [38], to improve the functioning of ZigBee network under WLAN interference. It uses a WLAN queuing model derived based on Markov chains. The work in [39] have proposed the CACCA algorithm for improving the performance of WSN in the coexisting mediums. The coexisting wireless technologies working in same frequency band are supporting each other. They have analyzed PER incurred by ZigBee network under the influence of Wi-Fi and achieved better ZigBee performance in terms of PER. Chih-Jan Mike Liang et al. [40] have put forward the BuzzBuzz algorithm. The algorithm is based on the quantified interference patterns between Wi-Fi and ZigBee networks at a bit-level. The algorithm also considered the effects of ZigBee node on the behavior of nearby Wi-Fi transmitters, producing symmetric interference among the both. Based on these observations, they introduced targeted redundancy mechanisms, namely multi-headers and error correction to improve 802.15.4 reception rates. The BuzzBuzz performance was also evaluated on TinyOS based implementation through stress tests on a testbed. TinyOS is an open source, BSD-licensed operating system designed for low-power wireless devices, such as those used in sensor networks. Peizhong Yi et al. [41] have introduced an interference avoidance algorithm based on frequency agility. This algorithm detects interference with WLAN using the energy detection scanning for ZigBee nodes. It avoids the interference by dynamically moving the node experiencing an interference to a safe channel.

Panlong Yang et al. [42] have proposed a sink based MIMO design (ZIMO) for avoiding the interference between ZigBee and high-powered Wi-Fi signals. ZIMO handles the interference from Wi-Fi access points by defending the ZigBee signals. The Wi-Fi signals interfered by ZigBee node can be recovered by the ZIMO sink. ZIMO consists of frame detection & identification, spectrum slicing, interference cancellation and interference nullification, and ZigBee decoder. Ruitao Xu et al. [43] have proposed an interference avoidance technique for Multi-channel ZigBee networks (MuZi). It has three main functionalities: interference estimation, channel exchanging and connectivity maintenance. While estimating the Wi-Fi interference, the intensity and density of interference are also considered. In channel exchanging, the optimum channel is selected based on these above parameters. Yubo Yan et al. [44] have presented a Wise ZigBee coexistence system (WizBee) having single antenna sink. It applies interference cancellation technique to avoid Wi-Fi interference and obtain ZigBee signals. For Wi-Fi data decoding, it uses Soft-Viterbi decoding algorithm on each sub carriers. The decoded data is used for channel coefficient estimation. WizBee does not require any modification to the existing ZigBee protocols and ZigBee devices.

The following tables summarize the characteristics of the protocols and works considered above. Tab. 3 summarize all the works considered in this section in terms of mathematical parameters, simulation or experimental parameters considered for evaluation. The notations in terms of alphabets can be considered as follows, (A). Channel Utilization, (B). Signal-to-Interference-Plus-Noise Ratio (SINR) or Received Signal Strength Indicator (RSSI), (C). Bit Error Rate (BER) or PER or PLR, (D). Delay, (E). Node mobility, (F). Throughput, (G). Energy Consumption, (H). Path Loss, (I). Distance. Tab. 4 signifies the parameters considered for evaluation of the work in terms of MAC approach. The Tab. 5 represents the detailed description of all the protocols considered in this section.
Table 3. Parameters considered for evaluation

| Reference Number | Mathematical | Simulation | Experimental |
|------------------|--------------|------------|--------------|
|                  | A | B | C | D | E | F | G | H | I | A | B | C | D | E | F | G | H | I | A | B | C | D | E | F | G | H | I |
| 28               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 29               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 30               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 31               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 32               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 33               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 34               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 35               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 36               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 37               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 38               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 39               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 40               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 41               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 42               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 43               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 44               | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Table 4. Parameters Considered in terms of MAC approach for understanding Interference

| Reference Number | Collision rate | Power consumed | Latency | Throughput | Reliability | Channel access | Spatial reuse | QoS support | Mobility |
|------------------|----------------|----------------|---------|------------|-------------|----------------|---------------|-------------|----------|
| 28               | Low            | Low            | High    | Medium     | High        | CSMA_CA        | Yes           | No          | No       |
| 29               | Low            | Low            | Medium  | High       | High        | CSMA_CA        | No            | Yes         | Yes       |
| 30               | Low            | Medium         | Medium  | Medium     | Medium      | TDMA           | No            | No          | No       |
| 31               | High           | Medium         | Low     | Low        | Medium      | CSMA_CA        | No            | No          | No       |
| 32               | Medium         | Medium         | Low     | Low        | Medium      | CSMA_CA        | No            | Yes         | No       |
| 33               | High           | High           | Low     | Medium     | Medium      | CSMA_CA        | Yes           | Yes         | Yes       |
| 34               | Low            | Low            | High    | Medium     | Medium      | CSMA_CA        | No            | No          | No       |
| 35               | Low            | High           | Low     | Medium     | High        | CSMA_CA        | Yes           | Yes         | Yes       |
| 36               | Low            | Low            | Medium  | High       | Low         | CSMA_CA        | No            | No          | No       |
| 37               | Low            | Small          | High    | High       | Low         | CSMA_CA        | No            | Yes         | No       |
| 38               | Low            | Medium         | Small   | High       | High        | CSMA_CA        | Yes           | Yes         | No       |
| 39               | Low            | Small          | High    | High       | High        | CSMA_CA        | No            | Yes         | No       |
| 40               | High           | Medium         | Medium  | Low        | Medium      | CSMA_CA        | Yes           | No          | No       |
| 41               | Medium         | Low            | Medium  | Low        | Low         | CSMA_CA        | Yes           | Yes         | Yes       |
| 42               | Low            | Medium         | Low     | High       | Medium      | CSMA_CA        | No            | Yes         | No       |
| 43               | Low            | Low            | Medium  | Medium     | Medium      | CSMA_CA        | No            | Yes         | No       |
| 44               | Low            | Medium         | Small   | Medium     | Medium      | CSMA_CA        | No            | Yes         | No       |

Table 5. Detailed description of the Considered Protocols

| Reference Number | Algorithm | Technologies Considered | Important parameter | Inference | Simulation/ Experimentation |
|------------------|-----------|-------------------------|---------------------|-----------|----------------------------|
| 28               | Throughput Analysis | ZigBee-WiFi (IEEE 802.11) | Channel Utilization Capacity | Channel parameters of Wi-Fi need to be adjusted for efficient ZigBee network operation. | MATLAB |
| 29               | Algorithm 1-Home Gateway Operation. Algorithm 2- Zigbee coordinator Operation interference avoidance algorithm | Zigbee-WLAN (IEEE 802.11b/g) | Time Delay | WLAN traffic was controlled, when Zigbee transmissions are going on. | ns-2 |
| 30               | Measurements methodology | Zigbee-WLAN (IEEE 802.11b/g) | Clear Channel Assessment and collision probability | Algorithm controls ZigBee frame length and improves the ZigBee performance both under saturated and non-saturated WLAN. | OPNET and MATLAB |
| 31               | Measurements methodology | IEEE 802.15.4 | SINR, Path Loss | Interference has a huge impact on the transmission delay and throughput. Above parameters increases if distance between ZigBee and Wi-Fi node increases. | Experimentation using testbed. |
| 32               | Measurements methodology | IEEE 802.11b/g | Throughput, Packets Received Ratio | 802.11b has high impact on 802.15.4 compared to 802.11g. Different modulation techniques has different impact on link quality indices of 802.15.4 | Experimentation |
The coexistence of WSN, Wi-Fi, and Bluetooth networks in the common area.

Bluetooth works based on frequency hopping spread spectrum (FHSS). When using FHSS, each available frequency band is divided into sub-frequencies, and signals rapidly change ("hop") among these in a predetermined order. Hence, interference at a specific frequency will only affect the signal during that short interval. FHSS can, however, cause interference with adjacent direct-sequence spread spectrum (DSSS) systems. This makes Bluetooth robust to interference in the unlicensed 2.4GHz frequency band [25]. In the coexistence environment, the packet losses of Bluetooth are negligible when compared to that of ZigBee [21]. Boano et al. [45] have analyzed the effects of Bluetooth on WSN (ZigBee). It is inferred that the effects of Bluetooth have a very low impact on ZigBee when compared to that of Wi-Fi devices or microwave ovens. Soo Young Shin et al. [46] have developed an analytical model to evaluate the performance of ZigBee under WLAN and Bluetooth interference. It was observed as the performance of ZigBee is more affected because of Bluetooth than Wi-Fi in the coexisting mediums. Rosario G. Garroppo et al. [47] have conducted an experimental study for analyzing the mutual interference among ZigBee, Wi-Fi and Bluetooth devices. Apart from mutual interference among each pair of devices, simultaneous interference among all the three devices is also analyzed. In all the experiment scenarios, the Frame Error Rate (FER) and goodput parameters of ZigBee are being affected in the presence of WLAN and Bluetooth.

Kuruvilla Mathew et al. [48] have investigated the effects of signal penetration of Bluetooth and ZigBee in regions having thick shrubs. They have also investigated the effects of environmental conditions considering both technological and environmental interferences. From the experimental results, they have shown that ZigBee signal penetration is degraded when there is interference from other signals. Jaana Suhonen et al. [49] have analyzed the performance of ZigBee and Bluetooth robot cars. Both the cars are operated under the interference caused by sources like Bluetooth and WLAN. For each interference source, the utilized bandwidth is independently measured. The properties of the power spectrum and noise resistance of both the cars are analyzed and observed as ZigBee performance is getting affected in the presence of Bluetooth.

The Coexistence of WSN network with domestic appliances

The electromagnetic interference has a great influence on wireless propagation and severely affects the data communication in the 2.4GHz frequency band [51]. The Microwave oven used for the domestic kitchen purposes radiate electromagnetic interference. Zhou et al. [50] have evaluated the effects of electromagnetic interference from microwave oven on wireless networks. It is inferred that it is affecting almost half of the spectrum available in 2.4GHz band using spectrum analyzer. Boano et al. [45] have analyzed the influence of Microwave ovens using the RSSI sampling by employing the off-the-shelf motes. They have modeled the interference generated based on the periodicity of generated pattern. Then they have also proposed solution for quantifying the impact of interference on the packet reception ratio (PRR) of WSN. Wenqi Guo et al. [52] have investigated the problems disturbing coexistence of ZigBee systems with other technologies. A systematic experimental study was conducted on the ZigBee performance under the influence of microwave ovens for several different link configurations. The experimentation arranged has tested the wireless propagation...
of ZigBee between source and receiver for a particular time period with respect to distance between nodes and channel variations. The above experimentation was mainly conducted to understand the consistency of ZigBee under the influence of electromagnetic interference from microwave oven. The ZigBee consistency was understood based on the PER, RSSI and Link quality indicator (LQI). It was very clear from the results obtained that the performance of ZigBee was severely getting affected when Microwave oven is switched ON.

The following tables summarize the characteristics of the protocols and works considered above. The Tab. 6 summarize all the works considered in this section in terms of mathematical parameters, Simulation or experimental parameters considered for evaluation. The notations in terms of alphabets can be considered as follows, (A). Channel Utilization, (B). RSSI or SINR, (C). BER or PER or Packet Loss Ratio (PLR), (D). Delay, (E). Node mobility, (F). Throughput, (G). Energy Consumption, (H). Path Loss, (I). Distance. Tab. 7 signifies the parameters considered for evaluation of the work in terms of MAC approach. The Tab. 8 represents the detailed description of all the protocols considered in this section.

Table 6. Parameters considered for evaluation

| Reference Number | Mathematical | Simulation | Experimental |
|------------------|--------------|------------|--------------|
|                  | A  | B  | C  | D  | E  | F  | G  | H  | I  |     | A  | B  | C  | D  | E  | F  | G  | H  | I  |
| 45               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 46               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 47               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 48               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 49               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 50               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 51               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |

Table 7. Parameters Considered in terms of MAC approach for understanding interference

| Reference Number | Collision access | Power consumed | Latency | Throughput | Reliability | Channel access | Spatial reuse | QOS support | Mobility |
|------------------|------------------|----------------|---------|------------|-------------|----------------|---------------|--------------|----------|
| 45               | Medium           | Low            | Medium  | Good       | High        | CSMA_CA        | Yes           | Yes         | No       |
| 46               | Medium           | Low            | High    | High       | Medium      | CSMA_CA        | No            | Yes         | No       |
| 47               | High             | Low            | High    | Low        | High        | CSMA_CA        | No            | Yes         | No       |
| 48               | Low              | High           | Medium  | High       | Medium      | TDMA           | No            | No          | No       |
| 49               | Medium           | Low            | Low     | High       | High        | CSMA_CA        | Yes           | Yes         | Yes      |
| 50               | High             | Medium         | Low     | Medium     | Medium      | CSMA_CA        | No            | Yes         | Yes      |
| 51               | High             | Medium         | Low     | Medium     | Medium      | CSMA_CA        | No            | Yes         | No       |

Table 8. Detailed description of the Considered Protocols

| Reference Number | Algorithm                  | Technologies Considered | Important parameter               | Inference                                                                 | Simulation/Experimentation |
|------------------|----------------------------|-------------------------|-----------------------------------|---------------------------------------------------------------------------|-----------------------------|
| 45               | JAM Lab Experimental test bed | ZigBee, Bluetooth, Wi-Fi, Microwave oven | RSSI, PRR | A JAM Lab is an interference testing platform to the best accuracy levels. It can test both spatial and temporal patterns. | Experimentation developed a test bed |
| 46               | Simulation                 | ZigBee-Bluetooth-Wi-Fi  | PER-BER, SINR                     | The distance between the different types of technologies affects each other performance. The best suited distances is presented. | OPNET Simulator |
| 47               | Hardware based analysis    | ZigBee-Bluetooth-Wi-Fi  | Frame Error Rate, Goodput         | WiFi has affected badly to a level of 41% drop for Zigbee and to a level of 68% drop for Bluetooth. WiFi performance was almost unaffected because of the other two. | Experimental Analysis using hardware. |
| 48               | Hardware based analysis    | Bluetooth-Zigbee        | Distance and environmental effects | The environmental effects on the Bluetooth and the Zigbee Propagation and their mutual effects on performance. | Experimental analysis |
| 49               | Hardware based analysis    | Bluetooth-Zigbee        | RSSI, Frequency, distance         | The mutual effects of different technologies upon each other performance is studied. | Experimental analysis |
| 50               | Self-Adaptive Spectrum(SAS) management | 2.4GHz is considered | PRR, Throughput, time, Energy | SAS improves the performance of the Single frequency MAC protocol to coexist with multi-frequency capability. | Experimental analysis |
| 51               | Hardware analysis          | ZigBee-Bluetooth-Wi-Fi  | PER-Packet Loss Ratio             | Mutual effects of different 2.4GHz based technologies is studied. | Experimental Analysis |

B. Interference from the nodes of same network

For the efficient performance of the WSN not only the external interference but also the internal interference has to be considered with equal importance. Internal interference is because of the disturbances experienced from the nodes of the same network. Most of the times internal interference is
because of the concurrent transmission of the data by multiple nodes in the same network at the same instance.

a. The performance of network when concurrent (parallel) transmission is scheduled

Most of the QoS based research performed on WSN is based on assumptions such as that the network is built collision free or has some form of interference cancellation mechanism incorporated, works with low power and observes pure channel behavior. The research performed in [157] [170] is based on the WSN (ZigBee) built for indoor environments and have considered that there is no effect of other technologies in terms of interference. But the authors have stated the essence of the considering the disturbances, to increase the reliability of WSN. In [53] [54], the authors have performed research on the concurrent transmissions by the low power data communication. Authors have inferred that the concurrent transmission in WSN leads to the interference that shows the impact on the link quality. The experimentation was carried based on the measurements of SINR conducted by Mica motes based CC100 radios and observed following. Firstly, for efficient data communication between two nodes the SINR should exceed the threshold. Then it is assumed as link quality is high for the transmission of the data and the packet reception ratio (PRR) is above 90 percent in this case and this falls under connected region. If the SINR is below the threshold, then perhaps there are chances of transmission getting successful in spite of concurrent transmissions but the PRR will be less than 90 percent generally this type of connections are assumed as transitional or disconnected regions. Secondly, SINR threshold value is different based on the type of hardware and so the transmission power levels also vary accordingly so SINR does not depend on the location of the network.

b. Though nodes are invisible to each other even then concurrent transmissions have impact of the performance of WSN

The authors in [55], have performed research on real road tunnels, with precise concurrent transmissions. They have designed a network with three nodes in real time. Two nodes communicate with each other and the third node is distant and is not visible from the first two. The authors have noticed that the third node has created a significant noise for the first two nodes communication and observed that there is a substantial reduction in the packet delivery ratio than estimated.

c. Internal Interference from adjacent channels

It is very important to study the cross-channel interference on the performance of WSN. It results in the significant increase in the PLR. The research works proposed in [55] [58] have shown the effects of cross channel interference on WSN and have inferred that there is a significant increase in data collisions and hence measured in terms of increased PLR. Yafeng Wu et al. [59] [60] have implemented the WSN practically using MicaZ motes and introduced adjacent channel interference. It was inferred that the PRR decreased by 40%. The works in [61] & [62] have proposed the hardware solutions to reduce the load on multi-channel interference quantities by utilizing the spectral power density of the transmitter.

The following tables summarize the characteristics of the protocols and works considered above. The table 9 summarize all the works considered in this section in terms of mathematical parameters, Simulation or experimental parameters considered for evaluation. The notations in terms of alphabets can be considered as follows, (A). Duty cycle, (B). RSSI or SINR, (C). BER or PER or PLR, (D). Delay, (E). Node mobility, (F). Throughput, (G). Energy Consumption, (H). Path Loss, (I). Distance. Table 10 signifies the parameters considered for evaluation of the work in terms of MAC approach for assessing the internal interference. The table 11 represents the detailed description of all the protocols considered for evaluating the internal interference, in this section.

Table 9. Parameters considered for evaluation

| Reference Number | Mathematical | Simulation | Experimental |
|------------------|--------------|------------|--------------|
|                  | A  | B  | C  | D  | E  | F  | G  | H  | I  | A  | B  | C  | D  | E  | F  | G  | H  | I  | A  | B  | C  | D  | E  | F  | G  | H  | I  |
| 53               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 54               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 55               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 56               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 57               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 58               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 60               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 61               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| 62               | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |

Table 10. Parameters Considered in terms of MAC approach for assessing Internal Interference

| Reference Number | Collision rate | Power consumed | Latency | Throughput | Reliability | Channel access | Spatial reuse | QOS support | Mobility |
|------------------|----------------|----------------|---------|------------|-------------|----------|---------------|--------------|-------------|----------|
| 53               | Medium         | High           | Medium  | Medium     | Low         | CSMA-CA   | No            | Yes          | No         |
| 54               | Low            | Very Low       | Low     | High       | CSMA-CA     | No       | Yes           | No           | No         |
| 55               | Low            | Medium         | Medium  | High       | CSMA-CA     | No       | Yes           | No           | No         |
| 56               | Low            | Low            | Low     | High       | CSMA_CA     | No       | Yes           | No           | No         |
| 57               | Medium         | Low            | Medium  | High       | CSMA-CA     | No       | Yes           | No           | No         |
| 58               | Low            | Low            | Low     | High       | CSMA-CA     | No       | Yes           | No           | No         |
| 60               | Low            | Medium         | Medium  | Medium     | CSMA-CA     | No       | Yes           | No           | No         |
| 61               | Low            | Medium         | Medium  | Medium     | CSMA-CA     | No       | Yes           | No           | No         |
| 62               | High           | Medium         | Medium  | Medium     | CSMA-CA     | No       | Yes           | No           | No         |

Table 11. Detailed description of the Considered Protocols for evaluating the internal interference
3. Measurement and Modeling Of Interference

The external interference shows a great impact on the characteristics of the wireless transmission. The assessment of the network parameters is unpredictable as it depends on the indoor and outdoor environments. The interference is intermittent in nature; the effect may be temporary making the unavailability of the channel considered. Hence it is very important to understand the effects of interference on data communications while designing WSN. The WSN can become robust by adapting the dynamically changing interference patterns [63]. The WSN can be adjusted to different interference patterns dynamically by accurate measurement of parameters associated to interference and can reduce the effects to a great extent. Firstly, there is a need for understanding the parameters in relative to surrounding interference (indoor or outdoor environment) and there is a need for accurate measurement of those parameters [64]. The measurement should be simple and energy effective in terms of node life. Secondly, selection of essential metrics must be done for estimating the interference based on the obtained measurements. Based on the metrics selected, WSN can dynamically switch according to the changing interference patterns either by dynamic channel selection or by ranking based channel selection. Thirdly the effective lightweight algorithms must be designed to dynamically adjust the parameters as soon as the changes in the surrounding environment is observed [65].

A. Measurement of Interference Using Sensor Nodes

The WSN considers the RF Noise (floor) value for measuring the interference level, this value is estimated based on the signal power at receiver side [24]. In ZigBee radio the RF noise measurements are typically measured from energy detection method defined by IEEE 802.15.4 as a part of channel selection process. All measurements are typically measured from energy detection at receiver side [24]. In ZigBee radio the RF noise (floor) value for measuring the interference level, this value is estimated based on the signal power at receiver side [24]. The measurement of interference using sensor nodes can be simple and energy effective in terms of node life.
the transmitter and receiver. There are also other parameters, considered for measuring the interference and those are Link Quality Indicator (LQI) and PRR, but these values can be obtained only when the packet is received at the receiver [67]. Using RF noise, one can estimate the presence of the interference at any point in the considered environment. Whereas using the RSSI, LQI and PRR, one can identify the interference only upon packet reception and can react accordingly (by switching channel) to reduce high packet loss [68]. The low LQI value is not only because of external interference but also may be because of the unreliable link quality. Similarly, PRR may be low because of some routing or software issues other than external interference [69].

The work proposed in [70] have measured the interference at each channel of ZigBee node using RF noise levels at a sampling rate of 20 samples per second under the presence of Wi-Fi. They have also proposed some important metrics used for better understanding of interference levels. Firstly, they have collected the cardinality of RSSI values at every channel. If the channel experiences the high cardinality, then it has high interference and the channels having low cardinality then channels experience low interference [71]. Based on the application requirement the authors [72] have considered RSSI values in between range 0 to-80dBm (this range is considered as optimal) as the number is increasing then the interference is going to be decreasing. If the number of RSSI values measured are above the threshold, then signal is said to highly interfered. The work in [73] considered -90dBm as threshold which may not be optimal because the off the shelf nodes are not typically calibrated. Most of the authors have also used RF noise measurement system by using the energy detection(ED) system. But as low power wireless node relies on battery, this type of measuring system was found as costlier in terms of high operating energy. As the sensor node should be active mode during the measurement process it leads to the depletion of battery levels. Based on this authors of [69] [74][75][76] have used PRR or clear channel assessment (CCA) based failure measurement for estimating the interference level. Main drawback of above papers is that they can be assessed only after the interference has affected and can only be learnt at receiver side.

B. Interferer Identification

The precise measurement of interference based on different methods as stated above can help in the identification of the source of the interference. Identification of the source of interference (interferer) can help in increasing the reliability and robustness of the WSN. Based on the RF noise measurements type the interferers is identified. Also, there are some other hardware estimators for identifying interferers based on LQI, PRR, RSSI, and Signal to noise ratio (SNR). Kaushik R. C et al. [77] have presented an algorithm to identify the interferer based on the obtained channel power measurements. Based on this interferer’s characteristics a better channel is chosen for data transmission and packet scheduling. It is also observed that there is a considerable amount of energy saving, thereby increasing the life time of the nodes in the network. The authors in [78] have proposed a method to detect the interference based on classification mechanism. A ZigBee node scans the available channels to detect the interference that is generated by Wi-Fi devices or Microwave ovens. The mechanism proposed creates a signature for all the available of ZigBee channels. The signature is useful in determining the interference. Based on signature an adaptive channel selection scheme was proposed for proper channel scheduling and packet scheduling.

Zacharia et al. [79] have introduced an algorithm to identify the source of interference using the RSSI readings. The algorithm allows the channel to record the RSSI samples for one second. Based on the samples the algorithm determines interferer and the causes of interference and classifies the type of interferers also. Although this work has estimated many samples, still there is a drawback, like it is unclear with ongoing interference when multiple sources of interference occur at the same time. Frederik H et al. in [80] have proposed an interferer detection based on the LQI and RSSI combined properties. The algorithm proposed is based on the light weight detection. The type of interference classification is very simple and is based on WSN regular operation. The LQI is useful, when the packet is transmitted and is received with high link strength but fails the cyclic redundancy check (CRC). Then algorithm checks for RSSI values for each sample per payload byte. This information is useful in identifying the exact portion of the corrupted packet. Based on supervised training the classifier assigned to each corrupted packet will group them into a class based on the type of interferer. N. Boers et al. [81] [82] proposed a work based on the characteristics of the interference type. The authors define the interference based on the types of spikes (infrequent, periodic, periodic and frequent spikes) obtained based on the RF noise. The RSSI sample values are also recorded and taken in to consideration for estimating the type of the interference. If the channel is unclear with above types, then it is estimated based on dominant pattern. The decision trees are defined based on the above three patterns for a classifier to identify the type of interferer.

C. Modeling Interference

The hardware limitations like low energy usage-based network operations make it very difficult to build algorithms for modeling interference. The important problems of WSN are connectivity, coverage, routing, and end-to-end delay and in addition, complex computation increases the load on the nodes. Hence, a precise and simple methodology must be proposed to understand the complexity of WSN and interference-based problems [85]. A two state – Markov model [87] was proposed for modeling interference that was simple in design and has less computational overhead. The methodology proposed uses the RF noise measurements for assessing the interference. When the RSSI values inferred from the RF noise measurement are greater than the certain threshold then channel is treated as busy, otherwise, the channel is treated as idle. The protocol parameters are estimated using two-state Markov interference model in the coexistence environment, for understanding the interference effects on the performance of WSN. The authors in [86] have considered the channel quality parameter by measuring the accessibility of channel over the time. This system is systematically differentiating the channels based on the availability and ranking for efficient use. The categorization is based on firstly, the channels with sudden or small interval-based interference will have high inactive periods, and secondly channel with high-frequency periodic interference will also affects the performance of WSN. Among both, the first type channels are better compared to second type. It was inferred as the former channels are assuring high successful packet transmission compared to later group of channels.

The work in [26] have estimated the initial end to end delay, the RSSI value, and channel occupancy ratio. In the second stage using the hidden Markov model, the estimation of interference effects caused by dynamic sources is measured. Then for every transmission, the delay is compared with threshold delay and RSSI values are estimated. Then based upon obtained values the better channel is chosen. The authors
in [45] have modeled the external interference pattern for every device and based on the type of interfering source. The characteristics considered are like period of the signal, duty cycle, and output power. Particularly they have used this for understanding the microwave oven-based interference. The work in [87] has proposed bursty interferer model for estimating the interference caused by Wi-Fi and Bluetooth. Interference follows two states ON-OFF. This transition between two states is modeled by Bernoulli’s random variable. The variable is further used to control the duration of interference and the business. Based on this a second model was proposed, semi-periodic interferer model. This produces the continuous blocks of interference and is very useful in estimating the periodic data collection.

1. Experimenting with Interference

The interference is considered as an important concern by many researchers because it has a huge impact on the performance of the WSN [88]. For assuring stable and efficient performance of the WSN, the changing interference patterns from other technologies need to be understood. The simulation work carried must be taken to real-time implementation and the accurate performance of the WSN must be validated. Lack of tests may lead to limited or complete system failure [89]. An accurate performance needs to be tested and requires proper hardware infrastructure. Implementing through hardware also needs expertise and understanding of the co-design mechanisms to build accurate patterns. Particularly the design and implementation of interference patterns and validations under interference may consume lot of time and resources [90] [91]. There are a plethora of variables affecting the real-time implementation of WSN, that includes, antenna design, geometry (static or mobile), environmental conditions (temperature), the presence of obstacles [92]. The parameters like routing, multipath fading, and shadowing are also important for real-time implementation. The above may be considered in simulation-based implementation but while real-time implementation the properties of each device may be different and cannot be estimated easily [93]. The process of experimentation in terms of real-world applications with different types of radio interference can be the frustrating issue because several key aspects need to be addressed [94].

A. Requirements for Real-Time Implementation

The summary of the properties on the experiments of WSN carried through simulation and hardware implementation involving the interference characteristics are discussed below.

Realism and accuracy: In the real-time generally the interference patterns do not hold for longer periods of the time and they are bursty in nature. It is very important to generate bursty patterns from different kind of sources operating in the same environment [95]. Often to build expected type or planned type of scenario it is very complex either in simulation or real-time scenarios. For accuracy and robustness of WSN against interference, systematic and realistic arrangements must be installed for getting better validation of results [96].

Device Diversity: A WSN protocol designed considering the bursty nature of Wi-Fi may suffer randomness of Bluetooth or may be despairing to Microwave oven characteristics [97]. In the presence of multiple devices with the dissimilar operation, a multichannel protocol avoids the congested channels and may give good results under only single source of interference. Operating concurrently with different types of devices, is often complex and protocol may perform poorly [98].

Spatial Diversity: The wireless propagation and antenna design characteristics play a most important role in the building suitable network. The placement of these nodes should be adjusted for creating appropriate cases for testing the performance of WSN. The worst scenario cannot be created in real-time scenario. It is because the nodes may not always operate whenever user wishes them to work. The placement of the node has an important role and significantly affects the performance of the WSN [99].

Temporal Diversity: The node mobility effects the wireless propagation. The characteristics of different wireless nodes changes based on the type of location and timing. Often the transport protocols, experience this kind of variations. In the implementation side for executing real-time it is very complex than spatial diversity problem [100]. Wi-Fi working gets affected because of following problems, the wireless propagations vary based on timing i.e., day and night, and on different traffic scenarios, so this characteristic is complex in simulation rather than real-time. Hence it is very confusing and difficult for generating the interference patterns for testing the temporal characteristics [101].

Scalability and Controllability: The WSN cases proposed and interference patterns should be working as per the proposed plan. The planning and execution are very intricate. For example, set up of several micro wave ovens for activation of external interference and may not be possible if the network devices are not programmed properly, may not certainly possible in simulation [102].

Repeatability: For an instance, the properties of a WSN were tested under some Wi-Fi nodes and noted the performance. If a user wants to repeat the test under the same conditions, then certainly the parameters may differ slightly or entirely under the same conditions. Often, it very difficult to predict the characteristics of wireless nodes at different times and different locations [103].

B. Experimenting with Simulators

The algorithms designed and implemented using simulations give much recommended results but still, they are lagging in terms of real-time implementations [104]. The most important advantage with simulators is that, they offer satisfactory scalability, repeatability, and controllability [105]. The issues in WSN implementation start with physical layer modeling like log-normal shadowing model (path loss, routing) and unit disk model (latency) [106] [107]. This problem can be rectified by relocating the nodes for better communication and also it is very important to locate the interferers in the network which severely affect the network performance [108].

The identification of the network parameters is very important for increasing the efficiency and making the results obtained more realistic [109]. For example, TOSSIM has limited capabilities in terms of trace-based models and cannot perform noise-based estimations effectively that allows the burstiness [110]. The work in [111] is based on TOSSIM and developed the mechanism for locating jamming nodes in the network. The simulators should allow the programmer in selecting the parameters and based on their requirement. Often the simulations are implemented with limited capabilities thereby user may not be encouraged further to extend than available. For example, if a user wants to study the effects of different types of interferers at the same time then this may not be allowed by software functionalities. In general designing, the software and coding in the software based on the current research requirement is very time taking process [112].
The software design should give the results accurately and should match with the results of real-time experiments. In some cases, there are some important patterns that should be generated to interpret the correct results. In real-time the results obtained using hardware experiments must be incorporated in the simulation so as to obtain the results in the most accurate and realistic levels. The software COOJA will support with above capabilities. The work in [115] is based on the multichannel protocol for avoiding the interference from disturbing nodes and avoids usage of selected channels, this work was implemented using COOJA. The results presented in [26] [58] are implemented using the ns-2.34 simulator, the authors of above papers have implemented algorithms for avoiding interference. The ns-2.34 is open source software and allows the user to develop their own libraries based on the requirements. The coding is generally done based on the TCL and C++. There is also another open source software ns-3 available for network researchers, but many libraries are still in the developing stage and the working language is based on C++ in combination with Python. Both ns-2 and ns-3 are popular for network designing and there is a need for effective programming for creating libraries for analyzing the interference patterns [116]. The essential characteristics of interference like (path loss exponent, the line of sight, payload size, receiver sensitivity, CCA threshold) are embedded in software OPNET. The proposed work in [117] [118] is based on OPNET.

Though the above simulators have implemented the interference patterns to a great extent, some works have extended the capabilities of existing simulators with the new type of interference cases or implemented with the new type of simulators. The proposed work in [120] has used OMNeT++ software for studying the coexistence parameters and their performance in coexistence environment of IEEE 802.15.4 and IEEE 802.11b based networks. The work in [121] [122] is based on the Wireless HART, have used this simulator thoroughly for examining the coexistence issues and nodes behavior in 2.4GHz ISM band. A new SIDE-based emulator is proposed for testing interference using scripted external impulsive patterns defined based on user- required configuration [123]. The work in [124] is based on the C++ based simulator, the work is aimed at testing the performance of IEEE 802.11b within WSN with the varied number of nodes and data rates respectively. The Tab. 12 below presents, the description of different software’s and emulators used for developing and evaluating WSN in coexisting environments.

### Table 12. The Simulation tools and EMULATORs used for the designing and Evaluating WSN.

| S.No | Software      | Description                                                                 | Merits                                                                 | Demerits                                                                 |
|------|---------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------|
| 1.   | ns-2          | The Simulator ‘REAL’ developed in 1988 by Cornell University. The ns-2 has emerged as a variant of the REAL in 1989. Later ns-2 was supported by DARPA (many other corporate research centers) in 1995. The ns2 is a open source free software. It is very useful for academia and networking research. It is basically a discrete event simulator based on C++ and OTCL (Object oriented Tool Command Language). The C++ is generally used for extending the existing libraries, according to the research requirements. The OTCL is used for the implementation and execution of the networks programs. | ns-2 is available at free of cost. Easy to add new protocol coding. ns-2 is compatible for LINUX, Macintosh and Windows (using third party software using Cygwin). Supports Standards like IEEE 802.11, 802.15, 802.16, IR, and UWB. Widedly used by networking-based community. Frameworks like Mannasim, SensorSim, and NRL Sensorsim can enhance ns-2 performance. Supports Standards like IEEE 802.11, 802.15, 802.16, IR, UWB, 6LoWPAN. Supports routing protocol got low power and lossy networks (RPL). ns-3 has overcome the difficulties of ns-2, important memory management and overhead. The detailed analysis on Physical layer is possible. The software can effectively analyze the performance of protocol. | ns-2 cannot support real-time experiments. Source code still had bugs and need to be fixed. Need to learn programming. |
| 2.   | ns-3          | ns-3 is an open source free software launched in 2008. It is a discrete event scheduler based on C++ with Python bindings.                                           | ns-3 is an open source and available at free of cost. ns-3 is compatible for LINUX and Windows (using Cygwin). Supports Standards like IEEE 802.11, 802.15, 802.16, IR, UWB, 6LoWPAN. Supports routing protocol got low power and lossy networks (RPL). ns-3 has overcome the difficulties of ns-2, important memory management and overhead. The detailed analysis on Physical layer is possible. The software can effectively analyze the performance of protocol. | ns-3 in developing mode. ns-3 has less number of written codes when compared to ns-2. Works efficiently in Linux version. In case of Windows the Python binding does not work with Cygwin. |
| 3.   | MATLAB/Simulink | MATLAB is most efficient and reliable software for researchers. It supports many mathematical functions and give solutions to numerous problems. It supports FORTRAN algorithms, C language and JAVA for programming. | The detailed analysis on Physical layer is possible. The software can effectively analyze the performance of protocol. | Commercial software but affordable to individual, requires license for running software. |
4. **OPNET**
   - [117] [118] [156]
   - OPNET is an efficient and powerful networking software. OPNET is based on the interactive GUI interface for designing the network interfaces. OPNET is initially designed for the Military applications. OPNET is very expensive for commercial usage. OPNET is a high-level event-based network simulation tool. It contains huge database of accurate network models which assure accurate results even at packet level. 
   - The software is an advanced networking based commercial software from Scalable Technologies. The Initial version was known as GloMoSim, served basically for educational purpose. QualNet is very useful for the design and analysis of the network aimed for various networks. The GUI based virtual models are available for all the wired and wireless models. There are many libraries available for providing all the advanced features. The designing of wired, wireless networks, GSM and satellite network systems are also possible with QualNet.

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   - QualNet software is an advanced networking based commercial software from Scalable Technologies. The Initial version was known as GloMoSim, served basically for educational purpose. QualNet is very useful for the design and analysis of the network aimed for various networks. The GUI based virtual models are available for all the wired and wireless models. There are many libraries available for providing all the advanced features. The designing of wired, wireless networks, GSM and satellite network systems are also possible with QualNet.

6. **OMNeT++**, Mixim or Castlia
   - [160] [161]
   - OMNeT++ is a discrete event simulator. Extensively used for modeling communication networks. OMNeT++ addresses the gap between open-source, research-oriented simulation software such as ns-2 and expensive commercial alternatives like OPNET. OMNeT++ is based on C++ simulation library. Compatible with Windows, Linux versions and Macintosh. Commercial version is called as “OMNEST”.

7. **NetSim**
   - [162] [163] [164]
   - NetSim supports hardware implementation and simulation of both CISCO products. It supports stochastic discrete network models. Supports various protocols for establishing networking requirements. The results obtained through simulation are almost identical to hardware implementation. This software works only with Windows. The programming is based on C and JAVA.

8. **TOSSIM simulator**
   - [165] [166] [167]
   - TOSSIM is a discrete event-based network simulator for Tiny OS. It was built on Python and C++ coding and also supports Nes C. It works very efficiently and capture the results at bit level also. Supports many protocols effectively. It can work both on Linux and Windows (Cygwin). Supports numerous models up to last node in the network. 
   - TOSSIM is an open source software and available at free of cost. 
   - It is considered as simple and powerful emulator for wireless sensor networks.

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**MATLAB** is enriched with Simulink. The Simulink supports GUI (graphical User Interface) and supports all the linear and non-linear systems. 

- The implementation of WSN using MATLAB can be quite difficult depending on parameters to measure.
- The problems of compatibility also exist.
- Installation on Linux systems is very difficult.
- The software is proprietary.
- It allows only single event discrete simulation.
- The Java based user interface work slowly.
- The resources available in the library are limited.
- Very expensive software.
- The problems of compatibility also exist.
- Expensive
- Latest version (5.0) is compatible for Solaris platforms.
- Demand modelling.
- Models requires huge memory.
- Less tutorial.
- Buggy, deep-rooted and hard to modify ready-made models.
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C. Experimenting with the Hardware

The WSN implemented using real-time hardware will give more accurate results when compared to the simulation experiments [125]. Though the results obtained in this format are more reliable but real-time implementation is very costlier. The other way of testing is through the laboratory testbeds. The problems with the testbeds are that they are already available, for testing the performance of WSN in coexisting environment, they may not have the capabilities to generate the interference patterns. To introduce the interference pattern to the existing testbeds it is again costlier and time taking. Introduction of the Wi-Fi or Microwave modules cannot be placed easily on to the test bed [126]. The relocation of the testing items based on the requirement of the experiment is also a difficult task [127]. The Easiest [128] is a tested bed implemented for understanding the coexistence issues between the Wi-Fi and ZigBee, but the resources involved are limited. In [129] authors have recommended the associations for the testbed federation based on the software defined radios (SDR) for testing performance of difference radio-based networks. Using SDR one can easily examine the performance of different nodes under different interference patterns. The availability of SDR hardware is costlier. The most important aspect in the research of WSN is misinterpretation of the data. While testing the WSN environment, many assumptions were taken in to consideration. For an example there is a myth like the effects of interference on WSN during the night times is almost negligible when compared to the day time. Consideration of the obstacles in the testing may or may not affect the wireless propagation of data [130]. The important consideration in the real-time hardware WSN experiments is that there is no instance in the system that can be once again repeated as wireless propagation is dependent on innumerable factors.

D. WSN based on noisy environments

Many authors have evaluated enormous amounts of information on the interference patterns under realistic conditions in relation with the WSN. The authors of the following papers have evaluated the performance of the WSNs under noisy environments. Near the test-case, the presence of cordless phone, microwave ovens, and people moving in the WSN surroundings were considerable effects on the performance of WSN in terms of shadowing and multi-path fading that makes the experimentation more realistic [131-134]. The authors in [135] and [136] have conducted the tests near university campuses and have evaluated the performance of WSN under the coexistence of Wi-Fi nodes. The work in [137] has conducted research on bursty interference surrounded by the university library and have reported heavy traffic from other networks. The works in [138],[139] were based on the spectrum usage of the residential environment and have proposed a frequency adaptive control mechanism for coexistence area. The advantage of this type of environment is that this environment is available naturally and doesn’t require extra effort for generating the interference based test case. The disadvantage of this type of environment however is that interference exists by default in the location considered, but experiments were carried at the expense of non-repeatability of the interference patterns.

E. WSN under Specific Interference Patterns

Some research groups have studied the influence of interference on WSN by generating specific type of interference patterns. Thus, based on the necessity of testing, the required module is generated to test the performance of the WSN. The proposed work in [140] was tested based on the university testbed using 94 TelosB nodes. The performance of
the WSN was verified when transferring a file near Wi-Fi nodes. It was observed that no information was transferred to the destination. The work in [141] is based on the indoor WSN using 40 motes testbed and two Wi-Fi nodes. Backpressure algorithm was implemented in real-time and it was observed that there was a significant improvement in the packet delivery even under the extreme interference conditions. The performance of Wi-Fi networks under the presence of 24 WSN nodes were tested in indoor office environments. It was observed that the localization error increases to a 141% and affects the performance of Wi-Fi nodes [142]. The performance of a protocol for Wi-Fi network was tested in the presence of WPAN nodes testbed [143].

The authors in the [144] and [145] have evaluated their protocol in real-time for improving the performance of ZigBee under the presence of the WLAN nodes. The interference estimators were implemented using the off-the-shelf radio-based motes to detect the interference from the Wi-Fi nodes for improving ZigBee nodes performance. In this case it was observed as the packet loss rate had been reduced to a great extent because the estimators had switched the frequency of the node as soon as the interference was detected [146]. The impact of high interference level was measured and reduced in [147], the measurements and implementation were carried in a two-storied building and have tested the performance of WSN under the presence of WLAN. The testbed proposed in [148] EasiTest is supporting multiple technologies for understanding the effects of interference at the packet level.

Generating a certain interference pattern using the existing infrastructure is the most popular approach. The setup time for generating required interference time is very less. But only disadvantage of this type of approach is, it cannot avoid the sudden disturbances from other devices appearing instantly.

2. Applications of WSN under the Influence of Wi-Fi

The advances in technologies like automation, monitoring and controlling are trusting WSN particularly for remote and automatic operations. WSN is considered by many advanced applications like Smart Grid, Smart cities, IoT, Green Building Automation, Wireless Body Area Networks, and Industrial Automation. Figure 4 is a pictorial representation of WSN applications. The following applications employ WSN for some automation applications. All the nodes of WSN are under the vicinity of coexisting technologies. Hence interference avoidance is an important parameter to be considered for efficient operation of the WSN. Some of the important works proposed based on the type of application is presented below.

A. Smart Grid Applications

Smart Grid has introduced modern information and communication technologies (ICT) for existing electrical power systems. The extension of ICT towards the consumer side (domestic applications) is generally done through WSN [174]. Etimad Fadel et al. [175] have presented a detailed survey on the role of WSN for various smart grid applications. Irfans Anbagi et al. [176] have proposed two WSN algorithms, DRX and FDRX algorithms for monitoring Smart Grid applications using WSN. Primarily the research proposed is on improving the QoS parameters of ZigBee communication and have not considered the interference issues, but for future research scope the authors have expressed concern of testing their proposed algorithm under the presence of Wi-Fi nodes. The algorithm PSOLACES was proposed in [150], the authors have analyzed the interference in indoor environment. A solution for avoiding interference using PSOLACES was proposed by improving ZigBee performance working under the influence of Wi-Fi and the work presented was specifically for consumer premises in smart grid applications. The CMCMAC [26] and FEC-CMCMAC [9] were proposed with an aim for improving the ZigBee network performance in terms of latency requirements even under the influence of the Wi-Fi aimed for smart grid applications. The proposed mechanism in [37] aimed at improving ZigBee performance by controlling WLAN transmission in the smart home was developed for smart metering applications.

B. Wireless Body Area Networks

Advanced health monitoring is increasing in the developing countries. The utilization of WBAN based information is becoming a medical need for understanding and estimating the patient health issues and is also very useful for providing promising solutions [177]. Mengjiao Tang et al. [178] have proposed a system for WBAN based coexisting medium. The proposed model will utilize the Hidden Markov model for analyzing the ZigBee and Wi-Fi conflicts on channel issues. Based on the data obtained the system suppresses Wi-Fi interference (ZigBee-Wi-Fi) and cross interference (ZigBee–
Wi-Fi based. Thus SIM-BBN addresses both the internal and external interferences. Y. Kim et al. [180] have proposed a detailed mathematical model for analyzing the interference in coexisting environment of ZigBee-WBAN and Wi-Fi. They proposed an adaptive control algorithm for enhancing the performance of the ZigBee-WBAN by guaranteeing the data transmission from source to destination within the maximum tolerable delay even under the influence of Wi-Fi.

C. Internet of Things

IoT uses different technologies like ZigBee, Wireless HART that work based on IEEE 802.15.4 standard. The work proposed in [193] employs WSN based IoT for industrial automation and recommends to reduce the interference issue for the efficient operation of WSN in the coexisting environment. The author has proposed the adaptive frequency hopping mechanism and proactive routing mechanism for avoiding the shadowing effects caused because of other coexisting wireless technologies. B. A. Nahaset al. [194] has proposed MiCMAC algorithm for 6LoWPAN based IoT network based on efficient channel hopping and reduces the effects of interference from the Wi-Fi. The authors in [195] have proposed interference avoidance mechanism for the IoT based body to body area networks. The authors have analyzed cross technology interference and proposed an optimization model for mitigating the interference in the IoT network.

3. Discussion

With the increased use of monitoring and automation technologies, there is a need for improving the QoS parameters in terms of interoperability standards worldwide. Based on the above literature review, for almost a decade now there has been a significant experimentation and research carried out for interference issues. But still, the topic is unclear and unripe when finding reasons of interference and therefore it requires further research for making WSN applications robust. There are only a few studies performed to analyze the performance of a protocol under the interference conditions considering different patterns. The heavy traffic and propagation in 2.4GHz ISM band should be studied extensively, and the communication protocols and their behavior under different interoperable conditions must also be considered. There is some relevant research performed and presented on identifying interference conditions and avoiding it, but still, the comprehensive study on different interference patterns has not been presented yet. The following points are observed based on the literature above,

- The experimentation using the simulators is considered as complex by many researchers because still precise variables of different interference patterns are unavailable. Hence majority experiments are carried in real-time and are limited to prove the effects of interference. Very few works have been proposed to avoid interference.
- Most of the experiments in real-time are set up using a small number of nodes coexisting with one or two interfering nodes. The above set can only disturb some packets of data during wireless transmission. But the experimentation may not hold good enough, for cases like strong interference or noise, which may destroy the network communication within the small area or cluster.

- Most of the times WSN interference experimentation is carried under the consideration of Wi-Fi. Some works are considered under the interference of Bluetooth or Microwave oven. Specifically, interference study is considered between ZigBee and Wi-Fi often other technologies are neglected.

- It was observed from the above literature that most of the experiments either in simulation or in the real-time, data transfer is continuous which is not true in the real world. Multichannel WSN scenarios often show some congested channels and making them restricted, affecting the operation of WSN. There is a requirement to withstand the intermittent or bursty interference among various channels.

The proposed works in [38] and [39], have significantly improved the throughput of ZigBee nodes in spite of external interference issues between WSN and Wi-Fi networks. The authors in [41] have presented the effects of temporal variations occurring in WSN because of Wi-Fi. The authors of [42] have proposed a better optimization model addressing the cross-technology interference issue, which occur between the wireless technologies operating in the coexistence to each other working in the same frequency band. This methodology also has addressed internal and external interference efficiently. The authors in [150] have proposed a better channel selection methodology by considering external interference conditions and significantly reduced the frame error rate in WSN.

The following measurement methods for assessing the interference are highly recommended. The work proposed in [44] is based on assessment of degree of density and intensity. The effects of Wi-Fi on the WSN link quality can be understood based on the above assessment and this increased throughput for almost 3 times to the initial condition before assessment. The work proposed [67] has efficiently decreased errors in the LQI. The ELQET [68] has significantly improved the quality of WSN transmission and reduced the data loss to a great extent. The model proposed in [70] has reduced the end-to-end delay even under external interference conditions.

7. Open Research Issues

The efficient data communication in WSN is very important. Hence in this section some open research issues are discussed to strengthen the future research on WSN in relation to interference avoidance,

1. Reliability of data communication: For obtaining the high reliability in WSN it is very important to consider factors like interference, proper placement and distance between nodes, effects of mobile nodes, building material and weather conditions [183]. Reliability is a factor of the bandwidth and latency. The Reliability for WSN is obtained by calculating the packet error ratio. It is very difficult to assess the reliability parameter in WSN because the transmitter node and receiver node are unaware of each other in the network. Also nodes are not sure whether data is received successfully or not. Hence for determining reliability there are also other parameters like RSSI and LQI can be considered. Based on the value obtained one can determine the quality of the link. RSSI can be estimated on the receiver side with values ‘mW or dB’ this define the link quality. LQI is determined on the scale of ‘0 to 108’ based on which one can estimate the effects caused because of the
interference and multipath errors [184]. Still identification of various disturbances causing the interference can be carried systematically in future.

2. **Cross-layer dynamics:** The WSN most often experience problems like multi-path fading, path loss and shadowing problems. To overcome problems above the cross-layer designing between PHY and MAC layers is recommended to obtain the better results [192][124], [22]. The assessment of MAC performance analysis based on the interaction with the wireless channel will optimize the performance of the protocol and assure for the correctness of the design [185]. The effects of hidden terminals and multi-path fading (depends on network traffic and the distance between the nodes) decreases reliability of WSN and for optimizing this cases Cross-layer designing between PHY and MAC layer is highly recommended [186].

3. **MAC layer:** WSN is based on IEEE 802.15.4 that defines the PHY and MAC layer specifications. In spite of considerable research done, still IEEE 802.15.4 based MAC suffers several issues. In general, most of the IEEE 802.15.4 based technologies are operating under the influence of other technologies. Hence MAC parameters should be defined based on the interference conditions [187]. Another improvement in case of MAC can be achieved by adjusting the clear channel assessment (CCA) parameter. The increasing the CCA of a particular node will increase the priority of that particular node in the network and this is most important for WSN based actuator networks. The CCA is based on the network size and the traffic intensity, also improves the QoS parameters [188][189].

4. **Channel Selection:** After the establishment of the WSN, the ZigBee coordinator selects the best channel after energy detection-based scanning for network operation. For this, energy scanning is performed every time when a node is ready to transmit the data. The ZigBee node performs energy scanning for all the available 16 channels and finds the strongest channel for data transmission. There is also a need for performing additional research in this area for efficient channel selection among available [190] [191].

8 Conclusion

In the modern times the use of wireless devices is increasing every day and its market is expected to continue to grow as popular new wireless devices will only continue to increase and diversify, especially with the advent of IoT applications worldwide. As the numbers of wireless nodes deployed are increasing, particularly in the unlicensed band, there is a strong need for increasing the robustness of data-communications. Since the last decade there was a profound research going on for improving the QoS parameters of WSN but still, there is a lot to be done in terms of future work for making WSN reliable by considering the effects of interference. The research community has addressed only few works in relation to the interference avoidance. Most of the research communities have recommended the development of protocols based on following types of parameters like radio diversity, channel taxonomy, multichannel protocol, and data redundancy (Forward error correction and backward error correction). The improvements that were proposed is based on the above parameters, and to some extent improved the robustness of wireless protocols working in 2.4GHz ISM band.

In order to increase the reliability of WSN still further in the coexistence mediums, many new standards are emerging. Based on the recent research activities Ultra-wideband (UWB) based WSN were standardized. UWB devices are available at low cost, low complexities, and possess high immunity to interference. Based on the pace of increased use of WSN, new frequency bands should be allowed in order to avoid the interference problems currently appearing. For example, nodes working based on IEEE 802.11b/g in 2.4GHz are moving to IEEE 802.11ac going to work in 5GHz. However, increased dependence on WSN for monitoring and control will introduce many devices working in the same frequencies. Hence there is a need for research in increasing the reliability and robustness of such a system for harmonious coexistence. Based on the studies carried so far on the WSN research, there is a need for improving the self-learning capacity of wireless nodes. The wireless nodes must detect the channel conditions and should dynamically adjust by themselves for various channel parameters at runtime so as to increase the communication efficiency and increase the node lifetime. In the recent times, researchers have begun focusing on the prime objective of this paper, that is interference avoidance mechanisms and it is expected that WSN may also become self-learning in the near future.

References

[1] S. Misra, S. K. Roy, A. Roy, M. S. Obaidat and A. Jha, “MEGAN: Multipurpose Energy-Efficient, Adaptable, and Low-Cost Wireless Sensor Node for the Internet of Things,” in IEEE Systems Journal, pp. 144-151, (2020).

[2] Khan I, Belquisi F, Githo R, Crespi N, Morrow M, Polakos P. Wireless sensor network virtualization: A survey. IEEE Commun Surv Tutorials. 553–76, (2016).

[3] Kobo HI, Abu-Mahfouz AM, Hancke GP. A Survey on Software-Defined Wireless Sensor Networks: Challenges and Design Requirements. IEEE Access 1872–99, (2017).

[4] S. Chakraborty, N. K. Goyal and S. Soh, "On Area Coverage Reliability of Mobile Wireless Sensor Networks With Multistate Nodes," in IEEE Sensors Journal, 4992-5003, (2020).

[5] Borges LM, Velez FJ, Lebres AS. Survey on the characterization and classification of wireless sensor network applications. IEEE Commun Surv Tutorials. 1860–90, (2014).

[6] Zhang D, Chen Z, Ren J, Zhang N, Awad MK, Zhou H, et al. Energy-harvesting-aided spectrum sensing and data transmission in heterogeneous cognitive radio sensor network. IEEE Trans Veh Technology. 831–43, (2017).

[7] Rawat P, Singh KD, Bonnin JM. Cognitive radio for M2M and Internet of Things: A survey. Comput Commun 1–29, (2016).

[8] Vikram K, Sahoo SK, Narayana KVL. Forward Error Correction based Encoding Technique for Cross-layer Multi Channel MAC protocol. Energy Procedia. 847–54, (2017).

[9] Ferro E, Potortì F. Bluetooth and Wi-Fi wireless protocols: A survey and a comparison. IEEE Wireless Communications 12–26, (2005).
Conf of Wiinterference on Zigbee medical sensors
2011 Int Conf Wirel Commun Signal Process WCSP 2011
Elektrotechniczny, Time Appl Distrib Sens Networks
Analysis under IEEE 802.11 Interference. Int Symp Innov Real
protocol for wireless sensor networks in 2.4
IEEE Std 802.15.1
(MAC) and Physical Layer (PHY) S
Requirements Part 11: Wireless LAN Medium Access
Communications. 1–12, (2014).

Pan MS, Liu PL. Low latency scheduling for convergecast in
ZigBee tree-based wireless sensor networks. Journal Network
Computer Applications. 252–63, (2014).

Koubia A, Cunha A, Alves M, Tovar E. TDDBS: A time division
based scheduling mechanism in ZigBee cluster-tree wireless
sensor networks. Real-Time Systems. 321–54, (2008).

Riggio R, Miorandi D, De Pellegrini F, Granelli F, Chlamtac I. A
traffic aggregation and differentiation scheme for enhanced QoS in
IEEE 802.11-based Wireless Mesh Networks. Computer Communications. 1290–300, (2008).

Riggio R, Miorandi D, De Pellegrini F, Granelli F, Chlamtac I. A
traffic aggregation and differentiation scheme for enhanced QoS in
IEEE 802.11-based Wireless Mesh Networks. Comput Commun 1290–300, (2008).

Asif M, Khan S, Ahmad R, Sohail M, Singh D. Quality of service of
routing protocols in wireless sensor networks: A review. IEEE
Access, 1846–71, (2017).

Al-Roubaiey A, Sheltami A, Mahmoud A, Salah K. Reliable
Middleware for Wireless Sensor-Actuator Networks. IEEE
Access, 1–10, (2019).

IEEE Std 802.15.4-2003, IEEE Recommended Practice for Information Technology Part 15.2: Coexistence of Wireless
Personal Area Networks with Other Wireless Devices Operating in the Unlicensed Frequency Bands, Std., (2003).

Yan Y, Yang P, Li XY, Zhang Y, Lu J, You L, et al. WizBee: Wise
ZigBee Coexistence via Interference Cancellation with Single
Antenna. IEEE Trans Mob Comput. 2590–603, (2015).

IEEE 802.14.4 – 2011, IEEE Standard for Local and metropolitan
area networks— Part 15.4: Low-Rate Wireless Personal Area
Networks (LR-WPANs), (2011).

IEEE Std 802.11-2016, IEEE Standard for Information
Technology—Telecommunications and information exchange
between systems Local and metropolitan area networks Specific
Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, (2016).

IEEE Std 802.15.1-2002, IEEE Standard for Information
Technology—Telecommunications and information exchange between systems Local and metropolitan area networks Specific
Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless
Personal Area Networks (WPANs). (2002).

Vikram K, Narayana KVL. Cross-layer multi channel MAC
protocol for wireless sensor networks in 2.4-GHz ISM band. Int
Conf Comput Anal Secur Trends, CAST 2016 312–7, (2017).

Said O. Performance evaluation of WSN management system for
QoS guarantee. Eurasip J Wirel Commun Netw (2015).

Cihan Ta N, Sastry C, Song Z. IEEE 802.15.4 Throughput
Analysis under IEEE 802.11 Interference. Int Symp Innov Real
Time Appl Distrib Sens Networks (2014).

KRUPANEK B. Cooperation of wireless networks IEEE 802.15.4
and IEEE 802.11b/g – introduction and measurements. Przegląd
Elektrotechniczny, 134–7, (2016).

Mao Y, Zhao Z, Jia X. Understanding the indoor interference between IEEE 802.15.4 and IEEE 802.11b/g via measurements.
2011 Int Conf Wirel Comm Signal Process WCSP 2011, (2011).

Gláropoulos I, Lagana M, Fodor V, Petrioli C. Energy efficient
COGNitive-MAC for sensor networks under WLAN co-existence.
IEEE Trans Wirel Commun 4075–89, (2015).

Youn J, Chang B, Cho D-K, Gerla M. Minimizing 802.11 interference on Zigbee medical sensors. Int. conf. on Bodynets,
(2012).

Abrigandi MD, Buratti C, Frost L, Verdene R. Testing the impact of
Wi-Fi interference on Zigbee networks. 2014 Euro Med Telco
Conf - From Netw Infrastructures to Netw Fabr Revolut Edges,
EMTC 2014, (2014).

Srinivasan K, Dutta P, Tavakoli A, Levis P. An empirical study of
low-power wireless. ACM Trans Sens Networks.1–49, (2010).

Vatsal A. Impact of Frequency Offset on Interference between
Zigbee and WiFi for Smart Grid Applications. IJSR J Electron
Commun Eng, 59–64, (2013).

Croce D, Garlisi D, Giuliano F, Timmrinolo I. Learning from errors:
Detecting ZigBee interference in WiFi networks. 2014 13th Annu
Meditt Adv Hoc Netw Work MED-HOC-NET 2014. 158–63,
(2014).

Hong K, Lee S, Lee K. Performance improvement in Zigbee-
based home networks with coexisting WLANs. Pervasive Mobi
Comput 156–65, (2015).

Chong JW, Cho CH, Hwang HY, Sung DK. An Adaptive WLAN
Interference Mitigation Scheme for Zigbee Sensor Networks. Int
J Distrib Sens Networks 2015, (2015).

Y. Padmanaban and M. Muthukumarasamy, “Scalable Grid-Based
Data Gathering Algorithm for Environmental Monitoring Wireless
Sensor Networks,” in IEEE Access, 79357-79367, (2020).

Liang C-JM, Priyadharshini, Liu S, Toh A. Surviving wi-fi
interference in low power Zigbee networks, (2010).

Yi P, Iwayemi A, Zhou C. Developing Zigbee deployment
guideline under WiFi interference for smart grid applications.
IEEE Trans Smart Grid. 98–101, (2011).

Elia J, Paris S, Krunz M. Cross-technology interference
mitigation in body area networks: An optimization approach. IEEE
Trans Veh Technol 4144–57, (2015).

Xu R, Shi G, Luo J, Zhao Z, Shu Y. Mu2i: Multi-channel ZigBee
networks for avoiding WiFi interference. Proc - 2011 IEEE Int
Conf Internet Things Cyber, Phys Soc Comput ITThings/CPSCon
2011, 323–9, (2011).

Yan Y, Yang P, Li XY, Zhang Y, Lu J, You L, et al. WizBee: Wise
ZigBee Coexistence via Interference Cancellation with Single
Antenna. IEEE Trans Mob Computing, 2590–603, (2015).

Boano CA, Voigt T, Noda C, Romer K, Zuniga M. JamLab:
Augmenting sensornet testbeds with realistic and controlled
interference generation. Acm/IEEE Jpn 175–86, (2011).

Shin SY, Kang JS, Park HS. Packet error rate analysis of ZigBee
under interferences of multiple bluetooth piconets. IEEE Veh
Technol Conf. 2825–30, (2009).

Garroppe RG, Gazzarrini L, Giordano S, Tavanti L. Experimental
assessment of the coexistence of Wi-Fi, Zigbee, and bluetooth
devices. 2011 IEEE Int Symp a World Wireless, Mob Multimed
Networks, WoWMoM Proc 2011, (2011).

Mathew K, Tabassum M. Analysis of bluetooth and zigbee signal
penetration and interference in foliage. Proc Int MultiConference
Eng Comput Sci. 547–52, (2016).

Suhonen J, Haataja K, Päivinen N, Toivanen P. The effect of
interference in the operation of Zigbee and Bluetooth robot cars.
4th IEEE/IFIP Int Conf Cent Asia Internet, ICI 2008, (2008).

Vikram K., Sahoo S.K. Interference Aware Adaptive Transmission
Policies. IEEE/ACM Trans on Zigbee Wireless Networks. In:
Bhattacharyya P, Sastry K., Marriboyina V., Sharma R. (eds) Smart and Innovative Trends in Next Generation Computing Technologies. NGCT 2017. Communications in
Computer and Information Science, Springer, (2018).

Silkora A, Groza VF. Coexistence of IEEE802.15.4 with other
Systems in the 2.4 GHz-ISM-Band.1786–91, (2006).

Azní N, Kamarudin LM, Mahmudin M, Zakaria A, Shakaff
AYM, Khatun S, et al. Interference issues and mitigation method
in WSN 2.4GHz ISM band: A survey. 2014 2nd Int Conf Electron
Des ICED 2014, 403–4, (2016).

Son D, Krishnamachari B, Heidemann J. Experimental study of
concurrent transmission in wireless sensor networks, 237, (2007).

Zhang J, Reinhardt A, Hu W, Kanhere S.S. RFT: Identifying
Suitable Neighbors for Concurrent Transmissions in Point-to-
Point Communication System. IEEE J. Sel. Areas Commun 15 Proc 18TH ACM Int Conf
Model Anal Simul Wirel Mob Syst. 73–82, (2015).

Mottola L, Ceriotti M, Gunà S, Picco G Pietro, Murphy AL. Not
all wireless sensor networks are created equal. ACM Trans Sens
Networks, 1–33, (2010).

Yuan D, Hollick M. Let’s talk together: Understanding concurrent
transmission in wireless sensor networks. Proc - Conf Local
Comput Networks, LCN 219–27, (2013).

Bello L Lo, Toscano E. Coexistence issues of multiple Co-Located
IEEE 802.15.4/ZigBee Networks running on adjacent radio
channels in industrial environments. IEEE Trans Ind Informatics. 157–67, (2009).
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*Journal of Engineering Science and Technology Review* 13 (3) (2020) 59 - 81

[57] Kakarla J, Majhi B, Battula RB. IAMMAC: An interference-aware multichannel MAC protocol for wireless sensor-actor networks. Int J Commun Syst.801–22, (2016).

[58] Wu Y, Stankovic JA, He T, Lin S. Realistic and efficient multi-channel communications in wireless sensor networks. Proc - IEEE INFOCOM 2008.1867–75, (2008).

[59] Wu Y, Liu KS, He T, Lin S, Stankovic JA. Efficient Multichannel Communications in Wireless Sensor Networks. ACM Trans Sens Networks. 1–23, (2016).

[60] Xing G, Sha M, Huang J, Zhou G, Wang X, Liu S. Multi-channel interference measurement and modeling in low-power wireless networks. Proc - Real-Time Syst Symp. 248–57, (2009).

[61] Ahmed N, Kanhere S, Isha S. Posture Abstract: Multi-Channel Interference in Wireless Sensor Networks. 367–8, (2009).

[62] Chang X, Huang J, Liu S, Xing G, Zhang H, Wang J, et al. Accuracy-aware interference modeling and measurement in wireless sensor networks. IEEE Trans Mob Comput. 278–91, (2016).

[63] Gungor VC, Lu B, Hancke GP. Opportunities and challenges of wireless sensor networks in smart grid. IEEE Trans Ind Electron. 3557–64, (2010).

[64] Petrova M, Riihijarvi J, Mahonen P, Labella S. Performance study of IEEE 802.15.4 using measurements and simulations. 487–92, (2006).

[65] Xia B, Qi N, Liu L, Wu N. A low-power 2.4GHz ZigBee transceiver with inductor-less RF front-end for IoT applications. Midwest Symp Circuits Syst 2017; 1332–5, (2017).

[66] Yang T, Yang Q, Cheng L. Experimental study: a LQI-based ranging technique in ZigBee sensor networks. Int J Sens Networks. (2015).

[67] Jayasri T, Hemalatha M. Link Quality Estimation for Adaptive Data Streaming in WSN. Wireless Personal Commun 1543–62, (2017).

[68] Sha M, Hackmann G, Lu C. ARCH: Practical channel hopping for reliable home area sensor networks. Rea – Time Syst Symp, (2011).

[69] Liu H, Su J, Chou C. On Energy Efficient MAC Protocol for Wireless Sensor Networks. Energy. 67–71, (2011).

[70] Dooavenkatappa M, Chan MC, Leong B. Improving link quality interference through RSSI-based error recovery. Lect Notes Comput Sci (Including Subser Lect Notes Artif Intell Lect Notes Bioinformatics). 224–39, (2010).

[71] Chen Y, Terzis A. On the mechanisms and effects of calibrating RSSI measurements for 802.15.4 radios. Lect Notes Comput Science. LNCS.256–71,(2010).

[72] Doddavenkatappa M, Chan MC, Leong B. Improving link quality by exploiting channel diversity in wireless sensor networks. Proc - Real-Time Syst Symp.159–69,(2011).

[73] Iyer V, Woehrle M, Langendon K. Chryssos - A multi-channel approach to mitigate external interference. 2011 8th Ann IEEE Commom Soc Conf Sensor, Mes Ad Hoch Commom Networks, SECON 2011. 449–57, (2011).

[74] Tang L, Sun Y. EM-MAC: A Dynamic Multichannel Energy-Efficient MAC Protocol for Wireless Sensor Networks. Energy. 357–62, (2011).

[75] Diaz S, Mendez D, Kraemer R. ICI - Interference characterization and identification for WSN. Wirel Telecommun Symp. (2017).

[76] El-Darymli K, Ahmed MH. Wireless Sensor Network Testbeds. Wirel Sens Networks Energy Effic.148–205, (2012).

[77] Zacharias S, Newe T, Kouchkini H. Identifying Sources of Interference in RSSI Traces of a Single IEEE 802.15.4 Channel. Proc 8th Int Conf Wirel Mob Commun (ICWCMC 2012). 408–14, (2012).

[78] Hermans F, Rensfelt O, Voigt T, Ngai E, Nordén L–A, Gunnberg P. SoNIC: Classifying Interference Categories and Subject Descriptors. 2013 ACM/IEEE Int Conf Inf Process Sens Networks.55–66, (2013).

[79] Boes N, Nikolaidis I, Gburzynski P. Patterns in the RSSI traces from an indoor urban environment. 2010 15th IEEE Int Work Compaid Model Anal Des Commun Links Networks, CAMAD 2010. 61–5, (2010).

[80] Warrich EU, Aiello M, Tei K. A machine learning approach for identifying and classifying faults in wireless sensor networks. Proc - 15th IEEE Int Conf Comput Sci Eng CSE 2012 10th IEEE/IFIP Int Conf Embed Ubiquitous Comput EUC 2012. 618–25, (2012).

[81] Garcia-Armada A, Rodriguez BB, Jiménez VPG, Sánchez-Fernández M. Modelling, performance analysis and design of WPAN systems. Wirel Pers Commun. 367–86, (2007).

[82] Yuan W, Wang X, Limurtza JPMG, Niemegeers IJGMM. Coexistence performance of IEEE 802.15.4 wireless sensor networks under IEEE 802.11bg interference. Wirel Pers Commun. 281–302, (2013).

[83] Sergioi C, Antonio P, Vassiliou V. A comprehensive survey of congestion control protocols in wireless sensor networks. IEEE Commun Surv Tutorials 1839–59, (2014).

[84] Boano CA, Voigt T, Prabh S, Alves M, Noda C. Quantifying the channel quality for interference-aware wireless sensor networks. ACM SIGBED Rev. 43–8, (2012).

[85] Rayanchu S, Paci A, Banerjee S. Catching whales and minnows using WiFiNet: deconstructing non-WiFi interference using WiFi hardware. Proc 9th USENIX Conf Networked Syst Des. (2012).

[86] Mahmood MA, Seath WKG, Welch I. Reliability in wireless sensor networks: A survey and challenges ahead. Comput Networks. 166–87, (2015).

[87] Etildem Fadel, V.C. Gongur, Laila Nassef, Nadine Akkari, M.G. Abbas Maik, Suleiman Almasri, and Ian F. Akyildiz. 2015. A survey on wireless sensor networks for smart grid. Comput. Commun. 22-33, (2015).

[88] Garg K, Förster A, Paccinelli D, Giordano S. Towards realistic and credible wireless sensor network evaluation. Lect Notes Comput Sci Soc Telecommun Eng LNCSST. 49–64, (2012).

[89] Zonn IS, Kostianoy AG, Semenov A V. Salma. West Arctic Seas Encycl. (2017).

[90] Pease SG, Conway WP, West A.A. Hybrid ToF and RSSI real-time semantic tracking with an adaptive internet of things architecture. J Newt Comput Applications. 98–109, (2017).

[91] Boano CA, Tsiftes N, Voigt T, Brown J, Roedig U. The impact of temperature on outdoor industrial sensornet applications. IEEE Trans Ind Informatics. 451–9, (2010).

[92] Woehrle M. Testing of wireless sensor networks. (Ph.D. thesis, EidgenössischeTechnische Hochschule, Zürich, Switzerland), (2010).

[93] Bogliolo A, Lorello LS, Freschi V, Dromedari M, Peruzzini R, Lattanzi E. A fast and accurate energy source emulator for wireless sensor networks. EURASIP J Embed Syst 2016, (2016).

[94] Wittenburg G, Schiller J. A Quantitative Evaluation of the Simulation Accuracy of Wireless Sensor Networks. Proc 6th Fachgespräch(a)ch ”Drahthlose Sensornetze” Der GiItg-Fachgr Kommunikation Und Verteilte Syst 23–6, (2007).

[95] Adnan AI, Hanapi ZM, Othman M, Zulkarnain ZA, Sadiq A. A Reputation-based Routing Protocol for Wireless Sensor Networks 3–6, (2015).

[96] Kafi MA, Othman J Ben, Badache N. A Survey on Reliability Protocols in Wireless Sensor Networks. ACM Comput Surv. 1–47, (2017).

[97] Jamali MV, Member S, Salehi JA, Akhoudi F. Optical Communication Systems With Spatial Diversity : MIMO Scheme. 1176–92, (2017).

[98] S. Collolone, G. Zaharia, and G. El Zein, SCS 2003. Int. Sym. Signals, Circuits Syst. Proc. (Cat. No.03EXT20) 2, 417, (2003).

[99] Aboodi A, Wan TC. Evaluation of WiFi-based indoor (WBI) positioning algorithm. Proc - 2012 3rd FTRA Int Conf Mobile, Ubiquitous, Intell Comput Music 2012, 260–4, (2012).

[100] Batalla JM, Vasilakos A, Gajewski M. Secure Smart Homes. ACM Comput Surv. 1–32, (2017).

[101] Rensfelt O, Hermans F, Gunnberg P, Larzon LÅ, Björnemo E. Repeatable experiments with mobile nodes in a relocatable WSN testbed. Comp J. 1973–86, (2011).

[102] Corpa AE, Kamthe A, Miguel A. M. & M.: Multi-level Markov Model for Wireless Link Simulations n.d.:57–70, (2009).

[103] Lee H, Corpa A, Levin P. Improving Wireless Simulation Through Noise Modeling, 21–30, (2017).

[104] Liu H, Su J, Chou C. On Energy-Efficient Straight-Line Routing Protocol for Wireless Sensor Networks, IEEE Systems. 2374–82, (2017).

[105] Milosavljević N. On complexity of wireless gathering problems on unit-disk graphs. Lect Notes Comput Sci (Including Subser Lect Notes Artif Intell Lect Notes Bioinformatics) LNCS.308–21, (2011).

[106] Garg K, Förster A, Paccinelli D, Giordano S. Towards realistic and credible wireless sensor network evaluation. Lect Notes Int Comput Sci Soc Telecommun Eng LNCSST. 49–64, (2012).

78
networks. In EWSN, 133 reliable, ultra dependable monitoring in wire EasiTest: a multi perspective. Int J Distrib Sens Networks Procedia Technol Sensor Monitoring Services with Integrated WSN Testbed. Syst Softw simulation vs. real time deployment in wireless sensor networks. J avoidance in dense wireless sensor networks. Lect Notes Comput Conf Inf Autom IC 2017 experimental investigation of the packet loss rate of wireless (WSN). ECCE 2017 receiver initiated MAC protocol for wireless sensor network WBANs. IEEE J Biomed Heal Informatics dynamic coexistence of IEEE 802.15.4 2014 Int Conf Comput Sustain Glob Dev INDIACom 2014 simulation of AODV MANET routing protocol in NS2 & NS3. Commun Netw Conf WCNC 2011 Avoiding interference and enabling coexistence. 2011 IEEE Wirel communications in industrial wireless sensor applications: Avoiding interference and enabling coexistence. 2011 IEEE Wirel Comunet Conf WCNC 2011. 345–50, (2011). Rajaj Kumar Parimahani, Prinimisha P. Kambeshwaranchari B, Gnawali O. Routing without routes: the backpressure collection protocol. Proc ACM/IEEE Int Conf Inf Process Sens Networks, 2011 2nd Int Conf Wirel Commun Veh Technol Inf Technol Wirel VITAE 2011. Lin T-H, Lau S-Y, Ng I-H, Huang T-Y, Huang P. A measurement study of zigbee-based indoor localization systems under RF interference. 2015 Proc 14th Int Conf Inf Process Sens Networks. 716–9, (2015). Chi T, Yan H. A Dynamic Channel Assignment for Coexistence of ZigBee/WiFi 2017,142:1–4. doi:10.2991/titm-17. (2017). Gonga A, Landsiedel O, Soldati P, Johansson M. Multi-channel communication vs. adaptive routing for reliable communication in WSNs. (2012). Hithnawi A, Shafagh H, Duquennoy S. TIHM: Technology-Independent Interference Mitigation for Low-power Wireless Networks. IPSN ’15 Proc 14th Int Conf Inf Process Sens Networks.1–12, (2015). Rohde J, Tofftegaard TS. Mitigating the impact of high interference levels on energy consumption in wireless sensor networks. 2011 2nd Int Conf Wirel Commun Veh Technol Inf Theory Aerosp Electron Syst 2011. Zhao Z, Liu Q, Li VOK, Yang G-H, Cui L. Implementation and application of a multi-radio wireless sensor networks testbed. IET Wireless Sens Syst. 1–9, (2011). The Network Simulator-ns2-Available from: http://www.isi.edu/nsnam/ns [Accessed on: 11-June-2020]. Vikram K, Sahoo SK. A collaborative framework for avoiding interference between Zigbee and WiFi for effective smart metering applications. Electronics. 48-56, (2018). Ding Y, Hong SH, Lu R, Kim J, Lee YH, Xu A, et al. Experimental investigation of the packet loss rate of wireless industrial networks in real industrial environments. 2015 IEEE Int Conf Inf Autom ICA 2015. 1048–53, (2015). Khalil I, Hoossain A, Ahmed I. DURI-MAC: A dual channel receiver initiated MAC protocol for wireless sensor network (WSN). ECCE 2017 - Int Conf Electr Comput Commun Eng. 577–82, (2017). Vikram K, Sahoo SK, A collaborative framework for avoiding interference between Zigbee and WiFi for effective smart metering applications. Electronics. 48-56, (2018). Boers NM, Nikolaidis I, Ibzyrnis P. Impulsive interference avoidance in dense wireless sensor networks. Lect Notes Comput Sci (Including Subseries Lect Notes Artificial Intell Lect Notes Bioinformatics) LCNS:167–80, (2012). Vikram K, Venkata Lakshmi Narayana K. Cross-layer multi channel MAC protocol for interference mitigation. 2016 IEEE India Conf INDICON 2016, (2017). Shakshuki EM, Malik H, Sheltami TR. A comparative study on simulation vs. real time deployment in wireless sensor networks. J Syst Softw.45–55, (2011). Bisoi S, Bhunia SS, Roy S, Mukherjee N. sENSE: Intelligent Sensor Monitoring Services with Integrated WSN Testbed. Procedia Technol. 564-71, (2014). Kim H, Hong WK, Yoo J, Yoo SE. Experimental research testbeds for large-scale WSNs: A survey from the architectural perspective. J Int Distrb Sens Networks. (2015). Qiang Liu, Li Cui, Li VOK, Guang-Hua Yang, Ze Zhao. EasiTest: radio testbed for heterogeneous wireless sensor networks. 104–8, (2011). Sanchez A, Moerman I, Bouaouc S, Willkomm D, Hauer J, Khalil I, Hossain Deylami MN, Jovanov E. A distributed scheme to manage the interference levels on energy consumption in wireless sensor networks. IEEE Trans Netw Serv Manag 2014; 56, (2018). nd WiFi for effective smart metering NG, –509 –62 Journal of Engineering Science and Technology Review 13 (2017). M. Making ‘glossy’ networks accessible in dense wireless sensor networks. IET Meas Heterog Wirel Wired Networks 5(3), (2017). 45 104 9, (2017) 54 8 –79 M. Making ‘glossy’ networks accessible in dense wireless sensor networks. IET Meas Heterog Wirel Wired Networks 5(3), (2017). 45 104 9, (2017) 54 8 –79 M. Making ‘glossy’ networks accessible in dense wireless sensor networks. IET Meas Heterog Wirel Wired Networks 5(3), (2017). 45 104 9, (2017) 54 8 –79
Abbreviations

AP: Access Point
APS: Application Sub-layer
BPSK: Binary Phase Shift Keying
BER: Bit Error Rate
CCA: Clear Channel Assessment
CA: collision avoidance
CSMA: Carrier-Sense Multiple Access
CTS: Clear to Send
CRC: Cyclic Redundancy Check
dBm: decibels relative to one milliwatt
DSSS: Direct-Sequence Spread Spectrum
ED: Energy Detection
FEC: Forward Error Correction
FER: Frame Error Rate
FHSS: Frequency-Hopping Spread Spectrum
HGW: Home Gate Way

ICT: Information and Communication Technologies
IEEE: Institute of Electrical and Electronics Engineers
ISM: Industrial, Scientific, Medical
IoT: Internet of Things
IR: Infrared
LQI: Link Quality Indicator
MEMS: Micro-Electro-Mechanical Systems
MAC: Medium Access Control
NKW: Network Layer
ns: Network Simulator
OFDM: Orthogonal Frequency Division Modulation
PER: Packet Error Rate
PHY: Physical Layer
PLR: Packet Loss Rate
QoS: Quality of Service
| Abbreviation | Full Form |
|--------------|-----------|
| RF           | Radio Frequency |
| RSSI         | Received Signal Strength Indicator |
| RTS          | Request to Send |
| SINR         | Signal-to-Interference-Plus-Noise Ratio |
| TCL          | Tool Command Language |
| TDD          | Time Division Duplexing |
| TDMA         | Time Division Multiple Access |
| WLAN         | Wireless Local Area Network |
| Wi-Fi        | Wireless Fidelity |
| WSN          | Wireless Sensor Networks |
| WPAN         | Wireless Personal Area Networks |
| WBAN         | Wireless Body Area Networks |