Performance Evaluation of IEEE 802.15.4 PHY with Impulsive Network Interference in CupCarbon Simulator

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Abstract—IEEE 802.15.4 protocol is very much associated with ZigBee protocol and targets low data rate, low power consumption and low cost wireless networking that fits the requirements of wireless sensor networks (WSNs). Due to increase in radio frequency (RF) based communication devices and spectrum sharing between these devices makes it impossible to neglect the affect of interference on wireless communications. This paper provides brief description about technical features of IEEE standard 802.15.4 and ZigBee based physical layer structure and wireless channel impulsive interference modeling for wireless sensor networks in smart cities applications. For more accurate estimation of wireless channel characteristics, we have modeled it using alpha-stable distribution function. We have then estimated two out of four parameters of alpha-stable distribution depending on spatial density of wireless devices in specified area around the wireless node in a network. This allows better modeling and estimation of wireless channel conditions. We have analyzed IEEE standard 802.15.4 based communication system performance in terms of the bit error rate (BER). We have varied the total number of active nodes in specified area around sensor node and evaluates its affect on overall BER performance.

We have also integrated this PHY layer based on IEEE standard 802.15.4 in the CupCarbon simulator with the consideration of impulsive network interference and its modeling using alpha-stable distribution.

Keywords—*Wireless Communications; IEEE 802.15.4; ZigBee; Physical Layer; Impulsive Interference; Alpha-Stable Distribution; Wireless Sensor Networks; CupCarbon;*

I. INTRODUCTION

Recently there has been a growing interest in the development of wireless sensor networks (WSNs) that works on low power, low data rate and low cost manner in smart cities applications. 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. Unfortunately, power constrained devices are unable to operate for long duration of time and are expected to be replaced or recharged once they run out of energy. This is not an easy task especially in the case of implanted devices such as in sensor network. It is apparent that, a wireless standard is required to address problem of high energy cost, caused by wireless connectivity for low data rate networks.

Two of most common wireless standards for wireless communications in WSNs are IEEE 802.11 also known as WIFI and IEEE 802.14.5 also referred to as ZigBee, allows data transmission in standardized manner. Choosing which standard is best for particular application can be decided by examining its power consumption, required data rate and data transmission range. IEEE standard 802.15.4 has recently attained extensive attention in wireless sensor networking research because it offers a platform for wireless communications of low power, short range and low data rate applications [1], [2]. IEEE standard 802.15.4 is basis for ZigBee. ZigBee based sensor network can consists on upto 65000 inter-connected wireless nodes [3].

The emerging field of wireless sensor networks has a wide range of potential applications and comprised sensing (measuring), computation, and communication into a single tiny device called sensor node [4]. Wireless sensor networks typically consist on large number of heterogeneous sensor devices that contain processing capability, a sensor/actuator, a power source (batteries), multiple type of memory and a radio frequency (RF) based transceiver as shown in Fig. 1. These large number of sensors densely deployed over a large field and inter-networked together to monitor physical or environmental conditions that generates sensor readings and delivered them to sink node in order to be further processed [4].

Most of WSNs use unlicensed Industrial, Scientific and Medical (ISM) frequency band that makes interference probable phenomenon on a given channel. System throughput gets influenced by the interference as it can congests wireless
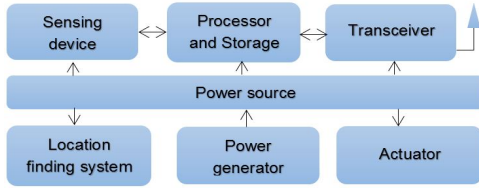
Fig. 1. Single sensor node architecture.

Fig. 2. IEEE 802.15.4 and ZigBee protocol stack architecture.

4 bytes	1 byte	1 byte	2 bytes	1 byte	4 or 10 bytes	Variable	2 bytes
PHY Frame							
Preamble Sequence	Start of Frame Delimiter	Frame Length	MAC Frame				
			Frame Control	Sequence Number	Addressing Fields	Frame Payload	Frame Check Sequence
SHR		PHR	MHR			MSDU	MFR
PLCP Protocol Data Unit (PPDU)							

Fig. 3. Schematic view of the general frame format.

medium, cause packet drops, re-transmissions, link instability and inconsistent protocol behavior [5]. Most of available literature on wireless sensor networks have not considered interference affect from inside or outside of the network unless nodes are in radio range of each other and system have unlimited radio spectrum. In contrast, real time wireless sensor networks are band limited and nodes can interfere with other nodes even if they are beyond their communication range [6], [7].

CupCarbon is an open source WSN simulator which allows users to verify new ideas and compare proposed future solutions in more realistic virtual environment for wireless sensor network applications. This simulator runs under the Java environment and can be downloaded from the Internet [1]. It supports wireless communication interference models and signal propagation models like Gaussian and alpha-stable models [8], [9]. The main objective of this work is to integrate physical layer based on IEEE standard 802.15.4 in CupCarbon simulator.

Rest of the article is organized as follows. Section II defines some of technical features associated with IEEE standard 802.15.4 and ZigBee. Section III explains considered system model and working of IEEE standard 802.15.4 based transceiver. Section IV describes alpha-stable distribution function and estimation of its two out of four parameters to model the wireless channel. We present simulation results using simulation tools MATLAB and Cupcarbon in Sections V. Conclusive remarks about this research are drawn at the end in Section VI.

II. 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 [10].

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,
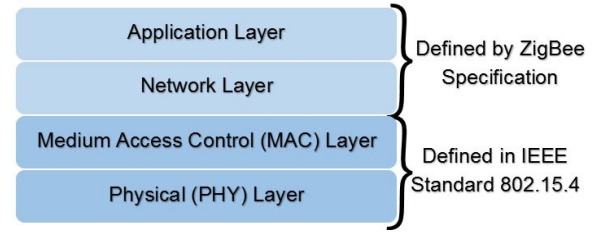
it defines the un-slotted carrier sense multiple access with collision avoidance CSMA/CA wireless medium access mechanism by which sensor nodes compete with each other to occupy the shared wireless medium for transmission [10].

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. 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 (see Fig. 2). Therefore, ZigBee based devices are also adaptive to IEEE 802.15.4 as well.

A. Network Topology

Based on the application requirements, IEEE standard 802.15.4 based wireless devices can adapt star topology and peer-to-peer topology for networking. In star topology, sensor nodes follow more structured star pattern and a coordinator of the network will essentially be the central node to initiate, terminate or route flows. Star topology provides contention-free and contention-based wireless medium access to member nodes. Peer-to-peer topology allows each sensor node to communicate with other nodes within its radio range, in the network. It supports only contention-based (unslotted CSMA/CA) wireless medium access [11].

In this work, we have considered that scattered sensor nodes follow Peer-to-peer topology.

B. Frame Structure

In IEEE 802.15.4 frame structures have been designed to lower the complexity while at the same time assuring their robustness for transmission on wireless channel. Each successive layer of OSI model adds their layer-specific headers and footers. IEEE 802.15.4 only specifies PHY and MAC
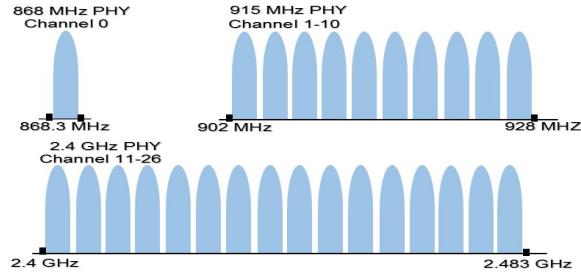
Fig. 4. IEEE 802.15.4 Operational Frequency Bands.

TABLE I
IEEE 802.15.4 DEFINED FREQUENCY BANDS AND ASSOCIATED
SPECIFICATIONS.

PHY(MHz)	Frequency Band (MHz)	Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868	868-868.6	300	BPSK	20	20	Binary
915	902-928	600	BPSK	40	40	Binary
2450	2400-2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

layers, other upper OSI model layers specifications are defined by ZigBee Alliance.

Fig. 3 shows schematic representation of general frame at MAC and PHY layer. MAC layer frames contain MAC footer (MFR) of 2-bytes, MAC service data unit (MSDU) of variable length and MAC header (MHR) of 7-bytes to 13-bytes. MAC footer (MFR) contains frame check sequence of 16-bits. MAC frames are then passed to PHY layer and prefixed with 1-byte of PHY header (PHR) and 5-bytes of synchronization header (SHR) [11]. IEEE 802.15.4 defines four frame structures [11]:

1) Beacon Frame: originates by MAC layer and is used by the network coordinator to send beacons in a beacon-enabled network .

2) Data Frame: originates from upper layers and used for the data representation.

3) Acknowledgment Frame: originates from MAC and used for sending confirmation of successful frame reception at receiver.

4) MAC Command Frame: originates from MAC and used for handling all MAC peer entity control transfers.

C. Overview of the Physical Layer Design

The general operation of PHY in IEEE standard 802.15.4 is activation and deactivation of radio frequency based transceiver, clear channel assessment using carrier sensing or energy detection modes, channel frequency selection and data transmission and reception using a certain radio frequency. 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 Fig. 4). Modulation techniques, chip rate and data rate information associated with each frequency band is given in Table I [10], [11].
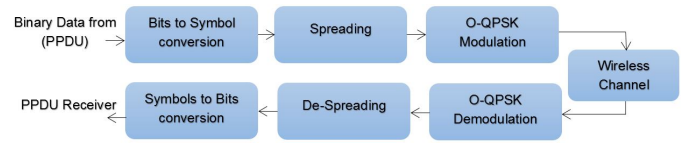

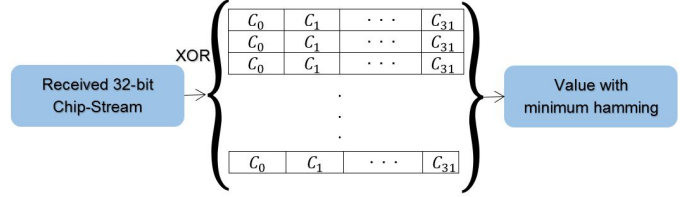Fig. 5. Functional block diagram of IEEE 802.15.4 transceiver.

Fig. 6. De-Spreading with minimum Hamming distance.

In this work we have utilized ISM Frequency band of 2.4 GHz with 16-channels and data rate of 250 kbps.

III. SYSTEM MODEL

A. IEEE 802.15.4 Transceiver

Fig. 5 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 sting 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 (as shown in Table II) and shares with receiver for reconstruction of the symbols. 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 as shown in Table II. 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 [12].

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 (see Fig. 6). 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.

B. Wireless Sensor Network Environment

In this work we have considered an urban environment for virtual deployment of sensor network. With the increase

TABLE II
SYMBOL-TO-CHIP MAPPING PN-SEQUENCE FOR 2.4 GHZ BAND SYSTEM

Symbols (dec)	Symbols (bin)	PN-Sequence $(C_0, C_1....C_{31})$
0	0000	11011001110000110101001000101110
1	0001	11101101100111000011010100100010
2	0010	00101110110110011100001101010010
3	0011	00100010111011011001110000110101
4	0100	01010010001011101101100111000011
5	0101	00110101001000101110110110011100
6	0110	11000011010100100010111011011001
7	0111	10011100001101010010001011101101
8	1000	10001100100101100000011101111011
9	1001	10111000110010010110000001110111
10	1010	01111011100011001001011000000111
11	1011	01110111101110001100100101100000
12	1100	00000111011110111000110010010110
13	1101	01100000011101111011100011001001
14	1110	10010110000001110111101110001100
15	1111	11001001011000000111011110111000

in radio communication devices in urban environment, the interference affect on wireless communications cannot be neglected. To better understand the radio environment, let a sensor network of n nodes with spatial density λ, if a node's transmitter T_0 transmits data to the other node with receiver R_x, the received signal will be:

$$Y = h_0 X_0 + \sum_{i=0}^{n} h_i X_i \qquad (1)$$

where X_0 is transmitted signal of antenna T_0 and convoluted with wireless channel response h_0. Term $\sum_{i=1}^{n} h_i X_i$ represents the accumulated interfering signals generated by other RF nodes or devices. These signals can be further divided into two parts and considered as sum of signals from weak interferers and strong interferers. Both types of interference can be modeled with Additive White Gaussian Noise (AWGN) model and alpha-stable noise models, respectively.

$$\sum_{i=1}^{n} h_i X_i = \underbrace{\sum_{i=1}^{u} h_i X_i}_{Impulsive\ Noise} + \underbrace{\sum_{i=u+1}^{n} h_i X_i}_{Gaussian\ Noise} \qquad (2)$$

Spatial density λ depends on total number of active nodes within the specified area around a transceiver. λ can be calculated as:

$$\lambda = \frac{n}{area} \times \%\ of\ active\ nodes \qquad (3)$$

where n is total number of nodes in a network or in specified area, and

$$area = \pi \times radio\_range^2 \qquad (4)$$

Spatial density λ of nodes and system performance are inversely proportional. Increase in the value of spatial density λ can cause BER performance degradation of communication system.

IV. INTERFERENCE MODELING

Interference modeling is an essential part of wireless channel modeling for the design and performance analysis of wireless network. Due to simplicity, Gaussian distribution is used to model wireless channels in many wireless network applications. Rare but high variations in noise samples cannot be captured by Gaussian model. In a wireless network, neighboring RF based devices from inside or outside of the network can transmit data with same or nearby frequency band which will cause interference in the network [13].

A. Alpha-Stable Distribution

Alpha-stable distribution has infinite variance and it employs heavy tail excluding the case when $\alpha = 2$, which is Gaussian distribution. Gaussian distribution is special form of stable distribution. Alpha-stable distribution is heavy tail distribution which means that it takes into account the large values of independent and identically distributed random interfering signals that are more possible to occur with significant mass [14].

There is no closed form expression or probability density function of the alpha-stable distribution, but it can be described by its characteristic function, given as [13]

$$\phi(\theta) = \begin{cases} exp\{-\sigma^\alpha |\theta|^\alpha (1 - i\beta sign(\theta) tan(\frac{\pi\alpha}{2})) + i\delta\theta\} & \alpha \neq 1 \\ exp\{-\sigma|\theta|(1 + i\beta\frac{2}{\pi} sign(\theta) ln|\theta|) + i\delta\theta\} & \alpha = 1 \end{cases}$$

where

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

and α, β, σ and δ are four parameters of alpha-stable distribution and can be explained as [13]:

• $\alpha \in (0, 2]$ is index of stability and sets the degree of the impulsiveness of the distribution.

• $\beta \in [-1, 1]$ is skewness parameter and specifies the distribution curve is skewed towards left or right.

• $\sigma \in [0, \infty)$ is scale/dispersion parameter and it measures the spread of the noise samples around the mean.

• $\delta \in \mathbb{R}$ is location parameter and it corresponds to the median for $0 < \alpha < 1$, and to the mean for $1 < \alpha \leq 2$.

B. Parameter Estimation of Alpha-Stable Distribution

Using the general results from (1) and (2), in this section we present our interference model. Let a set of distances $\{R_i\}_{i=1}^n$ between the receiver node and interferer nodes within the specified area in a network. An arbitrary random quantity $Q_i = [Q_1, Q_2, \cdots Q_n]$ is associated with each interferer i. Let Y denotes the accumulated interference at the receiver generated by interferers. Assume sevral interferer wireless nodes are scattered in a finite plane as stated in [15], hence

$$Y = \sum_{i=1}^{n} \frac{Q_i}{R_i^b} \qquad (5)$$

where b is channel amplitude attenuation coefficient, while corresponding power loss exponent is γ. The characteristic function will be

$$\phi_Y(w) = exp(-\sigma|w|^\alpha) \qquad (6)$$

where

$$\alpha = \frac{2}{b} \qquad (7)$$

and

$$\sigma = \lambda\pi C_{2/b}^{-1} E\{|Q_{i,n}|^{2/b}\} \qquad (8)$$

α is index of stability and it sets the degree of the impulsiveness of alpha-stable distribution. σ is scale/dispersion parameter and it measures spread of noise samples around the mean. C_α is some constant defined in [15] as

$$C_\alpha \triangleq \begin{cases} \frac{1-\alpha}{\Gamma(2-\alpha)\cos\frac{\pi\alpha}{2}}, & \alpha \neq 1 \\ \frac{2}{\pi}, & \alpha = 1 \end{cases} \qquad (9)$$

$\Gamma(\cdot)$ denotes gamma function.

Let a positive independent and identical variable a, follows Rayleigh distribution, its probability distribution function will be

$$f(a) = \frac{a}{\varepsilon^2} e^{-a^2/2\varepsilon^2} \quad \text{for} \quad a \geq 0 \qquad (10)$$

where ε is scale parameter of Rayleigh distribution. Its value determines statistical dispersion of Rayleigh distribution.

For $|Q_{i,n}|^{2/b}$ where let $|Q_{i,n}|$ is Raleigh distributed. Then expected value $E\{|Q_{i,n}|\}^{2/b}$ can be obtained as:

$$E[|Q_{i,n}|^p] = \int_0^\infty a^p \ f(a) \ da$$
$$\because p = \frac{2}{b} \quad \text{and} \quad a = |Q_{i,n}| \qquad (11)$$

$$E[|Q_{i,n}|^p] = \int_0^\infty \frac{a^{p+1}}{2} \ e^{-a^2/2\varepsilon^2} \ da$$

We will get:

$$E[|Q_{i,n}|^p] = 2^{p/2} \ \varepsilon^p \ \Gamma(p/2 + 1)$$
and $p = 2/b$, so

$$E[|Q_{i,n}|^{2/b}] = 2^{1/b} \ \varepsilon^{2/b} \ \Gamma\left(\frac{1}{b} + 1\right) \qquad (12)$$

Channel power loss exponent γ is 2 times channel amplitude attenuation coefficient b, we get

$$E[|Q_{i,n}|^{4/\gamma}] = 2^{2/\gamma} \ \varepsilon^{4/\gamma} \ \Gamma\left(\frac{2}{\gamma} + 1\right) \qquad (13)$$

Equations (6), (7) and (8) can be expressed as
$$Y \sim S\left(\alpha_Y = 2/b, \beta_Y = 0, \delta_Y = 0\right.$$
and $\sigma_Y = \lambda\pi C_{2/b}^{-1} E\{|Q_{i,n}|^{2/b}\}\Big)$
or
$$Y \sim S\left(\alpha_Y = 2/b, \beta_Y = 0, \delta_Y = 0\right.$$
and $\sigma_Y = \lambda\pi C_{2/b}^{-1} 2^{1/b} \ \varepsilon^{2/b} \ \Gamma\left(\frac{1}{b} + 1\right)\Big)$

V. SIMULATION RESULTS

In this paper, we have analyzed the performance of PHY layer based on IEEE standard 802.15.4 and ZigBee. We have assumed that unwanted wireless interferer signals are following alpha-stable distribution. This distribution considers more realistic wireless channel environment by taking into account the events that are rare and have significant mass.

Bit error rate (BER) can be calculated by comparing known transmitted bits with received bits. It is considered as performance analyzer of any digital communication system. We have analyzed the performance of proposed system in terms of its BER. Instead of assuming the parameters of alpha-stable distribution we have estimated two out of four parameters based on real time wireless environment. The system parameters used in this work are based on IEEE standard 802.15.4. All the simulations have been done in MATLAB. We have also embed this system into a wireless sensor network simulating tool called CupCarbon [9].

Simulations were repeated several times to obtain consistent results.

A. Using MATLAB

Fig. 7 shows the BER performance of IEEE standard 802.15.4 based wireless communication system with alpha-stable interference model in wireless sensor network applications. Vertical axis shows different bit error rate values. Horizontal axis shows different spatial density λ of the network within the specified area around a sensor node. λ can be calculated using (3). We have varied the spatial density λ of a network by varying the total number of wireless devices in the network. We have consider that 15% wireless devices are active at any time interval.

It can be seen from Fig. 7 that as the spatial density of network increases the bit error rate performances of the system decreases. From (3) and (4),

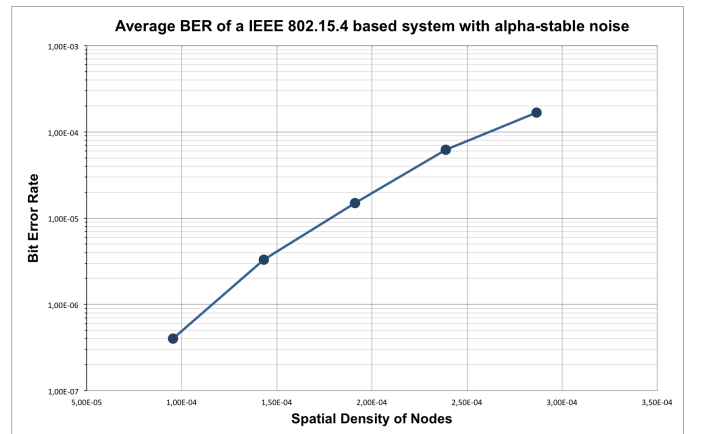$$\lambda = \frac{n}{\pi \times radio\_range^2} \times \frac{15}{100} \qquad (14)$$

Fig. 7. BER performance of PHY layer based on IEEE standard 802.15.4 with alpha-stable interference model ($\beta = 0, \delta = 0, b = 2, Radio\_range = 200m, \varepsilon = 10 \ dB$, and $data\_rate = 64 \ kbits$).
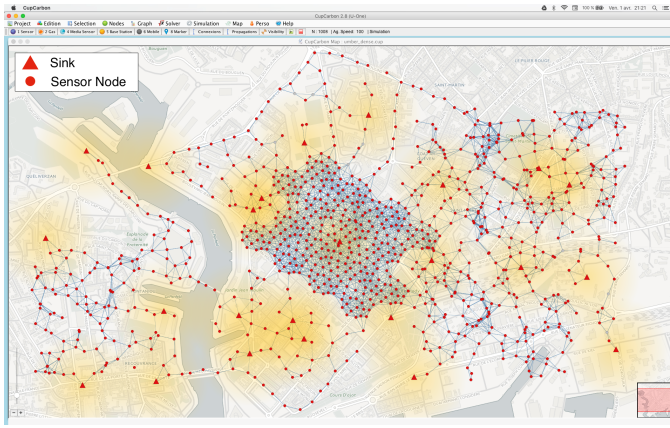
Fig. 8. Conceptual deployment of wireless sensor network in Brest, France using CupCarbon.

PHY frames used in transceiver simulations, follow structure as given in Fig. 3.

B. Using CupCarbon

We have integrated above IEEE standard 802.15.4 based PHY in CupCarbon simulator to offer an accurate and fast evaluation and understanding of the wireless network behavior before its deployment in real time environment. We have considered an urban environment. Number of deployed sensor nodes at any place in urban sensor network can vary depending on how dense a given environment is. Hence, instead of fixing number of wireless interferer devices. This flexible adaption allows sensor nodes to calculate spatial density λ of network using (3) and (4). We have seen in Fig. 7 that BER performance of the system is dependent on spatial density λ.

Fig. 8 shows a conceptual wireless sensor network with 1000 sensor nodes deployed in a city Brest, France. We have considered that 15% of total wireless devices are active at a same time, in specified area. Area can be calculate by (4).

VI. CONCLUSION

In this paper, we have proposed an optimal way to integrate and include PHY layer based on IEEE standard 802.15.4 in the CupCarbon simulator and we have also considered the alpha-stable network interference impact on wireless communications in WSN applications.

First, we done behavioral study of IEEE 802.15.4/ZigBee based wireless communication system with impulsive interference and then evaluate its performance in terms of bit error rate (BER) in MATLAB. We modeled the network interference using alpha-stable distribution function for an accurate representation of wireless channel. This allows us the better estimation of wireless channel. Alpha-stable distribution based wireless channel model demonstrates more realistic wireless channel conditions as compare to other light tailed distributions e.g. Gaussian model. We then estimate two system parameters of alpha-stable distribution, index of stability α and dispersion parameter σ.

We then include the IEEE 802.15.4 / ZigBee based PHY layer and the alpha-stable interference model in CupCarbon simulator that allows to verify new ideas and to compare proposed solutions in more realistic virtual environment. CupCarbon helps to avoid redundant, time-consuming and expensive hardware deployments for experimental purposes.

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