Energy detection for spectrum sensing
Addition to the
link level 5G Simulator

Internship Project Report

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1. INTRODUCTION

Cognitive Radio (CR) is an adaptive, intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run concurrently and also improve radio operating behavior. Cognitive radio uses several technologies including Adaptive Radio (where the communications system monitors and modifies its own performance) and Software Defined Radio (SDR) where traditional hardware components including mixers, modulators and amplifies have been replaced with intelligent software.

The need for higher data rates is increasing because of the transition from voice-only communications to multimedia type applications. Given the limitations of the natural frequency spectrum, it becomes obvious that the current static frequency allocation schemes cannot accommodate the requirements of an increasing number of higher data rate devices. As a result, innovative techniques that can offer new ways of exploiting the available spectrum are needed. Cognitive radio arises to be a tempting solution to the spectral congestion problem by introducing opportunistic usage of the frequency bands that are not heavily occupied by licensed users.

2. A BRIEF ABOUT COGNITIVE RADIOS

While there is no agreement on the formal definition of cognitive radio as of now, the concept has evolved recently to include various meanings in several contexts. In this paper, we use the definition adopted by Federal Communications Commission (FCC): “Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.” Hence, one main aspect of cognitive radio is related to autonomously exploiting locally unused spectrum to provide new paths to spectrum access.

One of the most important components of the cognitive radio concept is the ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, availability of spectrum and power, radio’s operating environment, user requirements and applications, available networks (infrastructures) and nodes, local policies and other operating restrictions. In cognitive radio terminology, primary users can be defined as the users who have higher priority or legacy rights on the usage of a specific part of the spectrum. On the other hand, secondary users, which have lower priority, exploit this spectrum in such a way that they do not cause interference to primary users. Therefore, secondary users need to have cognitive radio capabilities, such as sensing the spectrum reliably to check whether it is being used by a primary user and to change the radio parameters to exploit the unused part of the spectrum. This is accomplished by spectrum sensing.

3. SPECTRUM AND SPECTRUM SENSING

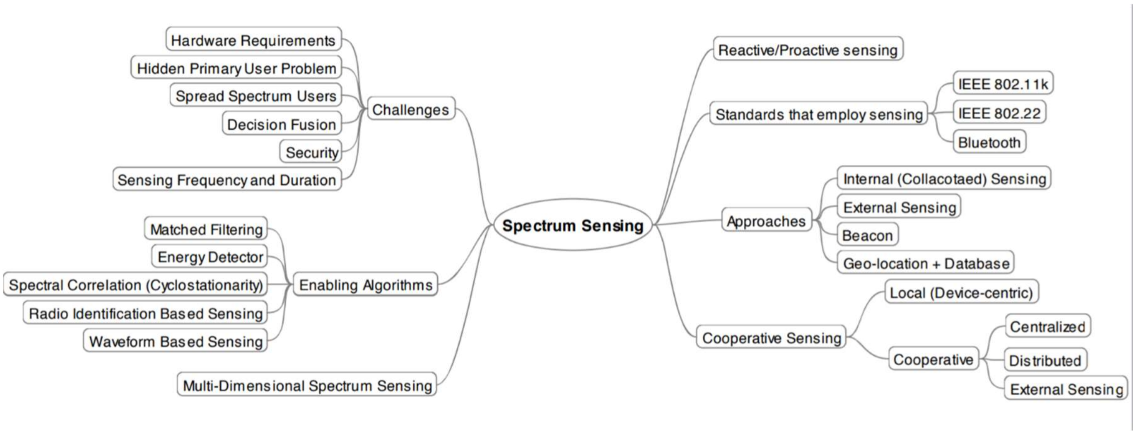


Figure 1 : Spectrum Sensing

The spectrum has been classified into three types: black spaces, grey spaces and white spaces by estimating the incoming RF stimuli. Grey spaces and white spaces are candidates for secondary use. A key problem in cognitive radio is that the secondary users need to detect the presence of primary users in a licensed spectrum and quit the frequency band as quickly as possible if the corresponding primary radio emerges in order to avoid interference to primary users. The technique is called spectrum sensing, which is a fundamental problem in cognitive radio.

3.1 Spectrum Sensing Techniques

Generally, spectrum sensing techniques can be divided into three categories: transmitter detection, cooperative detection and interference-based detection. A. Transmitter Detection Transmitter detection is based on the detection of the weak signal from a primary transmitter through the local observation of cognitive radios. Transmitter detection is non-cooperative detection; it can't avoid the hidden terminal problem. Transmitter detection is mainly included matched filter detection, energy detection and feature detection.

3.1.1 Matched filter detection

A matched filter is a linear filter designed to maximize the output signal to noise ratio for a given input signal. When secondary user has a priori knowledge of primary user signal, matched filter detection is applied.

- Advantages of matched filter detection: Matched filter detection needs less detection time because it requires only O(1/SNR) samples to meet a given probability of detection constraint. When the information of the primary user signal is known to the cognitive radio user, matched filter detection is optimal detection in stationary Gaussian noise.
- Disadvantages of matched filter detection: Matched filter detection requires a prior knowledge of every primary user, if this information is not accurate, the matched filter performs poorly.

3.1.2 Energy detection

Energy detection detects the spectrum by measuring the energy of the received signal in a certain frequency band, also called radiometry. It is the most common detection method for spectrum sensing in cognitive radio networks.

- Advantages of energy detection: Implementation simplicity and computational complexities low: an energy detector can be implemented similar to a spectrum analyzer by averaging frequency bins of an FFT. Since it is easy to implement, the recent work on detection of the primary user has generally adopted the energy detector. In addition, energy detection is the optimum detection if the primary user signal is not known.
- Disadvantages of energy detection: The performance of the energy detector is highly susceptible to noise level uncertainty. The noise uncertainty causes problems especially in the case of a simple energy detector because it is difficult to set the threshold properly without the knowledge of the accurate noise level. Secondly, an energy detector can't differentiate between modulated signals, noise, and interference. The performance of an energy detector in shadowing and fading environments degrades clearly. Moreover, it is hard to select the right threshold for energy detection.

3.1.3 Feature detection

Feature detection captures a specific signature of the primary user signal, such as pilot, segment sync, field sync, or cyclostationarity. Many of the signals used in wireless communication and radar systems possess this property. The idea of the cyclostationary feature detection is to utilize the built-in periodicity of the modulated signal.

- Advantages of feature detection: The main advantage of the feature detection is that it can discriminate the noise energy from the modulated signal energy. Furthermore, cyclostationary feature detection can detect the signals with low SNR.
- Disadvantages of feature detection: Feature detection requires long observation time and higher computationally complex. In addition, feature detection needs the prior knowledge of the primary users. B. Cooperative detection Cooperative detection by combining the observations of several cognitive radio users can be used to improve the performance of spectrum sensing.

3.1.4 Cooperative detection

Cooperative detection can be implemented in a distributed or centralized manner. The cooperative schemes can be classified into three regimes according to the cooperative level: decentralized uncoordinated techniques, centralized coordinated techniques and decentralized uncoordinated techniques.

- Advantages of cooperative detection: Lower detection sensitivity requirements. Channel impairments such as shadowing, multipath fading, and building penetration losses high sensitivity requirements on cognitive radios. The sensitivity requirement can be drastically reduced by cooperation detection. Improve the agility of the detection. One of the biggest challenges in cognitive radio is reduction of the overall detection time. Cooperative detection can reduce detection time compared to uncoordinated detection, so it can improve agility of the detection.

- Disadvantages of cooperative detection: Firstly, cooperation increases the overhead of the cognitive radio network. Secondly, cognitive radio users are usually low cost and low power devices that might not have dedicated hardware for cooperation. Therefore, data and cooperation information must be multiplexed that can cause degradation of throughput for the cognitive user. Lastly, cooperative detection needs control channels.

3.1.5 Interference based detection

Interference temperature is defined as the temperature equivalent of the total interference present in RF environment for a frequency band and a geographic location. Interference temperature model was introduced by FCC. The model attempts to regulate interference at the receives. If the cognitive radio users do not exceed the interference temperature limit, they can use the spectrum band. That is, during the interference-based detection, the cognitive radios must measure the interference temperature and adjust their transmission in a way that they avoid raising the interference temperature over the interference temperature limit.

- Advantages of interference-based detection: Interference based detection can avoid the hidden terminal problem.
- Disadvantages of interference-based detection: Firstly, it’s hard to measure interference temperature. Secondly, during the interfered based detection, cognitive radio users can’t distinguish between actual signals from the primary users and noise or interference.

Energy detection algorithm is the mist suitable for our simulator as we have the spectrum easily available during demodulation and as well as the noise variance.

4. ENERGY DETECTION ALGORITHM

When energy detection is considered for spectrum sensing, the energy contained over a spectrum band is measured and then compared with a threshold. If energy level is above the threshold, then the primary user is present, if the energy level is below the threshold, then the spectrum band is vacant. Even though energy detection is simpler than matched filtering and cyclostationary feature detection, it requires at least O(1/SNR2) samples for detection and it has several disadvantages. For example, energy detector performance is very susceptible to changing noise levels, and it cannot distinguish when energy comes from primary’s transmission, interference, or noise.

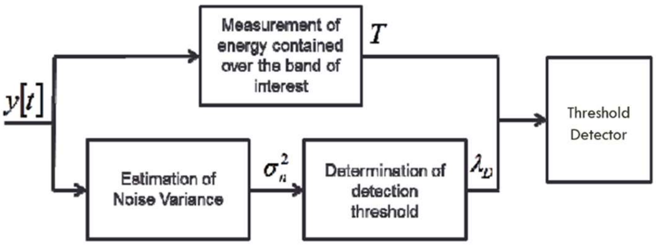


Figure 2: Energy Detection Algorithm

The performance of energy detector (or of other detectors) is characterized by using following metrics, which have been introduced based on the test statistic under the binary hypothesis:

4.1 False alarm probability (Pf):

The probability of deciding the signal is present while it is absent, a false alarm yields undetected spectrum holes. So, a large Pf contributes to poor spectrum usage by secondary users.

$$P_f(\epsilon,\tau) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - 1\right)\sqrt{\tau f_s}\right)$$

Equation 1

τ is the sensing time, fs is sampling frequency, ε is the threshold

4.2 Missed-detection probability (Pmd):

The probability of deciding the signal is absent while it is present, which is equivalent to identifying a spectrum hole where there is none. Consequently, large Pmd introduces unexpected interference to primary users.

4.3 Detection probability (Pd):

The probability of deciding the signal is present when it is there. Pd =1 – Pmd.

$$P_d = \mathcal{Q}\left(\frac{1}{\sqrt{2\gamma+1}}(\mathcal{Q}^{-1}(\bar{P}_f) - \sqrt{\tau f_s}\gamma)\right)$$

Equation 2

Where Q(x) is given by:

$$\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{t^2}{2}\right)dt.$$

Equation 3

5. SIMULATION SETUP AND IMPLEMENTING ENERGY DETECTION ALGORITHM

The wireless channels h_{ij} are indicated with double arrows where the first subscript *i* indicates the base station and the second subscript *j* indicates the user. Desired or primary channels are shown in solid black while interference or secondary channels are shown in dashed red. While all nodes belonging to a cell must have the same waveform, channel code, total number of subcarriers and number of symbols per frame (frame duration), these settings might be different for nodes of another cell. To enable discrete simulation of several nodes and many wireless channels, the sampling rate is a common parameter for all cells. Further, the frame duration, that is the number of samples per frame, must be equal for all cells, independent of the employed waveform and modulation such that interference and desired signals can be superimposed.

There is a schedule for each base station or cell. The total number of subcarriers is 72 and we chose to share them. Depending on the desired simulation scenario, the interference channel from user four to base station one is critical in this setup. If a high attenuation of interference channels is set cell one and cell two will not influence each other. If a low attenuation is selected, significant interference from user four to users one, two and three will occur.

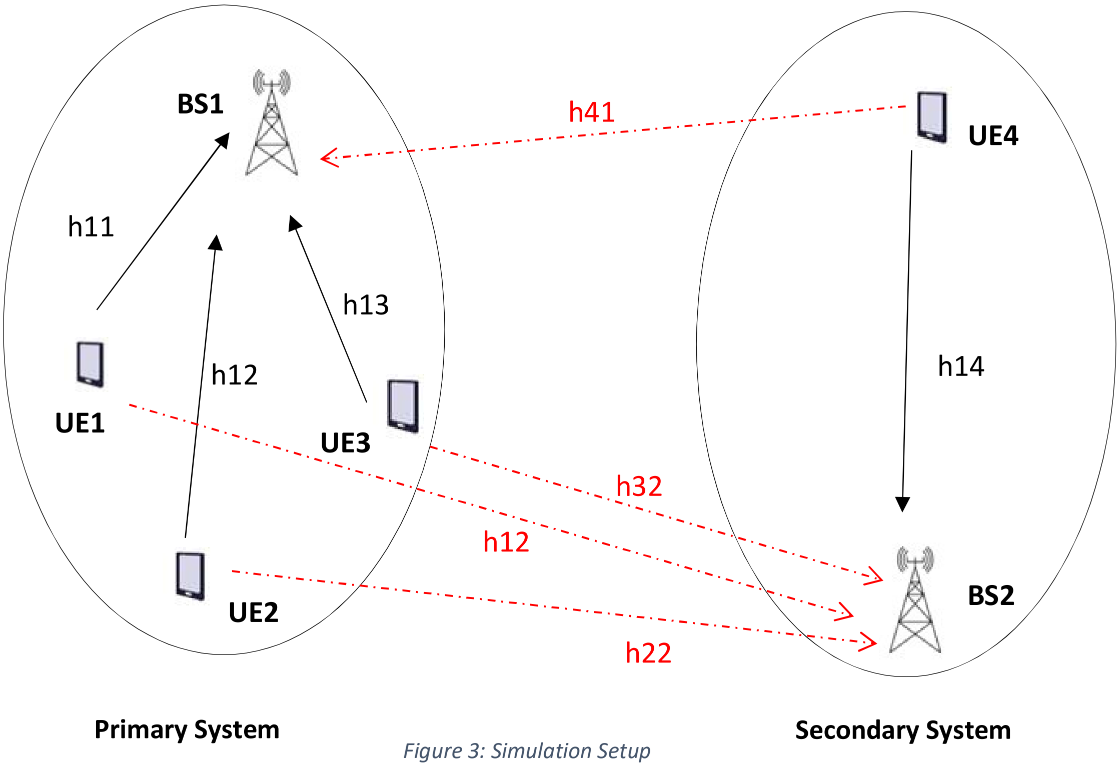


Figure 3: Simulation Setup

The model used for simulations consists of a primary system with one base station and three users with some random schedule, a communication channel (flat) and a secondary system with another base station and a fourth user. Energy detection is carried out at the secondary system to find out the spectrum hole in primary system and schedule the fourth user into that hole to save bandwidth and cause less interference. We want to study the effect of this new user on the primary users. This is reflected mostly on the throughputs of the users before and after the user is scheduled. The algorithm makes use of the probability of false alarm.

5.1 Elements of Algorithm

- `Pf = 0:0.01:1; % Pf = Probability of False Alarm`
- `for m = 1: length (Pf)`
- `thresh(m) = abs(y)*((qfuncinv (Pf(m)). *sqrt(L)) +L)`
- `L is the sample size.`

5.2 Implementation of Algorithm

When the signal is demodulated its energy is calculated of 14 OFDM symbols for each subcarrier (72 subcarriers). Received signal is padded and spectrum is calculated with Fast Fourier Transform (FFT). The spectrum has energy for each of the 14 symbols of OFDM. This is then averaged into mean energy for 72 subcarriers.

This energy is then compared with the threshold energy level, which is calculated by estimation of noise in the received spectrum, especially by use of noise variance, for 100 values of probability of false alarm. If the energy is above the threshold then a decision is made that user is present and the subcarrier is not vacant. The comparison of energy of the received spectrum with the threshold is a logical comparison. A vector is generated from the results of comparisons made, if the carrier is vacant then a 1 is put at that index else a 0 is put at the index. This vector has a size of 100 by 72. This is because the threshold is calculated for 100 values of Pf and for each of the 72 subcarriers.

```
vac_spec1 = [vac_spec1 (m_e <= thresh(m))]
```

The number of ones in the above vector gives us the number of vacant subcarriers, which will be used to schedule the new user.

We plot a Pd vs Pf curve for evaluating the performance of energy detector algorithm.

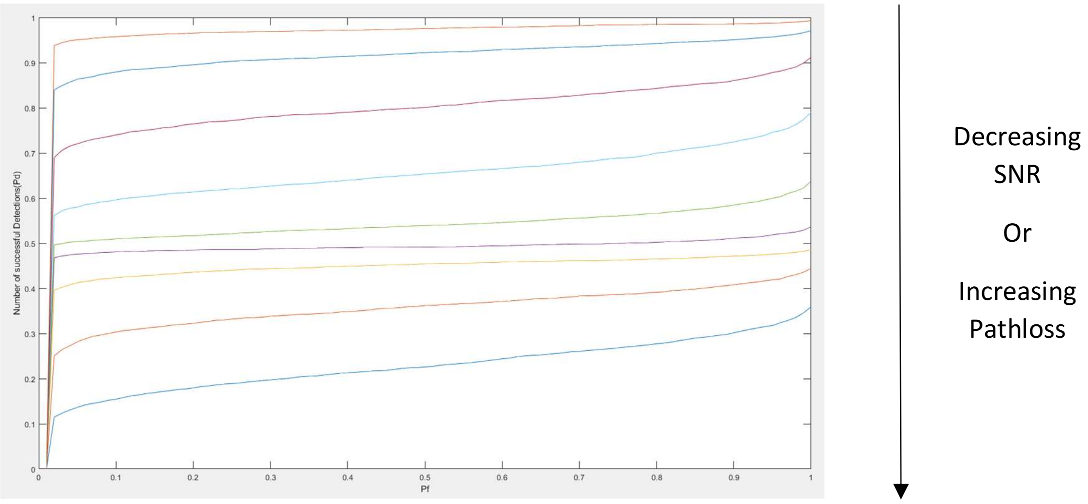


Figure 4: Pd vs Pf

5.3 Checking the validity of Algorithm

- This plot verifies that the detector is performing well. In the above plot we can see several curves plotted for Pd vs Pf. The curve which gives the probability of detection close to one is the curve we can extract information about. It is the curve which has the characteristics of best SNR during transmission.
- The concept is simple, if the simulator is not able to detect the presence and absence of primary user that is because of less SNR. Thus, the Pd will be 1 for the highest possible SNR. The number of subcarriers detected correctly is dependent on the SNR of the system and the CQI as well. The better the SNR the more is the probability of detection of users in the spectrum and thus the detector tells the number of subcarriers with more accuracy.
- We choose a specific value of SNR, and then simulate the primary system with 50 frames. Each frame has a different channel realization and thus there is a different value of SNR each frame at which it performs best.
- Beginning with values of Pf, if we consider the pf to be 0, i.e. spectrum is detected as empty even at the points where primary users are present. Therefore, the detector tells that all the 72 subcarriers are free. As we increase the value of Pf to 1, the number of free subcarriers drop to 0, as Pf = 1 means that spectrum is detected as occupied at all the time.

But this behavior is observed at a very specific value of SNR, the detector seems to have a step like function response for a wide range of SNR. It is only then if we narrow down the SNR that we can see the number of subcarriers going down from 72 to 0, and at some value of pf we will get a result exactly equal to the number of free carriers in the system.

5.4 Finding the optimum value of Pf

- To find this optimal value of Pf where the error in detecting number of free carriers is least and the detected carriers are approximately equal to the actual free carriers, we study the throughput of the system as a function of Pf.
- Now the next step will be to allocate the spectrum hole correctly, and not allocate already used spectrum that will cause interference. After allocating the spectrum the simulator is updated with the new schedule with the new user and secondary system in consideration. The addition of the new user will affect the throughput of the primary users.
- We take primary user one as a reference user and store its throughput as reference throughput (tpr say) when there is no secondary system. After addition of new user, we again calculate the throughput for primary user one (tp1 say) and for the new user (tpn say). We define a parameter delta. The value of Pf where delta is maximum is the optimal value of Pf. This delta is mathematically represented as below:

$$\Delta = \frac{\textbf{Throughput of new user + Throughput of Primary user after allocation of spectrum to new user}}{\textbf{Throughput of Primary reference user before allocation of spectrum to new user}}$$

i.e.

$$\Delta = \frac{tpn + tp1}{tpr}$$

Equation 4

5.5 Parameters that affect throughput

The throughput is dependent on the allocation of new user in the spectrum hole. If the estimation of detection algorithm is accurate the new user will only be allocated the unused part of the spectrum without causing an interference with the primary users. This depends if the start and stop of the spectrum hole is estimated correctly which is further dependent on the channel realization, modulation waveform, CQI, SNR and the Probability of false alarm. Thus, it is safe to state that factor delta (Δ), is a function of Pf for a given SNR, CQI and channel realization. To find Pf and to conclude results we must average out the results for a fixed number of simulations for a given configuration at different Pf values. In addition to throughput the simulator also calculates Bit Error Rate, Frame Error Rate.

6. MODULATION WAVEFORMS

The simulator can run the simulations for different types of modulation waveforms namely:

```
OFDM Orthogonal Frequency Division Multiplexing
f-OFDM filtered OFDM
FBMC Filter Bank Multicarrier
UFMC Universal Filtered Multicarrier
WOLA Weighted Overlap and Add
```

These modulation techniques vary slightly from each other and some of the most widely used are described in brief below:

6.1 Orthogonal Frequency-Division Multiplexing

CP-OFDM (CP-OFDM) is the most prominent multicarrier scheme and is applied, for example, in Wireless LAN and LTE-A. CP-OFDM employs a rectangular transmit and receive pulse, which greatly reduce the computational complexity. Furthermore, the CP implies that the transmit pulse is slightly longer than the receive pulse, preserving orthogonality in frequency selective channels. Thus, frequency-selective broadband channels transform into multiple, virtually frequency flat, sub-channels (subcarriers) without interference.

This allows the application of simple one-tap equalizers, corresponding to maximum likelihood symbol detection in case of Gaussian noise. Furthermore, the channel estimation process is simplified, adaptive modulation and coding techniques become applicable, and MIMO can be straightforwardly employed. Unfortunately, the rectangular pulse in OFDM leads to high out-of-band emissions. This is one of the biggest disadvantages of CP-OFDM. Additionally, the CP simplifies equalization in frequency- selective channels but also reduces the spectral efficiency. To reduce the OOB emissions, 3GPP is currently considering windowing and filtering, see the next subsections. One of our most important implementation aspects is that we consider a fixed sampling rate fs instead of a fixed Fast Fourier Transform (FFT) length NFFT, as often done in literature. The main reason for a fixed sampling rate is to enable a fair comparison between different subcarriers spacings and to guarantee that a specific channel power delay profile fits approximately the sampling rate. Additionally, the sampling rate is often predetermined by real world hardware and cannot be changed easily.

The relationship between FFT size, sampling rate and subcarrier spacing F is NFFT = fs/f.

Note that the FFT size must be larger or equal than the number of active subcarriers. In practice, the FFT size will always be larger than the number of active subcarriers. For example, in 10 MHz LTE-A, we have 600 active subcarriers and an FFT size of 1024. We also advise to use a (much) larger FFT size than the number of active subcarriers.

6.2 Filtered-OFDM

The second filter-based OFDM scheme considered within 3GPP is f-OFDM. Here, the number of subcarriers for one sub band is usually much higher than in UFMC and often includes all subcarriers belonging to a specific use case. The idea of f-OFDM is quite simple: we modify a conventional CP-OFDM transmission by applying digital filtering at both, transmitter and receiver. If the total CP length is longer than the combined filter length, we restore orthogonality in an AWGN channel. However, some (small) interference is usually acceptable to keep the overhead low. The induced interference can be adjusted by the filter length and the CP length (TCP,f). The filter itself is based on a sinc pulse (perfect rectangular filter) which is multiplied by a Hann window; other filters are also possible, but currently not implemented.

Again, this is similar to OFDM, but with the additional option of Tf,tx and Tf,rx, representing the filter length at the transmitter and at the receiver. Furthermore, we have an additional CP with length TCP,f to combat the effects of filtering.

The total CP overhead is then given TCP,total = TCP + TCP,f .

6.3 FBMC

Although 3GPP decided that FBMC will not be employed in 5G, FBMC still has many advantages over OFDM, namely, much lower OOB emissions and a maximum symbol density (i.e., no CP overhead). Those advantages, however, come at the price of sacrificing the complex orthogonality condition with the less strict real orthogonality condition. In many cases, however, this has either no, or only a minor influence on the performance. In other cases, such as channel estimation or some MIMO methods, on the other hand, special treatment of the imaginary interference becomes necessary. Fortunately, there exists many efficient methods to deal with those challenges [16]. The signal generation in FBMC is like that of windowed OFDM, see Fig. 8, whereas we ignored receive filtering to keep the illustration simple.

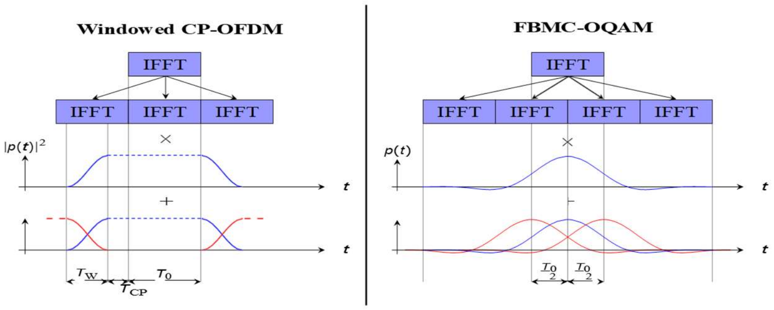


Figure 5: FBMC

7. CASE STUDY 1

Let’s take case 1 where the primary system has 3 users with the following configuration:

7.1 Simulation Parameters

```
Schedule for Primary System: ['UE1:18, UE2:15, none:25, UE3:14'].
Pathloss is set at 130 db.

Pf = 0:0.01:1; Probability of False Alarm is varied from 0 to 1.
pilotPattern is chosen as Diamond.
CQI is kept at 5.

Here Modulation waveform is OFDM.
Number of Subcarriers is 72          % per BS; number of used subcarriers
Subcarrier Spacing is 15e3           % per BS; per base station in Hz
Number of Symbols is 15              % per BS; total number of time-
symbols per frame
Number of Guard Symbols is 1.
Sampling Rate is set to 7.56MHz.
Number of Frames Simulated 50.
```

If any of the above-mentioned modulation schemes is used these modulation parameters will change accordingly.

In this case the simulation results for 3 primary users is as follows:

7.2 Results Without Secondary User:

7.2.1 BER: Bit Error Rate

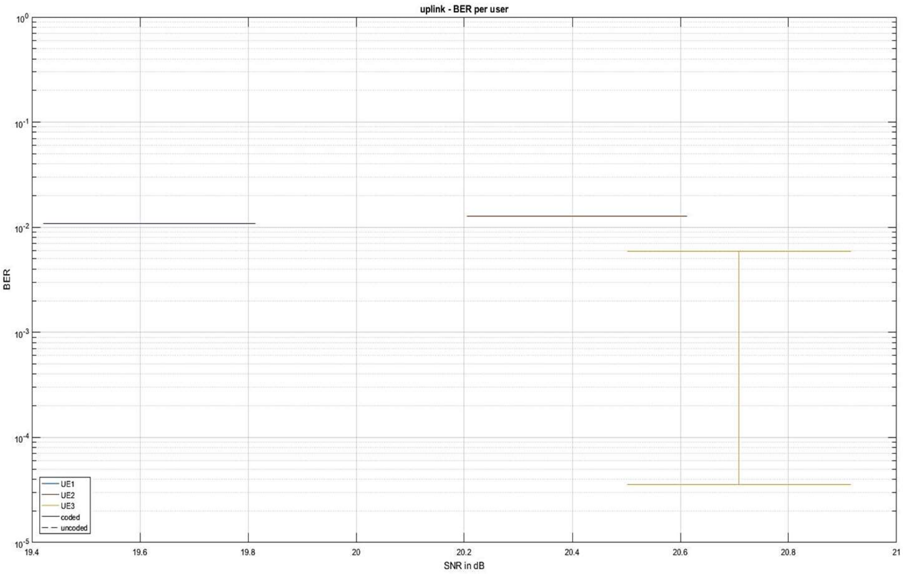


Figure 6: BER without secondary user (case 1)

7.2.2 FER: Frame Error Rate

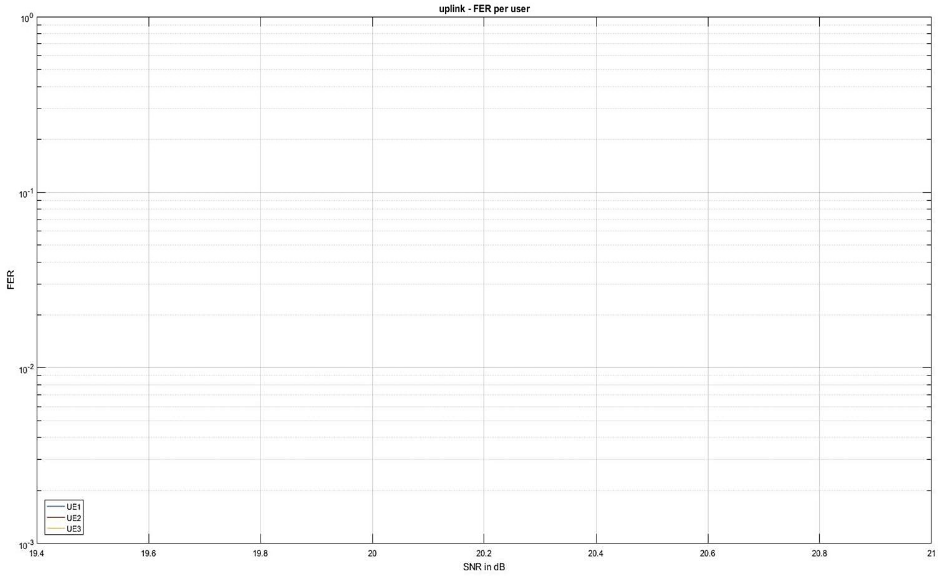


Figure 7: FER without secondary user (case 1)

7.2.3 Throughput

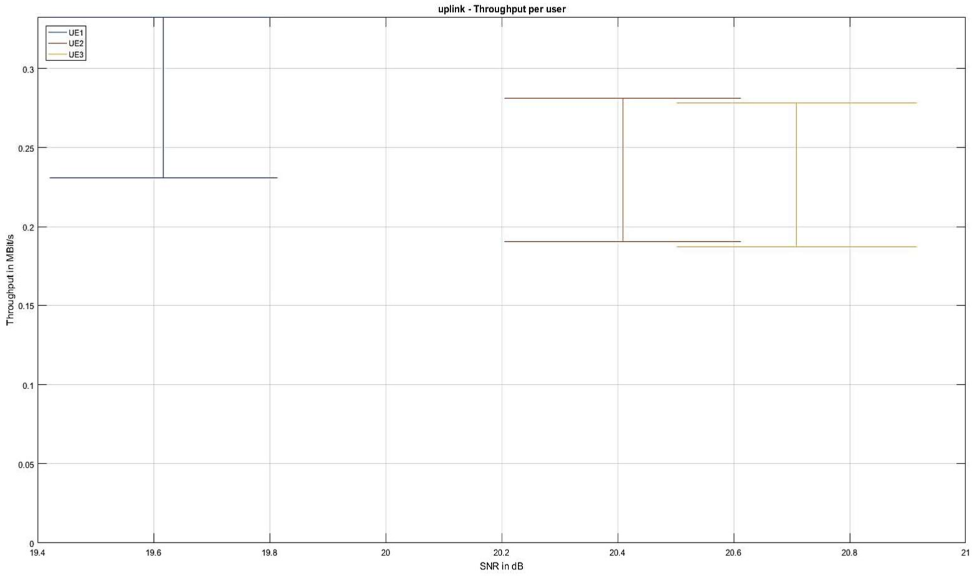


Figure 8: Throughput without secondary user (case 1)

7.2.4 *Observation*

The mean values of throughput of 3 users is 273240, 234160, 223660 in bits/second. We take the throughput for user 1 as the reference throughput (tpr). Thus, tpr = 273240 bits/second. The detector detects the number of subcarriers vacant and updates the schedule for second base station as well.

7.3 Results With Secondary User:

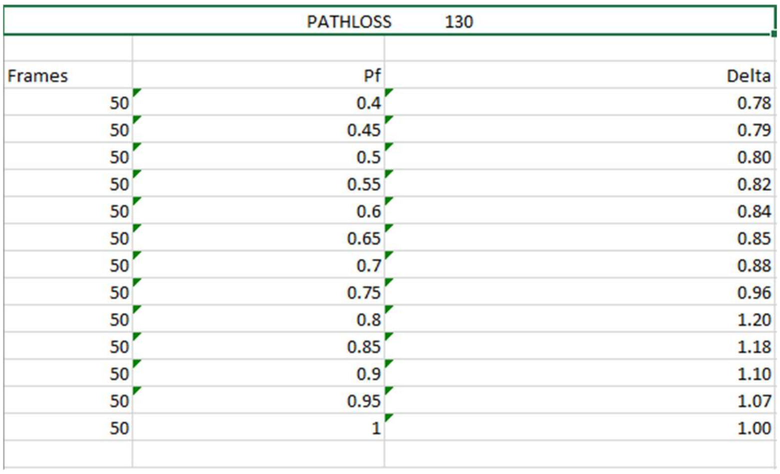
The updated schedule is as follows:

```
Schedule for Primary System: ['UE1:18, UE2:15, none:25, UE3:14'].
Schedule for Secondary System: ['none:33, UE4:25, none:14'].
```

The rest of the simulation and modulation parameters are kept constant as before. The simulator now simulates 50 frames with this setup and calculates throughputs for all values of Pf. The delta is calculated.

The relation of Pf and delta is tabulated:

Table 1:Pf and Delta (case 1)



	PATHLOSS	130
Frames	Pf	Delta
50	0.4	0.78
50	0.45	0.79
50	0.5	0.80
50	0.55	0.82
50	0.6	0.84
50	0.65	0.85
50	0.7	0.88
50	0.75	0.96
50	0.8	1.20
50	0.85	1.18
50	0.9	1.10
50	0.95	1.07
50	1	1.00

The above table is at a pathloss of 130 dB, and the best results are obtained when the gain in throughput is of the factor of 1.20. This occurs at a Pf of 0.80.

Thus, the system is now set at Pf of 0.80. The following plots were obtained after simulation.

7.3.1 BER: Bit Error Rate

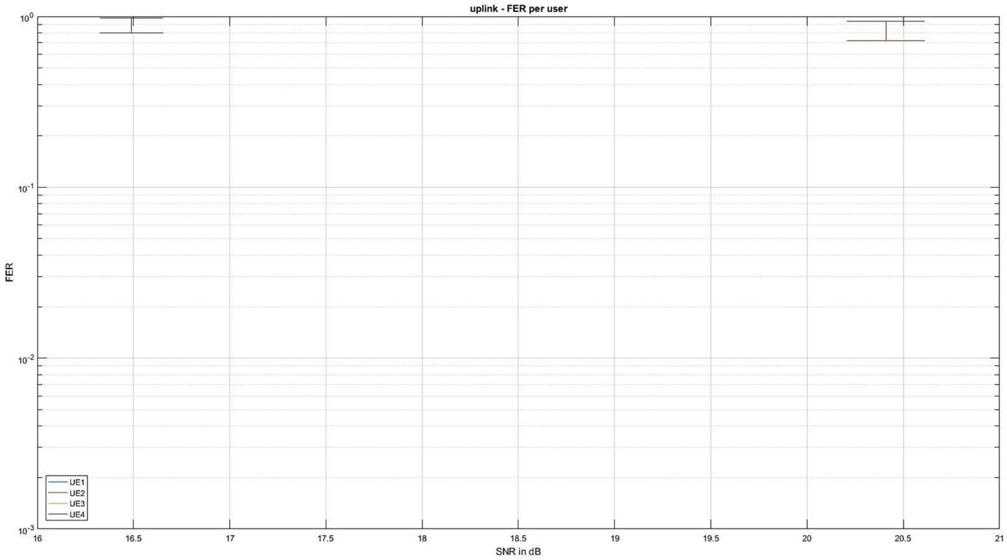


Figure 9: BER with secondary user (case 1)

7.3.2 FER: Frame Error Rate

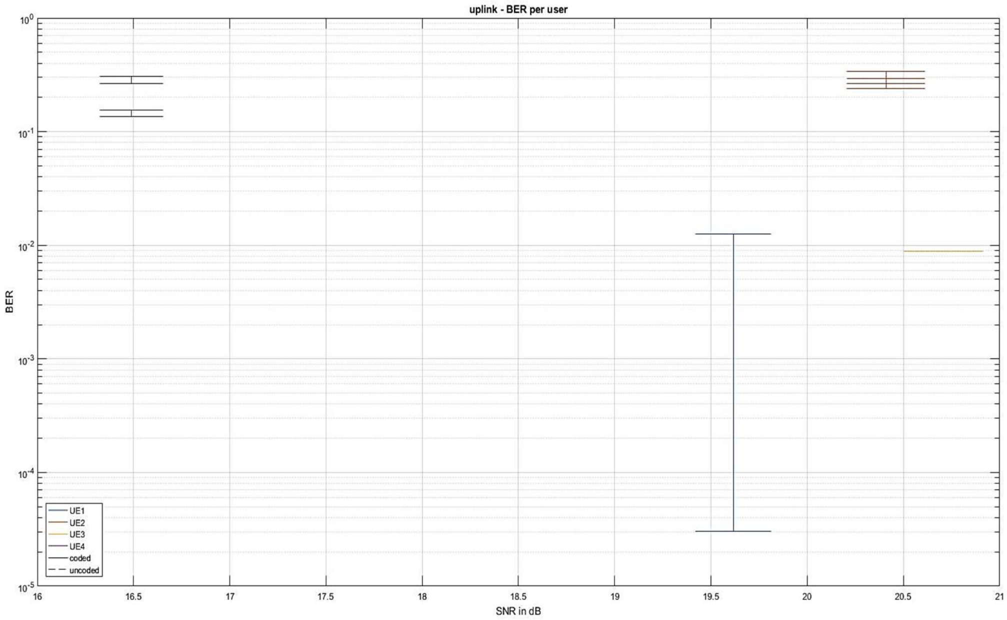


Figure 10: FER with secondary user (case 1)

7.3.3 Throughput

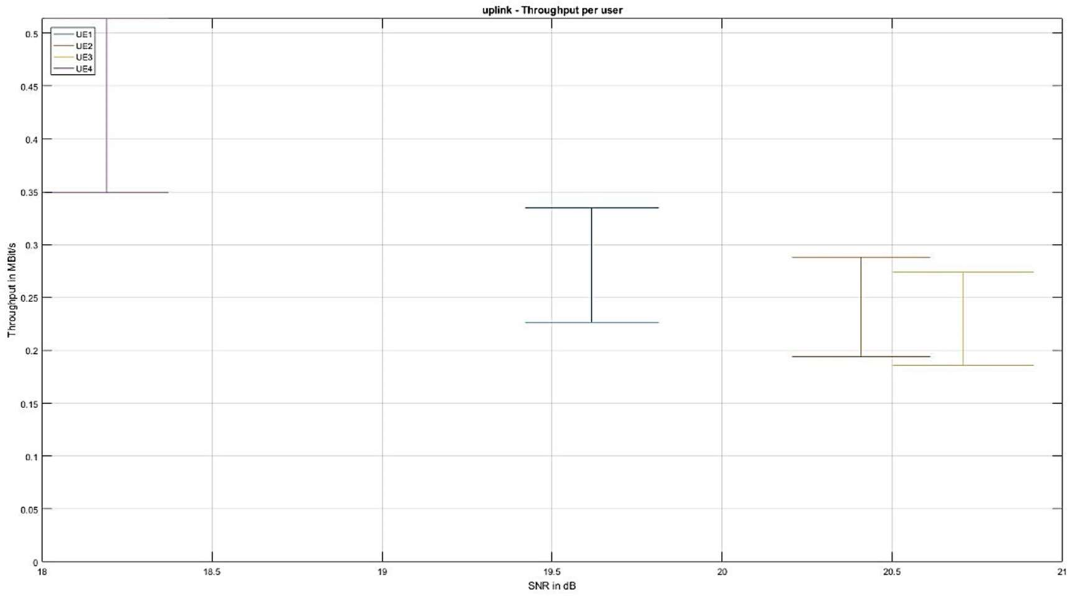


Figure 11: Throughput with secondary user (case 1)

7.3.4 *Observation*

We can see in the throughput curves there is addition of a fourth curve. This plot obtained clearly on comparison with figure __ yields that the fourth user has been added to the spectrum without affecting the throughput of primary users. This also shows that the user number 4 has highest throughput which is in accordance with the updated schedule as it has been allocated 25 subcarriers which is largest amongst the four. Thus, by using the energy detection algorithm the use of spectrum is now more efficient. The number of frames to be simulated solely depend on the computing power and to get a more precise result the results can be averaged out over 100 or 200 frames.

8. ROLE OF CQI

CQI stands for Channel Quality Indicator. As the name implies, it is an indicator carrying the information on how good/bad the communication channel quality is. CQI is the information that UE sends to the network and practically it implies the following two:

- Current Communication Channel Quality.
- Transport block size, which in turn can be directly converted into throughput.

This put in simpler terms means that higher the CQI, higher is the channel quality and higher is the throughput. To make our detection more accurate we may increase the CQI from 5 to 8 or 9.

9. CASE STUDY 2

Let’s take case 2 where the primary system has 3 users with the following configuration:

9.1 Simulation Parameters

```
Schedule for Primary System: ['UE1:18, UE2:15, none:25, UE3:14'].
Pathloss is set at 128 db.

Pf = 0:0.01:1; Probability of False Alarm is varied from 0 to 1.
pilotPattern is chosen as Diamond.
CQI is kept at 9.

Here Modulation waveform is FBMC.
Number of Subcarriers is 72        %per BS; number of used subcarriers
Subcarrier Spacing is 15e3         %per BS; per base station in Hz
Number of Symbols is 15 %per BS; total number of time-symbols per frame
Number of Guard Symbols is 0.
Sampling Rate is set to 2.16MHz.
Number of Frames Simulated 100.
```

In this case the simulation results for 3 primary users is as follows:

9.2 Results without Secondary user

9.2.1 BER: Bit Error Rate

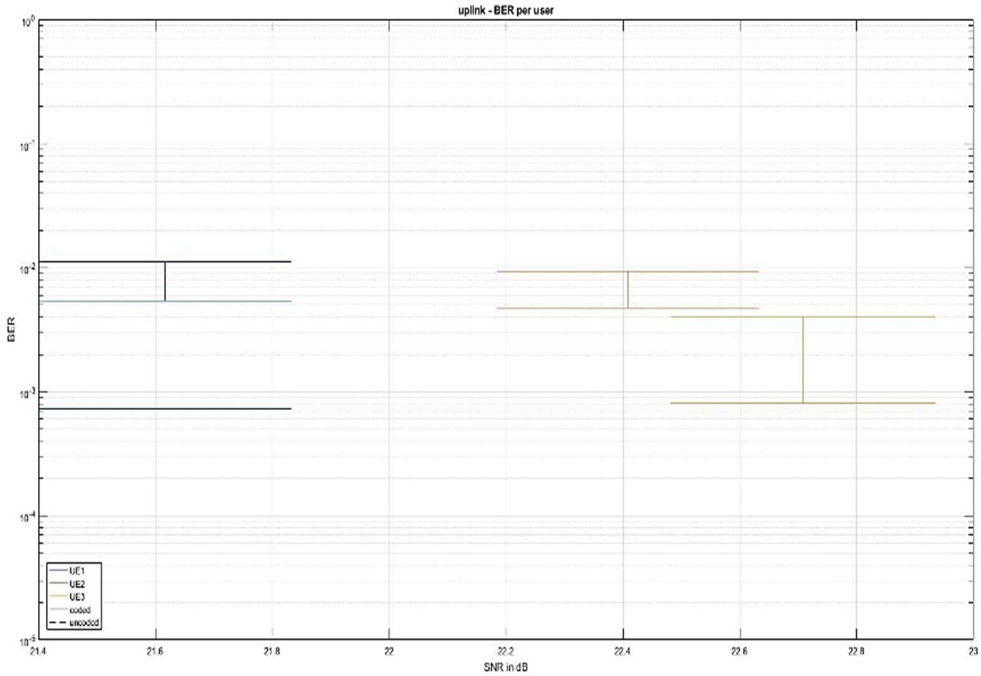


Figure 12: BER without secondary user (case 2)

9.2.2 *FER: Frame Error Rate*

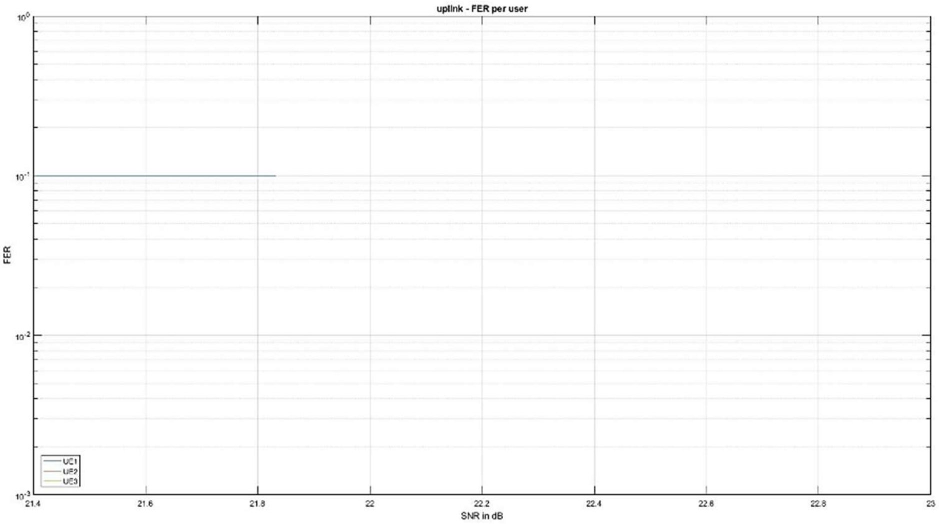


Figure 13: FER without secondary user (case 2)

9.2.3 *Throughput*

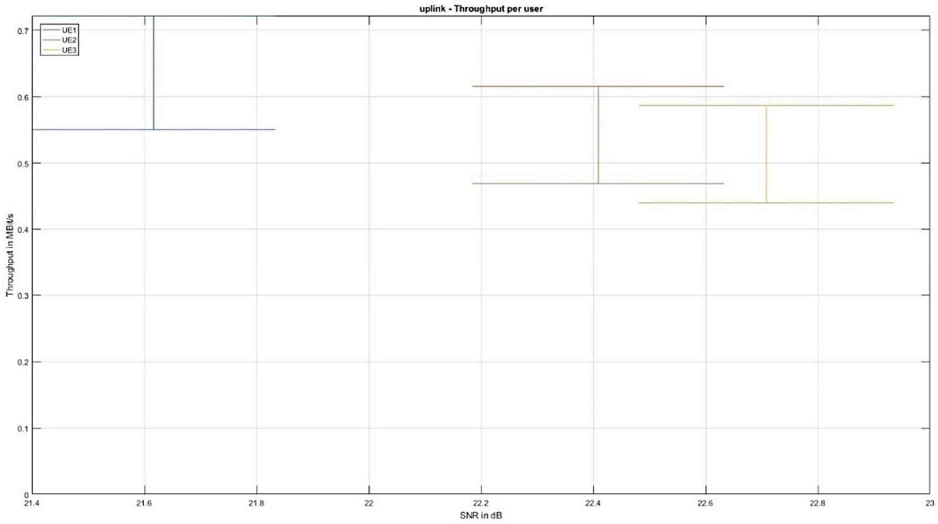


Figure14: Throughput without secondary user (case 2)

9.2.4 Observation

The mean values of throughput of 3 users is 633160, 539120, 509800in bits/second. We take the throughput for user 1 as the reference throughput (tpr). Thus, tpr = 633160 bits/second. The detector detects the number of subcarriers vacant and updates the schedule for second base station as well.

We can compare figure 11 with 14 and observe that there is a significant increase in throughput of the primary users due to change in modulation waveform (FBMC) and due to the change in CQI from 5 to 9.

9.3 Results with Secondary User

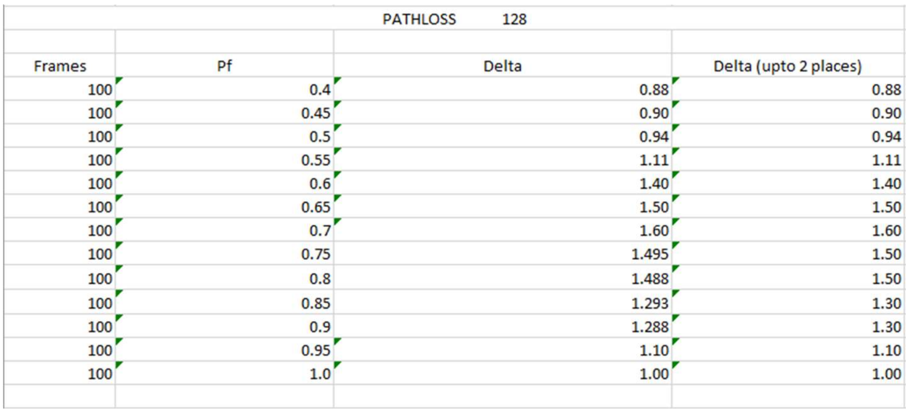
The updated schedule is as follows:

`Schedule for Primary System: ['UE1:18, UE2:15, none:25, UE3:14'].`
`Schedule for Secondary System: ['none:33, UE4:25, none:14'].`

The rest of the simulation and modulation parameters are kept constant as before. The simulator now simulates 100 frames with this setup and calculates throughputs for all values of Pf. The delta is calculated.

The relation of Pf and delta is tabulated:

Table 2: Pf and Delta (case 2)



		PATHLOSS 128	
Frames	Pf	Delta	Delta (upto 2 places)
100	0.4	0.88	0.88
100	0.45	0.90	0.90
100	0.5	0.94	0.94
100	0.55	1.11	1.11
100	0.6	1.40	1.40
100	0.65	1.50	1.50
100	0.7	1.60	1.60
100	0.75	1.495	1.50
100	0.8	1.488	1.50
100	0.85	1.293	1.30
100	0.9	1.288	1.30
100	0.95	1.10	1.10
100	1.0	1.00	1.00

The above table is at a pathloss of 128 dB, and the best results are obtained when the gain in throughput is of the factor of 1.60. This occurs at a Pf of 0.70.

Thus, the system is now set at Pf of 0.70. The following plots were obtained after simulation.

9.3.1 BER: Bit Error Rate

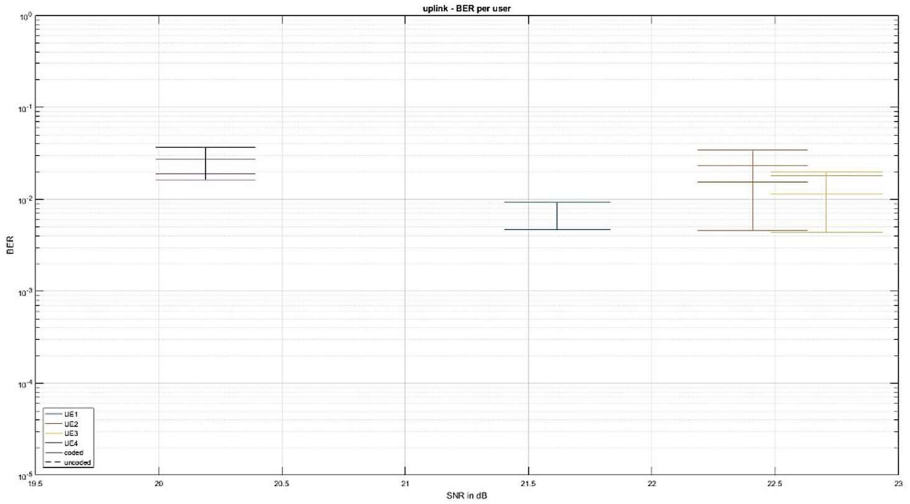


Figure 15: BER with secondary user (case 2)

9.3.2 *FER: Frame Error Rate*

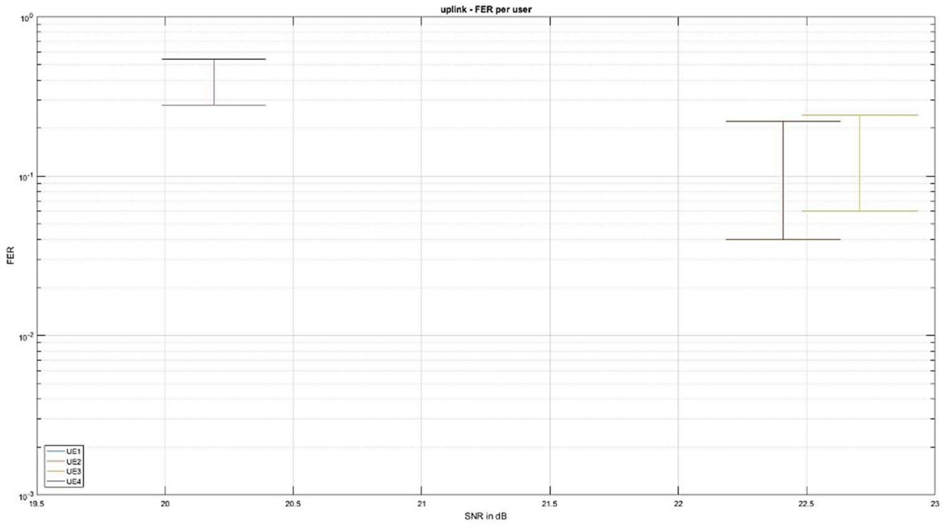


Figure16: FER with secondary user (case 2)

9.3.3 *Throughput*

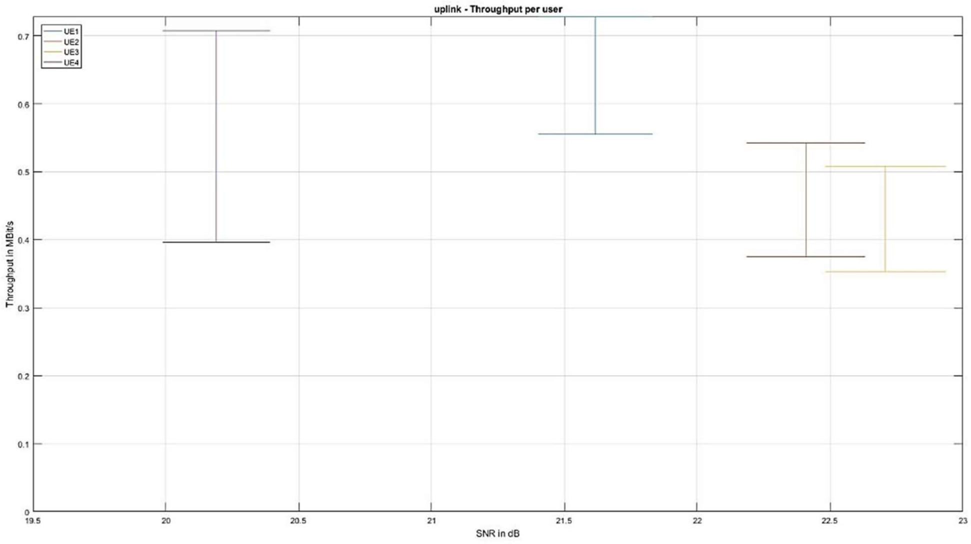


Figure 17: Throughput with secondary user (case 2)

9.3.4 Observations

We can see in the throughput curves there is addition of a fourth curve. This plot obtained clearly on comparison with figure 14 yields that the fourth user has been added to the spectrum without affecting the throughput of primary users. In this case the increase in throughput is as high as a factor of 1.60.

10. CONCLUSION

The above two cases are concluded in the following plot, the y axis represents the gain in throughput (delta) and x axis represents probability of false alarm.

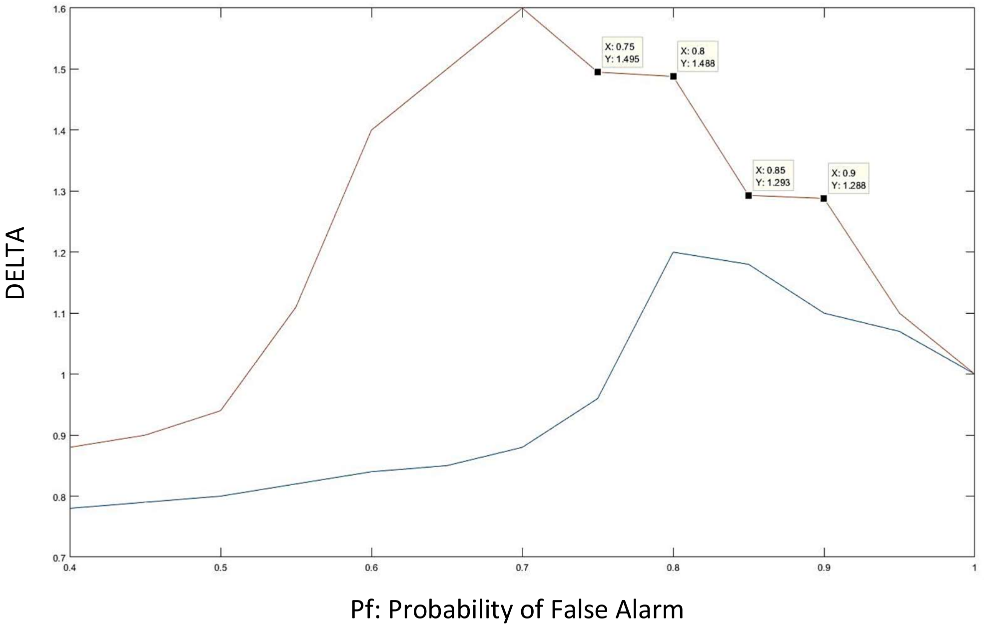


Figure 18: Delta vs Pf

10.1 Dependency of Pf on SNR

In the above figure the red curve is for a pathloss of 128dB and blue curve is for the pathloss of 130dB. The pathloss indirectly is the SNR, the lower pathloss corresponds to a higher value of SNR and vice versa. Both curves rise almost linearly in the beginning up to a Pf of 0.40 to 0.50, but for the higher SNR curve we see a rise in the curve around 0.70, this the probability value where the gain in throughput is maximum.

The curve may seem to be flat between Pf 0.7 to 0.8 and 0.85 to 0.90 however it is not the case, this flatness arises due to little change in the value of delta for the two ranges. If we look at the tale of Pf and delta it can be inferred that for these two specific ranges of Pf the delta goes from 1.495 to 1.488 and 1.293 to 1.288, these when rounded off to two decimal places yield approximately same value.

It is interpreted from this plot that the gain in the throughput is more for a lower of value of pathloss (128dB) i.e. a higher SNR (in red). Also, the Pf is less as compared to the plot for pathloss of 130 dB (Lower SNR comparatively).

10.2 Intricacies of the plot

There are two observations of the plot which are important to conclude the simulation as a whole:

If we observe the plot with more detail, we see that the plots end at delta equal to 1. This in simpler terms translates to the fact that the throughput of new user is essentially zero (then only delta can be one). This is governed by the fact that at a probability value of 1 the detection algorithm will predict that the spectrum is fully occupied and that none of the 72 subcarriers can be allocated to new user, thus resulting in zero subcarriers for new user thus a zero throughput. Point to be kept in mind is that this does not affect the primary users and during simulation if pf is kept at one, the new user is never scheduled, the second base station is simply not added to the system. Thus, explaining why, the throughputs of primary users remain same and delta turns out to be 1.

Based on above discussion, the opposite should happen when pf is kept at zero. Pf value of zero intrinsically means that detection algorithm predicts spectrum to be completely empty and that all the 72 subcarriers should be allotted to the new user. This case can be true and false as well, we cannot say without inspection that the prediction is wrong, maybe the spectrum eventually turns out to be empty when the simulation at a higher value of pf is carried out and thus the new user is scheduled with a second base station added to the system.

The throughput curve is plotted:

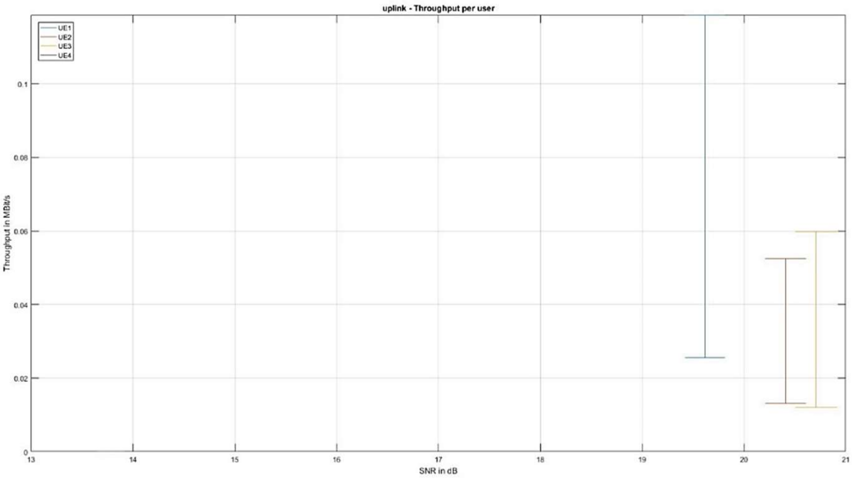


Figure 19: Throughput with secondary user when all 72 are allocated to new user

It can be observed that due to the allocation of already assigned subcarriers the new user has its throughput equal to zero. This happens because of high interference, this also results in the throughput of primary users to drop significantly. On comparing this plot with the above plots for 2 cases, the throughput values are as low as 24378 bits/second i.e. reduced by a factor of 100. Thus, delta when calculated is not completely zero but is of the order of zero.

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