PROJECT

Coexistence of WiFi and ZigBee networks

Work done
by

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Chapter 1: Motivation

The industrial, scientific and medical radio band (ISM band) refers to a group of radio bands or parts of the radio spectrum that are internationally reserved for the use of radio frequency (RF) energy intended for scientific, medical and industrial requirements. In recent years ISM bands have also been shared with (non-ISM) license-free error-tolerant communications applications such as wireless sensor networks in the 915 MHz and 2.450 GHz bands, wireless LANs and cordless phones in the 915 MHz, 2.450 GHz, and 5.800 GHz bands, 802.15.4 Low-Rate Wireless Personal Area Network (LR- WPAN), IEEE 802.15.3 and Bluetooth Networks. The ISM spectrum is becoming increasingly populated by emerging wireless networks. Thus Spectrum sharing mechanisms need to be carefully designed to enable inter-technology coexistence in the unlicensed bands.

Problem Description

The Objective is to design a mechanism to enable the coexistence of heterogeneous networks: IEEE 802.11b Wireless LANs and IEEE 802.15.4 Low-Rate Wireless Personal Area Network in the ISM band . Spectrum sharing among the same network types can be implemented by the MAC protocol (CSMA) but the incompatible PHY layers of heterogeneous networks severely degrade the effectiveness of traditional MAC.

In the coexistence of IEEE 802.15.4 and IEEE 802.11b, the main concern is the performance degradation of ZigBee networks caused by the interference of WiFi. The underlying causes for the challenges in their coexistence are

- The WiFi node uses a longer range radio than ZigBee system, thus it can give radio interference to ZigBee system in a large area and from a long distance. Therefore, large-scale ZigBee based sensor network system is vulnerable to the interference from WiFi network.
- ZigBee packets are transmitted with 20dB lower power than WiFi packets, and tend to be invisible to, and often interrupted by WiFi transmitters.
- ZigBee allows for TDMA mode, which operates without carrier sensing, and may arbitrarily collide with an ongoing WiFi transmission.

Chapter 2: Introduction

The industrial, scientific and medical radio band (ISM band) are internationally reserved for the use of radio frequency (RF) energy intended for scientific, medical and industrial requirements. In recent years ISM bands have also been shared with (non-ISM) license-free error-tolerant communications applications such as wireless LANs and IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LR- WPAN). Wireless LANs have become popular for use in the home, offices and commercial complexes due to their ease of installation and use. IEEE 802.15.4 is used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. In most cases they are expected to run simultaneously in close proximity. Thus Spectrum sharing mechanisms need to be carefully designed to enable inter-technology coexistence in the unlicensed bands. Spectrum sharing among the same network types can be implemented by the MAC protocol (CSMA) but the incompatible PHY layers of heterogeneous networks severely degrade the effectiveness of traditional MAC.

In the coexistence of IEEE 802.15.4 and IEEE 802.11b, the main concern is the performance degradation of IEEE 802.1.5.4 caused by the interference of WiFi. IEEE 802.11b uses a longer range radio than IEEE 802.15.4 system ,thus it can give radio interference to IEEE 802.15.4 system in a large area and from a long distance. Therefore, large-scale IEEE 802.15.4 based sensor network system is vulnerable to the interference from IEEE 802.11b.

In [2], the earlier mechanism used to avoid interference between the IEEE 802.11b and IEEE 802.15.4 networks is to allocate ZigBee devices to channels that are not or less used by WiFi devices. However , there are only a limited number of orthogonal WiFi channels on the ISM band, and thus frequency separation is difficult to achieve in a densely deployed WiFi environment, where colocated APs tend to occupy different parts of the spectrum to avoid intercell interference.

ZigBee packets are transmitted with 20dB lower power than WiFi packets, and tend to be invisible to, and often interrupted by WiFi transmitters. ZigBee transceiver has a longer response time, and is often preempted by WiFi, when it switches from sensing to transmission, or transmission to reception mode. It allows for TDMA mode, which operates without carrier sensing, and may arbitrarily collide with an ongoing WiFi transmission. The characteristics of Zigbee makes it vulnerable to the interference from IEEE 802.11b.

In [7], the mechanism proposed is called the cooperative carrier signaling (CCS) that enables the reliable coexistence between WiFi and ZigBee Networks. CCS runs atop the ZigBee MAC/PHY layers. CCS employs a separate ZigBee node to emit a carrier signal (busy tone) concurrently with the desired ZigBee's data transmission, thereby enhancing the ZigBee's visibility to WiFi. The busy tone persists throughout the data and ACK round trip, thus preventing the WiFi's preemption in the rx/tx switching gap . A key challenge to CCS is that the signaler's busy tone must occur concurrently with the data transmission without affecting its transmission. To overcome this difficulty, a temporary channel-hopping mechanism is employed that separates the carrier signaling from the data transmission in frequency domain, also ensures WiFi to sense the presence of ZigBee transmission. The testbed includes both WiFi and ZigBee nodes, deployed in an office environment. The floorplan and measurement points are studied. The WiFi transceivers adopt Atheros 5413 NIC with the MadWiFi v0.9.4 driver, default transmit power 15 dBm. The ZigBee nodes are MICAz motes programmed with openzb , an open-source implementation of the ZigBee MAC/PHY. The motes uses default transmit power 5 dBm. To isolate the ambient interference, the WiFi link is tuned to a channel least used by nearby WLANs, and all measurements are made in the night.

Chapter 3: Taxonomy of Solutions

One of the approaches for enabling ZigBee–WiFi coexistence is frequency planning. In [2], a adaptive radio channel allocation is used for supporting coexistence of IEEE 802.15.4 and IEEE 802.11b. The proposed scheme uses multiple radio channels for the coexistence of IEEE 802.15.4 WPAN and IEEE 802.11b WLAN. The solution becomes ineffective when the network density is high. However, this approach is less effective when WiFi WLANs are: 1) unmanaged and may change channels unpredictably; or 2) densely deployed, since three non-overlapping channels can occupy the majority of 2.4-GHz ISM bands. Strict frequency separation may also underutilize bandwidth. When WiFi traffic becomes intensive, ZigBee may adaptively switch to other idle channels [4]. However, this approach does not resolve bursty collisions—it responds only after collision had occurred. Adaptive channel allocation also incurs long "blackout time" due to scanning and reassociation [17], which can be on the order of several seconds and increases with the network size.

The second approach to enable coexistence between ZigBee and WiFi networks is by sending a busy signal during the ZigBee transmission to make their communication visible to the WiFi access points. In [7], the mechanism proposed is called the cooperative carrier signaling (CCS) that enables the reliable coexistence between WiFi and ZigBee Networks. CCS runs atop the ZigBee MAC/PHY layers. CCS employs a separate ZigBee node to emit a carrier signal (busy tone) concurrently with the desired ZigBee's data transmission, thereby enhancing the ZigBee's visibility to WiFi. The busy tone persists throughout the data and ACK round trip, thus preventing the WiFi's preemption in the rx/tx switching gap . A key challenge to CCS is that the signaler's busy tone must occur concurrently with the data transmission without affecting its transmission. To overcome this difficulty, a temporary channel-hopping mechanism is employed that separates the carrier signaling from the data transmission in frequency domain, also ensures WiFi to sense the presence of ZigBee transmission.

Tobagi and Kleinrock were the first to adopt the Busy-tone-based signaling mechanism as a solution to the hidden terminal problem in CSMA protocols in [15]. [16], [17] tried to extended the mechanism to enhance the performance of CSMA for ad hoc and sensor networks These protocols require two radios on each transceiver: one for data transmission, and the other transmitting a dedicated narrowband signal as the busy tone. In contrast CCS adopts a cooperative busy-tone mechanism, which can be realized using off-the-shelf ZigBee devices. The difference between the CCS mechanism and previous busy-tone mechanisms is that it enables the coexistence between heterogeneous MAC protocols.

The third approach to enable coexistence between ZigBee and WiFi networks is by employing a central coordinator which coordinates the transmission of all the heterogeneous networks. In [12], the coordinator hardware(Metronome) provides a flexible mechanism that allows a network operator to specify constraints on receiver performance metrics such as throughput or loss rates. The coordinator then configures each participating transmitter with appropriate channel, bandwidth, and transmission power settings automatically. A Metronome user deploys monitors over the area where some wireless receiver's performance are degraded because of interference from other networks. The user employs a sharing policy in the policy server in the form of constraints on the SINR levels that different receivers. The monitors periodically sample the energy across the band of interest, use a parameterized matched filter to associate that activity with a device type (e.g., WiFi, ZigBee, Bluetooth, etc.), and periodically send the information to the policy server. The server then sends these settings to the transmitters, which modify their behavior accordingly. In [18], a spectrum survey based method is introduced to improve the coexistence of WPAN–WLAN by adjusting transmit power and carrier-sensing threshold. This mechanism is suitable for fixed topology networks and tries to achieve throughput fairness between heterogeneous networks in long term ,but short-term performance metrics (e.g., delay and collision rate) are equally important to the monitoring and control applications typically seen on ZigBee networks.

Chapter 4: Existing Solutions

[7] Cooperative Carrier Signaling: Harmonizing : Coexisting WPAN and WLAN Devices.

The coexistence of ZigBee and WiFi nodes is challenging due to these factors. First, the transmission power of ZigBee is 20 dB lower than WiFi's transmission power, hence, its visibility to WiFi is poor. The ZigBee's MAC-layer backoff timer duration and wait time for acknowledgement is large, and it can easily be preempted by WiFi in the middle of a rx/tx transition (e.g., sensing-to-transmission or data-to-ACK transition),and thus causing collision. Third, the ZigBee allows for TDMA mode, which does not involve carrier sensing, hence, may collide with an ongoing WiFi transmission. The disparate transmit power, time resolution, and scheduling mode also make the coexistence of Wifi and Zigbee nodes difficult.

Design Proposed :

In this paper the first and the second challenges in the coexistence of Zigbee and Wifi networks are overcome by following mechanism.

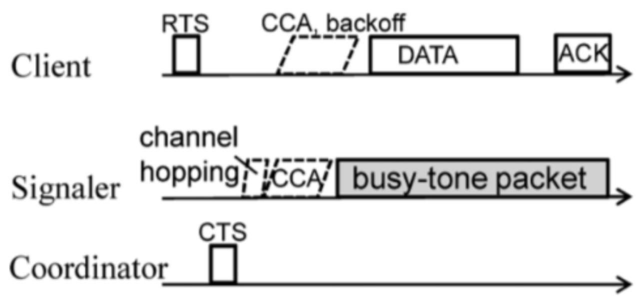
- The CCS employs a separate ZigBee node called signaler to send out a carrier signal (busy tone) concurrently with the desired ZigBee's data transmission, thereby the ZigBee's visibility to WiFi is improved.

- The signaler have a higher transmit power than normal ZigBee transmitters, thus allowing the WiFi nodes to sense the ZigBee transmitter's presence indirectly by detecting the busy tone. The busy tone persists throughout the data and ACK round trip, thus preventing the WiFi's from preempting the ZignBee node's transmission in the rx/tx switching gap.

- The concurrent busy tone and data transmission is achieved by temporary channel-Hopping mechanism that separates the carrier signaling from the data transmission in frequency domain, and enables WiFi to sense the presence of ZigBee transmission.In the 2.4-GHz spectrum, the width of each WiFi channel is 20 MHz and the adjacent channels partially overlap with each other. Each ZigBee channel occupies a bandwidth of 4 MHz, with 1 MHz guard band between adjacent channels. As a result, each WiFi channel overlaps with four ZigBee channels. When running the temporary channel-hopper, a ZigBee signaler switches to a nearby adjacent channel before its scheduled signaling and returns to the original channel immediately after the busy tone is sent. Thus ensures that signaling is decoupled from ZigBee transmission in frequency domain since the adjacent ZigBee channels are orthogonal. However, the busy tone still overlaps with the WiFi spectrum and can inform WiFi of a ZigBee transmission, as long as its power exceeds the WiFi's carrier-sensing threshold

Implementaion :

CCS for ZigBee nodes that employs CSMA:



1. A sender sends RTS to the receiver before delivering data, and the receiver returns a
confirmation packet when it is ready to receive .

2. On receiving the CTS confirmation, the signaler starts the temporary channel-hopper and sends the busy tone immediately.

3. The busy tone duration equals the length of the data packet length and the ACK wait duration plus a guard period

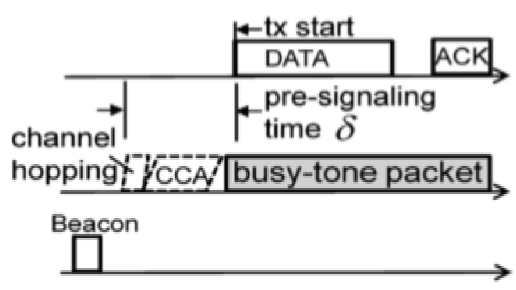
4.	The ACK wait duration equals the airtime of ACK packet (352 micro seconds), the rx/tx switching time (192 micro seconds), plus a backoff slot (320 micro seconds) to ensure slot boundary alignment.

5.	The signaler senses the channel after switching to the new channel and starts signaling only if the channel is idle for one CCA slot. The signaler aborts the signaling if it finds the channel to be busy over five consecutive CCA time slots to avoid unnecessary interruptions to WiFi.

6.	Since the signaler does not perform backoff and only needs one CCA slot to assess a clear channel, it tends to send the busy tone before the data transmission. The busy tone is extended for a guard period equal to a CCA slot plus half of the maximum backoff window (four backoff slots) to compensate for offset.

7. The RTS/CTS packets are transmitted without performing carrier sensing to reduce the overhead due to excessive CCA and backoff. Due to this the RTS/CTS may be lost due to collision with WiFi packets. However, since the RTS/CTS packets are much shorter than data packets, the collision probability is lower. Every RTS packet is retransmitted for RETX times, and the receiver replies with a CTS whenever it receivers an RTS. The RETX value is piggybacked as a tag in the CTS packet. The signaler schedules its signaling time according to the first tagged CTS packet it receives.

CCS for ZigBee nodes that employs CSMA:



1. In TDMA mode, CCS exploits the guaranteed time slot(GTS) mechanism in ZigBee to allocate fixed slots to clients, thus eliminating the need for handshake for each packet.

2. The coordinator’s beacon message carries the slot allocation information. Both the client and the signaler send a confirmation packet using CSMA after receiving a beacon. The beacon is retransmitted if the confirmation is missing. On a successful slot allocation, the signaler will send the busy tone whenever a scheduled TDMA slot fires.

3. The signaler starts sensing the channel CCA units of time earlier (called pre-signaling time) than the scheduled ZigBee transmission to avoid unnecessary interference to an ongoing WiFi transmission. It starts signaling on the first idle CCA and aborts the signaling if the channel remains busy for duration of five CCA time slots before the TDMA transmission.

4. The pre-signaling time could serve two purposes: 1) it tolerates imperfect synchronization due to the clock between the signaler and transmitter; 2) it can be used to raise the priority level of ZigBee when running delay-sensitive applications (e.g., real-time monitoring). A larger value of pre-signalling time allows the signaler to find an idle slot with a higher probability.

5. The coordinator transmits a CTS packet immediately before transmitting the beacon, which will be used to trigger the signaler as a sync message for starting a busy tone to protect the beacon. The beacon is critical since only on the successful reception of a beacon for the corresponding superframe the ZigBee allows for TDMA packet transmission. If the beacon gets corrupted the data transmission is postponed to next beacon.

6. Since beacons are short and relatively sent infrequently, they tenf to have high priority, hence, the signaler is forced to send the busy tone at the due time of each beacon, assuming that WiFi can promptly recover itself via backoffs and retransmissions, even if collision occurs and corrupts its data transmission.

Critique :

1. The RTS packets are transmitted by the sender ZigBee node without carrier sensing in a burst. This may cause interference to the ongoing WiFi transmissions and lead to corruption and may trigger unwanted retransmission on WiFi packets.

2. The solution claims that " *placing a single signaler near the coordinator, CCS can prevent the entire WPAN from being interfered with by randomly located WiFi transmitters"*

- In this case, since the transmission range of the signaler is fixed, this set limit on the boundary area over which the ZigBee nodes could be distributed.
- The signaler could not protect the ZigBee nodes outside its range from Wifi interference since the busy tone transmitted becomes feeble and is not visible to the WiFi nodes.

3. Placing the signaler nodes near every ZigBee node may increase the hardware cost for implementation.

4. The proposed solution must be compatible with the existing ZigBee standards and this solution requires coordination between the signaler and ZigBee node which may not be possible compatible with existing standard.

5. In channel-hopping mechanism the ZigBee channel under interference may reside at the edge of a WiFi band,so CCS must decide on hopping to the left-side or right-side adjacent channel.

- If the ZigBee channel under interference reside at the right-most edge of the WiFi band and the CCS hops to the right-side of the adjacent channel, in that cast the signaling becomes ineffective, hence, it has to hop to the left-side of the adjacent channel.

- If the ZigBee channel under interference reside at the left-most edge of the WiFi band and the CCS hops to the left-side of the adjacent channel, in that cast the signaling becomes ineffective, hence, it has to hop to the right-side of the adjacent channel.

6. The experiments are performed in an office environment at night with predefined fixed positions for the WiFi nodes and the ZigBee nodes. The location of the nodes may favor the algorithm and also
since the experiments are conducted at night, it may not include interference from people and other disturbances. The node boundaries are fixed too, which favors the algorithm.

7. The proposed solution involves implementation of additional hardware(signaler) and does not talk about the cost of its implementation and adding it to the ZigBee nodes.

8. The signaler has to transmit busy tone with a signal strength larger than the carrier sensing threshold of the Wifi nodes, hence, they require larger battery power than the ZigBee nodes. The paper doesn't provide details on the power requirement.

[15] **- Dual Busy Tone Multiple Access (DBTMA)-A Multiple Access Control Scheme for Ad Hoc Networks**

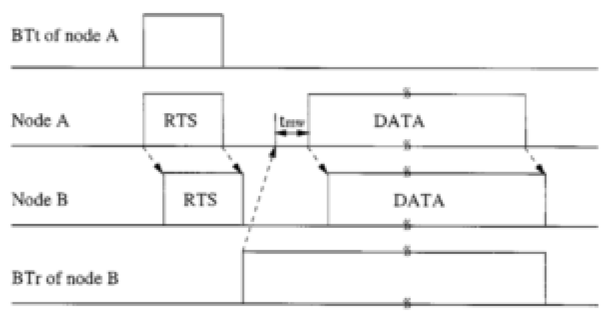
The paper proposes a new MAC protocol, termed the dual busy tone multiple access (DBTMA) to overcome the problem of hidden and exposed terminals. The operation of the DBTMA protocol is based on the RTS packet and two narrow-bandwidth which are out-of-band busy tones. The RTS packet along with the receive busy tone, which is set up by the receiver is used to solve the hidden- and the exposed- terminal problems. The busy tone, which is set up by the transmitter along with the RTS, provides protection for the RTS packets, increasing the probability of successful RTS reception and, thereby, increasing the throughput**.**

Algorithm :

A node implementing the DBTMA protocol can be in one of the following states:

- IDLE - A node which has got no packets to send stays in this state.

- CONTEND - When a node has got a packet to send, but the channel is not free and hence it is not allowed to send the RTS packet, it stays in the CONTEND state.
- S_RTS - Nodes sending RTS are in the S_RTS .
- S_DATA - Nodes sending DATA packets are in the S_DATA states.
- WF_BTR - The sender waits for the acknowledgment from its intended receiver in the WF_BTR state.
- WF_DATA - The receiver waits for the data packet in the WF_DATA state.



1. When sender has got a data packet to send while it is in the IDLE state, it tries to sense the BTr and the BTt busy tone signals.

2. If the channel is idle (which means that no one in sender's transmission area is receiving data packet or sending RTS packets), it turns on its BTtsignal, sends an RTS packet to receiver, and it enters the S_RTS state.

3. If the channel is busy, it sets a random timer and enters the CONTEND state. By the end of the RTS transmission, the sender stops sending its BTtsignal, sets a timer, and enters the WF_BTR state.

4. When the receiver receives the RTS packet, it sends its BTrsignal, replying to sender and indicating that it is awaiting for the incoming data packet. Then it sets up a timer and goes into the WF_DATA state.

5. The sender continuously senses for the BTrsignal when it is in the WF_BTR state. When a BTr signal is sensed, it knows that its RTS has reached the receiver and the channel request has been successful . Before sender sends the data packet, it waits for a waiting time in the WAIT state.This mandatory waiting time is set to allow all possible RTS transmissions in the range of the receiver to be aborted.

6. When the timer timeout in the WAIT state, sender enters the S_DATA state and sends the data packet. By the end of its transmission, sender enters the IDLE state.

7. On successful reception of the data packet, the receiver stops sending the BTr signal and goes into the IDLE state, terminating the communication. If the receiver does not receive the data packet before the timer expires, it stops sending the BTr signal and goes into the IDLE state.

8. On timeout in the CONTEND state, the sender sends its signal and RTS packet if no busy tone signal is sensed. Otherwise, it goes back into the IDLE state. From the perspective of the other nodes in the neighborhood, their operations can be described as following: When either the BTt or the BTr signal is or both the signals are sensed, a node is not allowed to send any RTS request. When the start of a BTr ignal is sensed while a node is in the S_RTS state, it aborts its RTS transmission, stops sending its BTt signal, and goes back to the IDLE state.

Critique :

1. The algorithm does not have any acknowledgement on successful reception of the data by receiver. It assumes that the neighboring nodes would back off and does not interfere with the transmitted data on sensing the busy tone, hence, it has not implemented acknowledgement. However, the transmission fails if the packets are corrupted by interferences from other sources and sender doesn’t know if the transmission was successful.

2. The DBTMA mechanism requires extra hardware. Two busy tone transmitters and sensing circuits need to be employed into each communication node.

3. The busy tones may consume considerable bandwidth. The paper doesn't talk about the channel in which the busy tone is sent. If the same channel used by busy tone is being used by nodes of the neighboring networks for communication, then the ZigBee nodes may misinterpret it as busy tone and remain in idle state.

4. Sending the busy tone involve energy requirement for their transmission in addition to that for data transmission and reception.

[11] **Metronome: Coordinating Spectrum Sharing in Heterogeneous Wireless Networks**

Metronome is a spectrum-survey-based method is introduced to improve WPAN–WLAN coexistence by adjusting transmit power and carrier-sensing threshold. Metronome provides a flexible mechansim that allows a network operator to specify constraints on receiver performance metrics such as throughput or loss rates. Metronome then configures each participating transmitter with appropriate channel, bandwidth, and transmission power settings automatically.

Design :

1. A Metronome user deploys monitors over the area where some wireless receiver's performance are degraded because of interference from other networks. The user employs a sharing policy in the policy server in the form of constraints on the SINR levels that different receivers .

2. The monitors periodically sample the energy across the band of interest, use a parameterized matched filter to associate that activity with a device type (e.g., WiFi, ZigBee, Bluetooth, etc.), and periodically send the information to the policy server.

3. The policy server on receiving the data from the monitors calculate the interference that are contributed of each transmitter.

4. Based on the report the policy server then runs an optimization procedure and the specified policy to determine the optimum transmit power and channel settings (center frequency and bandwidth) for the participating transmitters.

5. The server then sends these settings to the transmitters, which modify their behavior accordingly. This parameter setting ability not only enables Metronome to coordinate sharing between heterogeneous transmitters, but it also optimizes the transmitters under its control around fixed interference that is outside its control. Metronome ensures that its transmitters don't use any TV channels withing a region that are sensed as being used by external TV transmitters (TV transmitters are not shown).

6. Metronome employs separate mechanisms for identifying which transmitters contribute to observed interference from the policy of what to do about it. It differs from traditional channel access wisdom by proposing a centralized policy engine to compute the right transmission parameters for each participating transmitter, rather than developing a fully distributed solution where each transmitter makes its own decisions.

Critique :

1. This approach is may be suitable for static networks and aims for long-term throughput fairness between heterogeneous networks.

2. It does not account for short term performance metrics (e.g., delay and collision rate),which are important to the monitoring and control applications as seen on ZigBee networks.

3. This is a centralized approach and it is a single point of failure. The failure of the monitor node or the server may lead to failure of the coexistence of the networks.

[17] **Packet Switching in Radio Channels: PartIl-The Hidden TerminalProblem in Carrier Sense Multiple-Access and the Busy-ToneSolution**

The paper proposed and studied the Split-channel Reservation Multiple Access (SRMA) scheme for a network with one central station and a number of terminals. The whole channel is split into two sub-channels, one for message transmission and the other for control packet transmission (RAM mode), or into three sub-channels, one for message transmission, one for request transmission, and the other for answer-to-request transmission (RA mode). A ready node sends its request to the central station on the request channel using an ALOHA or CSMA manner. The central station would acknowledge the successful requests before the data packet is transmitted.

Algorithm :

1. The total available bandwidth is to be divided into two sub channels : a message channel and a busy-tone (BT) channel.
2. It transmits a busy-tone signal on the busy-tone channel as long as the station senses carrier on the incoming message channel.
3. Whenever a terminal has got a packet for transmission, it senses the busy-tone channel for t seconds (the detection time)
4. If the channel is idle (busy-tone signal is absent) it transmits the packet) and if the channel is busy it invokes a back off timer and reschedules the packet for transmission .
5. After the timer expires, it senses the busy-tone channel and repeats the algorithm. If congestion occurs the terminal learns about it by failing to receive an acknowledgment from the station, the terminal again reschedules the transmission of the packet for some later time, and repeats the above process.

Critique :

1. These protocol require two radios on each transceiver: one for data transmission, and the other emitting a dedicated narrowband signal as the busy tone. It increases the hardware cost.

2. The paper doesn't account for the interference between the busy-tone and message. There is no mechanism proposed in the algorithm to avoid interference between the message signal and busy-tone signal.

3. The available bandwidth is divided into two sub channels : one for the busy tone and other for message. Since the bandwidth is limited the throughput of message is limited by the occupancy of the bandwidth by the busy-tone.

4. The two radios on each transceiver requires battery power and may demand higher battery capacity than the existing model.

5. The author makes an assumption that the environment consists of a large number of terminals communicating with a single station over a shared radio channel. All terminals are in line of sight and within range of the station but not necessarily with respect to each other .The efficiency of the algorithm is measured for central control. It does not work for distributed networks.

Chapter 5: Proposed Solution

The coexistence of ZigBee and WiFi nodes is challenging due to the following factors.

1. The transmission power of ZigBee is 20 dB lower than WiFi's transmission power, hence, its visibility to WiFi is poor.
2. The ZigBee's MAC-layer backoff timer duration and wait time for acknowledgement is large, and it can easily be preempted by WiFi in the middle of a rx/tx transition (e.g., sensing-to-transmission or data-to-ACK transition), and thus causing collision.
3. Third, the ZigBee allows for TDMA mode, which does not involve carrier sensing, hence, may collide with an ongoing WiFi transmission.

The disparate transmit power, time resolution, and scheduling mode makes the coexistence of Wifi and Zigbee nodes difficult.

The proposed solution employs an external Channel Allocator(CA) to make the wireless medium available to ZigBee network for communication. The channel allocator consists of a spectrum analyzer, scheduler and a transceiver. The RSS threshold value of the spectrum analyzer is set to the transmit power level of the ZigBee nodes i.e the CA captures all the transmitted signals whose signal strength is greater than the ZigBee node's transmitted signal strength, thus the channel allocator will have the complete idea of the channel occupancy and the networks contending for the channel. The channel allocator determines the average time between the beacons of each WiFi access point and it also determines the different ZigBee networks present. The CA runs a dynamic TDMA scheme to make the channel available to Zigbee networks for communication.

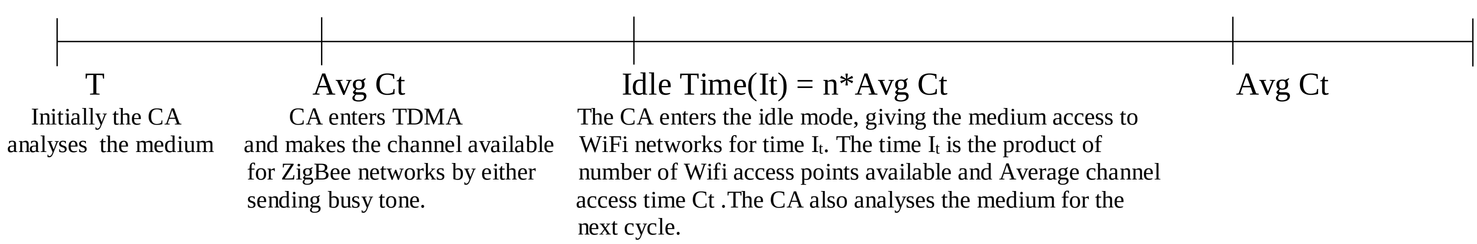


Figure 1

Spectrum Analyzing by Channel Allocator

Initially the channel allocator analyzes the spectrum for time T(Initiation time), which is sufficiently large enough to determine the WiFi access points and Zigbee nodes available and the channel being used by them respectively for communication.

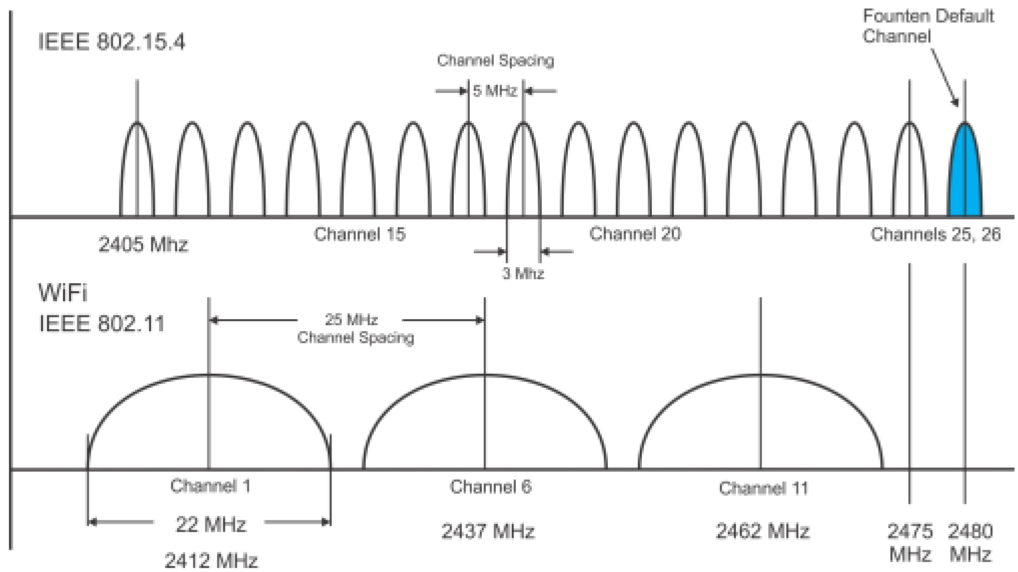


Figure 2

From [7], in the 2.4-GHz spectrum, the width of each WiFi channel is 22 MHz, and the ith channel is centered at (2.407+ 0.005i) GHz , i ∈ [1,11] and the adjacent channels partially overlap with each other. For a ZigBee channel, the nth channel is centered at [2.405 + 0.005(n-11)] GHz, n ∈[11,26]. Each ZigBee channel occupies 5 MHz and the adjacent channels are non-overlapping. As a result, each WiFi channel overlaps with four ZigBee channels. The figure 2 shows the different channels available for WiFi and Zigbee nodes for communication and their corresponding center frequency.

The CA listens to the channel and identifies the beacon signals sent out by the access points of the WiFi networks to determine the access points available within its range and also it determines the time interval between the successive beacons from a single access point to estimate contention free repetition interval of that corresponding access point. The CA estimates the Average Channel Time (C_t) by taking average of the inter-beacon duration of all the access points available.

Data Structures

C_w - Channels used by Wifi network
C_z - Channels used by Zigbee network
C_B - Channels used for busy tone
B_n - Beacon Signal of nth access point
t_{iBn} - timestamp of ith beacon from the nth access point
N_w - Number of access points
N_z - Number of ZigBee networks
C_t - Average channel access time

Determining the Average Ct

$$C_t = \sum_{n \in (1,2,\ldots n)} (t_{i+1Bn} - t_{ibn}) / N$$

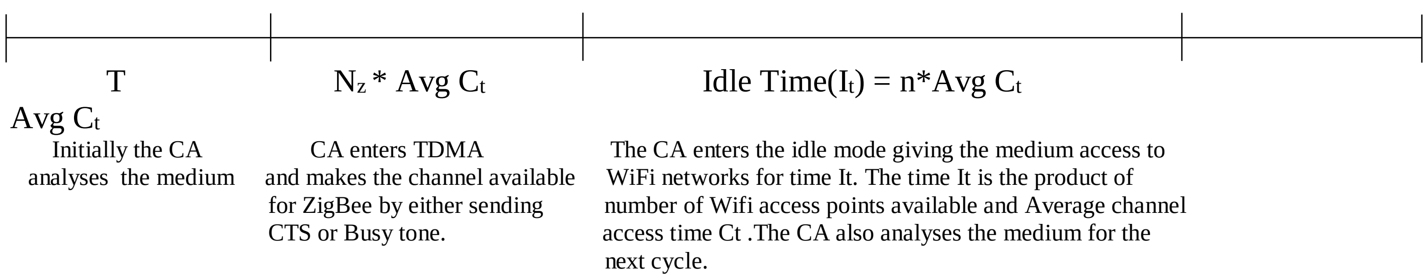


Figure 3

Allocating Channel for ZigBee network

Once the CA has determined the Average Channel Time (C_t) during the period T, the CA enters the dynamic TDMA mode. The CA selects the appropriate channel for

sending the busy tone, then transmits the busy tone for the estimated average channel time(C_t). During this period the ZigBee network gets access to the medium and could exchange their data. The channels used for sending the busy tone and the ZigBee network's data are orthogonal, hence there is no interference between the data sent by ZigBee and busy tone sent by CA, and also the busy tone is within the range of WiFi channel, hence the WiFi nodes backoff on receiving the busy tone.

After the Ct period the CA enters into the Idle state and analyses the channel for Idle Time(I_t). During this period, the CA makes the estimation for the Average Channel Time(C_t) and number of WiFi access points available for the next cycle.

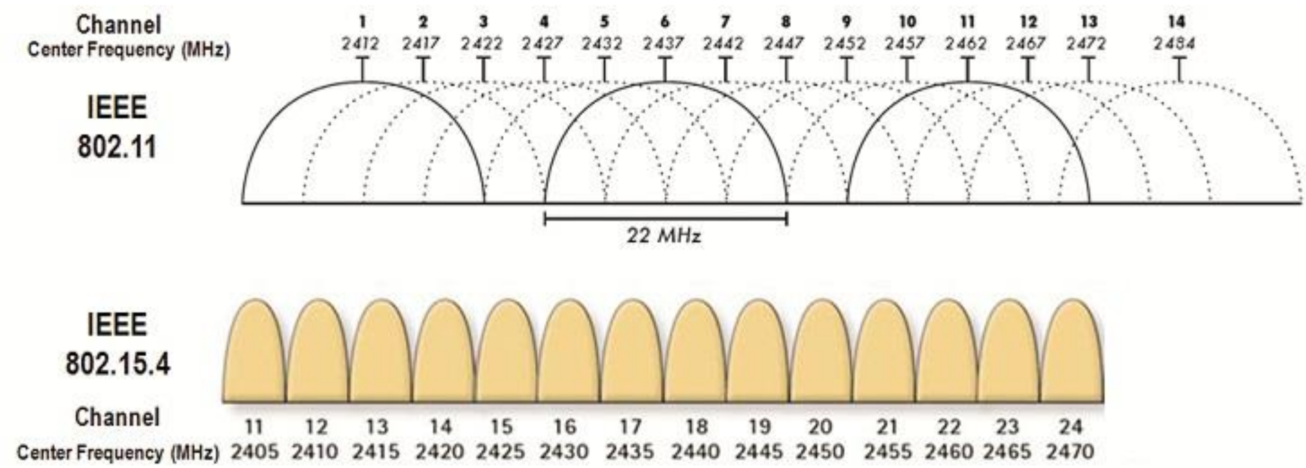
$$\textbf{Idle Time}(I_t) = N_w * C_t$$

Based on the number of WiFi access points and ZigBee networks available the CA allocates fair share of medium to all the networks.

Determining the channel for busy tone :

From figure 2, one could see that the WiFi channel overlaps with four ZigBee channels. From the spectrum analyzer, the CA could determine the channel used by WiFi access point and the Zigbee network. Since there are remaining three ZigBee channels unoccupied within the range of the corresponding WiFi channel, the CA could use one among those channel for sending the busy tone. Thus the DATA signal of ZigBee and the busy tone of CA are orthogonal and there is no interference between them.

Let us now analyze the possible cases of channel occupancy by ZigBee and Wifi networks.



Case 1:

There is single WiFi access point using channel 6 and a single ZigBee network occupying channel 17. In this case the channel allocator (CA) determines the inter-beacon interval of the access point and allocates the medium to the ZigBee network for the time period C_t. The CA uses either channel 16, 18 or 19 for sending the busy tone channel.

$C_w \in (6)$

$C_z \in (17)$

$C_B \in (16,18,19)$

Avg $C_{t} = t_{(i+1)B1} - t_{iB1}$

$N_w = 1$

$N_z = 1$

Avg $C_{t} = t_{(i+1)B1} - t_{iB1}$

T	Avg C_t	Idle Time(I_t) = N_w*Avg C_t = Avg C_t	Avg C_t
Initially the CA analyses the medium	CA enters TDMA and makes the channel available for ZigBee by sending Busy tone.	The CA enters the idle mode giving the medium access to WiFi networks for time I_t. The time I_t is the product of number of Wifi access points available and Average channel access time Ct .The CA also analyses the medium for the next cycle.	

Case 2 :

There is single WiFi access point using channel 6 and three ZigBee networks Z1, Z2 and Z3 occupying channels 16, 17 and 18 respectively. In this case the channel allocator (CA) determines the inter-beacon interval of the access points and allocates the medium to the ZigBee networks for the time period N_z*C_t. The CA uses either channel 16, 18 or 19 for sending the busy tone channel.

$C_w \in (6)$
$C_z \in (16,17,18)$
$C_B \in (19)$
$\text{Avg } C_{t\,=}\ t_{(i+1)B1} - t_{iB1}$

$N_w = 1$
$N_z = 3$

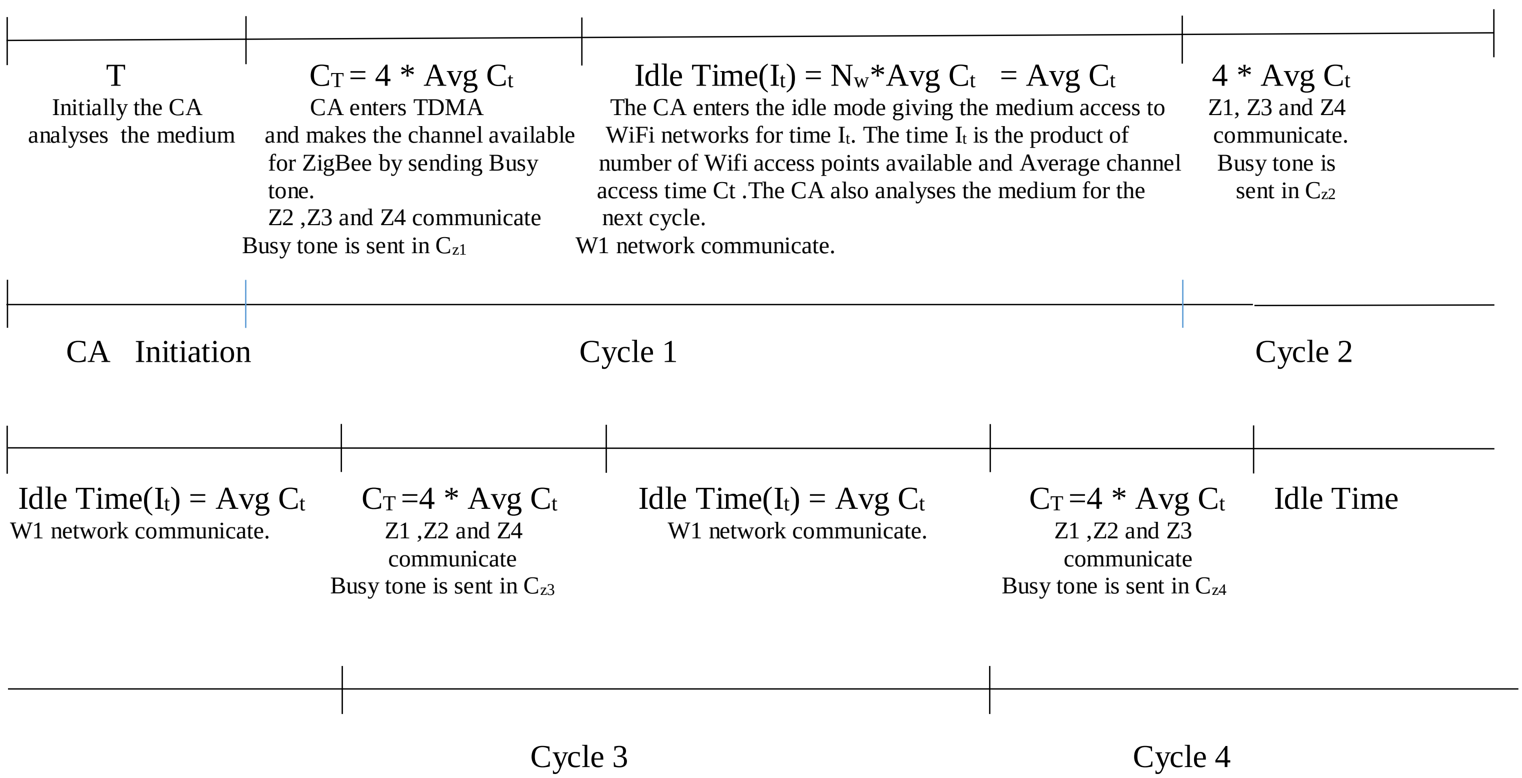
$C_T = N_z * \text{Avg } C_t$
$\quad = 3 * \text{Avg } C_t$

T	$C_T = 3 * \text{Avg } C_t$	Idle Time(I_t) = N_w*Avg C_t = Avg C_t	3 * Avg C_t
Initially the CA analyses the medium	CA enters TDMA and makes the channel available for ZigBee by sending Busy tone.	The CA enters the idle mode giving the medium access to WiFi networks for time I_t. The time I_t is the product of number of Wifi access points available and Average channel access time Ct .The CA also analyses the medium for the next cycle	

Case 3 :

There is single WiFi access point using channel 6 and four ZigBee networks Z1, Z2 ,Z3 and Z4 occupying channels 16, 17, 18 and 19 respectively. In this case the channel allocator (CA) determines the inter-beacon interval of the access point and allocates the medium to the ZigBee networks for the time period N_z* Avg C_t.

The CA do not have any unoccupied ZigBee channel within the channel range of the access point for sending the busy tone. In this case, the CA makes a compromise on the transmission of a single ZigBee network in turns per cycle. For the first cycle the CA uses the channel 16 of Z1for sending the busy tone. During the second cycle, it uses channel 17 of Z2 for sending the busy tone making the channel 16 available to Z1 for communication and the channel selection for busy tone take place in a loop. The Channel selection for busy tone start from the leftmost Zigbee channel within the access point's channel range to the rightmost channel and then go in loop.



$C_w \in (6)$
$C_z \in (16,17,18,19)$
$C_B \in (-)$
Avg $C_t = t_{(i+1)B1} - t_{iB1}$
$N_w = 1$
$N_z = 4$

$C_T = N_z * Avg\ C_t$
$= 4 * Avg\ C_t$

Case 4 :

There are two WiFi access points using channel 6 and channel 7 and one ZigBee network Z1 occupying channel 17. In this case the channel allocator (CA) determines the inter-beacon interval of the access points and estimates their average to determine Avg C_t and allocates the medium to the ZigBee networks for the time period N_z* Avg C_t. The CA uses the ZigBee channels that are within the range of channels of both the WiFi access points W_1 and W_2 for sending the busy tone. In this case the busy tone is sent in either channel 18 and 19. Since the channel 17 is occupied by Z1 it cannot be used for sending the busy tone even though it is within the range of channels C_{w1} and C_{w2}.

$C_w \in (6,7)$
$C_z \in (17)$
$C_B \in (17,18,19)$ since channel 17 is occupied by Z1 $C_B \in (18,19)$
Avg $C_{t} = t_{(i+1)B1} - t_{iB1}$

$N_w = 2$
$N_z = 1$

$$C_T = N_z * \text{Avg } C_t$$
$$= \text{Avg } C_t$$
$$I_t = N_w * \text{Avg } C_t$$
$$= 2*\text{Avg } C_t$$

T	C_T = Avg C_t	Idle Time(I_t) = N_w*Avg C_t = 2*Avg C_t	Avg C_t
Initially the CA analyses the medium	CA enters TDMA and makes the channel available for ZigBee by sending Busy tone. Z1 communicate. Busy tone is sent in C_B	The CA enters the idle mode giving the medium access to WiFi networks for time I_t. The time I_t is the product of number of Wifi access points available and Average channel access time Ct .The CA also analyses the medium for the next cycle. W1and W2 network communicate.	Z1 communicate. Busy tone is sent in C_B

Case 5 :

There are two Wifi access points using channel 6 and 11 and a single ZigBee network occupying channel 14. In this case, since the channels occupied by all the networks are orthogonal, there is no interference between the networks and there is no need for scheduling by the channel allocator. In this situation the channel allocator remains in the Idle mode and listens to the channel.

Case 6 : (Special Case)

There are two Wifi access points using the channel 6 and channel 8 and a single ZigBee network occupying channel 19. In this case the ZigBee channels that are within the range of channels of both the WiFi access points W_1 and W_2 for sending the busy tone is only channel 19 . Since the Zigbee network is using channel 19 for its transmission, it could not be used for sending the busy tone by CA. In this case the CA would have to send two busy tones one in the channel range of W1 and the other in the channel range of W2.

$C_w \in (6,8)$
$C_z \in (19)$
$C_B \in (19)$ since channel 19 is occupied $C_B \in$ (empty)
$C_{B1} \in (16,17,18)$
$C_{B1} \in (20,21,22)$

$\text{Avg } C_t = t_{(i+1)B1} - t_{iB1}$
$N_w = 2$
$N_z = 1$
$C_T = N_z * \text{Avg } C_t$
$= \text{Avg } C_t$
$I_t = N_w * \text{Avg } C_t$
$= 2*\text{Avg } C_t$

T	C_T = Avg C_t	Idle Time(I_t) = N_w*Avg C_t = 2*Avg C_t	Avg C_t
Initially the CA analyses the medium	CA enters TDMA and makes the channel available for ZigBee by sending Busy tone. Z1 communicate. Busy tone is sent in C_{B1} and Busy tone is sent in C_{B2}	The CA enters the idle mode giving the medium access to WiFi networks for time I_t. The time I_t is the product of number of Wifi access points available and Average channel access time Ct .The CA also analyses the medium for the next cycle. W1and W2 network communicate.	Z1 communicate. Busy tone is sent in C_{B1} and C_{B2}

Case 7 :

There are three Wifi access points using the channel 1, 6 and channel 11 and three ZigBee networks occupying channel 11, 17 and 21. In this case the algorithm is run independents for every ZigBee network for each cycle .i.e for the first cycle the medium is made available to Z1, for the second cycle it is made available to Z2 ,for the third cycle it is made available to Z3 and the loop goes on .

- For the first cycle, the CA makes the medium available to Z1 by selecting the channel within the channel range of access point W1 for sending the busy tone during the first cycle. The access points W2 and W3 operate simultaneously along with Z1 ,since the channels used by W2, W3 and Z1 are orthogonal there is no interference between them.

- For the second cycle, the CA makes the medium available to Z2 by selecting the channel within the channel range of access point W2 for sending the busy tone during the second cycle. The access points W1 and W3 operate simultaneously along with Z2 ,since the channels used by W1, W3 and Z2 are orthogonal there is no interference between them.

- For the third cycle, the CA makes the medium available to Z3 by selecting the channel within the channel range of access point W3 for sending the busy tone during the third cycle. The access points W1 and W2 operate simultaneously along with Z3 ,since the channels used by W1, W2 and Z3 are orthogonal there is no interference between them.

T Initially the CA analyses the medium	$C_T = 3* \text{Avg } C_t$ CA enters TDMA and makes the channel available for ZigBee by sending Busy tone. Z1 ,W2 and W3 communicate Busy tone is sent in C_{z1}	Idle Time(I_t) = 3*Avg C_t = Avg C_t The CA enters the idle mode giving the medium access to WiFi networks for time I_t. The time I_t is the product of number of Wifi access points available and Average channel access time Ct .The CA also analyses the medium for the next cycle. W1,W2 and W3 networks communicate.	3 * Avg C_t Z2, W1 and W3 communicate. Busy tone is sent in C_{z2}

CA Initiation — Cycle 1 — Cycle 2

Idle Time(I_t) = Avg C_t W1, W2 and W3 network communicate	C_T =4 * Avg C_t Z3 ,W1 and W2 communicate Busy tone is sent in C_{z3}	Idle Time(I_t) = Avg C_t W1,W2 and W3 network communicate.	C_T =4 * Avg C_t Z1 ,W2 and W3 communicate Busy tone is sent in C_{z1}	Idle Time

Cycle 3 — Cycle 4

$C_w \in (1,6,11)$

$C_z \in (11,17,21)$

$C_{z1} \in (12,13,14)$

$C_{z2} \in (18,19,20)$

$C_{z3} \in (22,23,24)$

$\text{Avg } C_t = t_{(i+1)B1} - t_{iB1}$

$N_w = 3$

$N_z = 3$

$$C_T = N_z * \text{Avg } C_t$$
$$= 3*\text{Avg } C_t$$
$$I_t = N_w * \text{Avg } C_t$$
$$= 3*\text{Avg } C_t$$

Chapter 6: Conclusion

Previous work have revealed severe ZigBee performance degradation in the presence of WiFi traffic, even if WiFi leaves a sufficient idle time (e.g., more than 67% airtime unused). The existing CCS method [7] employs a separate ZigBee node called a signaler with a higher transmit power to send out a carrier signal (busy tone) concurrently with the desired ZigBee's data transmission, thereby improving the ZigBee's visibility to WiFi is improved. The busy tone persists throughout the data and ACK round trip, thus preventing the WiFi's from preempting the ZignBee node's transmission in the rx/tx switching gap. The concurrent busy tone and data transmission is achieved by temporary channel-Hopping mechanism that separates the carrier signaling from the data transmission in frequency domain, and enables WiFi to sense the presence of ZigBee transmission.However in channel-hopping mechanism the ZigBee channel under interference may reside at the edge of a WiFi band, so CCS must decide on hopping to the left-side or right-side adjacent channel, if the ZigBee channel under interference reside at the right-most edge of the WiFi band and the CCS hops to the right-side of the adjacent channel, in that cast the signaling becomes ineffective and vice versa.

In this paper, the solution employs an external Channel Allocator(CA) to make the wireless medium available to ZigBee network for communication. The channel allocator consists of a spectrum analyzer, scheduler and a transceiver. The RSS threshold value of the spectrum analyzer is set to the transmit power level of the ZigBee nodes i.e the CA captures all the transmitted signals whose signal strength is greater than the ZigBee node's transmitted signal strength, thus the channel allocator will have the complete idea of the channel occupancy and the networks contending for the channel. The channel allocator determines the average time between the beacons of each WiFi access point and it also determines the different ZigBee networks present. The CA runs a dynamic TDMA scheme to make the channel available to Zigbee networks for communication.

The proposed solution works fine for environment consisting of a single WiFi access point and any number of ZigBee networks. The solution could achieve coexistence in case of multiple WiFi access points and ZigBee networks using a single transceiver, however for the special situation discussed in case 6, CA would require two transmitters for sending two busy tones.

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