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On Enhancing Technology Coexistence in the IoT Era: ZigBee and 802.11 Case

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ABSTRACT ZigBee is often chosen as a technology to connect things because of characteristics, such as network resilience, interoperability, and low power consumption. In addition, Zigbee Pro, with its Green Power feature, allows low-power networking capable of supporting more than 64 000 devices on a single network, making it an excellent choice to connect things. However, in recent years, we have witnessed the proliferation of smart devices using either 802.11 or ZigBee technologies, which operate in the same frequency band. Proposing and developing techniques that may improve the fair operation and performance of these technologies in coexistence scenarios have been a major concern in industry and academia. In this paper, we propose the use of traffic prioritization for ZigBee nodes in order to improve their performance when coexisting with IEEE 802.11 nodes. We develop an analytical model based on Markov chains, which captures the behavior of channel access mechanisms for both 802.11 nodes and different ZigBee priority class nodes. Based on extensive simulations, we validate the accuracy of the proposed model, and demonstrate how traffic prioritization of ZigBee nodes effectively improves their performance when coexisting with 802.11 nodes. We also demonstrate that this improvement comes at the cost of negligible degradation in the performance of the 802.11 nodes.

INDEX TERMS Internet of things, ZigBee, WiFi, cross technology interference.

I. INTRODUCTION

ZigBee is an open wireless standard designed to provide a foundation for the Internet of Things (IoT) by enabling everyday objects to work together. ZigBee is often chosen as a technology to connect things because of characteristics such as network resilience, interoperability, and low power consumption. ZigBee is based on mesh interconnectivity, wherein if an object is faulty, the other objects will continue to communicate. Objects using Zigbee are interoperable, as the standard specifies how objects interoperate in addition to how they communicate. Also, Zigbee Pro [1] with its Green Power feature, allows low-power networking capable of supporting more than 64,000 devices on a single network, making it an excellent choice to connect things. However, problems of coexistence between ZigBee and 802.11 networks (WiFi) which operate in the same frequency band can significantly degrade ZigBee nodes operation. In this paper, we are concerned about this serious coexistence issue.

Indeed, in recent years, we witnessed the proliferation of smart wireless devices such as smartphones, and tablets for ubiquitous Internet access, and sensors, or actuators within the home for home automation purposes [2]. Due to the lack of available spectrum, the technologies used by these smart devices (IEEE 802.11 for smartphones and tablets, or ZigBee for sensors and actuators) operate in the same 2.4 GHz unlicensed industrial, scientific, and medical (ISM) bands. Therefore, with the increasingly deployment of these smart wireless devices in the same environment, we assist to an excessive additional amount of interference which degrade the performance of these coexisting network, and this degradation is very pronounced for ZigBee nodes.

To avoid this Cross Technology Interference (CTI) problems, new standards for WiFi such as IEEE 802.11n [3] or IEEE 802.11ac [4] exploit the 5 GHz frequency band. However, the market migration to the 5 GHz band has not been complete. In fact, the 2.4 GHz band remains the most used unlicensed band in the world making it a technology candidate for wireless connectivity for the IoT paradigm. Hence, IEEE 802.11 and ZigBee CTI problems remain unsolved.

In general, techniques proposed in the literature to improve the coexistence of Wireless Local Area Networks (WLAN) using IEEE 802.11 and Wireless Personal

Area Networks (WPAN) using IEEE 802.15.4 (ZigBee and IEEE 802.15.4 will be used interchangeably in the rest of the paper) in the 2.4 GHz ISM band basically depend on several aspects such as the type of modulation, the transmission power, the spread spectrum, the load, packet size, the geographical distribution of the interacting nodes, etc. A survey of such techniques [5] pointed out that the solutions proposed to mitigate the CTI between 802.11 and 802.15.4 networks can be categorized to a set of solutions proposing to spatially separate 802.15.4 networks from 802.11 networks, and a set of solutions implementing additional mechanisms to make ZigBee networks and WiFi networks more friendly.

However, many of these works [6]–[16] reflect on experiments whose generalization depends on the data and environments considered. In order to bring about solutions to mitigate or solve CTI interference between 802.11 and 802.15.4, an accurate analytic modelling of their coexistence needs to be performed.

In this paper, we propose a systematic approach to study the coexistence of IEEE 802.15.4 and IEEE 802.11. Our approach relies on an analytical framework based on Markov chains; the advantage of such approach is that it captures the steady state behavior of the system, and allows the derivation of insight metrics such as the throughput, the probability of failed transmissions, etc. In addition, as a way to improve the coexistence between 802.11 nodes and 802.15.4 nodes, we propose the use of traffic prioritization of 802.15.4 nodes by tuning their minimum contention window and their number of CCA to be performed before transmitting.

Our contribution can be summarized as follows:

- We propose the use of traffic prioritization of 802.15.4 nodes by implementing two groups of 802.15.4 node classes which differ by the number of CCA to be performed before transmitting, and by the value of the minimum contention window.
- We propose an analytical framework based on Markov chains that models each type of node (802.11 nodes and 802.15.4 nodes of different class), and which takes into account the difference between the time slots in IEEE 802.11 and IEEE 802.15.4.
- Based on extensive simulations, we analyze the performance of several priority classes of 802.15.4 nodes in presence of 802.11 nodes.

The rest of the paper is organized as follows. We briefly give an overview of the channel access mechanisms in both IEEE 802.11 and the slotted IEEE 802.15.4 in Section II. In Section III, we present the most salient assumptions while emphazing some key notations used in this work. We detail, in Section IV, the analytical and system model for the coexistence of the 802.11 nodes and the 802.15.4 priority class nodes. In Section V, we derive the analytical metrics to evaluate the proposed model. In Section VI, we present the numerical results and we discuss the performance of both 802.11 nodes and 802.15.4 nodes. We present some related work in Section VII, and we conclude this work in Section VIII.

II. OVERVIEW OF CHANNEL ACCESS MECHANISMS IN IEEE 802.15.4 AND IEEE 802.11

A. OVERVIEW OF THE SLOTTED IEEE 802.15.4 CSMA/CA

In beacon-enabled mode [17], the coordinator periodically transmits a beacon to identify its network, to synchronize the nodes associated with it, and to delimit the superframe time structure that organizes communication in the network. The superframe comprises a beacon, followed by an active period in which all the communication takes place. Optionally, an inactive period may follow the active period to allow nodes to power down to conserve their energy. The active period further comprises a contention access period (CAP) in which nodes contend to access the channel using the slotted CSMA/CA algorithm; optionally the active period can also have a contention-free period (CFP) in which the coordinator controls the channel access by assigning guaranteed time slots (GTS) to those nodes which request them. Note that in the CAP, nodes are synchronized and can begin transmission only at the boundaries of time limits called *backoff slots*. The duration of one backoff slot is *aUnitBackoffPeriod* (default value=3.2 ms). When a node has a new data frame waiting for transmission at the MAC buffer, it first initializes the three relevant contention parameters, namely the number of random backoff stages experienced (NB) to 0, the current backoff exponent (BE) to *macMinBE* (default value $=$ 3) and the contention window (CW) (default value $= 2$). Then, the node selects a backoff counter value uniformly from the window $[0, 2^{BE} - 1]$. This backoff counter value is decremented by one for each backoff slot regardless of the channel state. When the backoff counter reaches zero, the node performs carrier sensing that consists of clear channel assessment (CCA) for the next CW consecutive backoff slots. If the channel is sensed idle during the first CCA, CW is decremented by one and the node performs the following CCA at the next backoff slot boundary. Only when the channel is assessed idle during the CW consecutive CCAs, the node will be able to start transmission in the next backoff slot. Otherwise, the node will enter the next backoff stage; it will increase the values of NB and BE by one, reset CW to its initial value and draw a new random number of backoff slots from the updated window $[0, 2^{BE} - 1]$ to wait before the channel may be sensed again. This procedure is repeated until the frame is transmitted, or a channel access failure is declared. The latter occurs when NB reaches a maximum number of *macMaxCSMABackoffs* allowed random backoff stages (default value=5). Note that BE shall not be incremented beyond its maximum value *aMaxBE* (default value=5); after this value, BE is frozen to *aMaxBE*.

B. OVERVIEW OF THE 802.11 DCF

A node which uses the 802.11 DCF scheme (802.11 node) to transmit a new packet senses the channel activity. If the channel is sensed idle for a period of time corresponding to the

Distributed InterFrame Space (DIFS),[1] the node transmits. Otherwise the node sets the backoff counter (BC) to a random backoff time uniformly chosen between 0 and $CW - 1$, where CW, the contention window, is set to the minimum value CW_{min} at the initiation of the transmission of a new packet. At any backoff state, if the channel is found busy, the BC is frozen until the channel is sensed idle for a DIFS period, at which time BC is decremented by one. When BC reaches zero, the node proceeds to the transmission. Upon successfully receiving a packet, the receiver has to send a short ACK packet after the channel is sensed idle for a Short InterFrame Space (SIFS) time. If the source node does not receive the ACK packet, the CW for backoff time is doubled up to the maximum value CW_{max}. When the value of CW exceeds CW_{max}, the packet is dropped.

III. SUMMARY OF ASSUMPTIONS AND NOTATIONS

We consider a 802.11-based network co-located with a 802.15.4-based network, and sharing the same spectrum band. For our analysis, the most important assumptions and approximations are herein summarized: (1) 802.11 nodes (resp. 802.15.4 nodes) can detect each other transmissions if they are in their detecting range; (2) 802.15.4 nodes packets are of the same size, and 802.11 packets are also of the same size; (3) all of the active period of the IEEE 802.15.4 superframe is dedicated to the CAP; (4) all the 802.15.4 nodes are time-synchronized with the coordinator's beacon; we consider only direct transmission and the coordinator does not acknowledge the reception of the packets; (5) we consider that nodes always have a packet ready for transmission; (6) in order to have the backoff procedure memoryless for simplicity of the IEEE 802.15.4 Markov chain analysis, we replace the uniform distribution specified in the IEEE 802.15.4 standard [17] with a geometric distribution of the same mean number of backoff slots; (7) we consider only one type of priority class of 802.15.4 nodes for each analysis; (8) we assume ideal channel conditions, i.e., a failure transmission occurs only upon collisions.

Notation: Unless stated otherwise, all probabilities associated with channel states have a superscript 'c' (e.g., p_i^c), and those associated with node states have a superscript 'w' for 802.11 nodes and 'z_q' for class-q 802.15.4 nodes (e.g., $\pi^w_{1,j,0}$; $p_t^{z_q}$).

IV. SYSTEM MODEL

A. 802.11 NODES STATE MODEL

For 802.11 node modelling, we use the Markov model presented by Foh and Tantra [18]. The behavior of each 802.11 node is by means of a discrete-time Markov chain as depicted in Fig. 1: the state of a 802.11 node at a particular time unit is represented by the triplet $\{i, j, k\}$, where i indicates whether the previous time unit was idle ($i = 0$) or busy ($i = 1$); $0 \leq j \leq m$ indicates the current backoff stage, and $0 \leq k \leq W_{j-1}$ is the current backoff counter, with $W_j = 2^j W_0$. Let p_0 (resp. p_1) be the probabilities (from a node point of view) that at least one of the other nodes (both 802.11 nodes and 802.15.4 nodes) transmits during a time unit after an idle (resp. busy) time unit period, we have

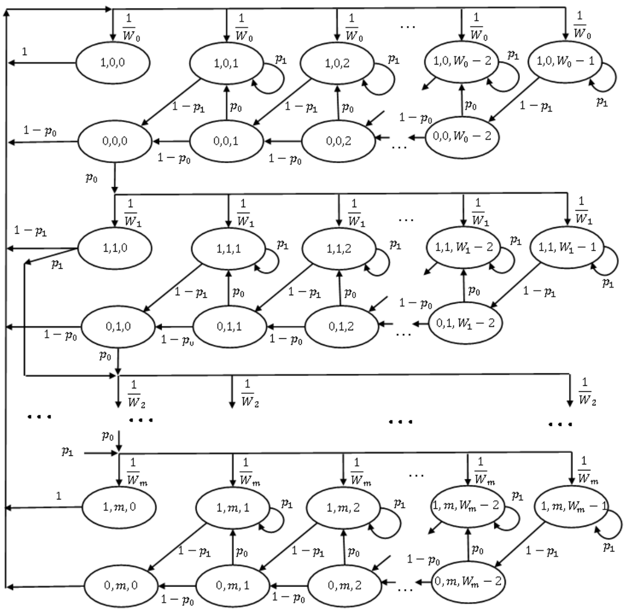

FIGURE 1. Embedded Markov chain model for 802.11 node.

$$p_0 = 1 - (1 - \tau_0^w)^{M-1}(1 - p_{t|i_J}^{z_q})^N, \tag{1}$$

$$p_1 = 1 - (1 - \tau_1^w)^{M-1}. \tag{2}$$

In (1) and (2) M representing the number of 802.11 nodes; N represents the number of 802.15.4 nodes; τ_0^w (resp. τ_1^w) is the probability that a 802.11 node accesses the channel after an idle (busy) period; and $p_{t|i_J}^{z_q}$ is the probability that a 802.15.4 node begins transmission given that it found the channel idle in the J previous time units. Owing to the chain regularities, we derive the steady-state probabilities as follows:

$$\pi^w_{1,0,0} = \frac{1}{W_0}\Big[\pi^w_{1,0,0} + \pi^w_{1,m,0} + \pi^w_{0,m,0} + (1-p_0) \times \sum_{u=0}^{m-1} \pi^w_{0,u,0} + (1-p_1)\sum_{u=1}^{m-1} \pi^w_{1,u,0}\Big] \tag{3}$$

$$\pi^w_{1,1,0} = \frac{p_0}{W_1}\pi^w_{0,0,0} \tag{4}$$

$$\pi^w_{1,j,0} = \frac{\sum_{i=0}^{1} p_i \pi^w_{i,j-1,0}}{W_j}, \quad 2 \leq j \leq m \tag{5}$$

$$\pi^w_{1,j,k} = \begin{cases} \dfrac{\pi^w_{1,j,0} + p_0 \pi^w_{0,j,k}}{1-p_1}, & 1 \leq k \leq W_j - 2, \quad \forall j \\ \dfrac{\pi^w_{1,j,0}}{1-p_1}, & k = W_j - 1, \quad \forall j \end{cases} \tag{6}$$

$$\pi^w_{0,j,k} = \begin{cases} \sum_{i=0}^{1}(1-p_i)\pi^w_{i,j,k+1}, & 0 \leq k \leq W_j - 3, \quad \forall j \\ (1-p_1)\pi^w_{1,j,k+1}, & k = W_j - 2, \quad \forall j \end{cases} \tag{7}$$

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[1] To avoid channel capture, even if the channel is sensed idle for a DIFS period, a node must delay a random backoff time between two consecutive new packets transmissions.

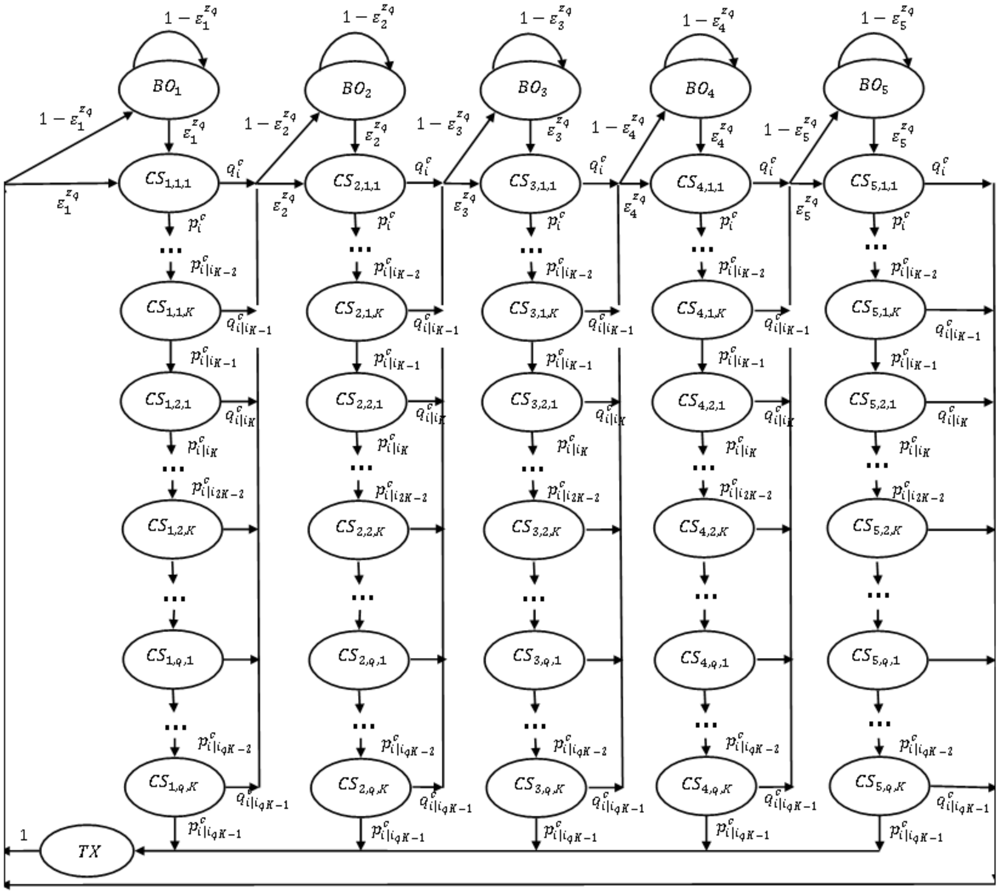

FIGURE 2. Embedded Markov chain model for 802.15.4 class-q node.

$$1 = \sum_{j=0}^{m}\left(\sum_{k=0}^{W_j-2}\pi^w_{0,j,k} + \sum_{k=0}^{W_j-1}\pi^w_{1,j,k}\right). \tag{8}$$

B. 802.15.4 NODES STATE MODELS

We present here, our modelling of the behavior of each proposed class of 802.15.4 node by means of a corresponding discrete-time Markov chain. Initially, a 802.15.4 class-q node spends in backoff state BO_1 a random number of 802.15.4 backoff slots X_1 geometrically distributed according to $P[X_1 = k] = (1-\varepsilon_1^{zq})^k\varepsilon_1^{zq}$ for $k = 0, 1, \cdots, \infty$, where the parameter ε_1^{zq} is set to $1/4.5$, so that the corresponding random distribution has the same mean number of 802.15.4 backoff slots as its counterpart IEEE 802.15.4 uniform backoff distribution, i.e., 3.5 [19], [20].

Upon leaving the backoff stage BO_1, a 802.15.4 class-q node moves to carrier sensing state CS_{111}, which corresponds to performing the first CCA. Since, we consider the presence of both 802.11 nodes and 802.15.4 nodes, and given that the carrier sensing duration of a 802.11 node is smaller than the CCA duration of 802.15.4 nodes, then in presence of 802.11 nodes, a CCA of 802.15.4 nodes is seen as $K = \lceil CCA/\delta_w \rceil$ consecutive smaller CCA which we refer to as CCA* of duration corresponding to DIFS_w.

Therefore, if the channel is found idle in the first CCA*, which occurs with some probability noted p_i^c, the 802.15.4 class-q node moves to state $CS_{1,1,2}$, and "proceeds" to the second CCA*. If the channel is again found idle with some probability noted $p^c_{i|i}$, this sensing process would be repeated until the 802.15.4 class-q is able to complete without interruption all the required $J = qK$ CCA* before the node moves into TX state (see Figure 2). Note that the number of CCA* required for a 802.15.4 class-1 node is K (corresponding to state $CS_{1,1,K}$), and the transition probability from state $CS_{1,1,j}$ to state $CS_{1,1,j+1}$ is the conditional probability, $p^c_{i|i_{j-1}}$, that the channel is found idle at the jth CCA* given that the channel was idle in the $j-1$ consecutive previous CCA*. After completing the first normal CCA, a 802.15.4 class-1 node will move into TX state, whereas a 802.15.4 class-2 node will start another round of K CCA* in order to complete the second normal CCA before going into TX state. We assume that the transmission duration for any 802.15.4 class-q node corresponds to L_z CCA* duration. If the channel is found busy in any carrier sensing state $CS_{1,1,j}$, $1 \le j \le 2K$, which happens with probability $1 - p^c_{i|i_{j-1}}$, then the 802.15.4 class-q node transitions into the second backoff stage BO_2. It then repeats the same backoff and clear channel assessment procedure as in the first stage, where the backoff parameter $\varepsilon_1^{z_q}$ is updated to $\varepsilon_2^{z_q} = 1/8.5$ to reflect the fact that $BE = 4$ for BO_2. The number of 802.15.4 backoff slots X_2 the node spends in BO_2 is again geometrically distributed: $P[X_2 = k] = (1-\varepsilon_2^{z_q})^k \varepsilon_2^{z_q}$. In general, we adopt the notation $BO_{1 \le i \le 5}$ to represent the 5 random backoff stages and $CS_{i,j,k} : 1 \le i \le 5; 1 \le j \le q; 1 \le k \le K$ to denote the kth CCA* of the jth normal CCA after the ith random backoff stage BO_i of a 802.15.4 class-q node. For completeness, note that $\varepsilon_3^{z_q} = \varepsilon_4^{z_q} = \varepsilon_5^{z_q} = 1/16.5$ since $BE = 5$ for $BO_{3 \le i \le 5}$ [19].

Let $p_t^{z_q}$ denote the probability that a 802.15.4 node begins transmission in a generic 802.15.4 backoff slot. According to Figure 2, a 802.15.4 class-q node will begin a transmission in the next 802.15.4 backoff slot if, being in the last carrier sensing state of any backoff stage, it senses the channel idle. Therefore, $p_t^{z_q}$ is given by:

$$p_t^{z_q} = \frac{\sum_{i=1}^{5} \pi_{cs_{i,q,J}}^{z_q}}{1 + (K-1)\sum_{j=1}^{5} \pi_{\mathrm{bo}_j}^{z_q} + (L_z - 1)\pi_{\mathrm{tx}}^{z_q}} p_{i|i_{J-1}}^{c} \tag{9}$$

where $\pi_{cs_{i,1,J}}^{z_q}$ and $\pi_{\mathrm{tx}}^{z_q}$ are respectively the long-run proportion of transitions into states $CS_{i,q,J}$ and TX of a 802.15.4 class-q node, and can be obtained by solving the system of equations (10)–(15) derived from the embedded 802.15.4 node Markov chain as follows:

$$\pi_{\mathrm{bo}_1}^{z_q} = \frac{1-\varepsilon_1^{z_q}}{\varepsilon_1^{z_q}} \left(\pi_{\mathrm{tx}}^{z_q} + \sum_{u=1}^{q} \sum_{v=1}^{K} \pi_{\mathrm{cs}_{5,u,v}}^{z_q} q_{i|i_{uv-1}}^{c} \right), \tag{10}$$

$$\pi_{\mathrm{bo}_j}^{z_q} = \frac{1-\varepsilon_j^{z_q}}{\varepsilon_j^{z_q}} \sum_{u=1}^{q} \sum_{v=1}^{K} \pi_{\mathrm{cs}_{j-1,u,v}}^{z_q} q_{i|i_{uv-1}}^{c}, \quad j = 2, \ldots, 5 \tag{11}$$

$$\pi_{\mathrm{cs}_{j,1,1}}^{z_q} = \frac{\varepsilon_j^{z_q}}{1-\varepsilon_j^{z_q}} \pi_{\mathrm{bo}_j}^{z_q}, \quad j = 1, \ldots, 5 \tag{12}$$

$$\pi_{\mathrm{cs}_{x,u,v}}^{z_q} = p_{i|i_{uv-1}}^{c} \pi_{\mathrm{cs}_{x,u,v-2}}^{z_q}, \tag{13}$$

$$\pi_{\mathrm{tx}}^{z_q} = p_{i|i_{qK-1}}^{c} \sum_{x=1}^{5} \pi_{\mathrm{cs}_{x,q,K}}^{z_q}, \tag{14}$$

$$1 = \sum_{x=1}^{5} \sum_{u=1}^{q} \sum_{v=1}^{K} \pi_{\mathrm{cs}_{x,u,v}}^{z_q} + \sum_{x=1}^{5} \pi_{\mathrm{bo}_x}^{z_q} + \pi_{\mathrm{tx}}^{z_q}, \tag{15}$$

where $q_{i|i_x}^{c} = 1 - p_{i|i_x}^{c}$ and $q_{i|i_0}^{c} = q_i^c = 1 - p_i^c$. Note that (13) is valid for $x = 1, \ldots, 5$; $u = 1, \ldots, q$ and $v = 1, \ldots, K$ excepted the case $u = v = 1$.

C. CHANNEL STATE MODEL

The channel behavior can be described using the discrete-time Markov chain of Figure 3, which is constructed as follows.

The event that the channel is idle in a time unit encompasses J channel states: namely J states $(I_j)_{1 \le j \le J}$ (where $J = qK$ for 802.15.4 class-q nodes), corresponding to the channel having been idle for j consecutive time slots. Additionally to these states, the channel may be in one of the busy states it experiences either at successful or a failed transmission. The channel busy state is discriminated into (1) B_w, for successful transmissions and collisions from 802.11 nodes, (2) B_z, for successful transmissions and collisions from 802.15.4 nodes, and (3) for collisions from both 802.11 node transmissions and 802.15.4 node transmissions. The following describes the possible channel state transitions and their respective probabilities, according to Figure 3.

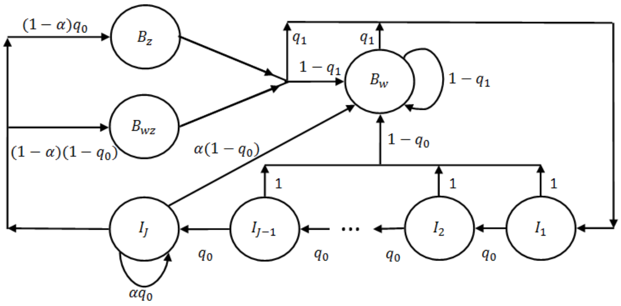

FIGURE 3. Embedded Markov chain model for the channel.

Let $p_{t|i_J}^{z_q}$ be the conditional probability that a 802.15.4 class-q node begins transmission given it has sensed the channel idle in the previous J consecutive time units, we have:

$$p_{t|i_J}^{z_q} = \frac{p_t^{z_q}}{p_{i_J}^{c}}, \tag{16}$$

where $p_{i_j}^{c}$ is the probability that the channel is idle in j consecutive time units.

When the channel is in state $(I_j)_{1 \le j \le J-1}$, it may transition into the two following states: (1) state (I_{j+1}) with probability

$$q_0 = (1 - \tau_0^w)^M, \tag{17}$$

which corresponds to the event that none of the M 802.11 nodes begins the transmission given that the channel was idle in the previous time unit; τ_0^w being the probability that a 802.11 node accesses the channel after a idle period. (2) state B_w with probability $1 - q_0$ corresponding to the event that at least a 802.11 node begins transmission in the current time unit. When the channel is in state (I_J), it remains in that state if none of the nodes (802.15.4 nodes and/or 802.11 nodes) begins transmission. This event occurs with probability αq_0, where

$$\alpha = (1 - p_{t|i_J}^{z_q})^N \tag{18}$$

is the probability that none of the 802.15.4 nodes begins transmission in the current time unit given that the channel was idle in the J consecutive previous time units. Otherwise, if at least one node (802.15.4 nodes and/or 802.11 nodes) begins transmission when the channel is in state (I_J), then the channel will go into one of the following three states: B_w, B_z, and $B_{w,z}$. The transition to B_w state occurs with probability $\alpha(1 - q_0)$, and corresponds to the event that only 802.11 nodes transmit while all 802.15.4 nodes abstain.

The transition to B_z state occurs with probability $(1-\alpha)q_0$, which corresponds to the event that only 802.15.4 nodes transmit while all 802.11 nodes abstain. Finally, the transition to $B_{w,z}$ state, which corresponds to collisions between at least one 802.11 node and at least one 802.15.4 node, happens with probability $(1-\alpha)(1-q_0)$. After any busy state B_w, B_{wz}, or B_z, the channel could transition into state I_1 with probability

$$q_1 = (1-\tau_1^w)^M \tag{19}$$

if none of the 802.11 nodes accesses the channel after the busy period, or it could remain/transition into state B_w with probability $1-q_1$ if at least one 802.11 node begins transmission after the busy period; τ_1^w is the probability that a 802.11 node accesses the channel after a busy period.

The Markov chain of Figure 3 can be solved to determine the long-run proportions of transitions into states $(I_j)_{1\le j\le J}$, B_z, B_w, and B_{wz} respectively. The steady-state probability, $p_{i_j}^c$, that the channel is in state $(I_j)_{1\le j\le J}$ is given by:

$$p_{i_j}^c = \frac{\pi_{i_j}^c}{\sum_{k\epsilon\Omega} T_k \pi_k^c} \tag{20}$$

where k, T_k denote channel state k and its corresponding dwell time in time units, k belongs to the set of possible channel states $\Omega = \{I_{j(1\le j\le J)}, B_w, B_z, B_{wz}\}$. Given the packet length of each type of node, we have in time unit, $T_{i_j} = 1$, $T_{B_w} = L_w$, $T_{B_z} = L_z$, and $T_{B_{wz}} = L_m = \max(L_w, L_z)$.

Owing to chain regularities, we have

$$\begin{aligned}
\pi_{i_j}^c &= q_0 \pi_{i_{j-1}}^c, \quad j = 2, \ldots, J-1 && (21)\\
\pi_{i_J}^c &= q_0 \pi_{i_{J-1}}^c + \alpha q_0 \pi_{i_J}^c, && (22)\\
\pi_{i_1}^c &= q_1(\pi_{b_w}^c + \pi_{b_{wz}}^c + \pi_{b_z}^c), && (23)\\
\pi_{b_w}^c &= (1-q_0)\sum_{k=1}^{J-1} \pi_{i_k}^c + \alpha(1-q_0)\pi_{i_J}^c \\
&\quad + (1-q_1)(\pi_{b_w}^c + \pi_{b_{wz}}^c), && (24)\\
\pi_{b_{wz}}^c &= (1-\alpha)(1-q_0)\pi_{i_J}^c, && (25)\\
\pi_{b_z}^c &= (1-\alpha)q_0 \pi_{i_J}^c, && (26)\\
1 &= \sum_{k=1}^{J} \pi_{i_k}^c + \pi_{b_z}^c + \pi_{b_w}^c + \pi_{b_{wz}}^c. && (27)
\end{aligned}$$

Solving the balance equations, we easily find that:

$$\pi_{i_1}^c = \frac{1}{\frac{1}{q_1} + \frac{1-q_0^{J-1}}{1-q_0} + \frac{q_0^{J-1}}{1-\alpha q_0}}, \tag{28}$$

$$\pi_{i_j}^c = \begin{cases} q_0^{j-1}\pi_{i_1}^c, & 1 \le j \le J-1 \\ \dfrac{q_0^{J-1}}{1-\alpha q_0}\pi_{i_1}^c, & j = J, \end{cases} \tag{29}$$

and (assuming $L_m = Lz$)

$$\sum_{k\epsilon\Omega} T_k \pi_k^c = 1 + \Big[\frac{(L_z - L_w)(1-\alpha)q_0^{J-1}}{1-\alpha q_0} + \frac{L_w - 1}{q_1}\Big]\pi_{i_1}^c \tag{30}$$

Let us denote as π_i^c, the long-run proportion of transitions into the set of idle states $(I_j)_{1\le j\le J}$, we have

$$\pi_i^c = \sum_{j=1}^{J} \pi_{i_j}^c = \frac{1-\alpha q_0 - (1-\alpha)q_0^J}{(1-q_0)(1-\alpha q_0)}\pi_{i_1}^c. \tag{31}$$

Substituting $\pi_{i_1}^c$ given in (28) into (31), we have

$$\pi_i^c = \frac{q_1(1-\alpha q_0 - (1-\alpha)q_0^J)}{1 + q_1 - [1+\alpha(1-q_0+q_1)]q_0 - (1-\alpha)q_0^J q_1}. \tag{32}$$

Considering that the steady state probability, p_i^c, that the channel is idle in a time unit is given by $p_i^c = \sum_{j=1}^{J} p_{i_j}^c$, with $p_{i_j}^c$ given in (20), we have:

$$p_i^c = \frac{\pi_i^c}{\sum_{k\epsilon\Omega} T_k \pi_k^c}, \tag{33}$$

where π_i^c and $\sum_{k\epsilon\Omega} T_k \pi_k^c$ are given in (32) and (30) respectively.

V. METRICS FORMULATION

In this section, we derive the most relevant metrics capturing the traffic prioritization of 802.15.4 nodes when coexisting with 802.11 nodes.

A. CHANNEL ACCESS PROBABILITY

For each type of node, this probability corresponds to the probability that the node begins transmission in a generic time unit. For 802.11 nodes, this probability depends on whether the previous time unit was idle (τ_0^w) or busy (τ_1^w). It is given by

$$\tau_0^w = \frac{\sum_{j=0}^{m} \pi_{0,j,0}^w}{\pi_i^c}, \tag{34}$$

$$\tau_1^w = \frac{\sum_{j=0}^{m} \pi_{1,j,0}^w}{1-\pi_i^c}, \tag{35}$$

where π_i^c is given in (32), and $\pi_{0,j,0}^w$ and $\pi_{1,j,0}^w$ are derived from the system of equations (3)–(8). For class-q 802.15.4 nodes, the channel access probability is given by (9).

B. AGGREGATE CHANNEL THROUGHPUT

The aggregate throughput of 802.11 (resp. 802.15.4) nodes is defined as the fraction of time 802.11 nodes (resp. 802.15.4 nodes) spend in the success state. The aggregate throughput of 802.11 (resp. 802.15.4) nodes corresponds to the steady-state probability, S_w (resp. S_{z_q}), of the channel being in the success state.

Let us first determine the fraction of time 802.11 nodes (resp. 802.15.4 nodes) spend in the busy state B_w (resp. B_z). Based on the channel Markov chain in Figure 3 we have:

$$P_{b_w} = \frac{L_w \pi_{b_w}^c}{\sum_{k\epsilon\Omega} T_k \pi_k^c}, \quad P_{b_z} = \frac{L_z \pi_{b_{zq}}^c}{\sum_{k\epsilon\Omega} T_k \pi_k^c},$$
$$P_{b_{wz}} = \frac{L_z \pi_{b_{wz}}^c}{\sum_{k\epsilon\Omega} T_k \pi_k^c} \tag{36}$$

where the denominator $\sum_{k \in \Omega} T_k \pi_k^c$ is given by (30), and the long-run proportion of transitions into channel states, B_w, B_z, and B_{wz} are derived from the system of equations (21)–(27).

Let $t_0 = M\tau_0^w(1-\tau_0^w)^{M-1}$ (resp. $t_1 = M\tau_1^w(1-\tau_1^w)^{M-1}$) be the probabbility that only one 802.11 node begins transmission given that the channel was idle (resp. busy) in the previous time unit, and let $\alpha_0 = Np_{t|i_J}^{z_q}(1-p_{t|i_J}^{z_q})^{N-1}$ be the probability that only one 802.15.4 node begins transmission in the current time unit given that the channel was idle in the J consecutive previous time units.

Therefore, considering the different transition probabilities into busy state B_w (resp. B_z), we have:

$$S_w = \frac{(J-1+\alpha)t_0+3t_1}{2+\alpha+J-[3q_1+(\alpha+J-1)q_0]}P_{b_w} \qquad (37)$$

$$S_z = \frac{\alpha_0}{1-\alpha}P_{b_z} \qquad (38)$$

VI. PERFORMANCE ANALYSIS OF THE COEXISTENCE BETWEEN 802.11 AND 802.15.4

In this section, we present the different simulation scenarios used to compare the performance of the coexistence between the 802.11 nodes and the 802.15.4 nodes with several classes of prioritization; and we discuss the results obtained.

A. SIMULATION SCENARIOS

For each scenario, we consider a fixed number N of 802.15.4 nodes and a fixed number M of 802.11 nodes. We assume that nodes do not change their position during each analysis. We further assume that the hidden node problem is not present, and the nodes of the same type have the same "view" of the network (they are in the same neighborhood). In each scenario, we assume that both the 802.11 nodes and the 802.15.4 nodes can detect each other transmissions. We consider ideal channel conditions. Therefore, a failed transmission may occur only upon collision. We consider that each node (both 802.11 nodes and 802.15.4 nodes) always has a packet ready for transmission in its buffer at the end of a transmission (succeeded or failed).

Without loss of generality, and in order to capture the performance of accessing the channel, we assume that the packet duration of both 802.11 nodes and 802.15.4 nodes is the same in each scenario. We evaluate the fraction of time that the channel is in the success/collision state for both 802.11 nodes and 802.15.4 nodes. For an in-depth analysis, we consider scenarios with a limited number of nodes to examine their behavior and performance in the presence of each other. We consider the following cases: (1) $N = 2$, and $M = 0$; (2) $N = 1$, and $M = 1$; and (3) $N = 2$, and $M = 2$. For each case, we suppose that all 802.15.4 nodes are of the same class, and we distinguish 10 types of 802.15.4 classes which we divide into 2 groups of 5 subclasses each. In the first group, $q = 1$, that is, only one 802.15.4 CCA is required to the 802.15.4 nodes before transmitting. In the second group, $q = 2$, and the 802.15.4 nodes have to perform 2 consecutive 802.15.4 CCA before transmitting. In each group, the subclasses differ by the minimum value of the contention window; we have the following subclasses: (a) $W_{z_{\min}} = 3$; (b) $W_{z_{\min}} = 4$; (c) $W_{z_{\min}} = 5$; (d) $W_{z_{\min}} = 6$; (e) $W_{z_{\min}} = 7$. The 802.11 nodes have no particular priority, and we suppose that $W_{w_{\min}} = 15$.

In order to capture the performance of coexistence between 802.11 nodes and 802.15.4 nodes in steady state conditions, we assume a very large amount of packets (the same for both 802.11 nodes and 802.15.4 nodes) to be transmitted. The simulation ends once a type of node (either 802.11 nodes or 802.15.4 nodes) finishes its transmissions.

B. PERFORMANCE ANALYSIS

The results are presented in Fig.4–Fig.9. In these figures, *Succ-w, Succ-q* ($q = 1, 2$) notations are used to represent the successful transmission case of 802.11 nodes and 802.15.4 class-q nodes respectively; and *Coll-w, Coll-q, Coll-wz* are used to specify the case of collisions between 802.11 nodes transmissions only, between 802.15.4 class-q nodes transmissions only, and between 802.11 nodes and 802.15.4 nodes transmissions, respectively.

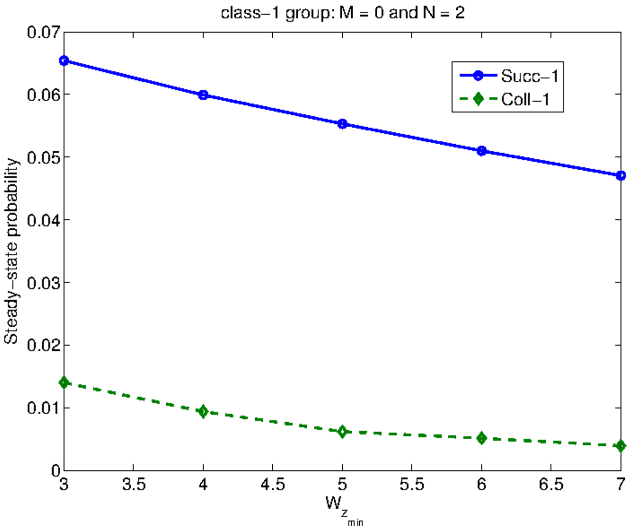

FIGURE 4. **Scenario *M* = 0 and *N* = 2 class-1.**

1) CASE WHERE M=0, AND N=2

Fig.4 and Fig.5 are used as reference to show the performance of 802.15.4 nodes of class-1 and class-2 in the absence of 802.11 nodes.

Fig. 4 and Fig. 5 basically show how the priority of a 802.15.4 class node affects channel access probability. We observe that as the priority of a 802.15.4 class node increases (i.e., both q and $W_{z_{\min}}$ decrease), higher is the probability of successful transmissions. The use of one 802.15.4 CCA instead of two CCA as specified in the standard does lead to an improvement of more than 40%. When we compare the highest priority class of 802.15.4 nodes ($q = 1$ and $W_{z_{\min}} = 3$) with standard parameters ($q = 2$ and $W_{z_{\min}} = 7$),

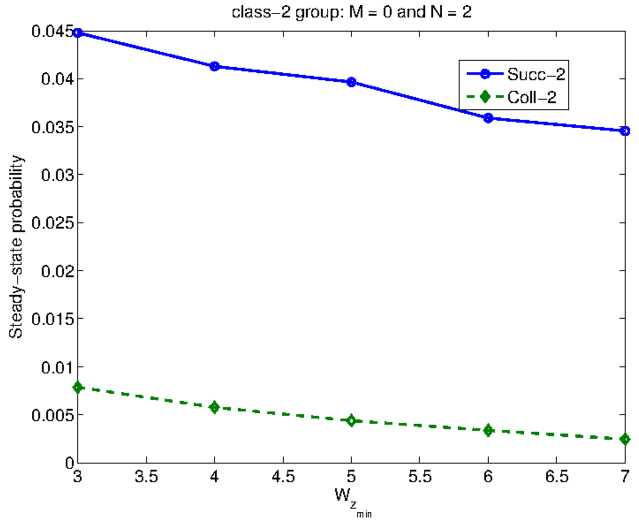

FIGURE 5. Scenario $M = 0$ and $N = 2$ class-2.

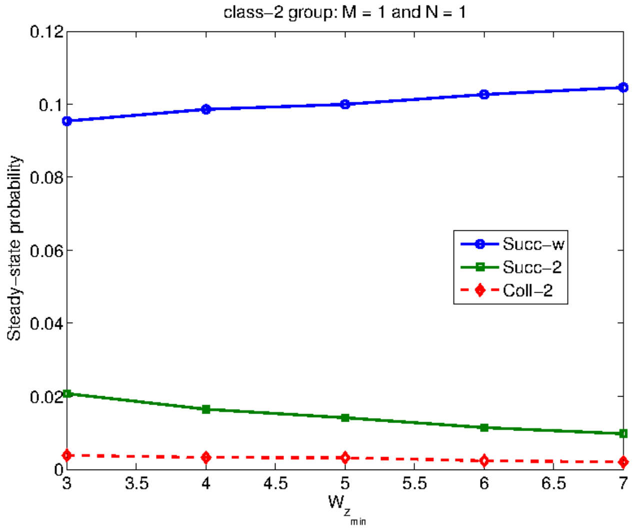

FIGURE 7. Scenario $M = 1$ and $N = 1$ class-2.

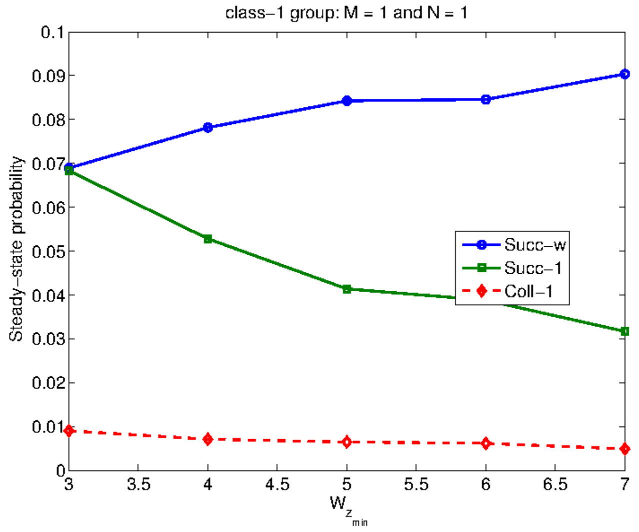

FIGURE 6. Scenario $M = 1$ and $N = 1$ class-1.

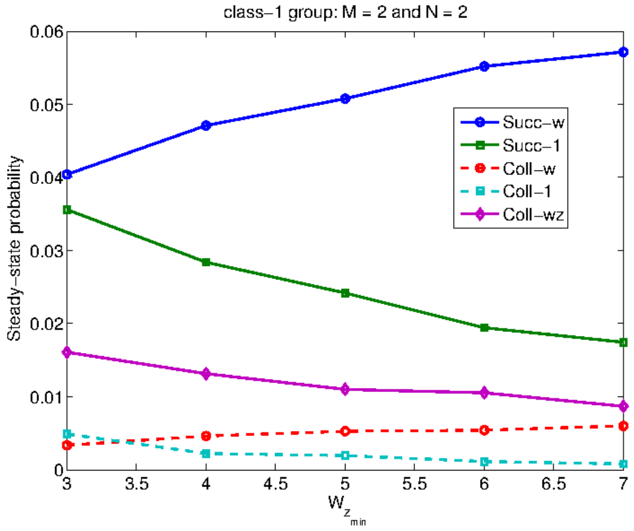

FIGURE 8. Scenario $M = 2$ and $N = 2$ class-1.

we observe an improvement of around 65%. In the second scenario, we replace a 802.15.4 node by a 802.11 node.

2) CASE WHERE M=1, AND N=1

The performances of both the 802.11 node and the 802.15.4 node are shown in Fig. 6 and Fig. 7 for a 802.15.4 class-1 node and a 802.15.4 class-2 node respectively.

The observation of Fig. 7 shows how the performance of a 802.15.4 node using standard parameters is degraded in the presence of a 802.11 node. As compared to Fig. 5 for $W_{z_{\min}} = 7$, the performance drops for around 55%, and the use of a low $W_{z_{\min}}$, for example, $W_{z_{\min}} = 3$ limits the drop to 40%. When we use a higher priority class $q = 1$, the improvement of the 802.15.4 node performance is evident as shown in Fig. 6.

As the minimum contention window of the 802.15.4 node decreases, the 802.15.4 node performance increases up to the performance of the 802.11 node. For example for $W_{z_{\min}} = 3$, we have an improvement of around 365% in comparison to the standard case ($q = 2$ and $W_{z_{\min}} = 7$); the 802.15.4 node starts to perform as good as the 802.11 node.

3) CASE WHERE M=2, AND N=2

To see how this prioritization policy works with more nodes, we consider the scenario of $N = 2$ and $M = 2$; the results are shown in Fig. 8 and Fig. 9 for 802.15.4 class-1 nodes and 802.15.4 class-2 nodes, respectively. As expected, the performance of 802.15.4 class-1 nodes with $W_{z_{\min}} = 3$ is still close to the one of 802.11 nodes. The performance is three times larger than the performance of 802.15.4 nodes with standard settings. However, if we compare Fig. 6 and Fig. 7 to Fig. 8 and Fig. 9 respectively, we see that as the number of contending nodes (for both 802.11 nodes and 802.15.4 nodes)

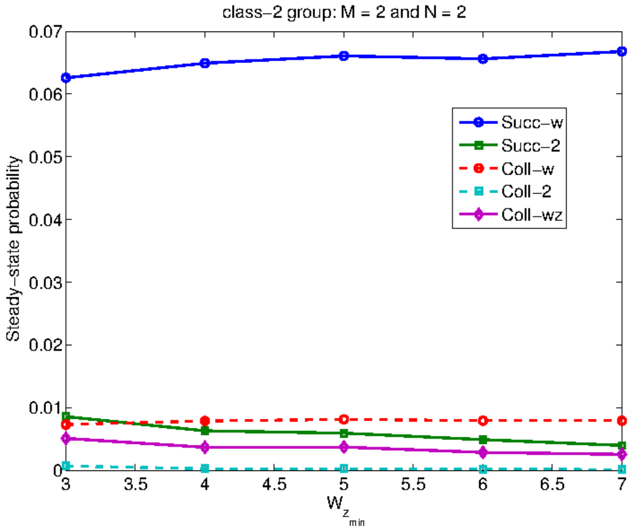

FIGURE 9. **Scenario $M = 1$ and $N = 1$ class-2.**

increases in the network, the gap between the performance of the 802.11 nodes and the 802.15.4 nodes starts to increase in favor of 802.11 nodes.

VII. RELATED WORK

Several techniques are proposed in the literature to improve the coexistence of 802.11 and 802.15.4 in the 2.4 GHz ISM band. For instance, Liang *et al.* [6] quantify the interference patterns between 802.11 and 802.15.4 networks at a bit-level granularity, and they introduce a mechanism, named BuzzBuzz, to improve the reception rate of the 802.15.4 nodes through header and payload redundancy. Jun *et al.* [8] proposed a protocol named WISE which controls ZigBee (based on 802.15.4) frames in order to mitigate the coexistence of ZigBee with WiFi. Mangir *et al.* [7] proposed an experiment-based approach using Cognitive Radio as spectrum analyzer to study the effect of WiFi interference on ZigBee channels. Kim *et al.* [9] proposed an algorithm that satisfies the delay requirement for emergency messages by controlling WiFi traffic for health telemonitoring systems; they control only WiFi traffic which is not stringently delay-sensitive. Hao *et al.* [10] proposed a WSN (Wireless Sensor Network) time synchronization called WizSync which employs digital signal processing (DSP) techniques to detect periodic WiFi beacons, and use them to calibrate the frequency of 802.15.4 node native clocks. Yan *et al.* [11] presented WizBee (i.e. Wise ZigBee system) as extension to current ZigBee networks with an intelligent sink node; the observation that a WiFi signal is much stronger than a ZigBee one when they collide, leaves much room for applying interference cancellation techniques, especially in symmetric areas. To recover a ZigBee packet during a WiFi/ZigBee collision, WizBee first extracts the WiFi packet, then subtracts WiFi interference and decodes the ZigBee packet. Zhao *et al.* [12] established a testbed composed of one 802.11n network and one 802.15.4 network to carry out the coexistence experiments between their nodes at the 2.4 GHz band. They focused on features of 802.11n such as MIMO and channel bonding, and they checked their impact on 802.15.4 and vice versa. Wang *et al.* [13] proposed WiCop, a policing framework to address the coexistence problem between 802.15.4 and 802.11 in the 2.4 GHz band. WiCop aims to control the temporal white-spaces between consecutive WiFi transmissions, to utilize them for delivering low duty-cycle medical WPAN traffic with minimum impacts on WiFi. Zhang *et al.* [14] proposed a cooperative carrier signaling (CCS), to facilitate ZigBees coexistence with WiFi. In their approach, a separate ZigBee node called signaler, has higher power than normal ZigBee transmitters, and behaves as proxy to perform carrier signaling. WiFi nodes can sense ZigBee transmitters' presence indirectly by detecting the busy tone. The difficulty with this technique is the additional complexity required to manage the busy tone. Tao *et al.* [15] proposed an approach to evaluate the coexistence performance for WiFi and Zigbee which is based on the fact that when ZigBee nodes work in lower transmit power, the interference is reflected on the packet payload as corrupted bytes. Liu *et al.* [16] conducted a set of experiments to observe the node-to-node ZigBee communication performance in all 16 channels under WiFi interference.

Other works [21], [22] focus on improving the Clear Channel Assessment (CCA) in order to bring about solutions to mitigate or solve CTI interference between 802.11 and 802.15.4. Tytgat *et al.* [21] recently introduced the concept of coexistence aware clear channel assessment (CACCA) to support the coexistence of technologies in the 2.4 GHz band. With the CACCA concept, 802.11 nodes, for example, are allowed to detect and backoff when there are ongoing 802.15.4 transmissions in order to lower the level of interference.

VIII. CONCLUSION

In this work, we proposed the use of traffic prioritization for ZigBee nodes to improve their performance in a coexistence scenario with 802.11 nodes operating in the same band. As the number of diverse "things" using ZigBee in a network becomes important problems of coexistence will become exacerbated. We developed an analytical framework based on Markov chains models of the nodes and the channel. We showed that traffic prioritization of ZigBee nodes effectively improves their performance when coexisting with 802.11.

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