802.11 interference. Furthermore, Static channel assignment may not work as planned use to node mobility [1] and incremental Wi-Fi deployments.

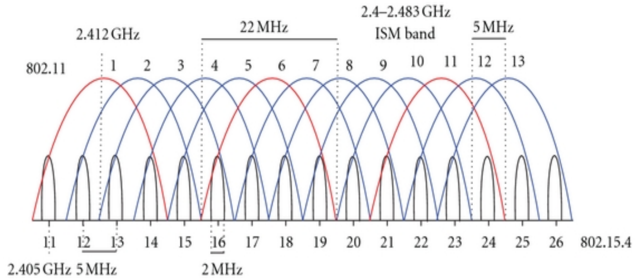

Figure 2: 802.11 b/g and 802.15.4 frequency channels in the 2.4 GHz ISM band. Each 802.11 channel is 22 MHz wide, while 802.15.4 channels are 2 MHz wide

In dynamic channel assignment schemes, different nodes in a sensor network, or the same node over different points in time, will use different 802.15.4 channels to avoid interference from nearby Wi-Fi sources. These mechanisms face two challenges: detect the presence of 802.11 traffic [1, 2, and 4] and coordinate channel selection among 802.15.4 senders and receivers [5]. In addition to the coordination complexity, interference avoidance mechanisms leave large portions of the spectrum unused even when there is little 802.11 traffic in them. This inefficiency is especially damaging for large and dense sensor networks that cannot support the desired application throughput using a single 802.15.4 channel [3, 6]. Instead of trying to avoid interference from 802.11 traffic, the goal of this paper is to study and compare the performance of coexistence of 802.15.4 and 802.11 networks that operate in the overlapping frequency channels. In particular, we make several key observations that previous work has overlooked.

We found that in the time domain, 802.11 packets are typically much shorter than 802.15.4 packets, so they cause burst bit errors in 802.15.4 packets. And large percentage of dropped 802.15.4 packets is due to corruptions in the packet headers, especially when the 802.15.4 transmitter is close to an 802.11 transmitter. More ever when a 802.15.4 node is close to an 802.11 transmitter, a 802.15.4 packet can actually cause the 802.11 transmitter to back off, due to elevated channel energy. When this happens, 802.11 only corrupts the 802.15.4 packet header (which causes frequent packet losses), but the remainder of the 802.15.4 packet is left unaffected. Depending on how 802.11 and 802.15.4 transmitters interact, we partition the interfere domain of the two radios into symmetric and asymmetric regions. We employ simple yet effective header redundancy mechanisms, called Multiple-Headers (MH), to address this packet header corruption problem. MH ends the header multiple times in a single 802.15.4 packet. The first (corrupted) header will cause the 802.11 transmitter to back off, ensuring that the second header can be correctly detected by the 802.15.4 receiver. In asymmetric regions, the 802.15.4 signal is too weak to affect 802.11behaviour.

1. OVERVIEW OF WIFI

Wi-Fi networks are almost ubiquitous in office buildings, homes, and even outdoors in urban areas. Considering that 802.11b, 802.11g, and 802.11n share the same 2.4 GHz ISM band with 802.15.4, 802.11 transmissions can interfere with co-located 802.15.4 networks. In practice, since most Wi-Fi networks use channels 1, 6, and 11, 15.4 channels 15 and 20 can also be interference-free [3]. The potential for 802.11 transmissions to overwhelm 802.15.4 receivers is amplified by the fact that 802.11 radios transmit at 10 to 100 times higher power than 802.15.4 radios. Figure 4, which presents the key features of the 802.11 MAC protocol through a timing diagram, helps us understand how Wi-Fi nodes use the wireless medium. The 802.11 standard specifies using CSMA/CA with ACKs as the MAC protocol, optionally with the addition of RTS/CTS packets [7]. The protocol also specifies the SIFS and DIFS intervals when nodes should defer using the medium. A time period, called the contention window, follows the DIFS as shown in Fig 3. This window is divided into slots Nodes use a uniform random distribution to select a slot and wait for that slot before attempting to access the medium. The node that selects the earliest slot wins while others defeat.

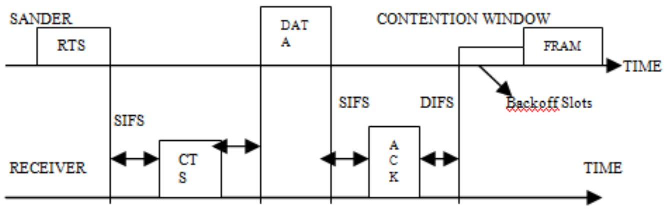

Figure 3: Messages and delays defined in the 802.11MAC protocol. Durations of packet transmissions and time intervals depend on the 802.11 variant used. The leading RTS/CTS exchange is used only for large packets

Nodes initialize their contention window (CW) to 31 slots and double it every time they fail to access the medium, until CW reaches a maximum size of 1023 slots. Table 1 summarizes the duration of the DIFS, SIFS, and back off slots for 802.11b and 802.11g. Also shown are the maximum and minimum packet sizes for 802.11b, 802.11g, and 802.15.4. It is worth noting that for many 802.11b and 802.11g packets, the entire air time is smaller than a 802.15.4 slot time. Based on the relatively small time intervals between 802.11 transmissions, one can easily see that a backlogged 802.11 sender can potentially corrupt the vast Majority of 802.15.4 packets.

Table I. Packet and interval durations for 802.11 and 802.15.4. The length of the contention windows (CW) for 802.15.4 corresponds to the MAC used by TinyOS.

Parameter	802.15.4	802.11b	802.11g
SIFS	N/A	30 µs	10 µs
DIF	N/A	50 µs	28 µs
Slot time	320 µs	20 µs	9 µs
Initial CW	1-32	0-31	0-31

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Successive CWs	1-8	BEB	BEB
Min length packet	352 µs	202 µs	194 µs
Max length packet	4,256 µs	1,906 µs	542 µs

2. OVERVIEW OF ZIGBEE

The IEEE 802.15.4 standard defines a PHY layer for low-rate wireless networks operating in the 2.4 GHz ISM band [9]. The standard defines 16 channels within this band, each 2 MHz wide with 3 MHz inter-channel gap-bands (see Figure 2). According to the standard, outgoing bytes are divided into two 4-bit symbols and each symbol is mapped to one of 16 pseudo-random, 32-chip sequences. The radio encodes these chip sequences using orthogonal quadrature phase shift keying (O-QPSK) and transmits them at 2 M-Chips/s (i.e., 250 kbps).

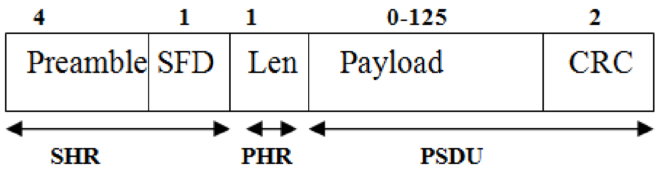

Figure 4: Format of a 15.4 packet. Field sizes are in bytes.

Figure 3 shows the format of a 802.15.4 packet including the Synchronization Header (SHR) and the PHY Header (PHR), shown in grey. The SHR header includes a 4-byte preamble sequence (all bytes set to 0x00) and a 1-byte Start of Frame Delimiter (SFD) set to 0x7A. The PHR includes a 1- byte Length field that describes the number of bytes in the packet's payload, including the 2-byte CRC. The maximum packet size is 133 bytes, including all the headers. The MAC protocol in the 802.15.4 standard defines both beacon-enabled and non-beacon modes. In the beaconless mode, the standard specifies using a CSMA/CA protocol [8]. While the CSMA/CA protocol uses binary exponential backoff, in practice the CSMA/CA protocol implemented in nyOS uses a fixed-length backoff interval [9].

We note that some 802.15.4 radios (e.g., CC2420 [10]) provide a user-defined correlation threshold that controls the maximum Hamming distance between the received 32-chip sequence and the valid SFD sequence that the receiver is willing to tolerate. If this threshold is high, the received signal must closely match the ideal signal, hence the signalto- noise ratio should be high. If this threshold is low, the receiver allows a low signal-to-noise ratio at the expense of potentially interpreting corrupted packets or channel noise as valid packets. The new short range, low power, low rate wireless networking Zigbee complements the high data rate technologies such as WLAN and open the door for many new applications. This standard operates at two bands, the 2.4 GHz band with a maximum rate of 250 kbps and the 868-928 MHz band with data rates between 20 and 40 kbps. Zigbee is based on DSSS and it uses binary phase shift keying (BPSK) in the 868/928 MHz bands and offset quadrature phase shift keying (O-QPSK) at the 2.4 GHz band. While Zigbee is better suited for low rate sensors and devices used for control applications that do not require high data rate but must have long battery life, low user interventions and mobile topology.

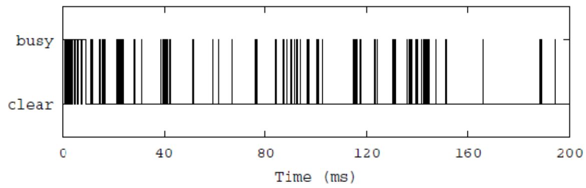

Figure 5: Wi-Fi channel state trace (white spaces between frame clusters)

In fact, the channel utilization ratio in a 802.11-based network is often quite low. As shown in Fig.5, the network traffic is highly bursty with considerable amount of white spaces between frame clusters. Even if this issue can be solved by adopting energy-based CCA, there may be other problems like low power of Zigbee devices. Zigbee devices have a power that is typically 20dB lower than that of Wi-Fi devices. So the Zigbee signals can barely be sensed by Wi-Fi devices while Wi-Fi signals can easily be sensed by Zigbee devices. Even the in-air Zigbee packets can be sensed by Wi-Fi devices, a Zigbee transceiver has a 16 times longer response time and is thus often preempted by Wi-Fi when it switches from sensing to transmission, or from transmission to reception mode.

3. RELATED WORK

1. Based on a study of Zigbee and Wi-Fi coexistence, we reveal that Wi-Fi nodes are often blind terminals of Zigbee nodes due to inadequate carrier sensing mechanism of 802.11 and transmit power asymmetry between Zigbee and Wi-Fi. A Wi-Fi blind terminal fails to detect Zigbee signals and hence can easily corrupt ongoing Zigbee packet reception, which is a major cause of poor Zigbee performance in coexisting environments.

2. Extensive statistical analysis of data traces captured in real-life Wi-Fi networks was conducted. to that, in a channel shared by a group of 802.11 devices, Wi-Fi frames are highly clustered and the arrival process of clusters has the feature of self-similarity. then a Pareto model was presented that accurately characterizes the white space between Wi-Fi frame clusters.

3. An analytical framework that models the performance of a Zigbee link in the presence of Wi-Fi blind terminals. Based on the white space model was proposed, and derive the expected frame collision probability and channel utilization ratio. The results will help a network designer analyse and predict the performance of Zigbee links coexisting with Wi-Fi networks.

Adaptive Frequency Hopping (AFH) is proposed for Bluetooth and Wi-Fi coexistence. AFH is further improved in [14] by sensing and predicting the Wi-Fi behavior using the model proposed in [15]. oPPtX protocol was proposed by Srinivasan et al.[16] to improve the performance of bursty 802.15.4 links. Xinyu Zhang, etc [17] proposed the Cooperative Busy Tone (CBT) mechanism which

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designates a separate node (either a Zigbee client closer to the Wi-Fi transmitter, or a dedicated high-power Zigbee transceiver) as a signaler that emits the busy tone to prevent Wi-Fi preemption. However, all these approaches neglected the probabilistic feature of channel white space. The WISE frame control protocol proposed in [18] exploited the channel white space between frame clusters, but they imposed a relatively simple probabilistic distribution-Pareto distribution of the inter-arrival time of frame clusters over each time windows. By observing Fig.3 we can observe that there are tough correlations between the adjacent white spaces. The inter-arrival times of Wi-Fi frame clusters within a sliding window are not independent of each other.

However, these approaches are calculated for frequency hopping systems, and require the support of cognitive radios for spectrum sensing. Several recent studies have been conducted to mitigate the busty interference on low power 802.15.4 links. [16] Proposed an opportune transmission (OppTx) protocol to improve the performance of busty 802.15.4 links. OppTx measures and quantifies the correlations in packet delivery and loss, and use them to set transmission backoff delay. However, OppTx is oblivious to the probabilistic feature of white space, and hence cannot explicitly utilize the white space in WiFi channel.

4. WHITE SPACE MODELING IN 802.11 B/G NETWORKS

In this section, we study how to model the temporal white space of Wi-Fi networks. The white space model will be used to control the frame transmissions of Zigbee in presence of Wi-Fi blind terminals. Wide geometric analysis on data traces captured in Wi-Fi networks was conducted. That showed in a channel shared by a group of 802.11 devices, the arrival process of aggregate Wi-Fi frame clusters has the feature of self-similarity. Finally we present a Pareto model that accurately characterizes the white space.

4.1 FRAME CLUSTERING

The arrival of Wi-Fi frames is highly bursty and clustered. We observe that frames are clustered together with short intervals typically less than 1 ms, while the idle periods between clusters are significantly longer. The short frame intervals are attributed to the MAC layer contention mechanism of 802.11, in which senders back off for a short random time before each transmission. As in the 802.15.4 [18], the protocol header of Zigbee frame is 17 Bytes, which are transmitted at a rate of 250 Kbps. Therefore, it is very difficult for Zigbee senders to utilize the short Wi-Fi frame inter-arrival times for packet transmission. In the following, we will only focus on modelling the arrival process of Wi-Fi frame clusters where each cluster may include multiple frames spaced by intervals less than 1ms. We define the interval between frame clusters as inter-cluster space whiles the interval between the frames within the same cluster as intra-cluster space. Moreover, white space hereafter refers to inter-cluster space unless otherwise indicated.

5.2 PARETO MODEL 802.11 B/G WHITE SPACE

As discussed above, in a channel shared by a group of 802.11 devices, the arrival process of Wi-Fi frame clusters has the feature of self-similarity. According to [19], the self-similarity is a feature of arrival process with heavy tailed or power law distributed inter-arrival time. In the following, we first give the Pareto model of it with respect to real Wi-Fi data traces. We assume the inter-arrival time of frame clusters within time window T fits Pareto model. That is, the distribution of white spaces follows i.i.d Pareto distribution, which satisfies

$$P_r\{x > t\} = \begin{cases} (\alpha t)\beta, & t > \alpha \\ 1, & otherwise \end{cases} \quad (1)$$

where α and β are the scale and shape of Pareto model respectively. In Pareto model, β is given by $\lambda/\ \lambda-\alpha$, where λ is the average inter-arrival time of frame clusters.

5. WHITE SPACE ADAPTATION

As discussed in previous sections, Zigbee suffers poor PDR when its channel is shared by a closely deployed Wi-Fi network, due to the collision with packets from blind Wi-Fi terminals. A straight forward method to improve PDR is to use small packet size for Zigbee. However, considering the protocol overhead introduced by PHY and MAC layer headers, the throughput efficiency achieved by small packets is very low. It is therefore desirable to achieve a balance between PDR and efficiency. To this end, we propose a frame control protocol called White Space-aware frame adaptation (WISE) for Zigbee networks. WISE predicts the length of white space in Wi-Fi traffic based on the Pareto model, and intelligently adapts frame size to maximize the throughput efficiency.

By Optimizing Sub-Frame in Wi-Fi terminals which cannot sense the signal of Zigbee, if transmission of 802.15.4 is not completed and a next Wi-Fi frame cluster arrives collisions occurs. Therefore to minimized this chances of collision the time of Zigbee transmission should be shorter than the remaining time of current Wi-Fi frame space. Let ρ be the white space age when a frame is ready for transmission. As the lifetime of white space follows the Pareto model defined in Eq. (2), we have the following conditional collision probability $C(\tau, \rho)$ for a given frame size τ

$$C(T,\rho) = P_r\left\{ t < \rho + \frac{T}{D} \middle| \rho \right\} = 1 - \left(\frac{\rho}{\frac{T}{D}\middle|\rho} \right)^{\beta} \quad (2)$$

where D is the channel rate of Zigbee, α and β are the scale and shape of the Pareto model of white space. The aim of frame adaptation of WISE is to maximize the effectiveness of transmission while limiting the collision probability under requirement. Given a specific collision probability threshold T, the optimization problem of WISE frame adaptation can be formulated as follows:

$$\text{Maximize} \quad \tau \tag{3}$$

$$\text{Subject to} \quad C(\tau, \rho) < T \tag{4}$$

$$\tau \leq M \tag{5}$$

where M is the maximum frame size of Zigbee. Solving the problem, we obtain the optimal sub-frame size:

$$\tau = \text{Min}\,\{\rho \times \gamma, M\} \tag{6}$$

where γ is given by

$$\gamma = D \times \left((1-T)^{-\frac{\lambda-\alpha}{\lambda}} - 1\right) \tag{7}$$

Where λ is the mean in the Pareto model.

VII. ZIGBEE LINK MODELING

On the basis of Pareto white space model, we will derive the expected frame collision probability. In the presence of Wi-Fi interference the result will help network designers predict the performance of Zigbee networks. Wi-Fi blind terminal for a precise Zigbee link as follows: 1) Zigbee sender will defer if the blind terminal is transmitting; and 2) Zigbee frame will be colliding with the transmitting frames from the blind terminal. We list the notation used in our analysis in Tab. II. We assume that the channel is shared by a set of k blind terminals $\mathcal{B}$ = {$\mathcal{B}$i, i= 1...k}. The channel condition of a Zigbee sender is modelled by < α, β, u, w>, where w is the percentage of white space, u is the channel utilization ratio of $\mathcal{B}$. α and β are parameters of the Pareto model given in Eq. (1), which characterize the distribution n of the white space in the channel. We now derive the probability of collision between Zigbee and Wi-Fi frames. The main objective of our analysis is to characterize the expected performance of a Zigbee link solely based on the transmitter's view of channel condition. It will force a frame transmission if the maximum number of CCA tries is reached after each conduct of CSMA of Zigbee. A forced transmission will cause the Zigbee frame to collide with the in-air blind terminal frame. As all forced transmission is ignore the possibility because it occurs rarely. Therefore, by directly underestimate the overall collision probability. We analyse the following cases: a) the collision probability when Zigbee transmits a frame in intra-cluster space, denoted by $Ca(\tau)$, and b) the collision probability when Zigbee transmits a frame in inter-cluster space, denoted by $Cb(\tau)$, where τ is the Zigbee frame in-air time. For a arbitrarily arrived Zigbee frame, the probability that it starts to transmit between two Wi-Fi frames within the same frame cluster is the fraction of frame interval in the total clear channel time. It is given by

$$p_a = \frac{1-u-\omega}{1-u} \tag{8}$$

when the inter-arrival time of frames is shorter than 1 ms, the in-air time of a Zigbee frame of reasonable size will always be longer than the Wi-Fi frame intervals, which will cause a collision between Zigbee and Wi-Fi frames. So we have $Ca(\tau)$= 1. For a randomly arrived Zigbee frame, the probability that it starts to transmit in white space is the fraction of white space in the total clear channel time, which is given by

$$p_b = \frac{\omega}{1-u}.$$

TABLE II: NOTATION USED IN WHITE SPACE MODELING

τ	Packet size of Zigbee
H	Header size of Zigbee.
M.	Maximum packet size of Zigbee
D	Data rate of Zigbee.
λ	Average white space lifetime.
ω.	Fraction of channel time that is white space
u	Channel utilization ratio of Wi-Fi.

The CSMA of Zigbee will perform backoff if the channel is busy upon the arrival of frame. The backoff will always line up the start of Zigbee transmission with the start of white space. In this case collision occurs only when the white space lifetime is shorter than Zigbee frame in-air time. Note that there we will underestimate the collision probability since we ignore the actual age of white space when the Zigbee senses a clear channel. However, the inaccuracy caused by this assumption is not significant due to the short back off interval of Zigbee MACs. Denote the expected collision probability by $C_b^0(\tau)$, it satisfies

$$C_b^0(\tau) > F\left(\frac{\tau}{D}\right) = 1 - \left(\frac{\alpha}{\tau}\right) \tag{9}$$

Where F *is* the CDF of Pareto distribution.

When a Zigbee frame arrives within white space, Zigbee will send the frame without backoff. In this case the white space age is uniformly distributed over the entire white space lifetime. Given that the white space lifetime is ℓ, collision occurs if the frame arrives $\ell - \tau$ later than the start of the white space. Its probability is given by min $\left\{\frac{\tau}{\ell}, 1\right\}$. We consider an arrival process of *k frame* clusters *X* = {*X*1, ...,*Xk*}, and denote the set of white spaces by *L*= (ℓ1, ..., ℓk), where ℓi is the time interval between *Xi*−1 and *Xi*. The arrival time of Zigbee frame is uniform ally distributed over *L*. The probability that the Zigbee frame falls into the ℓi is given by $\frac{\ell i}{\sum_{j=1}^{k} \ell j}$ Denote the expected collision probability by $C_b^1(\tau)$, it is given by

$$C_b^1(\tau, k) = \sum_{i=1}^{k} \left(\frac{min\left(\frac{\tau}{D}, \ell i\right)}{\ell i} \times \frac{\ell i}{\frac{\ell i}{\sum_{j=1}^{k} \ell j}} \right) \tag{10}$$

As the number of frame clusters ranges from 1 to ∞, we have

$$C_b^1(\tau) = \frac{\int_0^\infty min\left(\frac{\tau}{D}, \ell i\right) fp(\ell) d\ell}{\int_0^\infty \ell\, f(\ell) d\ell} = 1 - \frac{1}{\beta}\left(\frac{\alpha D}{\tau}\right)^{\beta-1} \tag{11}$$

Where f(.) is the PDF of Pareto distribution.

The probability that the channel is busy upon the arrival of Zigbee frame is the fraction of Wi-Fi transmission time, which is given by Wi-Fi channel utilization *u*. Therefore the expected collision probability for transmission of frame in white space is given by

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$$\mathcal{C}_b(\tau) = u\mathcal{C}_b^0(1-u)\mathcal{C}_b^1(\tau) \quad (12)$$

According to Eq. (10) and Eq.(11), we have

$$\bar{\mathcal{C}}_b(\tau) > 1 - \left(\frac{\alpha \bar{D}}{\tau} + \frac{(1-\bar{u})}{\beta}\right)\left(\frac{\alpha D}{\tau}\right)^{\beta-1} \quad (13)$$

Note that for Pareto model, $\beta > 1$. Putting all together, the overall expected collision probability $\mathcal{C}(\tau)$ is given by

$$\mathcal{C}(\tau) = p_a\, \mathcal{C}_a(\tau) + p_b\, \mathcal{C}_b(\tau) \quad (14)$$

Since β is given by $\beta = \frac{\lambda}{\lambda-\alpha}$ and $\frac{\omega}{1-u} < 1$. Using Eq. (13) & Eq. (14), the overall expected collision probability satisfies:

$$\mathcal{C}(\tau) > 1 - \left(1 + \left(\frac{\alpha D}{\tau} - 1\right) u\right)\left(\frac{\alpha D}{\tau}\right)^{\frac{\alpha}{\lambda-\alpha}} \quad (15)$$

DISTRIBUTED ADAPTATION

Propose distributed channel selection algorithms to improve the 802.15.4 performance and robustness in presence of 802.11 interference. The effectiveness of these approaches will be assessed in a time varying environment. Scanning based distributed approaches it is possible to outperform the random frequency selection algorithm, since the considered 802.11 interference does not vary every 802.15.4 period. We propose here new scanning based approaches relying on the simulated annealing optimization method, which can be sophisticatedly implemented in the considered network setup. Simulated annealing is a very effective heuristic optimization strategy for finding a global optimum, developed by Metropolis [20]. The essential idea of the method is to sample the search space using a Gaussian distribution, and to anneal this distribution as the optimum is approached. Applied to the present context, nodes have to keep looking for another channel (i.e., sampling the search space). Every period, next to the node *i*s current frequency channel *fi*, another channel *frandom* is considered and its performance is assessed. This is done according to a given channel quality metric *G*. The latter metric is computed based on the one hand on the output of the built-in 802.15.4 energy detector [21] that enables to capture the presence of 802.11 interference, and on the other hand on the number of beacons heard in the scanned channel. It is assumed that no beacons can be heard in the presence of 802.11 interference. The metric *G* is defined as:

$$G = \begin{cases} \sum \text{beacons heard} + 1 & \text{if no energy detected,} \\ 0 & \text{if energy detected} \end{cases} \quad (16)$$

The channel quality is assumed to be equal to 0 (worst case) When 802.11 interference is present, When no 802.11 interference is present, the channel quality is assumed to be proportional to the number of heard beacons, augmented by one to distinguish from the aforesaid worst case. Typically, this annealing follows an exponential distribution. Obviously, the higher the quality metric *G*, the better the current solution and the closer the system is to the global optimum (i.e., full connectivity in a channel free of 802.11 interference). In the proposed algorithm, *frandom* is accepted with probability:

$$\exp\left(-G(fi)/A\right) \times \{G(frandom) > 0\}, \quad (17)$$

Where A is a normalization factor and where the second condition ($G(frandom) > 0$)) avoids the system to swap to a new channel where 802.11 interference is present (corresponding to G=0).

IX. ZIGBEE AND IT'S SPECTRUM SHARING WITH WLAN

At the physical layer Zigbee operates in the ISM band within three different frequency ranges. There is a single channel between the 868 and 868.6MHz, Ch 0, 10 channels between 902.0 and 928.0 MHz, Ch1-10, and 16 channels between 2.4 and 2.4835GHz, Ch11-26. The Zigbee standards specify a receiver sensitivity of -92 dbm in the 868/915 MHz band and -85 dbm in the 2.4 GHz band. The physical layer of both frequency bands uses the same common frame structure as shown in Figure 1. Having several channels in different frequency bands makes it possible to relocate within the available spectrum.

PREAMBLE 4 byte	Start of Packet 1 byte	Length Field 1byte	Physic layer Payload (2 – 127 bytes)

Figure 6: The frame structure for the IEEE 802.15.4 physical layer

The Zigbee standards define two types of devices, a full function device (FFD) and a reduced function device (RFD). The FFD can operate in three different modes, a personal area network (PAN) coordinator, a coordinator or a device. The RFD is intended for very simple applications that does not require the transfer of large amount of data and needs minimal resources. A WPAN is formed when at least two devices are communicating one being an FFD assuming the role of a coordinator. Depending on the application requirements, Zigbee devices might operate either in a star topology or a peer-to-peer topology. Figure 7 shows both topologies. As seen in Figure 7, in a star topology the flow of communication is established between devices and an FFD acting as the PAN coordinator. The PAN coordinator is a device that is responsible for initiating, terminating and routing information around the network. The star topology is mostly used in small areas such as home automation, personal health care management and hospital rooms while the peer-to-peer topology is used in larger scale and more complex networks. There are three types of data transfer mechanisms exist between Zigbee devices: from a coordinator to a device, from a device to a coordinator and between two peer devices. The data transfer mechanism used depends on whether the network supports the transmission of beacons or not. For example, in a non-beacon-enabled network, a device simply transmits its data frames using the un-slotted CSMA-CA, to the coordinator. However, in a beacon enabled network, the device first listens for the network beacon and at the right time, it transmits its data frames, using slotted CSMA-CA, to the coordinator. In a peer-to-peer network, every device can communicate with any other device within its transmission radius using one of two options: by constantly listening to the channel and transmitting its data using un-slotted CSMA-CA or by synchronizing with other nodes so that they can save power.

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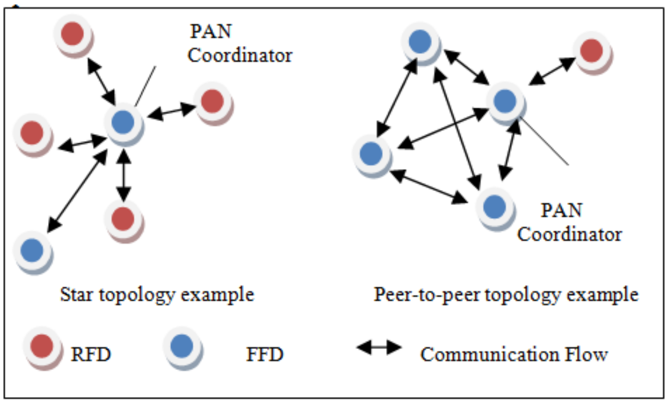

Figure 7: Zigbee star and peer-to-peer example topology

SPECTRUM SHARING

With the increased use of devices operating at the 2.4 GHz band the WLAN and Zigbee devices are likely to be in close proximity to one another with possible interference. To understand the aspects of this problem the RF spectrum at 2.4 GHz and available channels for Wi-Fi (IEEE 802.11 b, g) and Zigbee is shown in Figure 8. As seen in Figure 3, the RF channels in Zigbee and Wi-Fi overlap and that generates a concern when such devices are within close proximity.

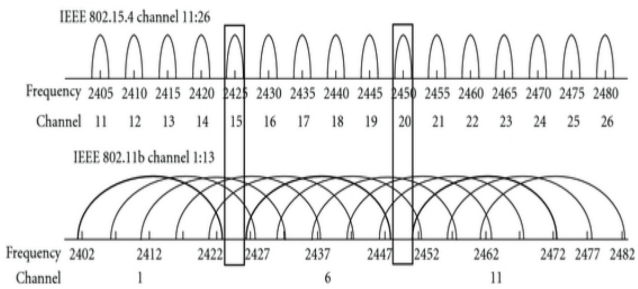

Figure 8: RF Spectrum for Zigbee and WiFi

EVALUATION

In this section, we study the evaluation results of WISE. Study the implemented WISE in TinyOS 2.x on TelosB motes equipped with 802.15.4 radios. We find without low power listening employ CSMA-based BMAC [14], which is the default MAC in TinyOS. Implementation of WISE did not require any change in B-MAC's implementation. Unless otherwise indicated, the transmit power is set to -7 dBm, which assures good delivery performance for each Zigbee link in our setup. Our evaluation focuses on three performance metrics: Frame delivery ratio, throughput, and throughput overhead. Throughput is measured as the total number of bytes of impactive payloads delivered in one second. Throughput overhead is defined as ——, where □□ is the total number of bytes transmitted per second, and □□ is the throughput. Thus the throughput overhead quantifies the additional bytes transmitted by the sender to deliver one byte of imp-active payload. We compare WISE to two baseline protocols: 1) B-MAC without WISE and 2) the opportune transmission (OppTx) protocol proposed in [16]. OppTx is a state-of-the-art low-power sensor network protocol designed to mitigate the impact of interference. It significantly improves the throughput of bursty links by transmitting back-to-back packets and controlling the back off delay when a failure occurs [16]. For a fair comparison, the back off delay of OppTx is always tuned to the optimal value. In contrast to WISE, OppTx is oblivious to Wi-Fi traffic and hence cannot explicitly utilize white space in Wi-Fi channels.

CONCLUSIONS

In this paper an extensive and comprehensive study was done to observe the interference effect of Zigbee devices on the throughput performance of the IEEE W-LAN and vice versa.

Zigbee interference has more effect on the IEEE 802.11g uplink rather than the downlink. Furthermore, the results show how IEEE 802.11g is greatly more affected by Bluetooth than Zigbee and how IEEE 802.11g affects the performance of Zigbee when the spectrum of the chosen channels of operation co-inside. Pareto model accurately characterize the white space in Wi-Fi traffic. WISE - a new Zigbee frame control protocol, which allows Zigbee networks co-existing with Wi-Fi to achieve desired link throughput and delivery ratio. WISE achieves 4x and 2x performance gains over B-MAC and a recent reliable transmission protocol, respectively, while only incurs 10.9% and 39.5% of their overhead. More ever adapting the number headers reduces wastage of power.

There is an optimal 802.11 packet length for which the channel utilization of any 802.15.4 network in its proximity doubles when compared with what it would be for normal 802.11 packet length of 1500 bytes.

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