Modeling Interference for Wireless Sensor Network Simulators

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ABSTRACT

Low power wide area networks (LPWAN) are the enabling technologies for large scale wireless sensor networks (WSNs). Effective cost, long range and energy efficiency of LPWANs make them most suitable candidates for smart city applications. These technologies offer novel communication paradigm to address discrete IoT's applications.

This paper presents the integration of physical layers based on ZigBee, Wi-Fi, and LoRa into a wireless sensor network simulator CupCarbon for IoT's applications. We have restructured the operations of PHYs, so it can be flexible and scalable to exploit the system services.

Keywords

Wireless sensor Networks; ZiBee; Wi-Fi; $LoRa^{TM}$; LPWAN; CupCarbon; Smart cities; Internet of things (IoTs).

1. INTRODUCTION

Wireless network industry is gradually changing their interest towards LPWAN. LPWAN technologies (SigFox, LoRa, Weightless-W, etc.) successfully propose wide area connectivity from a few to tens of kilometers for low data rate, low power, and low throughput applications. Their market is anticipated to be huge. Nearly a quarter of overall thirty billion IoT/M2M devices are assumed to be connected to the internet using LPWAN. Smart cities are considered as the biggest potential customers of LPWAN, which includes smart metering, optimized driving and walking routes, weather adaptive street lighting, structural health monitoring, air pollution monitoring, forest fire detection and so forth.

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 [1,2]. WSNs typically consist of a large number of heterogeneous sensor devices that contain processing capability, the sensor(s) and/or actuator(s), a power source (batteries and eventually some energy harvesting modules), multiple types of memory and a radio frequency (RF) based transceiver. This large number of sensors are 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 to be further processed [2].

In a wireless sensor network 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 signals propagation effects 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 known as shadowing), and the reception of multiple copies of the same transmitted signal (also called multipath fading). The thermal noise is introduced by the receiver electronics and is usually modeled as additive white Gaussian noise (AWGN). Also, 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 phenomenon is called interference, and it causes the performance degradation of communication networks [3]. Moreover, rapid growth in the field of wireless communications entails the need of creating new simulators that have more accurate capabilities to tackle interference and multipath propagation effects that are present in the wireless environment. Finding a suitable simulation environment that allows researchers to verify new ideas and compare proposed ultimate solutions in a virtual environment is a difficult task. In this paper, we have included three physical layers into CupCaron simulator with the consideration of impulsive network interference.

Rest of article is organized as follows. Section 2 defines some of WSN constraints. Section 3 defines some of the existing potential candidates for LPWAN technologies. Section 4 defines a newly proposed wireless sensor network simulator, CupCarbon. Conclusive remarks are drawn at the end in Sections 5.

2. 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 much more [4]. These aspects change the characteristics of the transmitted signal as it travels through the wireless channel and can make it difficult if not impossible to recover. This section gives an overview on the factors that influence communications in WSN in terms of constraints.

2.1 Low transmit power / short range

The transmission range continues to be a major issue and depends on link budget. The link budget is an accounting of all the losses and gains of a communication system. It can be enhanced by making good choices in modulation techniques and coding schemes. The energy resource is limited when in many cases it has to operate for many years or decades and can not be replaced. To reduce energy consumption, assigned power for transmission always remain small compared to other wireless communication systems.

2.2 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. 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 wireless sensor networks, 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 [7].

2.3 Interference

The performance of radio communication based WSNs is greatly influenced by the interference. Interference in WSNs cause packet loss, their retransmissions, link instability and inconsistent protocol behavior. Another way to resolve this is to license the frequency bands to primary network users. This method has been used in AM/FM radio, over-the-air TV broadcasts and even in cellular communications. The frequency bands are sold 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 has led to the use of shared or unlicensed frequency bands that can be utilized by multiple networks at the same time. The 2.4 GHz band is an example of this paradigm, used by 802.11 (Wi-Fi), 802.15.1 (Bluetooth) and 802.15.4 (ZigBee) data networks and even cordless telephones.

3. LOW POWER WIRELESS TECHNOLOGIES

Several low power wireless technologies can be utilized for WSNs. Choice of a particular technology for a particular application can be made by examining required data rates,

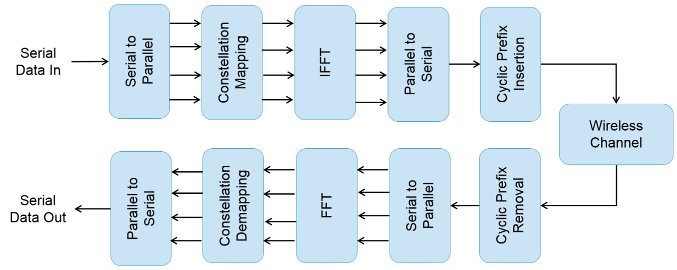

Figure 1: Functional block diagram of an OFDM communication system.

power consumption and range. Some of these major communication technologies, which utilizes licensed free ISM bands, have been discussed and compared further in this section.

3.1 Bluetooth

Bluetooth is a wireless personal area network (WPAN) technology based on IEEE standard 802.15.1. It was launched in 1994 by Ericsson. It utilizes licensed free 2.4 GHz frequency band with up to 1 MHz channel frequency band. Bluetooth has adopted frequency hopping spread spectrum (FHSS) transmission technique and offers maximum data rate up to 1Mb/s. Conventional Bluetooth can connect eight nodes to each other with seven slave nodes and one master node. Bluetooth based networks can be deployed in a point-to-point master-slave manner. The power consumption of any type of communication network strongly depends on the distance between transmitter and receiver nodes, the preferred power to be retained by the signal and most importantly type of data being exchanged. Bluetooth based networks can transfer more or less all kinds of data like multimedia or text etc. [8].

Another extension of Bluetooth was proposed as Bluetooth 4.0 also known as Bluetooth Low Energy (BLE) after the Bluetooth 1.0, 2.0 and 3.0. It was designed as an alternative low power solution to classic Bluetooth. Both bluetooth and BLE are used for different purposes. Conventional Bluetooth can handle almost all varieties of data, but it consumes more power. BLE is used for low data rate applications, and can, therefore, have longer battery life time. Like classic Bluetooth, BLE also utilizes license-free ISM band and offers 40 different channels. Three among them are labeled as advertising channels and are used to establish a connection. The remaining 37 channels are marked as data channels and as the name suggests, are used to exchanged data after the connection established between sender and receiver [8].

3.2 Wi-Fi

With the advancement in the fields of wireless and system on chip (SoC) technologies, a number of Wi-Fi based wireless sensor SoCs have been developed for low power wireless sensor applications [9]. Wi-Fi is a wireless local area network (LAN) technology based on IEEE standard 802.11. In literature though, IEEE standard 802.11 and Wi-Fi is used interchangeably, and we will also follow the same convention in this paper. IEEE standard 802.11 provides set of specifications for media access control (MAC) and physical layer (PHY) for implementing wireless WLAN in the frequency band of 900 MHz, 2.4 GHz, 3.6 GHz, 5 GHz and

60 GHz [10]. 2.4 GHz frequency operation band is most common in many extensions of IEEE standard 802.11, with 14 distinct channels. Wi-Fi based WSNs could be network-centered or data-centered networks and consists of a large number of low power nodes distributed over a large area. Wi-Fi offers a data rate of $11Mbps$ to $54Mbps$ (250 $Mbps$: Wi-Fi Direct) with 100 m transmission range. The number of nodes in the network depends on the number of IP addresses.

Orthogonal Frequency Division Multiplexing (OFDM) is the variant of Multi-Carrier Modulation and is used in various IEEE Wireless Local Area Network (WLAN) standards, i.e. 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) [11].

Figure 1 shows the block diagram of the OFDM communication system. 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.

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

The required amplitude and phase of individual sub-carrier are calculated using predefined modulation technique (e.g. BPSK, QPSK or QAM). Then demultiplexing is applied to load OFDM symbols over each sub-carrier. Then these OFDM symbols are transferred to the IFFT block for IFFT operation to generate the transmit samples. For l^{th} sample we get:

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

where k represents 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 a serial stream. The parallel OFDM symbols are converted into the serial stream through the process called multiplexing. At the receiver, two consecutive OFDM samples can interfere with each other which is called Inter Block Interference (IBI). At this point, a cyclic prefix of length L is added to the serial data to avoid IBI at the receiver and signal will become:

$$x_n[N-L], .., x_n[N-1], x_n[0], x_n[1], .., x_n[N-L], .., x_n[N-1]$$

where L represents the length of the cyclic prefix. At the receiver, this cyclic prefix is discarded because it gets affected by IBI. 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 1.

3.3 ZigBee

The IEEE standard 802.15.4 commonly known as ZigBee is the most popular choice in Low Rate Wireless Personal Area Networks (LR-WPAN) and WSNs. IEEE standard 802.15.4 has only defined the characteristics of physical (PHY) layer and Medium Access Control (MAC) layer. These characteristics have been adopted by ZigBee. ZigBee has established the specifications for network layer and application layer. In wireless networks, MAC layer allows efficient access of wireless physical medium, wireless node associations, data frame validation and security services. Based on the application requirements, ZigBee based networks can be centralized and/or decentralized [12].

ZigBee based networks can adapt star topology and/or peer-to-peer topology. Star topology offers both contention-based and contention-free wireless medium access to its member nodes. In peer-to-peer topology, nodes can communicate with other nodes within their radio range. Decentralized or peer-to-peer topology based networks support contention-based un-slotted carrier sense multiple access with collision avoidance CSMA/CA wireless MAC protocol. In CSMA/CA protocol nodes compete with each other to access the shared wireless medium. More than 64000 nodes can be connected in ZigBee. ZigBee uses direct spread spectrum sequence (DSSS) transmission technique and offers up to 250 $kbps$ of the data rate in 2.4 GHz frequency band [13] [14]. Spreading techniques are applied to increase the signal bandwidth (BW). DSSS phase shifts a sine wave pseudo-randomly with "chips". These continuous strings or chips are called pseudo-noise (PN) code symbols or PN-sequence. This phenomenon helps to increase the signal power, decrease the interference effects on received signal, allows sharing of spectrum among multiple users and provides resistance against intended or unintended signal jamming. PN-sequence remains known at transmitter and receiver [15].

Fig. 2 shows functional block diagram of IEEE 802.15.4 transceiver. It uses the DSSS as spreading technique. Spreading techniques are utilized to increase the bandwidth of transmitted signal. DSSS phase shifts a sine wave pseudo-randomly with the continuous string of pseudo-noise (PN) code symbols called "chips". This phenomenon 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 the receiver for reconstruction of the symbols. DSSS technique in IEEE 802.15.4 transceiver provides resistance to transmitted signals against intentional or unintentional jamming and allows sharing of a single channel among multiple users. The 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 to $32 - bit$ 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 [16].

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.

3.4 LoRa

$LoRa^{TM}$ is low power wide area wireless network (LP-WAN) protocol for IoTs applications. LoRa utilizes wider band usually of 125 kHz or more to broadcast the signal. LoRa uses the entire channel bandwidth to broadcast a sig-

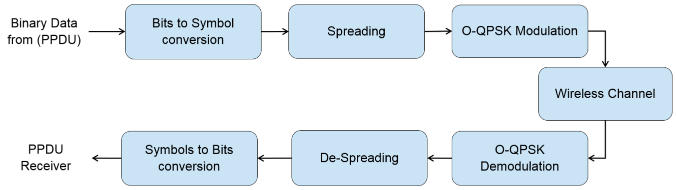

Figure 2: Functional block diagram of IEEE 802.15.4 transceiver.

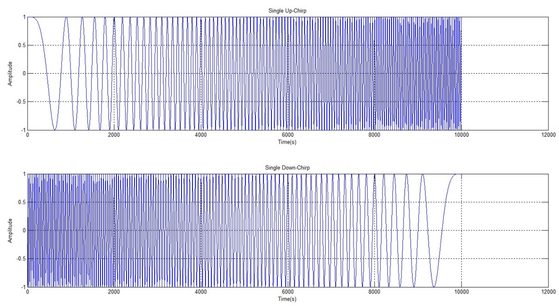

Figure 3: Up-chirp and down-chirp waveform

nal which makes it resistant to channel noise, long term relative frequency, doppler effects and fading. LoRa allows the usage of scalable BW of $125kHz, 250kHz$ or $500kHz$ [17]. Spreading a narrowband signal over wider band makes less efficient use of spectrum unless the end-devices utilize orthogonal sequences and/or different channels which result higher overall system capacity.

The transmitter generates chirp signals by varying their frequency over time and keeping phase between adjacent symbols constant. The transmitted signal is noise alike signal which is resistant to multipath fading and doppler shifts, robust to interferences and jamming attacks and difficult to decode by the eavesdropper. Receiver can decode even a severely attenuated signal 19.5 dBs below the noise level [18]. Chirp spread spectrum (CSS) is a subcategory of DSSS, and it allows to send one bit per each chirp. It takes much larger BW for transmission than actually required for the considered data rate. A single chirp waveform can be defined as:

$$c(t) = \begin{cases} exp(j\phi(t)), & -\frac{T}{2} \leq t \leq \frac{T}{2} \\ 0, & otherwise \end{cases} \tag{2}$$

where $\phi(t)$ is the phase of chirp waveform. Examples of up-chirp and a down-chirp waveform are shown in Figure 3.

4. CUPCARBON SIMULATOR

The simulation of networks is an essential tool for testing the protocols to analyze their performance before deployment. Researchers often use network simulators to test and validate proposed protocols and algorithms. Indeed, such an establishment may be costly and difficult, especially when talking about a large number of nodes distributed over large scale. This is the reason for which the simulation of networks is essential. A network simulator should be quite reliable, accurate and fast. However, the accuracy does not only depends on the implementation of protocols but also on the interference model [19].

CupCarbon [20,21] is a Smart City and Internet of Things WSN simulator. Its objective is to design, visualize, debug and validate distributed algorithms for monitoring, etc., and to create environmental scenarios generally within educational and scientific projects. It can help to visually explain the basic concepts of sensor networks and how they work. It may also support scientists to test their wireless topologies, protocols, etc.

CupCarbon offers two simulation environments. The first environment enables the design of mobility scenarios and the generation of events such as fires and gas as well as the simulation of mobiles such as vehicles and flying objects (e.g. UAVs, insects, etc.). The second simulation environment represents a discrete event simulation of wireless sensor networks which takes into account the scenario designed by the first environment.

Networks can be designed and prototyped by an ergonomic and easy to use interface using the OpenStreetMap (OSM) framework to deploy sensors directly on the map. It includes a script called SenScript, which allows to program and to configure each sensor node individually. From this script, it is also possible to generate codes for hardware platforms such as Arduino/XBee. CupCarbon simulation is mainly based on the application layer of the nodes. This makes it a real complement to existing simulators. It does not simulate all protocol layers due to the complex nature of urban networks which need to incorporate other complex and resource consuming information such as buildings, roads, mobility, and signals etc.

4.1 Sending Process

Figure 4 shows the flow chart to explain the mechanism that is used in CupCarbon. Where N shows the number of attempts, a transmitter can make to send a data packet to receiver node. S is the waiting time in seconds for the acknowledgment from the receiver node, and i is a loop variable. A node will transmit data to another node in the network and will wait for $S = 1sec$ for ACK response. If transmitter node receives the ACK message from the receiver node in $< 1sec$ then it will either continue the communication by sending next data packets or exit the communication otherwise transmitter node will resend its previous data packet assuming that it was lost in the first place. Transmitter node can retransmit the data packet to the receiver for the maximum of $N = 3$ times and will wait for the ACK response for $S = 1sec$ after each transmission. If ACK message from the receiver will not receive at transmitter node, then the receiver node will be considered a dead node.

4.2 Acknowledgments in Transmission

Figure 5 depicts the packet delivery realization. In this case, we have considered two sensor nodes $S3$ and $S4$ in the urban environment, and both nodes are within the radio range of each other in a wireless sensor network. Right up part of the Figure 5 shows that node $S3$ has initialized the communication and transmits data to node $S4$ over the wireless medium, transmission of data is marked by a red arrow in the direction from node $S3$ to node $S4$. Right bottom part of the Figure 5 shows that node $S4$ has successfully received data from node $S3$ and send him an ACK message which is marked by a black arrow in the opposite

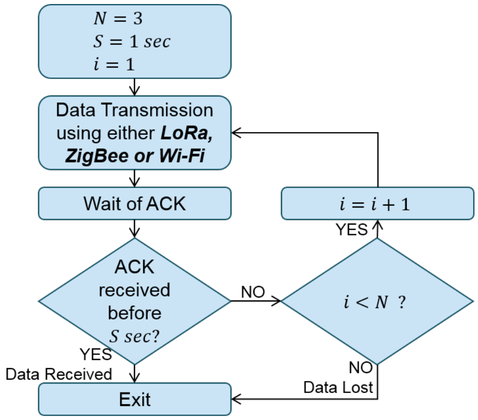

Figure 4: Flow chart for node to node data transmission in CupCarbon.

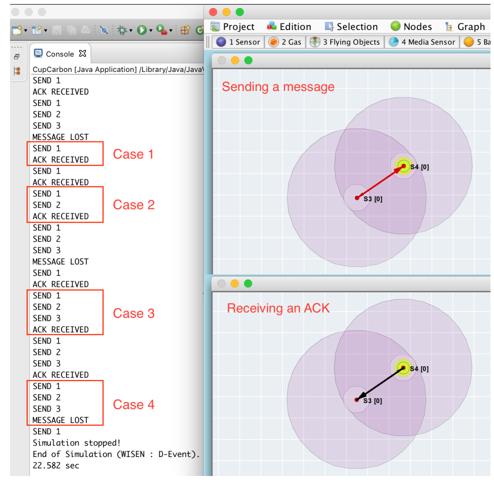

Figure 5: Data transmission and Acknowledgment message visualization in CupCarbon.

direction. According to the retransmission algorithm that is also shown in Figure 11. This transmission over the wireless channel can be affected by impulsive noise and can face four different cases as shown in left part of the Figure 5, which are explained below:

- Case 1: node $S4$ will successfully receives data in first transmission by node $S3$ and will send an ACK message back to transmitter node.
- Case 2: node $S4$ will receive the data in second retransmission by node $S3$ and will send an ACK message back to transmitter node.
- Case 3: node $S4$ will receive the data in third retransmission by node $S3$ and will send an ACK message back to transmitter node.
- Case 4: if $S3$ will not receive ACK message from node $S4$ within $S = 1sec$, then after third retransmission of data it will declare node $S4$ as a dead node and will not make any communication link in future.

4.3 SenScript

SenScript is the script used to program sensor nodes of the CupCarbon simulator. It is a script where variables are not declared, but they can be initialized (set command). For string variables, it is not necessary to use the quotes. A variable is used by its name, and its value is determined by $. It is possible to use the instruction function to add complex and additional functions programmed in Java (in a source code mode only).

4.4 Send Command

Some of the transmission commands used in CupCarbon are mentioned below:

- send hello 2: Sends hello to the sensor having an $id = 2$
- send $\$p$ 2: Sends the value of p to the sensor having an $id = 2$
- send $\$p$: Sends the value of p in a broadcast mode
- send $\$p\ *$: Sends the value of p in a broadcast mode(the same as sens $\$p$)
- send $\$p\ *\ 3$: Sends the value of p in broadcast except the sensor having an $id = 3$
- send $\$p$ 0 4: Sends the value of p to sensors having a MY address equal to 4

5. CONCLUSION

In this work, we have analyzed the performance of PHYs based on Wi-Fi, ZigBee and LoRa technologies. We have proposed an optimal way to integrate their models into CupCarbon, which is a simulator for wireless sensor networks dedicated to smart-cities and IoTs. It is recently developed for a better analysis and understanding of WSNs. It allows to verify new ideas and to compare proposed solutions in a more realistic virtual environment this helps to avoid redundancy, time-consuming and expensive hardware deployments.

6. ACKNOWLEDGMENT

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