Modélisation d'interférence pour simulateur 3D de réseaux de capteurs dédiés aux villes intelligentes
(Interference Modeling for 3D simulator sensor networks)

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1. Introduction

The simulation of networks is an essential tool for testing protocols and their prior performance deploy. Researchers often use network simulators to test and validate proposed protocols and algorithms before their real time deployment. Indeed, such an establishment may be costly and difficult, especially when talking about a large number of nodes distributed large scale. This is the reason for which the simulation of networks is essential. Moreover, rapid growth in the field of wireless communications entails the need of creating new simulators that have more specific capabilities to tackle interference and multipath propagation effects that are present in wireless environment. Finding a suitable simulation environment that allows researchers to verify new ideas and compare proposed future solutions in a virtual environment is a difficult task. A network simulator must be quite reliable, accurate and fast to be really usable. However, the accuracy is not only depends on the implementation of protocols and layers of the OSI model but also the interference model implemented [1]. In this document, we will discuss the interference models in the context of urban wireless sensor networks (WSNs) for short range.

2. Wireless Sensor Networks

The evolving field of WSNs has an extensive range of potential applications in industry, science, transportation, civil infrastructure, and security etc. WSNs comprised sensing (measuring), computation, and communication into a single tiny device called sensor node [2] [3]. WSNs typically consist in a large number of heterogeneous sensor devices that contain processing capability, sensor(s) and/or actuator, a power source (a battery and eventually some energy harvesting modules), multiple type of memory and a radio frequency (RF) based transceiver as shown in Figure 1.

![Figure 1. Single sensor node architecture](image-url)
These large number of sensors densely deployed over a large field and inter-networked together. They monitor physical or environmental conditions that generate sensor readings and deliver them to a sink node in order to be further processed [3].

Wireless communication systems provide flexibility, ease and cost saving solutions in deployment and maintenance of sensor network. WSNs utilize numerous wireless communication protocols, such as Bluetooth, ZigBee, ultra-wideband, and Wi-Fi. Two of most common wireless standards for wireless communications in WSNs are IEEE 802.11 also known as Wi-Fi and IEEE 802.15.4 also referred to as ZigBee, allow data transmission in standardized manner. In literature though, IEEE standard 802.11 and Wi-Fi is used interchangeably and we will also follow the same convention in this document. Choosing which standard is best for particular application can be decided by examining its power consumption, required data rate and data transmission range. Wireless connectivity is an essential part in sensor networking, however it comes at a cost of increased energy usage, mainly due to the high power consumption during data transmission. WSNs based on IEEE standard 802.11 or Wi-Fi have become pervasive in enterprise and industrial environments. No doubt, IEEE standard 802.11 was not intended with sensor applications in mind, but innovations in implementations have enabled the use of this standard, while sustaining all sensor requirements [4]. Wi-Fi is the term for certain types of wireless local area network (WLAN) system that builds upon the IEEE standards 802.11 (a, b, g and ac etc.). With the rapid development of Wi-Fi in recent years, infrastructure facilities have been improved. Moreover, the coverage of wireless access points (AP) have already been widely deployed and are available in cheap prices. IEEE standard 802.11 provides high data rate and ensures long range transmission, but requires high power [4].

3. Wireless Sensor Network Constraints

Some aspects of wireless channel make wireless communication more challenging as compare to wired communication like probabilistic wireless channel behavior, limited radio range, interference from other radio devices and many more [5]. These aspects change the characteristics of the transmitted signal as it travels through the wireless channel and can make difficult if not impossible to recover.
3.1. **Low transmit power / short range**

A sensor node is equipped with an energy source (battery) as shown in Figure 1. This energy resource is limited. Wireless sensor nodes remain on high energy constraint which is not protocol specific. To reduce energy consumption, assigned power for transmission always remain low compared to other wireless communication systems. Minimum transmit power defined by the physical layer (IEEE 802.15.4 – 2003) is 1 mW (0 dBm) [6].

3.2. **Multi-hop Communication**

In the radio module of a node, the wireless transmission is often done using an Omni-directional antenna. Ideal Omni-directional antennas, called "isotropic" do not exist, it is a theoretical antenna which broadcasts the same signal in every direction. In reality, the electromagnetic wave radiations are unevenly distributed in space, determined by the antenna radiation pattern. While wireless communication is a core technique in WSNs, a direct communication between a sender and a receiver is faced with limitations. In particular, communication over long distances is only possible using prohibitively high transmission power. The use of intermediate nodes as relays can reduce the total required power. Hence, for many forms of WSNs, so-called multi-hop communication will be a necessary ingredient [8].

3.3. **Interferences**

Performance of radio communication based WSNs is greatly influenced by the interference. Interference in WSNs cause packet lost, their retransmissions, link instability and inconsistent protocol behavior. The traditional way to solve this problem is to license frequency bands to primary network users who are the only ones allowed to transmit in that frequency. This method is been used in AM/FM radio, over-the-air TV broadcasts and even in cellular communications. The frequency bands are auctioned to wireless telephone carriers. This approach has removed interference problem, meanwhile it results in low utilization when the primary owner does not use the allocated frequency spectrum frequently. This disadvantage of static frequency allocations has led to the use of shared or unlicensed frequency bands that can be used by multiple networks at the same time. The 2.4 GHz band is an example of this paradigm, used by 802.11 (WiFi), 802.15.1 (Bluetooth) and 802.15.4 (Zigbee) data networks and even cordless telephones.

Next section reviews some of interference models for WSNs that can also embed into WSN simulators.
4. Interference in Wireless Sensor Networks

In a WSNs composed of many spatially scattered wireless nodes, communication is constrained by various impairments such as the wireless propagation effects, network interference, and thermal noise. The effects of signals propagation in the wireless environment include the attenuation of radiated signals with distance (also called path loss), the blocking of signals caused by large obstacles (also called shadowing), and the reception of multiple copies of the same transmitted signal (also called multipath fading). The network interference is due to accumulation of unwanted signals radiated by other transmitters from inside or outside of the network, which undesirably affect signal reception at receiver nodes in the network. The thermal noise is introduced by the receiver electronics and is usually modeled as additive white Gaussian noise (AWGN).

Due to the scarcity of radio spectrum, it is not completely possible for large wireless networks to communicate without interference. Probably other radio devices will make transmission using the same radio frequency band at the same time. Consequently, at the receiver, many undesired signals from interfering transmitters will add to the desired transmitter’s signal. This phenomena is called interference and it causes a performance degradation of communication networks [10].

Reconstruction of the input signal is possible if we have an appropriate model of the medium or channel between the transmitter and the receiver. This model is called channel model and it should be accurate enough to represent the behavior of the wireless channel. To mitigate the noise effect from the received signal, the channel model plays a key role. Let $x(t)$ be the transmitted signal. After passing through the wireless channel $h(t)$ the received signal $y(t)$ will be: (also shown in Figure 2):

$$ y(t) = h(t) * x(t) + Z(t) $$

where $*$ is the convolution operator and $Z(t) = I(t) + N(t)$ is the sum of the interference and the thermal noise.

![Figure 2. Wireless channel effect on transmitted data.](image)
The densification of radio networks make modeling of wireless network interference is an important question, with numerous applications to the analysis and design of wireless communication systems, the development of new interference mitigation techniques, and the control of electromagnetic wave emissions, among many others. Recently, wireless interference modeling has been receiving increased interest in the context of ad hoc and cellular networks but also in the case of ultra-wide band communications. The traditional approach is to model the interference by Gaussian random process [11] - [14] which can be seen as a logical consequence of the central limit theorem. It has however been shown that this assumption is not accurate in many practical situations and WSNs can be one of them.

5. Interference Models for Wireless Channels

Channel modeling helps performance analyzing of large wireless communication systems like WSN. Channel model provides information about how wireless channel parameters (e.g. carrier frequency, bandwidth (BW), delay spread and Doppler spread) affects the transmitted signal.

Low power wide area networks (LPWAN) technology specialized for interconnecting devices with low transmission power. Low power technologies are primarily designed for machine to machine networking environments. The data rates associated to LPWAN technologies are very low, as is the power consumption of connected devices. There is a battle going on for the most suitable infrastructure technology for WSNs. Among these the two most talked about contenders are Sigfox and LoRa. This section provides details of protocols suitable for LPWAN.

- **SigFox**: it supports narrowband (or ultra narrowband) technology with standard radio transmission method called binary phase-shift keying (BPSK) (going up). Which allows the receiver to only listen in a very small part of spectrum that mitigates the noise impact. It requires an inexpensive endpoint radio and a more sophisticated base station to manage the network. These transmissions use unlicensed frequency bands [15].

- **LoRa**: Stands for Long Range Radio. It is a spread spectrum technology with a wider band (usually 125 kHz or more). LoRa uses the entire channel bandwidth to broadcast a signal which makes it resistant to channel noise, long term relative frequency, doppler effects and fading [16].
According to [17] [18] wireless interference models can be viewed as the combination of the following three components.

- **Propagation model**: it describes the radio propagation impact on received signal, such as deterministic path loss, small-scale fading and large-scale fading [17].
- **Interferers (i.e., other transmitters) spatial distribution model**: it specifies how possible interferers are distributed over the given network area, ranging from a random distribution and terminal placement [17].
- **Network operation model**: it defines inter-relationship among terminals of a sensor network. This inter-relationship is mainly defined by the medium access control (MAC) technique implemented in the network, which can be classified as random access techniques (e.g., CSMA and Aloha) or deterministic access techniques (e.g., TDMA, CDMA and FDMA). The MAC technique determines when and which nodes will access the medium (radio channel) in the communication network [17].
- **Traffic model**: it defines the transmitter activity.

In [17] interference models are divided into three broad classes also shown in Figure 3:

- **Statistical models**: these models focus on the unwanted signals or interference signal at receiver modeled as a random process, and provide a statistical characterization of this process, typically stated in terms of distribution functions or some related function. A significant model in this class is based on the assumption that wireless nodes are randomly distributed according to Poisson Point Process (PPP), that, under certain additional conditions, leads to an $\alpha$-stable distribution for the aggregate interference model. Statistical model class also includes models based on the assumption that wireless nodes are arbitrarily positioned, such that randomness of interference results from propagation effects or user activity [17].
- **Models that describe the effects of interference**: Two largely used interference models namely, the Protocol Interference Model and the Physical Interference Model belong to this class. The Protocol Interference Model defines a pairwise interference relationship between wireless nodes, and is based on local constraints. On the other hand, Physical Interference Model assumes aggregate interference observed by the receiver, due to all other wireless transmitters. When the Protocol and Physical models are interpreted in the context of Graph Theory, we have the graph-based interference models [17].
• **Graph-based models:** These models are particularly suitable for solving problems in the context of topology control and transmission scheduling.

![Diagram](image.png)

**Figure 3. Unified view of interference models shown in [17].**

In [19] [20], Alberto Rabbachin et al proposed a statistical model for aggregate interference in cognitive networks which accounts for the sensing procedure, spatial distribution of wireless terminals, secondary spatial reuse protocol, and environment-dependent conditions (e.g. path loss, shadowing, and channel fading). They considered two types of secondary spatial reuse protocols:

- **Single threshold protocol:** the $i^{th}$ secondary user is active if $\frac{KP_pY_i}{R_i^b} \leq \beta$ or $R_i^{2b}Y_i \leq \zeta$. where $\beta$ is the activating threshold, $\zeta$ is the normalized threshold, $P_p$ is the transmitted power of the primary user, $Y_i$ is the squared fading path gain of the channel from the primary user to the $i^{th}$ secondary user, $K$ is the gain accounting for the loss in the nearfield, $R_i$ is the distance between the primary and the $i^{th}$ secondary user, and $b$ is the amplitude pass-loss exponent. Activity of secondary network users can be characterized by Bernoulli random variables [19].

- **Multiple threshold protocol:** Transmission power of the secondary network users is sets according to the detected power level of the primary network uplink signal.
They considered $N - 1$ normalized threshold values to identify $N$ different sets of active secondary users [19] [20].

Their obtained results are also shown in Figure 4 (Bit error probability versus $E_b/N_0$ for BPSK system) and Figure 5 (Unified BEP of BPSK as a function of the normalized activating threshold $\zeta$ for the single-threshold protocol).

![Figure 4](image1.png)  
**Figure 4.** Bit error probability of BPSK versus $E_b/N_0$ in the presence of the cognitive network interference. $\lambda = 0.1$ users/m$^2$ and $\zeta = -40$ dBm. For comparison, the BEP in the without interference is also plotted (dashed line).

![Figure 5](image2.png)  
**Figure 5.** Unified BEP of BPSK as a function of the normalized activating threshold $\zeta$ for the single-threshold protocol. $E_b/N_0 = 10$ dB and SIR = $-10$ dB. For comparison, the BEP in the without interference is also plotted (dashed line).

In [21] Mario and Nikolaos offered a framework for the approximation of interference distribution in wireless networks with spatial randomness. They utilized known probability density functions using the moment matching method for three node distributions:

- Poisson Point Process (PPP)
- Strauss
- Poisson Cluster Point
In order to approximate the interference distribution, they proposed to use generalized distributions, like normal inverse Gaussian and the generalized inverse Gaussian distributions, as well as simpler, two-parameter probability distributions, such as the inverse Gaussian, the inverse gamma, and the gamma distribution. Their numerical results show the effectiveness of inverse Gaussian distribution in approximating the interference as shown in Figure 6, created by base stations distributed according to the Strauss point process, as well for Poisson cluster processes. The inverse gamma distribution also gives satisfactory results in certain cases, while the normal distribution fails significantly to model the aggregate interference.

![Figure 6](image1.png)

Figure 6. (a) Empirical PDF of interference for the PPP and the corresponding fits. (b) Empirical PDF of interference for the Strauss process and the corresponding fits. (c) Empirical PDF of interference for the Poisson cluster process and the corresponding fits.

6. Interference models implemented in the network simulators

The objective of this section is to list the different interference models implemented in the best-known WSNs or general wireless network simulators.

6.1. NS-2

Ns-2 ([http://www.isi.edu/nsnam/ns/](http://www.isi.edu/nsnam/ns/)) is one of the most known network simulator. The protocols behavior and simulator itself are C++ based, while interpreted scripts performing the simulation itself are to be OTcl based. In spite the fact that ns-2 is considered to be too general and inappropriate for WSNs simulations by some researchers, an example of ns-2 usage is a simulation of Low Energy Adaptive Clustering Hierarchy (LEACH) protocol used for routing and clustering of sensor nodes in a network. The ns-2 has a rich set of IP network focused protocols [22], because it has never been intended to design for WSNs, that’s why it does not scale very well and has some troubles if the number of nodes count in a network exceeds the
number of 100. It also cannot simulate problems of the bandwidth or the power consumption constraint in WSNs.

6.2. **Castalia**

Castalia is a simulator for WSNs, Body Area Networks (BAN) and general networks (e.g. low-power embedded devices etc.). Since 2007, it is developed in the Networked Systems theme at NICTA [23]. Castalia is used by researchers and developers to test their proposed or already existed distributed algorithms and/or protocols in realistic wireless channel and radio models, with a realistic wireless nodes behavior especially relating to access of the radio channel. Castalia’s significant features include: model for temporal variation of path loss, fine-grain interference and RSSI calculation, physical process modeling, node clock drift, and several popular MAC protocols implemented. Castalia provides tools to help run large parametric simulations, process and visualize the results.

6.3. **MiXiM**

MiXiM is an OMNeT++ modeling framework created for mobile and fixed wireless networks (e.g. WSNs, body area networks, ad-hoc networks, vehicular networks, etc.). MiXiM simulator focusses on the lower layers of the protocol stack, and proposes comprehensive models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols. MiXiM is merger of several earlier OMNeT++ frameworks. It is planned to merge MiXiM into the INET Framework [24].

6.4. **Worldsens**

Worldsens (http://www.senslab.info/?cat=13) consists of two simulators: WSNet and WSim. WSNet is an event-driven simulator based on C language [25]. It allows simulations of large scale WSNs. The so-called blocs simulate components of the wireless terminals and properties of the radio channel. WSim also allows simulation of hardware platform using microcontroller binary codes [26].

6.5. **TOSSIM**

TOSSIM (http://docs.tinyos.net/index.php/TOSSIM) is a simulator based on TinyOS operating system. It enables simulation of application written in nesC language (network embedded system C) for real hardware. The simulation scenario can be written either in Python or C++ [27].
Table 1 shows summary the channel/interference models associated with some of the wireless network simulators.

**TABLE 1. SUMMARIZES THE INTERFERENCE MODELS ASSOCIATED WITH EACH NETWORK SIMULATOR.**

<table>
<thead>
<tr>
<th>Simulator</th>
<th>Online availability</th>
<th>General or specific simulator</th>
<th>Wireless channel noise model</th>
</tr>
</thead>
</table>
| **NS-2** *(simulator)* | yes                 | General simulator              | • Free space.  
• Two ray ground reflection.  
• Log normal shadowing. |
| **Castalia** *(simulator)* | yes                 | WSN simulator                  | • Free space  
• Log normal shadowing.  
• Temporal variation.  
• Additive interference. |
| **MiXiM** *(simulator)* | yes                 | General simulator              | • Free space.  
• Log normal shadowing using adapted free space.  
• Jakes Fading. |
| **WSNet** *(simulator)* | yes                 | General simulator              | • Disk Model.  
• Free space.  
• Two-ray ground reflection.  
• Log normal shadowing.  
• Rayleigh fading.  
• ITU indoor model.  
• Nakagami fading. |
| **TOSSIM** *(emulator)* | yes                 | designed for WSNs              | • Log normal shadowing  
• Noise modeling |

7. Mathematical Interference Models

Channel noise modeling or interference modeling has very long history. At first it were done using Gaussian random process which has finite variance and very light tail [28] but what if there are much more variation in noise samples that couldn’t be captured by Gaussian
distribution. In a wireless network, neighboring radio devices from inside or outside of the network can transmit data using the same or nearby radio frequency band at the same time which will cause interference in the network [29] [30].

7.1. Additive White Gaussian Noise (AWGN)

For the wireless channel the fundamental performance analyzer parameter is its capacity. The channel capacity is the maximum rate of communication for which negligible error probability can be assured. Unlike the AWGN channel, there is no single definition of wireless channel capacity that is appropriate for all scenarios. Gaussian model or AWGN model is appropriate, for example, when the interference is the accumulation of a large number of independent signals, where no term dominates the sum, and thus the central limit theorem (CLT) applies [31].

There are many ways proposed in the literature to model interference [32] [33]. The most common approach is by using Gaussian random process. This is appropriate when the interference is accumulation of large number of independent signals and no term dominates the sum thus the Central Limit Theorem (CLT) can be applied. In (Equation 1), noise $Z(t)$ can be model with Gaussian distribution or Additive White Gaussian Noise (AWGN) with zero mean and a variance $N_0: Z \sim N(0, N_0)$, only if the noise samples are considered independent and identically distributed (iid) [32]. For wireless channel, fundamental performance analyzer parameter is its capacity. The channel capacity is the maximum rate of communication for which negligible error probability can be assured. Unlike the AWGN or Gaussian channel model, there is no single definition of wireless channel capacity that is appropriate for all scenarios.

Let us understand the Gaussian distribution in context of wireless communication channel. Consider a sensor network with $n$ number of transmitting nodes and a receiver. If the node with transmitter $T_0$ wants to send data to the node with receiver $R_x$, the received signal will be:

$$\text{Received Signal } R_x = h_0X_0 + \sum_{i=1}^{n} h_iX_i$$

(1)

where $X_0$ is desired transmitted signal convolved with channel response $h_0$. $X_i$ is the accumulated interfering signals coming from the other wireless devices and each signal convolved with their respective channel response $h_i$. If we assume that these received samples
\( \sum_{i=1}^{n} h_i X_i \) are following the Gaussian distribution then they can be mathematically expressed by following probability density function (PDF):

\[
f_X(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

where \( \mu \) is the mean and \( \sigma \) is the noise variance. For zero mean noise \( (\mu = 0) \), Equation 2 will become:

\[
f_X(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}
\]

Gaussian distribution has many well suited properties in the modeling of wireless channel but there are several scenarios where CLT is not applicable. It is when, the number of interferers are large in number but there are some dominant interferers present in the environment and makes noise non-Gaussian or impulsive in nature [34]. Impulsive noise is a noise which often occurs in wireless and wireline communications in the indoor and outdoor environments. Impulsive noise or non-Gaussian noise can be a major source of error in data transmission and also can be a contributor in the increase of total error rate of the system. In more real wireless environmental circumstances, some noises are impulsive in nature; e.g. atmospheric noise which is caused by lighting, radar noise and so on [35]. In particular these rare events with large amplitude have high impact on communication links but cannot be modeled with the Gaussian process. In this case, another mathematical model is required to model such interference.

### 7.2. Alpha-Stable distribution Model

Alpha-stable distribution has infinite variance and heavy tail expect the case when \( \alpha = 2 \), it becomes Gaussian distribution [36]. Alpha-stable distribution is heavy tail distribution which means that large values of independent and identically distributed random interfering signals are possible and could have significant mass. It can be seen from Figure 7 that distribution of OFDM samples over 1024 orthogonal subcarriers are same in both interference models but the only difference is rare presence of high amplitude impulses in alpha-stable noise model.

There is no closed form expression or probability density function of the alpha-stable distribution, but it can be described by its characteristic function [36], which is:
\[ \Phi(\theta) = \begin{cases} 
\exp\left\{ -\sigma^\alpha |\theta|^\alpha \left( 1 - i\beta \text{sign}(\theta) \tan \frac{\pi \alpha}{2} \right) + i\delta \theta \right\} & \text{if } \alpha \neq 1 \\
\exp\left\{ -\sigma |\theta| \left( 1 + i\beta \frac{2}{\pi} \text{sign}(\theta) \ln |\theta| \right) + i\delta \theta \right\} & \text{if } \alpha = 1 
\end{cases} \]

where \( \text{sign}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\
0 & \text{if } \theta = 0 \\
-1 & \text{if } \theta < 0 \end{cases} \)

\( \alpha, \beta, \sigma \) and \( \delta \) are the four parameters of alpha-stable distribution and are explained below [10]:

- \( \alpha \in (0, 2] \) index of stability: sets the degree of the impulsiveness of the distribution. At \( \alpha = 2 \) distribution becomes Gaussian distribution.
- \( \beta \in [-1, 1] \) skewness parameter: specifies distribution curve is skewed towards right or left.
- \( \sigma \in [0, \infty) \) scale/dispersion parameter: measures the spread of the noise samples around the mean.
- \( \delta \in \mathbb{R} \) location parameter: corresponds to the median for \( 0 < \alpha < 1 \), and to the mean for \( 1 < \alpha \leq 2 \).

Figure 7. Distribution of noise impulses using AWGN and alpha-stable models
8. System Model

8.1. Wireless Sensor Network Environment

Let a sensor network of \( n \) nodes and spatial density \( \lambda \), if a node with transmitter \( T_0 \) transmits data to the node with receiver \( R_x \), the received signal from (Equation 1) is:

\[
Y = h_0 X_0 + \sum_{i=1}^{n} h_i X_i
\]

where \( X_0 \) is desired transmitted signal convolved with channel response \( h_0 \). \( \sum_{i=1}^{n} h_i X_i \) is the accumulated interfering signals coming from the other wireless devices. Spatial density \( \lambda \) depends on total number of active nodes within the specified area around a node. \( \lambda \) can be calculate as

\[
\lambda = \frac{n}{\text{area}} \times \% \text{ of active nodes}
\]  

(5)

where \( n \) is total number of nodes in specified area, and

\[
\text{area} = \pi \times \text{radio \_range}^2
\]  

(6)

Spatial density \( \lambda \) and system performance are inversely proportional to each other. As the value of \( \lambda \) increase due to increase in total number of nodes the performance of communication system will decrease which means communication system will have more bit errors and packet errors.

8.2. IEEE Standard 802.15.4

The IEEE standard 802.15.4 is for Low Rate Wireless Personal Area Networks (LR-WPAN). LR-WPAN includes home automation, healthcare monitoring, environmental surveillance, military application, Smart cities and so forth. IEEE standard 802.15.4 defines the characteristics of physical (PHY) layer and Medium Access Control (MAC) layer for the wireless communication systems that does not require high data rates. MAC layer manages access to the wireless physical medium, frame validation, guaranteed services, wireless node associations and security services of wireless networks [37]. IEEE 802.15.4 LR-WPAN assumes centralized and decentralized networks that allow wireless devices to communicate with other wireless devices within their radio transmission range. For a peer-to-peer or decentralized wireless network, it defines the un-slotted carrier sense multiple access with collision avoidance CSMA/CA wireless medium access mechanism by which sensor nodes
compete with each other to occupy the shared wireless medium for transmission [38]. In this work, we have considered that scattered sensor nodes follow Peer-to-peer topology. The specifications for physical layer and medium access control layer of wireless networking are defined by IEEE standard 802.15.4. This standard does not have any requirements for higher networking layers in Open System Interconnection (OSI) model. IEEE standard 802.15.4 was developed by IEEE standards 802 committee and was initially released in 2003 [39]. The ZigBee standard defines only the networking, applications and security layers of the protocol and adopts IEEE standard 802.15.4 PHY and MAC layers as a part of the ZigBee networking protocol. Therefore, ZigBee based devices are also adaptive to IEEE 802.15.4 as well.

IEEE 802.15.4 offers 2.4 GHz, 915 MHz and 868 MHz operational frequency bands. A total of 27 channels, numbered from 0 to 26, are specified by IEEE 802.15.4 across three unlicensed operational frequency bands. Sixteen channels are available in the 2.4 GHz frequency band, ten in the 915 MHz frequency band, and 868 MHz frequency band based system occupies one channel (see Figure 8). Modulation techniques, chip rate and data rate information associated with each frequency band is given in Table 2 [38] [40].

![Figure 8. Frequency band used by IEEE standard 802.15.4](image)

<table>
<thead>
<tr>
<th>PHY (MHz)</th>
<th>Frequency Band (MHz)</th>
<th>Chip rate (kchips/s)</th>
<th>Modulation</th>
<th>Bit rate (kb/s)</th>
<th>Symbol rate (ksymbol/s)</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>868</td>
<td>868-868.6</td>
<td>300</td>
<td>BPSK</td>
<td>20</td>
<td>20</td>
<td>Binary</td>
</tr>
<tr>
<td>915</td>
<td>902-928</td>
<td>600</td>
<td>BPSK</td>
<td>40</td>
<td>40</td>
<td>Binary</td>
</tr>
<tr>
<td>2450</td>
<td>2400-2483.5</td>
<td>2000</td>
<td>O-QPSK</td>
<td>250</td>
<td>62.5</td>
<td>16-ary</td>
</tr>
</tbody>
</table>

Orthogonal
Figure 9 shows functional block diagram of IEEE 802.15.4 transceiver. It uses the Direct Sequence Spread Spectrum (DSSS) as spreading technique. Spreading techniques are utilized to increase the bandwidth of transmitted signal. DSSS phase shifts a sine wave pseudo randomly with continuous string of pseudo noise (PN) code symbols called ”chips”. This phenomena is called symbol-to-chip mapping and helps to increase the transmitted power of the signal and decrease the interference influence on received signal. DSSS uses a signal structure in which transmitter produce PN-sequence and shares with receiver for reconstruction of the symbols.

**Figure 9. Functional block diagram of IEEE 802.15.4 transceiver.**

DSSS technique in IEEE 802.15.4 transceiver provides resistance to transmitted signal against intended or unintended jamming and allows sharing of single channel among multiple users. System with frequency band 2.4 GHz utilizes Orthogonal Quadrature Phase Shift Keying (O-QPSK) technique for chip modulation. Each 4-bit symbol is mapped over 32-bit pseudo random code. Digital systems operating on 868 MHz and 915 MHz frequency bands use 15-bit PN-sequence to map one symbol and Binary Phase Shift Keying (BPSK) modulation technique [39]. At the receiver the despreading is done by comparing received 32-bit chip sequence with each given 32-bit chip sequence. We have performed this comparison by applying XOR operation. The chip-to-symbol despreading block outputs the matching symbol which has smallest hamming distance. To lower the complexity of the system, setting a threshold of the hamming distance can be valuable, as it can reduce the number of 32-bit XOR operations for each received sequence [41].

### 8.3. IEEE Standard 802.11

Expression In recent decade there has been a significant growth in wireless communications. These days, the data rates of wireless communication systems are getting higher as tele technology is evolving. IEEE standard 802.11 provides set of specifications for media access control (MAC) and physical layer (PHY) for implementing wireless local area
network (WLAN) in frequency band of 900 MHz, 2.4GHz, 3.6GHz, 5GHz and 60 GHz [42]. 2.4 GHz frequency operation band is most common in many extensions of IEEE standard 802.11, with 14 distinct channels. Figure 10 shows these 14 channels from 1 to 14 spaced 5 MHz apart.

![Figure 10. Graphical representation of channels for 2.4GHz frequency band](image)

Orthogonal Frequency Division Multiplexing (OFDM) is the variant of Multi-Carrier Modulation and is employed in several IEEE Wireless Local Area Network (WLAN) standards like, IEEE 802.11a and IEEE 802.11g. IEEE standards 802.11n and 802.11ac also utilize OFDM modulation technique but coupled with a multiple input multiple output (MIMO) [43][44]. Figure 11 shows the block diagram for the OFDM communication system. To understand the concept, let us consider the input signal \( S(t) \) and its sampling version \( S[n] \) that will share over \( N \) sub-carriers. The input data is converted from serial to parallel OFDM symbols, as:

\[
\text{OFDM Symbols} = \sum_{k=0}^{N-1} X[k]
\]

![Figure 11. Block diagram of an OFDM based communication system](image)

Probability The required amplitude and phase of each sub-carrier is calculated using predefined modulation technique (16-QAM in our case). Then demultiplexing is applied to load
OFDM symbols over each sub-carrier [41]. Then these OFDM symbols are transferred to the IFFT block for IFFT operation to generate the transmit samples. For $l^{th}$ sample we get:

$$x_n[l] = \frac{1}{N} \sum_{k=0}^{N-1} X_n[k] \exp(j2\pi l \frac{k}{N}) ; \text{For } l = 0,1,2, \ldots, N-1$$

where $k$ represent the $k^{th}$ sub-carrier $N$ is the total number of sub-carriers. IFFT/FFT operation in OFDM helps to convert a frequency selective wireless channel into $N$ parallel flat fading channels by dividing the large bandwidth that causes the ISI. These samples are again converted to serial stream. The parallel OFDM symbols are converted into serial stream through the process called multiplexing. At the receiver two consecutive OFDM samples can interfere to each other which is called Inter Block Interference (IBI). Cyclic prefix of length $L$ is added to the serial data at this point to avoid IBI at the receiver and signal will become:

$$x_n[N-L], \ldots, x_n[N-1], x_n[0], x_n[1], \ldots, x_n[N-L], \ldots, x_n[N-1]$$

where $L$ is the length of cyclic prefix. At the receiver this cyclic prefix is discarded. This signal is transmitted over the wireless channel. The exact but opposite operation is taken place at the receiver to convert the received signal into data as shown in Figure 11 [45].

**Conclusion**

In this work we have presented some of already existing interference models for WSNs. This report also focused on physical layer specification of wireless communication systems based on IEEE standards 802.15.4 and 802.11, for the deployment of WSNs in urban environment.

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