Spectrum Utilization Assessment of Wi-Fi Network Using Qualcomm/Atheros 802.11 Wireless Chipset

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Abstract. Wireless spectrum is a scarce resource and with the market boom of wireless technology over the years, unlicensed spectrum has become overcrowded with different wireless standards. In this paper, we proposed and demonstrated a proof of concept solution using FFT spectral scan with two methodologies: MaxHold-RMS approach and percentage ratio count approach. Both approaches could be used to detect a free/best channel from different scanned channel on the spectrum. The subsequent contributions were made to knowledge: an FFT based visual spectrum analyzer tool, an algorithm to classify different frequency channel on a spectrum, an algorithm which calculate frequency channel scores using weighted sum model, and channel ranking model. After different experimental evaluations coupled with the FFT spectral sampling timing, operation, a one(1) second scan duration is enough to detect signal transmission from a permanent device on the frequency spectrum since management and control frame signals are always transmitted periodically, while there is little chance for detecting a sporadic signal transmission from the non-permanent user since the FFT spectral scan is performed in passive mode. But to guarantee detection of such sporadic signals then scanning longer at different time segment of the day on the spectrum will increase the probability of detecting such some sporadic signals. Also, the FFT spectral scan capability has shown a high degree of probability for detecting non-WiFi signal on the shared spectrum using Qualcomm/Atheros chipset.

Keywords: Frequency channel · Fast Fourier transform · Wi-Fi WiMAX · airFiber · LTE-U · Radar · WiBACK · OFDM · RMS SNR · RSSI · 5 GHz spectrum · FFT bins · WSM

1 Introduction

It's a known fact that the unlicensed wireless spectrum such as Industrial, Scientific and Medical (ISM) radio bands with operating frequency of 2.4 GHz and Unlicensed National Information Infrastructure (UNII) radio bands with operating frequency of 5 GHz are by nature vulnerable to interference and limited in resources (e.g. frequency, time and space) with numerous users competing for the same resources to push their

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data traffics on. These competitions are attributed to the recent growth in wireless technology which has brought about an heterogeneous network. In the unlicensed spectrum bands, interference is a major concern the user must contend with, and the predominant paradigm used against it is avoidance since you don't have control over the spectrum. Spectrum utilization assessment in the unlicensed spectrum is vital and should be given an utmost consideration because it would help in facilitating the sensing of signal energy on center frequency in bid to help determine how free or busy is a channel/frequency band, which is either a relative or an absolute measurement. This brings up the question of how to find the best frequency channel? With the 5 GHz unlicensed spectrum home to heterogeneous radio standards with different wireless technology such as WiMAX, AirMax/Airfiber, HiperLAN, LTE-U and Radar/DFS all sharing the same spectrum. The big question would now be, can 802.11 wireless chipsets detect the wireless frames signal from these heterogeneous radio standards?

Lastly, Qualcomm/Atheros 802.11xx chipset could scan in passive mode and report spectral samples using Discrete Fourier Transform (DCT) tool to compute Fast Fourier transform (FFT) in baseband, which could be used to detect wireless signals with inclusion of non-802.11 signals [1]. The question of how precise are Atheros/Qualcomm chipsets in terms of their FFT spectral scanning in power/energy sensitivity, signal spectral band, and signal duration need to be investigated. Looking at the foregoing, the above-listed motivations among others motivates us in carrying out this research work.

The remainder of the paper is structured as follows: Sect. 2 discussed the problem formulation, in Sect. 3 literatures was reviewed, Sect. 4 described proof of concept solution model, in Sect. 5 an experimental performance evaluation & analysis would be discussed, while Sect. 6 concludes the paper with conclusion & recommendation.

2 Problem Formulation

From the standpoint of this research paper objectives, background information and problem statement, the main scientific question shall be clarified, which is the best channel among a given set of channels?

To facilitate the answering of the main scientific question stated in the foregoing, the following scientific sub-questions were clarified as well:

i. What kind of interferers (WiFi, WiMAX, Airfiber, HiperLan, LTE-U and Radar/DFS) are expected and how to reliably detect them?
ii. What are the spectral characteristics of the signals/carriers for each interferer both in time and frequency domain?
iii. How precise are Atheros/Qualcomm chipset regarding FFT spectral analysis?
iv. What scan duration and FFT size are required to reliably detect likely expected wireless signals?
v. How to classify a channel and to compare them?

Based on the capability of hardware available for this research work which can report data from spectrum utilization using two scanning modes: WLAN scan and FFT spectral scan, several approaches were considered based on the aforementioned hardware capabilitz. In the context of this research two approaches (MaxHold-RMS and

Percentage count ratio) are proposed based on data samples reported from either FFT spectral scan mode alone or combination of both modes (FFT scan & WLAN scan).

3 Literature Review

There is a broad embodiment of literature on spectrum sensing techniques [2–5], with regards to the problem description of this paper quite a number of related work and state-of-the-art research can be found, but only a few of them would be reviewed because limited work in literature focused on the investigation of the possibilities of any non-IEEE802.11 wireless technology signals acting as a source of interference in the 5 GHz spectrum. This review was based on some requirements such as: (i) Only use the built-in radio and no external tool, (ii) FFT spectral scanner and/or WLAN scanner and (iii) Passive scanning mode.

Shravan et al. [2] proposed Airshark, a system that can detects non-WiFi RF devices (Microwave Oven, FHSS phone, Bluetooth, and ZigBee) signals operating in the 2.4 GHz Instrument, science and measurement (ISM) bands using the functionality provided by commodity WiFi hardware like Atheros AR9280 AGN wireless card. The paper detailed four steps used in the detection pipeline, namely spectral sampling, extracting signal data, generic feature extraction, and device detection. The authors used features such as pulse signature (duration, bandwidth, and center frequency), spectral signature, duty cycle, timing signature, pulse spread and device specific features were all used to detect devices. The authors in [2] evaluated the performance of Airshark using two metrics (detection accuracy and false positive rate). The authors claimed Airshark system has an average detection accuracy of 91–96%, even in the presence of multiple simultaneously active RF devices operating at a wide range of signal strengths (−80 to −30 dBm), while maintaining a low false positive rate. The major gap in this paper [2] was that no specifics on how to classify a channel as free or busy channel was provided. Likewise, the possibility of detecting non-WiFi signals in the 5 GHz band was left out as well.

Balid et al. [3] experimental work was performed using an energy detection technique providing systematics and experimental measurement of spectrum utilization using the concept of duty circle (DC) which was implemented in two stages by setting up two or three-pair 802.11b/g/n networks using Mikrotik router boards with Atheros chipsets. Authors [3] claimed noise level of −105 dBm was measured and provided two signal analysis process algorithms for time domain (TD) and frequency domain (FD) measurement. TD analysis algorithm process was proposed by the authors as follow: (i) calculation of instantaneous power values, (ii) smoothing the signal using moving average algorithm, that serves as a low pass filter (LPF), (iii) calculating the power signal threshold by determining the power histogram for data recording set, fitting a Gaussian distribution to the histogram's lowest power hill, and then setting the threshold five standard deviation from the peak, (iv) analyzing the entire data recording by comparing calculated power averages to the found threshold. The major gap in this paper was that the authors measured power from a vector spectrum analyzer and not from the Atheros wireless card. Likewise, no specific provision on how to classify a channel as free or busy was provided.

Xue et al. in [5] addressed an important problem in the wireless monitoring which is how to choose channels with best (or worst) qualities timely and accurately. They consider scenarios of one or more sniffers simultaneously monitoring multiple channels in the same area. Since the channel information is initially unknown to the sniffers, they adopted learning methods during the monitoring to predict the channel condition by a short time of observation. The authors [5] formulated this problem as a novel branch of the classic multi-armed bandit (MAB) problem, named exploration bandit problem, to achieve a trade-off between monitoring time/resource budget and the channel selection accuracy. The authors failed to describe which data from the sniffing monitoring tool was used for mean reward computation with no specific on how classify a channel as either free or busy in their work was provided, which are a gap in their work.

4 Proof of Concept Solution Model

In congruence with the problem statement of my paper alongside the aims & objectives of the research work, a proof of concept (POC) of my solution model as shown in Fig. 1 has five modules: spectral sample processing, statistics analysis/FFT sample data correction, decision making, multi-criteria decision making (MCDM), and channel ranking. Each of these modules would be briefly discussed in this section.

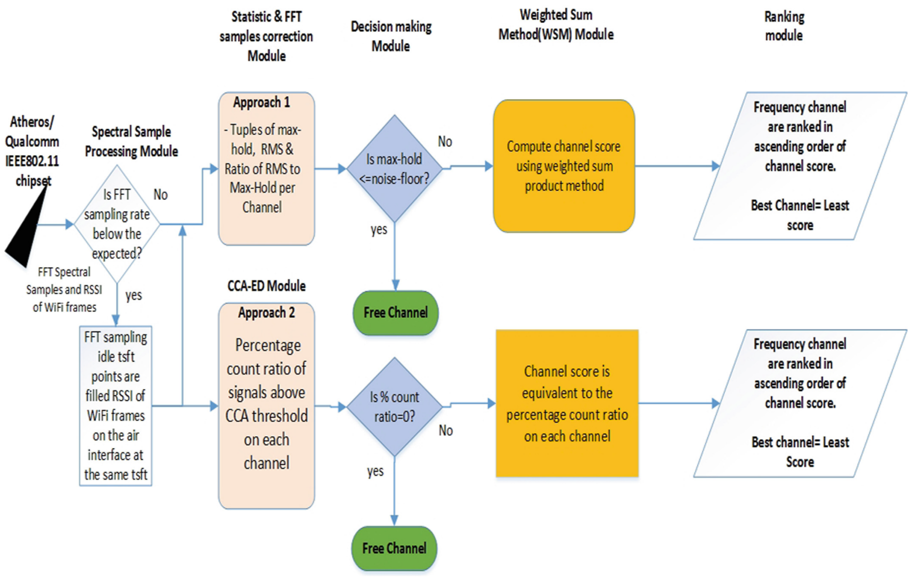

Fig. 1. Proof of concept architecture of the solution model

4.1 Spectral Sample Processing Module

This module describes how AthSpectralTool API spectral scan tool which is written in C++ programming language and built in Linux environment is used to activate FFT spectral scan features on any of the supported Atheros/Qualcomm chipsets on a frequency channel, in the context of this paper AR928x, AR9580 and QCA988x were evaluated. Spectral signal power was calculated based on [1] project using Eq. 1.1 on each FFT points frequency subcarrier using different FFT spectral coefficients from ath9k/ath10k driver.

$$SignalPower_i = nf + rssi + 10 * \log_{10}(b(i)^2) - 10 * \log_{10}(\sum_{i=1}^{56} b(i)^2). \qquad (1.1)$$

4.2 MaxHold-RMS and Percentage Count Ratio Approaches

With the MaxHold-RMS approach, the spectrum utilization assessment of wireless channel can be described using three metrics namely: maximum signal energy detected (max-hold), the computed root mean square (RMS) using Eq. 1.2 of all signal energy detected on each FFT subcarrier for any frequency channel, and the ratio of RMS to maximum signal energy detected to depicts utilization on the channel.

$$RMS_i = \sqrt{\frac{1}{n}(SNR_1^2 + SNR_2^2 + SNR_3^2 + \ldots + SNR_n^2)}. \qquad (1.2)$$

These three metrics could be used for channel ranking by the decision-making algorithm to classify frequency channels which would facilitate the choice of a best channel. Channel score would be calculated using Eq. 1.4 for each channel using weighted sum method concept.

For the percentage count ratio approach, the spectrum utilization assessment of a frequency channel can be described using a metric which is percentage count ratio which uses the concept of Clear Channel Assessment (CCA), from which FFT spectral power above a CCA threshold level are counted, divided by the total FFT spectral power samples computed, then the percentage would be computed per frequency channel. With percentage count ratio zero (0) indicates a free channel while the frequency channel with the least percentage is termed the best frequency channel using Eq. 1.3.

$$percentageCountRatio = \frac{SignalCount}{Total\,FTSamples} * 100. \qquad (1.3)$$

4.3 Multi-variable Decision-Making Module

This module explores the Weighted Sum Model (WSM) concept which is one of the multi-criteria decision-making methods presented by author [6], from which an algorithm was developed for WSM model using Eq. 1.4 where the alternatives are the sets of frequency subcarrier considered, while two criteria's (RMS and ratio) was proposed in this research work. The two criteria's (a_{ij}) are the factors affecting the preference of choice on the best alternatives using MaxHold-RMS approach, recalling that the alternatives are the sets of possible frequency subcarriers options to choose from.

$$ChannelScore_{wsm} = \sum_{i=1}^{n} a_{ij} * w_j. \tag{1.4}$$

From the Eq. 1.4 the relative weight (w_j) is a numerical value between 0 and 1 which depicts the relative importance of the criteria and their impacts on these alternatives [6]. The relative weight value attached to each criteria are based on subjective judgement, which are according to how significantly the criteria will impact the WSM score on each alternatives considered and by visual examination of different personal choice. Considering the two-subjective judgements used, relative weight of RMS value should be higher than that of ratio, since RMS indicates level of utilization on the channel while ratio is only a comparative metric between RMS and max-hold.

4.4 Ranking Module

This module takes care of the ranking of each frequency channel on a spectrum based on channel score computed using the concept described in Subsect. 4.3. Each frequency channel is ranked in ascending order of the scores computed, with the least score indicates the best channel while channel with highest score is classified as the busiest channel when considering either of the two approaches described in Subsect. 4.2.

5 Experimental Performance Evaluation and Analysis

In this section, an experimental performance evaluation would be carried out on the various Atheros/Qualcomm chipsets used in this research project.

5.1 Capability of Qualcomm/Atheros Chipset to Detect Narrowband Signals Such as Radar Signal with Good Power Sensitivity and Precision

This section describes the FFT spectrum scan capability of Atheros/Qualcomm 802.11x chipset to detect different narrow band signals since radar which are narrow band signal are expected on the 5 GHz frequency spectrum. In theory, a 20 MHz channel bandwidth with 64 FFT bins has frequency bandwidth of 312.5 kHz per bin, which implies that a single FFT bin is enough to capture narrow band signal between 1KHz-310 kHz. An experiment was set up with different signal generated using the generator provided by Rhode & Schwarz spectrum analyzer on frequency channel 5805 MHz at different power level instances (−50 dBm and −40 dBm). The signal generated has spectral bandwidth of 500 kHz, 100 MHz, 50 kHz, 20 kHz, 10 kHz, and 5 kHz respectively, at different power levels as shown on Figs. 2 and 3. For each signal generated at a particular power level, the FFT spectral scanner was initiated and the data sets are stored until all data are collected then the narrowband signal was plotted using the spectrum visualizer tool we designed. Figure 2 clearly shows narrowband signals captured from −50 dBm source power from the signal generator, where the blue, green, red, cyan, purple, and yellow lines are 500 kHz, 100 kHz, 50 kHz, 20 kHz, 10 kHz, and 5 kHz signals captured respectively.

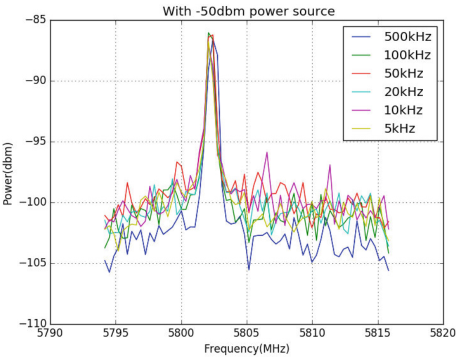

Fig. 2. Ath10k narrowband signal detection with −50 dBm source (Color figure online)

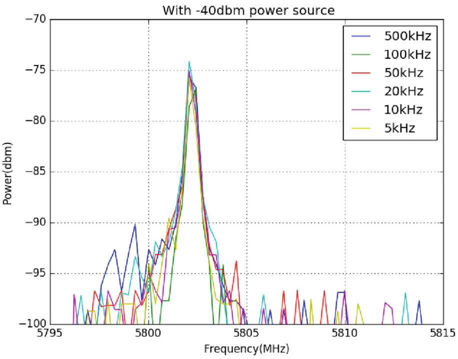

Fig. 3. Ath10k narrowband signal detection with −40 dBm source (Color figure online)

From Fig. 2 the highest signal was detected with −86 dBm from the signal generator at −50 dBm. Examining Fig. 3, increasing the signal power from the generator by 10 dBm to −40 dBm, the highest signal detected was about −76 dBm which is about 8 dBm ± 2 difference compared to the highest signal detected in Fig. 2. This clearly shows the capability of Qualcomm/Atheros chipset to detect narrowband signal such as radar signal with good power sensitivity and precision.

5.2 Finding the Best Channel

In the context of this paper, a free channel is one with its max-hold SNR value below 28 ± 3 dB (−96 dBm) decision threshold for MaxHold-RMS approach while for percentage ratio count approach is the one with signal count of zero(0) from the list of channels scanned for spectrum assessment as shown in Fig. 1, while the rest of the frequency channel are termed busy channel. From these busy frequency channels, one could compute channel score for each frequency channel with two metrics (RMS & duty cycle/ratio) for MaxHold-RMS approach and one metric (count of energy above threshold) for percentage count ratio approach using WSM concept. With the computed channel score, each frequency channel could be ranked in ascending order of their score, while the best channel is the one with the lowest channel score than the rest of the ranked frequency channel could be used by a wireless card in order of the rank.

A three-hops WiBACk wireless network with frequency 5310 MHz(40 MHz)/ 5230 MHz(40 MHz) was used for this experiment with an iPerf UDP bi-directional signal at data transmission rate of 70 Mb/s was initiated on the wireless link.

5.3 Evaluation of MaxHold-RMS Approach

Using AR928x and AR9580 chipsets to demonstrate the evaluation of this approach which involves couple of statistical analysis and different computation as described at Subsect. 4.2. While the iPerf UDP transmission is initiated on the wireless link, the FFT spectrum scanner perform a 1-s scan on each center frequency using my designed model, then statistical analysis was carried out on the FFT spectral samples on all subcarriers of each channel. Each channel analyzed obtains a score which is calculated using Eq. 1.4, with relative weight of RMS set to 0.7 dB and duty cycle/ratio set to 0.3 dB. The relative weight value chosen for each criterion are based on observation/experience which is empirical in nature.

On Fig. 4 the blue line is the max-hold, green line is the RMS, while the dot on red line, dot on the black line and the dot on the yellow indicates the average max-hold, average RMS and ratio/duty cycle on each center frequency. It would be deduced from the figure that the two center frequencies 5220 MHz and 5240 MHz that makes up the 40 MHz band for center frequency 5230 MHz used by one of the WiBACK wireless links. By visual examination, none of these channels are free so using the decision-making algorithm for calculating each channel score to help find the best channel from the scanned spectrum (5170 MHz–5330 MHz). Using AR9580 FFT spectral data, my algorithm will pick center frequency 5180 MHz as the best channel since it has the lowest computed channel score as seen on Fig. 4.

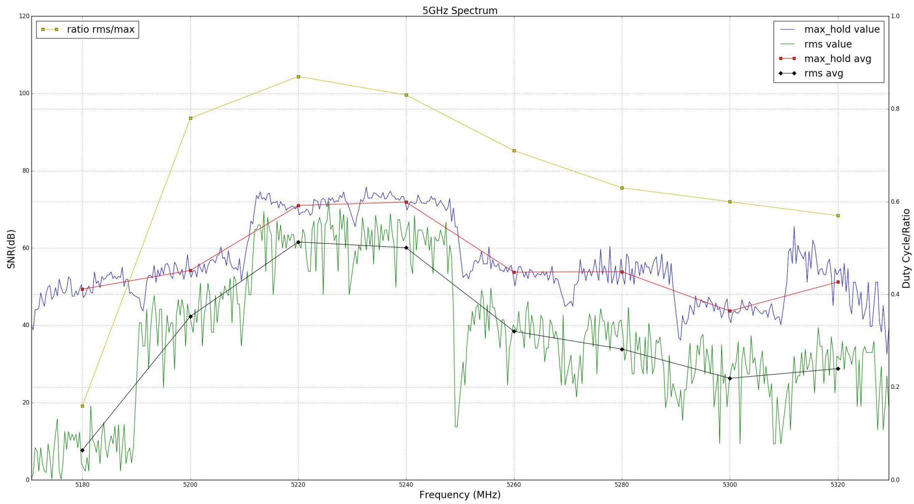

Fig. 4. AR9580 FFT spectral scan snapshot with MaxHold-RMS approach (Color figure online)

5.4 Percentage Ratio Count Approach

To perform this analysis the same FFT spectral samples collected in sub-Sect. 4.2 was used in percentage ratio count approach for counting of FFT spectral signal power above noise-floor (NF). Percentage ratio of signal counted on each frequency channel are computed by dividing the counted signal with the total FFT spectral samples. Each channel analyzed obtains a score which is calculated using Eq. 1.3 and afterwards ranking of channel are based on channel score, with lowest count percentage ratio indicating the least utilized/best channel while the highest value is the busiest channel.

Figure 5 shows spectrum utilization assessment using percentage count ratio approach which is the counting of signal power above a NF and averaging over the total FFT spectral samples received across each frequency channel. The blue, green, red, cyan and yellow lines represent percentage count ratio for different CCA threshold values of −95 dBm, −89 dBm, −83 dBm, −77 dBm, −71 dBm, −65 dBm respectively on each frequency channel. Presently ath9k & ath10k in the recent Linux kernel module has a fixed CCA value of −96 dBm, so the blue line which represents −96 dBm would be considered for the evaluation. Figure 5 clearly shows that at center frequency 5220 and 5240 MHz there you have the highest peak of signal counted for each NF value. This method is simple and doesn't require much computation and statistical analysis compared to MaxHold-RMS approach, but still yet depict same spectrum utilization status.

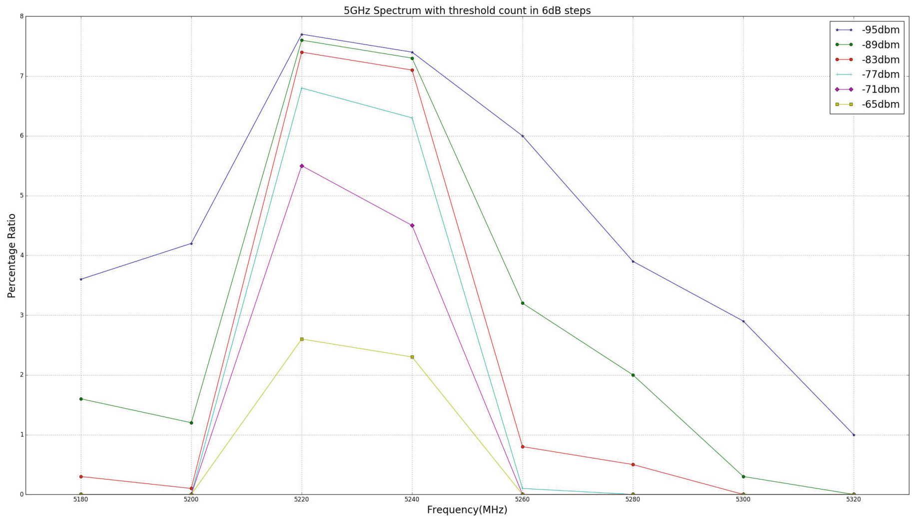

Fig. 5. AR928x FFT spectral scan snapshot with percentage count ratio approach (Color figure online)

Going by the count methodology in percentage ratio count approach, Fig. 5 depiction of the percentage ratio count on each frequency channel clearly shows the center frequency 5320 MHz is the best channel among the frequency channels scanned.

5.5 Scan Duration Required for Wireless Signal Detection on 5 GHz Spectrum

Scan duration is a vital metric which determines the percentage of certainty of signal detection, while going by the different modes of operation (access point (AP)-station, mesh, base station (BS)-subscriber station (SS)) of different wireless technologies there are management and control frames signals which are sent periodically even if there is no data frame transmission on the wireless link which are used for various management and control purposes. Each expected wireless technology uses similar concepts, but with varying signal durations. As described in the scope of this paper, only permanent device whose management/control frames are periodically sent are considered as non-permanent device's signal are only sporadically transmitted with no guarantee of detection during the scanning operation because such devices are non-permanent. A one second scan duration is sufficient to detect any signal from expected wireless technologies on the 5 GHz spectrum using FFT spectral scanning method.

5.6 Detection of Non-IEEE802.11 Wireless Signal

Expected non-802.11 signal on 5 GHz frequency spectrum (WiMAX, AirFiber, LTE-U, Radar) are of different wireless protocol which uses different technology. It is hard, if not practically impossible for an IEEE802.11 chipset from any silicon brand maker to decode any non-802.11 wireless signals on the shared spectrum by mere capturing of network traffic on its wireless interface using libPcap library in Unix-like system or winPcap in windows OS. FFT spectral scan features in Atheros/Qualcomm chipset has shown an ability detect non-802.11 spectrum on the 5 GHz spectrum going by experiments in Subsect. 5.1 where different narrow band were generated from a Rhode & Schwarz FSL spectrum analyzer using tracking generator features on the spectrum analyzer.

Considering the result from the experiment in Subsect. 5.1 and the time domain FFT spectral sampling capability of Qualcomm/Atheros Chipset as shown in Fig. 6, FFT spectral scanner samples a 20 MHz frequency band using sampling window duration of 4 μs, with 4 μs interval between successive sampling window and the chipset repeats these FFT sampling windowing sequence for 204 μs for each spectral scan mode until the scan duration elapses.

Each of the expected non-802.11 standard on the 5 GHz spectrum typically has different data frame and preamble durations: WiMAX (2.5 ms, 4 ms, 5 ms, 8 ms, 10 ms, 12.5 ms) [7], for Radar signals depending on the pulse width (0.6–1.9 μs) [8], HiperLan (8, 12, 16 μs) [9] and for LTE-U (5–10 ms) [10]. FFT spectral scan tool takes a snapshot of the whole 20 MHz in 4 μs with delay of 4 μs between successive FFT sampling window in a spectrum scan entry period of 204 μs. With the above-stated frame/subframe timing, alongside the FFT sampling timing then there is a high probability that these non-802.11 signals would be detected on the spectrum using the FFT spectral scan.

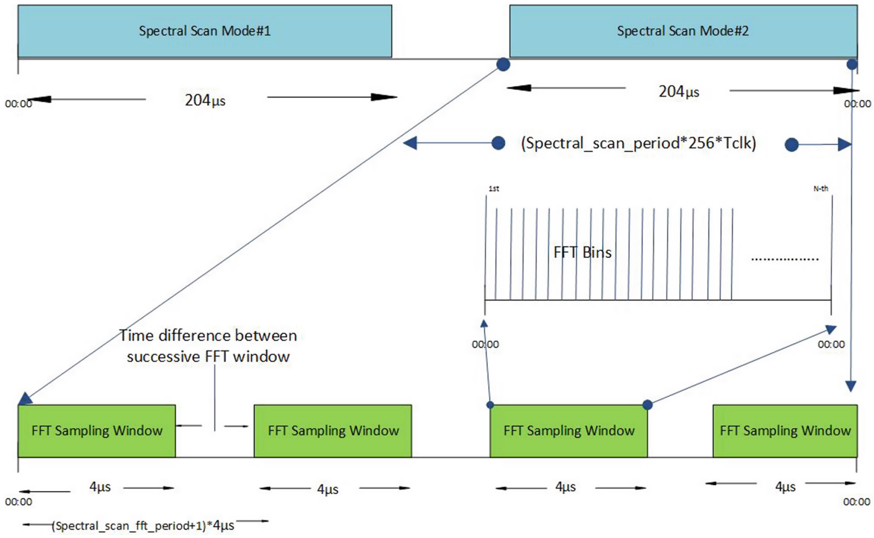

Fig. 6. Spectral scan timeline schematics for ath9k architecture

6 Conclusion and Recommendation

In this research work, which is all about "Spectrum Utilization Assessment of Wi-Fi Network using Atheros/Qualcomm 802.11 wireless chipset", a solution model was proposed using two approaches, where the spectrum utilization were analyzed using different Atheros/Qualcomm chipsets. FFT spectral samples was collected using AthSpectralTool from frequency subcarriers on each frequency channel using 64 FFT points, and the collected datasets for each channel was further analyzed using different statistical methods. With my proposed model, a free or busy can easily be figured out after scanning the spectrum using FFT spectral scan.

Summing up questions II to V, what are the requirements to detect any wireless signals on the 5 GHz spectrum? Answers to those research questions raised at Sect. 2 are provided based on results obtained from various experiments performed as follows:

- Signal time duration must be ≥1 µs
- Signal power level must be ≥−60 dBm
- Periodic interval of the signals must be <1 s for 1 s scan duration
- Accuracy of assessment tools must have a value close to upper limit
- FFT size of 64 points are enough for detecting signals on 20 MHz frequency channel bandwidth.

The expected non-IEEE802.11 wireless technology signals on the 5 GHz spectrum are IEEE802.16 (WiMAX, airFiber, HiperLAN, Radar, LTE-U).

The research presented in this paper made a couple of discoveries on different Atheros/Qualcomm chipsets which are out of scope of my paper work, one notable is the drastic reduction on FFT spectral sampling rate experienced during continuous wireless frames injection on a frequency channel.

My contributions to knowledge in this field are as follows:

- Development of a visual spectrum analyzer tool.
- Development of an algorithm that could be used to find the most "free" or "best" channel from sets of frequency channel.
- Methods that could use to show utilization on the frequency spectrum.
- Discoveries on different behavior of Atheros/Qualcomm wireless chipset

Lastly, due to unavailability of the expected non-802.11 wireless devices at FIT laboratory environment, a future work would be testing the efficiency of FFT spectral scan tool in an environment where these expected non-802.11 signals are present.

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