A Coexistence model of IEEE 802.11b/g IEEE 802.15.4 and LTE-U

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Contents

1 Problem Statement

Present a coexistence model of IEEE 802.11b/g, IEEE 802.15.4 and LTE-U to accurately explain their coexistence performances.

2 Network Model

Consider a network consisting an LTE-AP, N_{lte} LTE nodes, N_{WiFi} 802.11b/g nodes, N_{wsn} 802.15.4 nodes. Herein after 802.11b/g nodes are referred to as WiFi nodes and 802.15.4 nodes are referred to as Wsn nodes. LTE nodes and LTE-AP are expected to implement Fair LBT Algorithm described in [1]. LTE, WiFi and WSN Iare saturated networks to simulate continuous contention for medium access. Physical channel is expected to be error free and the only packet drops are due to collisions. All nodes are in co-channel interference range. WiFi nodes are expected to sense Wsn and LTE powers of transmission while Wsn nodes can sense transmit power levels of WiFi and LTE nodes. All three networks' nodes use the same 2.4Ghz channel and time share the medium to avoid interference and collisions. We now use this network model to understand and present a coexistence model of all three networks together.

3 Motivation

Wireless communication has become core of mobile communications. LTE communications happen in licensed bands brought by mobile service providers. With increase in mobile users, service providers have started looking to provide LTE communications in unlicensed bands since these bands are not highly occupied compared to licensed bands. However, this introduced new challenges where LTE needs to co-operate with incumbent technologies like WiFi, Bluetooth and Wsn. LTE when deployed without any modifications to its protocol in unlicensed band, would just kill the existing technologies in the same unlicensed band. To address such issues, LTE mac operation has been changed to on/off based duty cycling mode(LTE-U). Many studies have been conducted on duty cycle based LTE-U and one of existing technologies in 2.4Ghz. WiFi and Wsn coexistence has been studied extensively and introduction of LTE-U as dominant technology in unlicensed band has triggered further studies. LTE-U and WiFi coexistence has been studied extensively while coexistence of LTE-U and Wsn has also been studied although not extensively. WiFi has become core part of every home, office. Wsn is being used for many sensor and battery critical operations. With LTE in licensed band, most cellular communications use LTE. With LTE-U in unlicensed band, there is a great need to study the coexistence behaviour of LTE-U, WiFi and Wsn in the same unlicensed band together since many networks have all three technologies operating together.

4 Introduction

Coexistence of various networks in unlicensed band has been the focus of study for a long time now. 802.11, 802.15.4 and Bluetooth coexistence has been studied extensively in [2], [3], [4], [5], [6], [7], [8], [9]. Other modes of interferences including microwave ovens, cordless phones have also been studied in [10]. Recent advances have introduced LTE in unlicensed band and has led to extensive studies on coexistence of 802.11 or 802.15.4 with LTE-U and LAA based LTE in [11], [12], [1], [13], [14], [15]. 802.11, 802.15.4 and Bluetooth are the most common networks deployed in 2.4Ghz. [15] discusses coexistence of LTE with ZigBee in 2.4Ghz. Coexistence of these common networks together with LTE-U has not been studied thus far. Bluetooth has the option of jumping to non overlapping channel using FHSS. However CSMA/CA based 802.11 and 802.15.4 MAC layer operation needs to be studied together with LTE-U since LTE-U does not sense the channel before transmitting.

Today, most protocols in unlicensed are implemented in the same mobile device with WiFi being used for internet primarily, LTE being used for mobile communications and WSN being used for transmitting sensor data. WiFi and WSN follow CSMA/CA based mac operations and can coexist among themselves in unlicensed band. LTE, being TDMA protocol in licensed band, does not interfere with WiFi and WSN. Now that LTE is being introduced in unlicensed band and since its a TDMA protocol with higher power of transmission that WiFi, interferes with WiFi and WSN. There is a need to study the behaviour of these protocols when they coexist and develop efficient coexistence models which maximise overall network performance and minimise overall collisions among protocols. Before we study the coexistence behaviour, let us understand the current protocol operations in the unlicensed bands.

4.1 LTE operation in unlicensed band

LTE operation in unlicensed band can be classified into two behaviours.

- Based on 3GPP Rel. 12, LTE-U is the unlicensed flavor of LTE protocol in licensed bands. LTE TDMA based mac operation is applied to LTE-U in unlicensed bands without any change in mac protocol behaviour. However, duty cycling is introduced so that other technologies get a share of the medium being used to transmit.

- Licensed Assisted Access (LAA) is introduced in 3GPP release 13 as part of LTE Advanced Pro. It uses carrier aggregation in the downlink to combine LTE in unlicensed spectrum with LTE in the licensed band. It uses a contention protocol known as listen-before-talk (LBT), mandated in some European countries, to coexist with other Wi-Fi devices on the same band.

4.2 WiFi operation in unlicensed band

WiFi uses CSMA/CA based mac operation. It senses the channel for energy and transmit data if there is no energy in the medium for atleast few nano seconds(DIFS). To avoid collisions, it uses binary expontial back-off (BEB) counter before transmitting. Back-off counter is frozen when the medium is busy and is resumed when the medium is idle. Once the back-off counter reaches zero, WiFi transmits.

4.3 WSN operation in unlicensed band

WSN uses CSMA/CA based operation similar to WiFi except that back-off counter is not frozen when the medium is busy. This protocol is mainly used for low powered devices.

5 Classification of Coexistence Solutions

Coexistence of networks in the same unlicensed band can be studied based on three modes of separation.

- Spatial separation where networks are separated out of co-channel interference range.
- Temporal separation where networks using the same frequency time share the medium to avoid interference and collisions.
- Frequency separation where networks use different channels avoiding interference.

5.1 Channel selection using spatial separation

Devices separated from each other atleast out of co-channel interference range, can use the same channel for transmissions and reception of data. However, number of devices using wireless are growing day by day and spatial separation will not be a viable solution as number of devices grow.

5.2 Channel selection using frequency separation

Devices which are in the same co-channel interference range use different frequencies for transmission and reception of data. However, as density of devices grow in the same space, frequency separation will not be a viable solution due to the limited number of channels. Based on how channel selection happens, it can further be classified as

- Random channel selection where device selects a channel randomly and checks if any other device is using the same channel nearby.
- Distributed channel selection where devices co-ordinate among themselves and select a channel based on the outcome of distributed co-ordination.
- Centralized channel selection where a central authority, typically operator, assigns a channel to each device.

5.3 Channel sharing using temporal separation

Devices use the same channel in a time sharing fashion. Performance of the network is dependent on effective time sharing the channel. Coexistence can further be classified based on the mac operations of the protocols sharing the same channel.

- Mac Operation based on duty cycling A duty cycle is the fraction of one period in which a signal or system is active. A mac protocol using this mechanism has on and off periods. During on period, it transmits and receives data. During off period, it turns the transmission off and sleeps. Other protocols sharing the same channel can transmit/receive during its off period. LTE-U uses duty cycling based mechanism to coexist with other technologies in unlicensed band with the help of idle subframes in its frames.

- Mac operation based on Listen Before Talk(LBT) Listen Before Talk (LBT) or sometimes called Listen Before Transmit is a technique used whereby a radio transmitters first sense its radio environment before it starts a transmission. WiFi, WSN and Licensed Assisted Access (LAA) based LTE use this. Mac protocol listens to channel for energy, determines if the channel is idle. If the channel is idle for a period of time, it transmits. If the channel is not idle, it does not transmit and waits for the channel to become idle.

As technology advances, number of mac operations a device supports are increasing there by increasing the density of devices in the same area. It is imperative that eventually devices end up sharing the channel with temporal separation. Number of mobile communication devices using the channels has become so large that even after frequency separation we end up with time sharing the same channel. Spatial separation rules out interference however in a similar fashion mobile devices end up time sharing the channel since mobility is the core part of these devices.

LBT based LTE can coexist with WiFi and WSN better than LTE-U, since former uses mac operation similar to WiFi and WSN by listening to the channel and transmits only when channel is idle. It can employ other RTS/CTS based mechanisms to utilize the channel effectively. LTE-U, on the other hand, if deployed along with WiFi and WSN in the same unlicensed band, does not listen to the channel and transmits during its on period. This affects WiFi and WSN performance since both use adaptive data rates to reduce the rate of transmission on detecting multiple collisions, which further increases the amount of share they need for transmitting in the channel. LTE-U has the advantage of not modifying the existing LTE protocol which is used in licensed band. Here we focus on temporal separation of LTE-U, 802.11 and 802.15.4 to communicate and time share the medium, study the existing coexistence models and provide better solutions when few rules of coexistence mechanisms are violated.

6 Parameters of Coexistence model

Performance of the Coexistence model is dependent on how well channels of operation are separated out in Channel Selection based spectrum sharing and the types of MAC operations involved(CS, Duty Cycle), duration of each MAC operation in the same channel of operation for Time based MAC operations. So, model can be quantified by two indexes.

- Total system throughput: Total system throughput can be obtained by adding throughputs of all the networks in the model in a given period of time. The duration of MAC operation is directly proportional to total system throughput. Better the system throughput, better the network performance, hence better the model.

- Fairness: Consider a scenario where duty cycle based MAC and CS based MAC are contending for the channel. A simple coexistence model would yield high system throughput if duty cycle based MAC occupies the medium for a higher share in the given period of time. This would be unfair to CS based MAC. So, fairness is another index along with total system throughput that can measure the performance of coexistence model.

7 Related Works

Jeongho Jeon et al. in [14] showed introduction of LTE protocol as it is, had major effect on WLAN in unlicensed spectrum. CS based and duty cycle based MAC operations were studied and duty cycle based LTE was shown to be preferred when eNB is outdoor and WLAN is indoor. Results of case study by Andra M. Voicu et al. in [13] showed performance of coexistence MAC sharing were classified into two categories. Low interference coupling helps duty cylce based LTE outperform LBT based LTE in coexistence with WLAN while high interference coupling favors LBT based LTE. Number of idle subframes in LTE-U frame determines the total system throughput in coexistence with WiFi. Haneul Ko et al. in [1] proposed a fair LBT based algorithm to determine the number of idle subframes by estimating collisions caused by WiFi and considering fairness to achieve higher total system throughput. Imtiaz Parvez et al. in [15] studied the effect of LAA based LTE on ZigBee in 2.4Ghz and proposed methods to reduce the impact. Modification of transmission configurations and power control of LTE helped reduce the effect.

Experimental study by K. Shuaib et al. in [4] on the effect of interferece by ZigBee on WiFi and vice-versa showed that downlink of WiFi was greatly affected by ZigBee transmissions. However performance of ZigBee was greatly affected by WiFi transmissions when the channels of operation coinside. Lieven Tytgat in [8] examined packet loss due to collisions between WiFi and ZigBee and CACCA based MAC sensing solution was proposed to be implemented in WiFi. Wei Yuan in [7] provided a coexistence mechanism of WiFi and ZigBee. Three ranges of interference were studied based on spatial separation and power of transmission of both technologies. Throughput of ZigBee in presence of WiFi was estimated

7.1 Discussion of two existing models

In this section, we discuss the operation in two existing models and their measurement indexes used. 1. Duty Cycle based LTE MAC operation + CS based WiFi operation 2. CS based WiFi operation + CS based WSN operation

7.1.1 LTE and WiFi operation using F-LBT based coexistence model

A frame in LTE-U is divided into 10 subframes. Each subframe has 2 slots in it. Idle or blank subframe is transmitted with reduced power and is used only

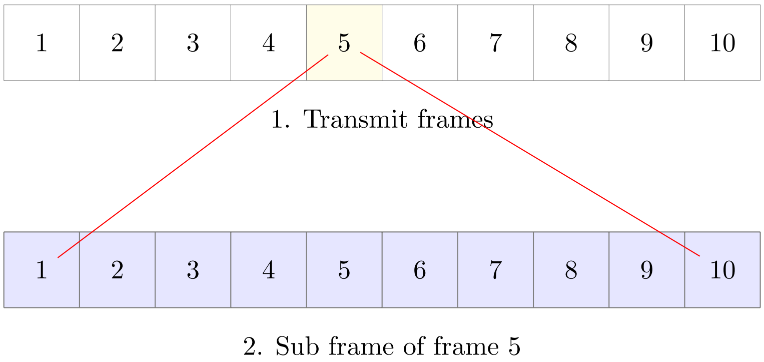

Figure 1: Transmit frames and its sub frames in LTE

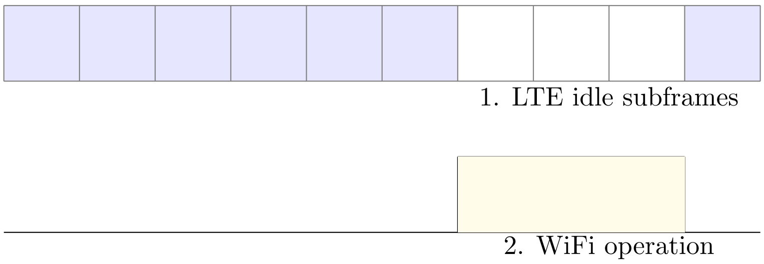

Figure 2: LTE-U, WiFi coexistence using idle subframes in LTE-U

for control signalling. No user data will be available in this subframe. Figure 1 depicts the frames in LTE. Figure 2 shows the coexistence mode of WiFi and LTE-U using idle subframes. Initially LTE-U AP listens to the channel to determine the idle probability and collision probability among WiFi nodes.

$$p_c^{AP} = \frac{N_c}{N_s} \tag{1}$$

$$p_i = \frac{N_i}{N_s} \tag{2}$$

where $\mathrm{N_c}$ is the number of collisions among WiFi nodes, $\mathrm{N_i}$ is the number of idle periods, $\mathrm{N_s}$ is the total number of slots listened. Number of WiFi nodes is estimated using the following equation.

$$log_{(1-T_{NO})} p_i = \frac{(T_{NO}-1)(p_c^A P + p_i - 1)}{p_i T_{NO}} \tag{3}$$

where $\mathrm{T_{NO}}$ is the transmission probability of WiFi node when LTE-U node does not transmit. Total system throughput($\mathrm{S_{N_i}}$) and Jain's fairness index($\mathrm{F_{N_i}}$) is defined by a reward function below.

$$R_{N_i} = \alpha S_{N_i} + (1-\alpha) F_{N_i} \tag{4}$$

α is the weighted factor. F-LBT selects $\mathrm{N_i}$ so that $\mathrm{R_{N_i}}$ is highest regardless of α. Higher the number of idle subframes, lower the reward value since channel is not utilized effectively by the randomness in WiFi operation.

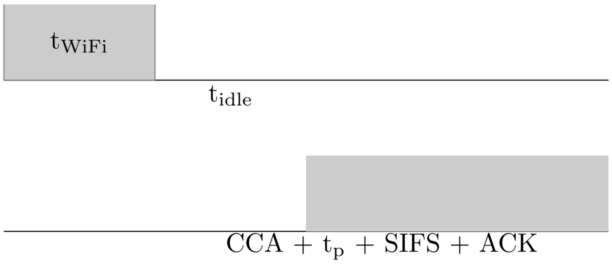

Figure 3: WSN transmission in case 1

7.1.2 WiFi and WSN coexistence model

A WiFi node idle time is given by following equation.

$$t_{idle} = DIFS + mT_{bs} \tag{5}$$

where DIFS is the distributed co-ordinate function value that varies according to WiFi specification, m is random variable uniformly distributed in [0, 2^{CW}] with CW being the contention window. $\mathrm{T_{bs}}$ is the backoff slot defined in specification. If the channel is idle for $\mathrm{t_{idle}}$, WiFi node begins transmission followed by SIFS and ACK.

WSN node senses the channel for CCA period and transmits only if the channel is idle during CCA period. Transmit period of WSN nodes is given by

$$CCA + t_p + SIFS + ACK \tag{6}$$

However, if channel is busy, WSN node backs off incrementing the contention window by 1(backoff time is doubled) and retries after backoff until maximum contention window. Packet is then dropped if channel is still busy.

[7] analyses the MAC operation of WiFi and WSN nodes in terms of power and timing aspects. WiFi, operating in 2.4Ghz has higher power of transmit compared to WSN. This difference powers lead to three different ranges of in terms of power aspect.

- Both WiFi and WSN nodes can sense the power of each other on the channel. For WSN nodes to transmit, channel sensing time of WSN nodes should be less than WiFi channel sensing time as depicted in figure 3.

  $$CCA \leq DIFS + mT_{bs} \tag{7}$$

  For m $\geq$ 4 in 802.11b and m $\geq$ 12 in 802.11g, WSN node can transmit successfully.

- WSN nodes can sense WiFi power while WiFi nodes cannot sense WSN nodes as shown in figure 4 If WSN nodes transmit during idle period of WiFi nodes, transmission will be successful.

  $$CCA + t_p + SIFS + ACK \leq DIFS + mT_{bs} \tag{8}$$

  This inequality doesn't hold. Transmission will be successful only when power at reception is high enough to recognize the transmission.

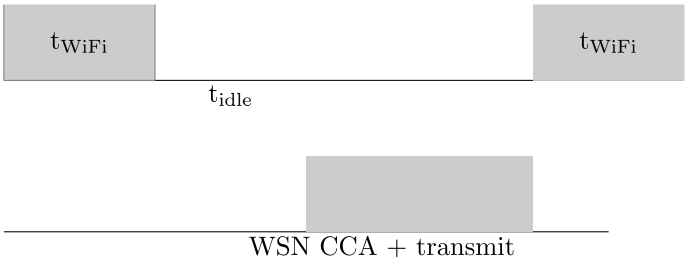

Figure 4: WSN transmission in case 2

- Both WiFi and WSN nodes do not sense each other, however since WiFi has longer range, interferes with WSN transmission(blind transmissions). In case of transmissions along with receipt of ACK, this case never holds for WSN nodes unless power at the reception is high enough to detect the transmission.

Throughput(S) of WSN node in presence of WiFi interference is given by the renewal process.

$$S = \frac{E[W_n]}{E[X]} \tag{9}$$

$$E[W_n] = pE[t_p] \sum_{i=0}^{4} (1-p)^i \tag{10}$$

$$E[X] = \sum_{i=0}^{4} [p(1-p)^i (\sum_{j=0}^{i} E[B_i] + (i+1)CCA + E[t_p])] + (1-p)^5 (\sum_{i=0}^{4} E[B_i] + 5CCA) \tag{11}$$

$$p = \frac{1}{CW_{min}+1} \sum_{m=a}^{CW_{min}} \frac{DIFS + mT_{bs} - CCA}{E[t_w] + DIFS + mT_{bs}} \tag{12}$$

where p is the probability of channel being idle for WSN transmission t_p, t_w is the transmission time of WiFi with SIFS and ACK. $E[B_i]$ is the expected value of backoff time B_i(uniformly distributed in $[0, 2^{BE_i}]$. a is either 4 or 12.

7.1.3 Need for better coexistence model

F-LBT based model uses WiFi collision probability to identify number of WiFi nodes in the network. Number of nodes is in turn used to estimate maximum reward. The key assumption here is, collisions as observed by LTE AP are due to WiFi transmissions only. Adding WSN into this model invalidates this assumption since collisions between WiFi and WSN need to be taken into account.

Coexistence model for WiFi and WSN estimates the channel idle probability during WSN CCA so that WSN node can transmit. Since WiFi and WSN are CSMA based MAC protocols, certain level of fairness is built in. Key assumption here is channel is idle when WSN and WiFi nodes do not transmit. Introducing LTE-U into this model invalidates this assumption. LTE-U takes unfair advantage in accessing the channel thereby reducing the channel idle probability to almost zero.

8 Proposed coexistence model

Let us assume a WSN node needs to transmit 1 byte payload. CCA is 0.128ms, SIFS is 0.192ms, and at 250Kbps 1 byte payload transmit time is 0.448ms, ACK with 0 byte payload is 0.435ms. Total air time in the best case(with random backoff set to 0) would be

$$CCA + 1bytetransmittime + SIFS + ACKtransmittime = 1.203ms \quad (13)$$

In presence of WSN, minimum number of idle slots that WSN node requires would be atleast 2 to accommodate best case transmission. WSN nodes' default retry limit is 4. Increasing the limit has more chances of finding the channel idle.

$$N_i \geq 2 \quad (14)$$

Consider the case where WiFi node needs to transmit 1500 byte payload. At 11Mbps rate, total time required to transmit and receive ack is around 1.374ms. At 6Mbps rate, total time is around 2.156ms. At 1Mbps rate, which is the lowest for 802.11 a/b/g/n, total time is approximately 12.780ms. With LTE-U, medium is never idle more than idle slots in a 10ms frame. So, WiFi operation needs to be adjusted to minimum rate of at least 6Mbps, and number of slots that should be left idle in 10ms LTE-U frame should be greater than 3.

$$N_i \geq 3 \quad (15)$$

LTE-U with F-LBT is capable of listening to the channel for a finite period of time. We leverage this to determine the transmit time of other protocols in the network i.e find the amount of time $\mathrm{T_p}$ that WiFi and WSN nodes keep the medium busy. Let the total period of time be $\mathrm{T_{total}}$. $\frac{T_{\mathrm{p}}}{T_{\mathrm{total}}}$ gives the approximate transmit probability of WiFi and WSN nodes. Number of idle slots that LTE-U needs to set is directly proportional to this ratio.

$$N_i \propto \frac{T_{\mathrm{p}}}{T_{\mathrm{total}}} \quad (16)$$

$\mathrm{N_i}$ could be identified as a simple linear function of $\frac{T_{\mathrm{p}}}{T_{\mathrm{total}}}$ with a range of [3, 10].

$$N_i = K + \lceil \alpha(\frac{T_{\mathrm{p}}}{T_{\mathrm{total}}}) \rceil \quad (17)$$

where K is a constant and is set to 3 for the model described here, α is a fairness indicator for the network and ranges between 0 and 7.

9 Analysis

Probability of collision, which was the existing solution for coexistence with LTE-U, does not give enough insight on protocol accessing the shared medium. Probability of a protocol accessing the medium to transmit is given by probability of transmission. Current solution uses probability of transmission rather than probability of collision to determine the number of idle slots in LTE-U frame. Once idle slots are determined, LTE-U transmits in the non idle slots only. WiFi and WSN can safely coexist in the idle slots provided 14 and 15 are satisfied.

9.1 Effect of α

α determines the weightage given to the fraction of the time other networks transmit. Higher the α, higher the number of idle slots and higher the fairness given to other networks by LTE-U. WiFi and WSN nodes share the medium without any idle perioids i.e. $\mathrm{T_p}$ is equal to $\mathrm{T_{total}}$, depending on α, $\mathrm{N_i}$ could be set in the range from 3 to 9. If α is biased to LTE-U, $\mathrm{N_i}$ is set to less than 5 and if α is biased towards the rest of the networks, $\mathrm{N_i}$ is set to greater than 8. WiFi and WSN nodes donot have any data to transmit i.e. $\mathrm{T_p}$ is 0. $\mathrm{N_i}$ is set to 3 to accommodate minimum fairness in the network in case WiFi and WSN nodes wish to transmit.

9.2 Effect of higher retry limit in WSN

Retry limit of WSN is set to higher value which increases the probability of WSN nodes transmission. However, this could cause reduction in lifetime of battery operated devices.

9.3 Effect of lower limit on data rates of WiFi

Minimum data rate of WiFi nodes is set to 6Mbps. Legacy devices which do not support high rates have very less chances of transmitting data.

10 Conclusion

In this paper we have identified the shortcomings of two existing coexistence models and analysed why we need a new coexistence model for LTE-U, WiFi and WSN to coexist. We have proposed a modification to F-LBT based LTE-U algorithm to determine the number of idle slots based on the channel occupancy time rather than probability of collision. This algorithm can be used in any model which adds any other protocols along with WiFi and WSN.

We have shown mathematically, increasing minimum data rate in WiFi and increasing retry limits of WSN yield better probability of transmissions in WiFi+WSN networks that coexist with LTE-U. In conclusion we have proposed a better coexistence model for LTE-U, WiFi and WSN. Future work includes experimental verifications and results of this proposal.

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