ABSTRACT
A dynamic spectrum access scheme for cognitive radio networks is proposed. The approach will allow secondary user to operate in the presence of a primary user. The cognitive capabilities of the system includes electromagnetic interference (EMI) awareness, ranging and transmit power to control the spectrum access among primary and secondary users. (The scheme is based on electromagnetic interference (EMI) control. Ranging and transmitter power are parameters that need to be calculated/controlled in order to control the EMI).

Key Words: Dynamic Spectrum Access (DSA), Electromagnetic Interference, Signal-Interference-Ratio (SIR), OPNET, Primary user, User, Secondary user, White Space, Medium Access Control (MAC), Talk and no-talk zones

INTRODUCTION
Wireless system is the oil of the 21st century economy; it’s the fuel for growth and innovations. Wireless systems have become central to business and daily life. There are more than five (5) billion mobile cellular users across the world [1] and the demand of the wireless technologies and services increases rapidly every year. Spectrum inefficient utilization and growing in demand of wireless services is one of the challenges facing the wireless communication systems as the spectrum is a finite resource. Therefore, there is no capacity for the growth in demand of wireless system. There is a need of much better and smarter exploitation of the spectrum with efficient utilization in order to accommodates the growing of the demand of the spectrum, IEEE 802.22 standard is a standard that describe a physical and media access layer of a W RAN (Wireless regional Area Networks) that aimed to make use of an unused TV spectrum band also known as spectrum hole (white space) in a non interfering basis. IEEE 802.22 specifies that the networks should operate in a point-to- multipoint basis. A base station which is a professionally installed entity will manage its own cell in which the number of consumer premise equipments (CPE) operates. Hence, there will be another infrastructure put in place to help the unlicensed users also termed as secondary or cognitive users to make use of the TV unused portion of the spectrum band also known as the white space. All CPE in the IEEE 802.22 system must have the ability to perform spectrum sensing i.e. ability to detect signals: Digital TV signals with receiver sensitivity of -116dBm, for analogue TV the sensitivity is -94dBm and wireless microphone signals that are as low as -107dBm.

To do all entities described, the networks must have cognitive capabilities i.e. it is a cognitive radio networks. A cognitive radio technique is used to allow the sharing of geographically unused spectrum holes in a non interfering basis. This problem can be solved by considering the TV spectrum licensed user as the primary user and the unlicensed user or cognitive users as secondary users. A channel access mechanism is designed for this cognitive system.

RELATED WORK
Joseph Mitola in 1999 [2] is considered as the father of cognitive radio, in the dissertation where the software define radio and the concept of cognitive radio networks was introduced. To implements dynamic spectrum access for cognitive radio networks, different approaches to MAC protocols have been designed [3, 4] for optimization and decision on spectrum sensing and spectrum access. Similarly in [5, 6], negotiations among secondary users for spectrum access to avoid collision due to simultaneous transmission have been reviewed.

To implement multiuser MAC protocol, several MAC protocols were proposed for wireless, in [7] Problems of spectrum sharing and managements in wireless systems was reviewed. However, the concepts of opportunistic dynamic spectrum access and interference and the issues related to the coexistence of primary and secondary users have not been addressed. In [8] an opportunistic medium access control protocol for wireless local area networks has been addressed using the CSMA/CA for IEEE 802.11 techniques. In [9] a group-based medium access control (MAC) protocol was proposed for QoS provisioning in cognitive radio networks. Similar approach was used in [10] cognitive network in provision of Qos in e-health applications by using a queuing technique to provide priority access for the primary users to avoid electromagnetic interference.

NETWORK REQUIREMENTS FOR MULTIUSER ACCESS
In this cognitive radio system, a licensed user has priority to access the channel, while the unlicensed user can only access the channel opportunistically. The transmission has to be controlled in such away that the primary user is protected against electromagnetic interference and excessive delay caused by the secondary users. When a client node or user (i.e. secondary user)

- 1 -
wishes to transmits on a channel it has to sense the channel if idle before attempting transmission, this is similar to IEEE 802.11 Therefore a CSMA/CA MAC protocol is adopted and modified to provide cognitive capabilities.

**SYSTEM MODEL**

Consider a simple case where the secondary user wishes to coexist with a primary system consisting of a co-located transmitter-receiver. Consider TV broadcast station (primary transmitter) on a high tower serving a large radius of about 40km as shown in fig 1.0 below. Spectrum holes could exist if the primary transmitter is not transmitting or the primary receivers (TV receivers) are not on. In this scenario attention is focused on area around the tower where the signal strength is very high and without careful consideration of activity of the primary user, the secondary user can cause harmful interference to the primary receiver. Modelling of interference will be very useful to study the effects of network parameters such as location, transmit power and the propagation details of the secondary user on the performance of the cognitive radio networks.

The main task of the secondary system is to determine its relative position with respect to the primary transmitters and receivers and to start transmission only if it is sure that it will not cause severe interference to primary receivers. In this model, TV transmitter, TV receiver and secondary user are referred to as primary transmitter (PTx), primary receiver (PRx) and secondary transmitter (SUTx) as shown in fig 2.0 below.

![Fig.1.0 Showing TV transmitter (Primary Transmitter)](image)

![Fig.2.0: Showing detection (rd) and protection (rp) radius for primary receiver (PRx) in the presence of transmissions from the secondary transmitter (SUTx)](image)

Fig 2.0 above shows the primary receiver located at a distance $D_1$ from the primary transmitter and $D_2$ is the distance between the secondary user transmitter and the primary receiver. If the transmitter of the secondary user is far from the primary receiver, depending on the interference temperature limit at the receiver of the primary user, both the primary user and the secondary user could transmit data simultaneously. In this case, the interference range is defined as the minimum distance that the secondary transmitter should be away from the primary receiver so that it does not cause unacceptable interference to a receiver of the primary user. This interference range is denoted by $D_2$ in Fig 2.0 above, a secondary user must be able to detect a signal from the primary transmitter within the range $D_1+D_2$. In the absence of interference from other sources, a receiver within the service area with radius $r_d$ would be able to decode a signal from the primary transmitter, while a receiver outside the area would not. To allow any secondary users transmission, the primary receiver needs to be able to tolerate some additional interference from the secondary user. When secondary user starts transmitting, the interference increases and the signal quality from the primary transmitter decreases thereby, shrinking the service area. Assuming the green area represents the service area after the secondary user start transmitting i.e. protection region ($r_p$) where the primary receiver is guaranteed of decoding the signal from the primary transmitter. Within each primary receiver, there exist regions a non-talk region, any secondary user transmission on the regions would cause severe interference to the primary receiver.

However, this depends on the nature of the secondary user transmission as shown in fig 3.0a and Fig 3.0b below.

![Fig3.0a](image)

![Fig3.0b](image)

Fig 3.0 showing the effects of secondary user transmits power on non-talk zones

If the secondary transmitter has low transmitted power as shown in fig 3.a above, the *non-talk zones* around each receiver can be...
small as such the allowable transmission distance (D2) between the primary receiver and the secondary transmitter would be large. If however, it has high transmitted power in fig 3.0, the radius of the non-talk zones becomes much larger and the maximum allowable transmission distance (D2) will become smaller. White spaces exist in various locations within the service area.

**Interference and channel Modelling**

One of the most challenging problems of cognitive radio system is the interference which occurs when the secondary user access the spectrum but fails to become aware of the presence of primary user and therefore, to know whether or not a secondary user is within the white space. To address this problem, the cognitive radio systems need to be designed to coexist with the primary users without causing severe interference. The main objective here is to model the interference which will be very useful to characterize the effects of network parameters such as range, transmit power and the propagation details of the secondary user on the performance of the cognitive radio networks. In fig 4.0 below at any transmission distance the primary receiver is from the primary transmitter, there exist unwanted signals (interference) as the result of secondary user transmission. The signal-to-interference ratio (SIR) at the primary receiver depends on transmit power and distance the secondary transmitter is from the primary receiver as a function of transmit power and location of the primary transmitter.

![Fig 4.0 Interference Modelling](image)

The main task here is:

- **To determine the minimum signal-to-interference ratio (SIR) at the primary user receivers for it to decode signal from the primary transmitter**
- **To set a margin for protection given to the primary receivers**
- **To determine the service area, non-talk zones and the maximum permissible transmission distance for secondary transmitter from the primary receiver at any given distance of the primary receiver from the primary transmitter as a function of transmit power of the secondary transmitter i.e. to determine the values of D1 and D2 in fig 4.0 above.**
- **To estimate the transmit power of the secondary transmitter based on the location of the primary user in order to limit the interference caused on the primary receivers.**

The signal strength at both the primary receiver and the secondary receiver is determined by the path loss. There are many published path loss models for a cognitive radio but the simplest is the free space propagation model \[11\]. The free space path loss (FSPL) at a given distance between any two users or access point is given by

\[
FSPL(dB) = 20 \times \log(d) + 20 \times \log(f) + 32.45
\]

Where d is the distance in km and f is the frequency in MHz. The received primary signal strength \( P_R \) (in dBm) at a distance \( r \) can be modelled as

\[
P_R = P_T - Loss
\]

Where the Loss is a combination of \( (L + S + M) \)

\( P_T \) is the power transmitted in (dBm), \( L \) is the loss power in (dB) due to attenuation at a distance \( r \) from the primary user transmitter, \( S \) is the loss due to shadowing effects and \( M \) is the loss due to multipath fading. In the absence of noise, shadowing and multipath effects, the received signal can be computed as:

\[
P_R = P_T - L, \text{ where } L \text{ is the loss due to attenuation at a given distance from the transmitter}
\]

The signal-to-interference ratio (SIR); is defined as the ratio of the wanted signal from the primary transmitter and the unwanted signal from the secondary transmitter when considering single primary receiver and secondary transmitter in fig 4.0 above.

\[
SIR = \frac{P_R}{P_I}
\]

Where \( P_I \) is the interference power from the secondary transmitter.

The simulation was carried out using wireless nodes with operating transmission frequency of 2.4GHz, receiver sensitivity of -95dBm and speed of propagation \( 3 \times 10^8 \) m/s for a distance of 0-3km between the secondary transmitter and the primary receiver. The results are shown in the figures below.

![Fig 5.0 Received signal strength at the secondary receiver](image)

In fig 5.0 above, the signal strength at the secondary receiver decreases when the distance between the secondary receiver and the primary transmitter increase. This varies as a function of transmit power of the primary transmitter. About -80.1dBm is measured when they are 1km apart and the primary transmitter power of 100mW, this increases to -73.1dBm when the primary user increase its transmits power to 500mW at the same distance. The secondary user has to monitor the activity of the primary transmitter so that it would transmit on the channel once the primary transmitter is not transmitting on the channel. The decision about the presence of the primary transmitter depends on the signal strength received at the secondary receiver.
level of the signal strength at the secondary receiver will play a key role in order to avoid uncertainty in the detection.

The primary receiver communicates with the primary transmitter whose signal varies with distance from its location. At the same time it received unwanted signals from the secondary transmitter which is located at some certain distance. The received signal quality at the primary receiver is typically measured by signal-to-interference ratio (SIR) which is the ratio of the power of the wanted signal and the aggregated power of the unwanted signals.

Fig 7.0 above shows the signal to interference ratio (SIR) at the primary receiver as a function of distance between the primary user receiver and the secondary user transmitter. When the transmit power of the primary transmitter is 100mW and the secondary user is transmitting at 5mW. At 0.2km from the primary transmitter and 0.2km from the secondary transmitter, the SIR is 13dB and this increases when the primary receiver moves away from the secondary transmitter and this can be up to 36.9dB when they are 3km apart. When the primary receiver moves 1km from the primary transmitter and 200m from the secondary transmitter, the SIR degrades to about 0dB. This shows that location of primary transmitter, transmit power of primary transmitter, secondary transmitter location and transmit power of secondary transmitter are the key parameters to be considered/controlled when modelling of interference. The main challenge is to determine the optimal transmit power and distance of the secondary user transmitter that will not degrade the SIR at the primary receiver below the threshold level. In order to correctly interpret the received signal at the primary receiver, the SIR must be above a given threshold. Different cellular systems require different SIR thresholds 18 dB, 14 dB, and 9 dB are required as the minimum acceptable SIR protection levels in Advanced Mobile Phone System (AMPS), Digital Time Division Multiple Access (TDMA) Such as IS-136, and Global System for Mobile Communication (GSM), respectively [12]. In this case 6dB is assumed as the minimum SIR at the primary receiver. Therefore, from the fig 7.0 above, when the primary receiver is 2km from the primary transmitter (PUTx), the minimum distance secondary transmitter has to be from primary receiver is 800m in other to meet the target of 6dB SIR (i.e. the protection margin or no-talk zone for the primary receiver is 0-800m radius and 800m-3km is considered as talk zone for secondary user transmission). This distance increases to 1.4km as the primary receiver moves 3km from the primary transmitter (PUTx).

The variation of interference power

Fig. 6.0 above shows the variation of interference power at the primary user (PRx) receiver with distance from the secondary transmitter (SUTx). The measured interference power at the primary receiver is -85.1dBm when the secondary transmitter is transmitting at 5mW and is 500m from the PRx. This decreases to -93dBm when distance between the SUTx and PRx is 1km and -103dBm when they are 3km apart. The interference power level decreases at the primary receiver when the distance from the secondary transmitter increases.

<table>
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<th>Distance Between PU receiver and SUTx Transmitter (km)</th>
<th>SIR 0.2 km from PTx</th>
<th>SIR 0.6km from PTx</th>
<th>SIR 1km from PTx</th>
<th>SIR 2km from PTx</th>
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Fig 7.0 signal-to-interference ratio (SIR) at the primary user

The variation of interference power from the SU Transmitter with distance from PU receiver as a function of SUTx power

Fig. 6.0 The variation of interference power
However, the talk and non-talk zones depends on the transmit power of the secondary user. Using the information in fig 7.0, the maximum permissible transmission distance for the secondary user is computed as a function of distances of the primary receiver from the primary transmitter and different transmit power level of the secondary user as shown in Fig.8.

In fig 8.0, when the PU receiver is 1km from the primary transmitter, the minimum distance the SU transmitter should be from the PU receiver is 0.6km. This distance increases to 1km when the PU receiver moves 2km away from the primary transmitter and 1.2km when the SU increase its transmit power to 10mW. As such the values of D’s from fig.4.0 can be obtained in fig 8.0. This figure provides a prototype of relative positions for primary receiver and secondary transmitter whereby the medium access model can be built. Transmit power control scheme have been designed and the relative positions of the secondary user with respect to the primary receiver have been determined, this will enable the coexistence of the secondary user without causing interference to the primary user in the cognitive radio network.

PERFORMANCE ANALYSIS

The performance of the cognitive CSMA/CA protocol in terms of electromagnetic interference immunity (EMI) avoidance is analysed by studying the interference the secondary user transmitter causes to the primary user receiver, and how this interference affects the performance of the cognitive radio networks in terms of retransmission as a results of packets loss and its impacts on the network throughput and delay. OPNET version 14.5 is the environment of choice for implementing this model, is considered the most well reliable network simulation tool available today [13]. The simulation area is 4km² with four (4) wireless local area network (WLAN) nodes, the primary transmitter, primary receiver, access point and the secondary user. All simulations are run for 5 min (300sec). Two access architectures have been considered. The first is a centralised access schemes where there is infrastructure put in place and the secondary users communicates with the central data base that collects all the information from a collaborative group of secondary users that learns about the primary user activity. The second is an infrastructure less or cognitive adhoc network where each secondary user makes a decision on dynamic spectrum access independently and autonomously without any central controller.

The data rate at each user is 11Mbps and the packets inter arrival rate follow the exponential distribution with a mean value of 1000 packet/sec. The packet size is also exponential distribution with the mean value of 1024 Bytes. Since the packet size is below the 2034 bytes limit, fragmentation is not needed. Direct sequence spread spectrum (DSSS) is the modulation technique for both users as it provides highest throughputs for all users on the network [14]. It also helps to create a secure communication channel that is resistant to interference and sharing of single channel among multiple users. Therefore, at data rates of 11Mbps and a packets size of 1024 Bytes (8192 bits), the packet duration corresponds to 0.74milliseconds and 0.74 sec when transmitting 1000 packets therefore, at a transmission period of 300 sec there are about 403 time slots. The channel access mechanism is based on the CSMA/CA MAC protocol and the IEEE 802.11b Standard channel sensing period (i.e. DIFS) of 50µs is used [15].

TRAFFIC GENERATION AND CHANNEL USAGE PATTERN

A traffic flow control mechanism based on an events based technique is deployed to model the primary user activity to generate an ON/OFF traffic over the period of 5min, the ON periods are the busy time and the OFF periods are the idle times. The secondary user has the ability to detect the OFF times of the primary user and transmit packets over the white space if it’s not
within the *non-talk zone* of the primary receiver. The black spaces are not good candidates for dynamic spectrum access as the secondary user will cause severe interference to the primary user which would degrade the minimum SIR at the primary receiver.

**NETWORK TOPOLOGY**

![Network Topology Diagram]

Fig 9.0 showing coordinates for network topology

In fig 9.0 above, the distance \( d \) between any two points of coordinates \( P_1(x_1, y_1) \) and \( P_2(x_2, y_2) \) is given by:

\[
d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}
\]

The WLAN access point (AP) was fixed at coordinates (2.025, 1.371) and primary transmitter (PTx) (1.93, 1.24) while the primary receiver (PRx) is free to move along the axis i.e. the coordinate \((x_1, y_1)\) at a distance \( D_1 \) from PTx, where \( D_1 \) is 0.2 to 3km. In the first scenario, the PRx was fixed at the location \((2.13, 1.24)\), using the relation above, the distance between the primary transmitter and primary receiver \((D_1)\) is 200m and from sensing analysis in fig 8.0 above, the corresponding maximum allowable transmission distance between the secondary transmitter (SUTx) and primary receiver (PRx) is 200m i.e. SUTx can move as close as 200m to the PRx. Therefore, the SUTx was fixed at the coordinates \((2.13, 1.49)\), and this implies the secondary transmitter is 250m from the primary receiver. The distance between the AP and the secondary user is 158.7m, while 320m from the primary transmitter.

The transmit power for primary transmitter and secondary transmitter are 5mW and 100mW respectively. Consider a case where the primary and secondary users are transmitting 1000 packets at a data rate of 11Mbps over the period of 300sec as shown in figure 10 below.

**PERFORMANCE IN TERMS OF ELECTROMAGNETIC INTERFERENCE AVOIDANCE (EMI) AND PACKET LOSS**

![Interference Avoidance Graph]

Fig 10 showing the interference at primary user receiver due to secondary user transmission using traditional CSMA/CA MAC protocol

A time slot RTS/CTS channel access mechanism was used by both primary and secondary user. Fig 10 above shows the interference at primary user receiver as a result of secondary user transmission using the traditional CSMA/CA protocol. The blue bars represent primary user transmission and the red bars denoted the secondary user transmission. Observed overlaps up to 90% around 3s and 4s. Analysis of the electromagnetic
interference awareness of the MAC protocol for the cognitive system using cognitive CSMA/CA MAC protocol have also been investigated as shown in figure 11. The thickness of the red bars indicates secondary user transmissions of packets twice or three times within the white space (since the secondary user’s transmission is continuous within the periods of white space to increase channel utilization). The transmission overlaps indicate interference at primary receiver due to secondary user transmission. The interference occurs when the status and activity of the primary user is incorrectly reported to the AP for access decisions. An overlap factor of 20% is assumed within acceptable interference range for primary user [16]. From the figure, about 5-10% overlaps were recorded around 1s and 5s which are all within the acceptable range of 20% for a primary receiver to completely decode the signal it receives from the primary transmitter and also the overlaps observed in 3s and 4s using the basic MAC protocol is reduced when using the proposed MAC protocol.

Therefore, the interference of the proposed dynamic spectrum access model is less than that of traditional CSMA/CA protocol. However, the cognitive CSMA/CA protocol limits the transmit power and range for the secondary transmission to avoid interference to the primary receiver. This provides optimal channel access control policy for the secondary users in cognitive radio networks. Based on the analysis of packets loss, up to 1.5% packets loss is measured using the traditional CSMA/CA while maximum of 0.001% loss is measured when employing the model and this shows that the degree of packets loss in the traditional CSMA/CA protocol is higher than the proposed cognitive CSMA/CA protocol and therefore, the overall network throughput of the cognitive protocol is better than that of traditional protocol. For loss intolerant applications such as VOIP even a packets loss of 1% can significantly degrade a VOIP call [16]. Further analysis on the effects of relative positions of the secondary transmitter to primary receiver on packets loss, more packets loss were recorded when the secondary user is transmitting within the non-talk zones i.e. distance less than 200m from the primary receiver. Further away the secondary user transmitter is from primary receiver, the less interference it caused and low packets loss was recorded. Conclusively, for optimum channel access control policy, the protection margins for the primary receiver must be maintained.

PERFORMANCE IN TERMS OF DELAY AS FUNCTION OF AMOUNT OF WHITE SPACE

Delay and packet loss are two major factors that have tremendous impacts on communication. Some applications are sensitive to delay while some can tolerate the delay. The figure below shows the variation of delay as a function of amount of the white space for a period of 1 min.

A time slot RTS/CTS channel access mechanism was used by both primary and secondary user. At the beginning of RTS time slots, the secondary user senses the channel is free and it sends a RTS message. Once the AP successfully receives an RTS message, the AP immediately transmits a CTS message to the user after a short inter frame space (SIFS) period during the CTS time slot. The rise in time between when the secondary user receives CTS message and when it starts transmitting on the channel accounts for the delay at that instant of time. The distribution of delay at different time slots gives the delay as a function of the amount of white space. The results shows variation in delay, the least been zero when no delay is experienced and the largest is 7.5milliseconds which occurred at delay around 39 sec. This delay could be as the results of packets loss due to interference from the primary user transmission: the secondary user is transmitting and suddenly the primary user resumes transmission since it has priority over secondary user as such this could interfere with the secondary user transmission and causes some packets loss which would results in retransmission and add delay on to the user. At 57sec no delay is experienced as the secondary user does not transmit any packets within the white space. The average delays experienced for centralized and distributed access are 1.9ms and 1.2ms respectively.

PERFORMANCE IN TERMS SPECTRUM UTILIZATION EFFICIENCY AS FUNCTION OF NUMBER OF SECONDARY USERS

Network throughput is the average rate of successful packet delivery over the channel. The throughput is usually measured in bits per second (bit/s or bps), and sometimes in data packets per second or data packets per time slot. Throughput can be normalized and measured in percentage relative to the channel bit rate in bits/s to obtain the channel utilization or bandwidth utilization. The channel bit rate is 11Mbps.
Fig 13 showing primary user transmission

Fig 13 above shows the channel utilization as a function of number of secondary users for both standard CSMA/CA MAC protocol and proposed cognitive MAC protocol. Initial, both protocols achieve the same channel utilization of about 15%, as the number of users increases, the proposed MAC protocol gives better throughputs than the standard CSMA/CA protocol, for it limits the transmit power and range for the secondary transmitter to avoid interference to the primary receiver. The channel utilization is 99.91% and 73.31% when five (5) secondary users are accessing the network for the proposed MAC protocol and standard CSMA/CA protocol respectively. It improves spectrum utilizations by about 27% while limiting the interference imposed on the primary receiver.

CONCLUSION

The design of efficient MAC protocol for DSA is the key to the success of cognitive radio networks. A MAC protocol for DSA has been design, Performance analysis of results shows that, the proposed schemes protects the primary user from harmful EMI from the secondary user and also achieves a low packets loss of about 0.001% which is three orders of magnitude lower than the basic CSMA/CA MAC protocol. Based on spectrum opportunities generated from primary user transmission, the proposed scheme provides an efficient way of exploiting the white spaces. In terms of delay, it was found that, packets arrival rates, data rates, distance and number of secondary users have significant effects on delay. The Schemes has proven an efficient way of allowing and usage of un-used TV spectrum in non interfering basis.

REFERENCES


