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A New Approach for WLAN Channel Selection Based on Outage Capacity

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***Abstract*—This paper introduces a new channel selection metric and its implementation for wireless networks. It is demonstrated that channel utilization and channel quality are two essential performance factors for wireless networks. Then, we define Non-Utilized Outage Capacity (NUOC) as a cross-layer channel metric which provides an intelligent adaptivity between these two performance factors. We also determine steps required for implementation of this new channel selection metric which includes measurement, decision and execution. The proposed mechanism in this paper is easy to implement in IEEE 802.11 standard which makes it very desirable and practical for these networks. Our simulation results show that our new scheme provides better performance compared to other well-known schemes.**

I. Introduction

IEEE 802.11n and 802.11ac standards have introduced significant advancements for throughput improvement in Wireless Local Area Networks (WLAN). Critical new features such as MIMO technology, higher bandwidth (40/80/160 MHz), higher modulation (up to 256 QAM), Multi-User MIMO (MU-MIMO) have dramatically improved the maximum achievable throughput of these networks. With these improvements, achieving maximum throughput of over 1 Gbps will be possible. But due to shared nature of wireless medium, there are still many challenges in these networks to provide users satisfactory performance for high bandwidth low latency applications. One of the these challenges and indeed one of the most difficult one is dealing with interference from neighboring networks.

Techniques such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Request to Send/Clear To Send (RTS/CTS) protocols are provided in IEEE 802.11 standard to improve channel utilization in the presence of co-channel interference. But even with these protocols, while multiple networks are sharing a common wireless channel, performance degradation for each network is inevitable.

Availability of over 5GHZ unlicensed bands in IEEE 802.11n and 802.11ac standards have provided less crowded frequency bands and temporarily lessened some of these interference concerns. But, by the advancement of technology, the number of wireless devices using these bands is growing. There were more than one billion WLAN devices shipped last year alone. Therefore, sooner or later, the interference will be a big challenge in these frequencies as well. As a result, system performance in existence of interference still remains as one of the most challenging issues for wireless technology and in particular WLAN.

Existence of several operating channels in each regulatory region has given system designers a flexibility to avoid high interference frequencies and to some extend alleviate interference problem. As a matter of fact, interference mitigation by efficient channel selection is one of the prominent methods to address interference issues in high density deployments.

IEEE 802.11k has also provided additional framework which can be used toward better measurement of channel quality and network load. These features are intended to improve the network traffic distribution by development and implementation of more advanced channel selection and user association schemes.

In this paper, we provide a theoretically derived metric along with a practically implementable framework for wireless channel selection. Our metric includes most important performance factors for wireless systems and our framework provides details for implementation of this metric.

The rest of this paper is organized as follows. Section II provides relevant previous work on channel selection. Section III, reviews how interference can impact the performance of wireless systems. Section IV, provides detail steps toward derivation of our metric. Implementation of our channel selection framework is explained in section V and simulation results for evaluation of our new scheme is provided in section VI. We conclude the paper in section VII.

II. Related work

There are many different techniques for WLAN channel selection. These techniques can be divided into two general categories of centralized and distributed approach. In *centralized* channel selection schemes [1]–[3], different Access Points (APs) are controlled by same administrative domain. APs transfer their local information to each other or a center node. The advantage of these schemes is that the channel selection module can optimize channel allocation based on information from different APs and their traffic distribution to minimize overall network interference. An applicable example of this scheme is for office or campus buildings where all APs are cooperating to serve common users. In a *distributed* scheme, each AP uses local optimization based on its surrounding information to decide which channel to use. The advantage of these schemes is their scalability and practicality and their disadvantage is sub-optimality in large scale networks. Also, with a distributed scheme, devices from different vendors can operate in a neighborhood without any requirement for additional controlling mechanism. As a result, distributed channel selection methods have been more popular for real life deployment scenarios. This paper presents a distributed channel selection method where each AP independently selects its operating channel without communicating with other APs.

Fixed channel assignment is a Simple channel allocation scheme which traditionally has been used by many vendors. In some cases, this methods is selected due to design limitations because performance of a particular channel might be better than others. But this method will result in poor performance if devices from the same vendor are closely deployed. Another simple distributed channel selection scheme is to select a channel randomly. Although this method generally works better than previous one, it still will not be a good approach for dense wireless deployments. We will show the performance improvement of our metric compared to these two methods as part of our simulation results.

In [4], authors have proposed a channel selection scheme based on detecting the existence of interference in a channel. This scheme works fairly well when only some channels are experiencing interference and other channels are interference-free. But, it does not provide any mechanism to compare the performance of different channels when all of them are experiencing interference. Also, it does not consider other parameters such as signal strength of each channel or noise/interference duty cycle.

In [5], a channel hopping algorithm called *MAXchop* is proposed for uncoordinated networks to improve the fairness of resource distribution among neighboring cells. This work focuses more on fair resource distribution by channel allocation rather than performance optimization.

An automatic distributed channel selection algorithm for IEEE 802.11 networks is presented in [6]. This algorithm uses clients' measurement communicated to AP through IEEE 802.11k standard measurements and messaging. AP averages channel load and noise levels received from all its clients for all channels. It will decide whether a channel change is required by comparing the channel load of current operating channel with a threshold. In [7], same authors have proposed a new algorithm which is an improved version of original algorithm to provide faster reaction time. The interference analysis included in these works is strong but the signal strength of different channels is not considered.

In [8], a distributed algorithm for channel selection and user association is proposed. The optimization criterion considers minimization of global interference for channel selection and minimal potential delay for user association. We will also compare our method with the method presented in this work.

In [9] a dynamic distributed channel selection scheme is proposed. This proposed scheme includes three steps of monitoring, evaluation and switching module. Measurement module works based on MAC delay. The evaluation module regularly checks whether the current channel is still satisfactory. When a channel switching is needed, the switching module will do it. Our method includes similar high level implementation steps as this work, but underlying components such as measured parameters, comparison method and decision logic are different.

Load-Aware Channel (LAC) allocation scheme based on *Airtime* cost metric adapted from IEEE 802.11s is proposed in [10]. This metric considers channel condition, number of users and their traffic-load for channel selection process. It also considers both uplink and downlink channel performance into the weight calculation and selects the channel with lowest *Airtime* cost metric. Although this approach has shown significant improvements compared to previous works, neighboring node traffic is ignored in load definition. We will show the comparison of our method to the scheme presented in this work.

In [11], authors have purposed a method to dynamically select channels based on collaborative reporting mechanism. This scheme works based on a weight metric which enables nodes of current cell and other neighboring cells to contribute in the interference calculation. APs perform channel selection after receiving information regarding Phy rate, frame size, Receive Signal Strength (RSS) of interfering sources. This technique considers interfering traffic on current channel as well as other adjacent channel. The advantage of using Phy rate and frame size is the capability to determine the amount of interference. But the disadvantage is that this method can only determine interference from 802.11 compliant devices and is not capable of determining interference from other noise/interference sources.

III. Performance Factors

Before going through metric derivation and implementation, we review performance evaluation of wireless system in presence of interference. This is important for derivation of a well-rounded metric.

Accurate consideration of interference in wireless systems requires evaluation of interference in terms of time and amplitude. Some of the previously introduced schemes have considered none or only one of the above two aspects of interference. One of the distinguishing characteristics of our new scheme is evaluation of both interference aspects while selecting wireless channel. In this work, the time aspect of interference is captured by considering channel utilization and amplitude aspect is captured by considering link quality through Signal to Interference plus Noise Ratio (SINR) measurement. The following sections provide more details on these two aspects.

A. Channel Utilization

Available Airtime of each channel provides a measure of the duty cycle when interference is occupying the channel which means channel is not available for transmission. Since wireless channel is a shared medium by nature, devices are allowed to transmit only if the channel is *idle*. As mandated by Distributed Coordination Function (DCF) which is the specific

Carrier Sense Multiple Access (CSMA) mechanism used in the 802.11 MAC, each device has to utilize Clear Channel Assessment (CCA) mechanism to monitor channel and make sure it is clean for a determined interval before starting data transmission [12]. For a *busy* channel, the device has to defer transmission until the channel goes back to *idle* mode. As a result, the time ratio when a device can transmit depends on neighborhood's traffic. Also, the total amount of data a device can transmit is a linear function of channel availability. Therefore, it is important to consider channel utilization during channel selection.

On the other hand, there is a limitations with CSMA mechanism. This mechanism considers interference as a binary element. Whenever, the average interference energy level over channel's frequency range is above a defined threshold, the channel is considered busy and transmission is not allowed. However, when the interference energy level is below this threshold, transmission is allowed assuming there is no other device simultaneously using this frequency band. In topologies where interference source is not very close to the transmitting device, the average interference energy level will not exceed the predetermined threshold but it can negatively impact channel SINR. This can result in poor performance. Therefore, SINR consideration is also beneficial to provide more granularity for accurate interference estimation. This issue will be discussed in the following section.

B. Channel Quality

Measuring channel quality through SINR provides an estimation of the influence of the performance when the channel is experiencing interfering signals.

As explained in previous section, when the channel is considered to be available, measuring channel quality through SINR provides an estimation of how significantly interference can reduce the system performance. SINR is a function of Received Signal Strength Indicator (RSSI) and noise/interfernece.

$$SINR_{ij} = \frac{RSSI_i j}{N + \sum_{k \epsilon \eta(j)} RSSI_{kj}}, \tag{1}$$

$SINR_{ij}$ is the SINR from transmitter node *i* to receiver node *j* and $\eta(j)$ is the set of interfering neighbors for the receiver *j* and *N* is the total noise power at the receiver.

The Received Signal Strength Indicator (RSSI) is defined as

$$RSSI_{ij} = \frac{P_i}{L_{ij}}, \tag{2}$$

where P_i is the transmit power and L_{ij} is the path loss or channel attenuation between transmitter and receiver. Therefore, RSSI itself is a function of transmit power and channel attenuation.

Although channel attenuation is in general very similar for all frequency bands, transmit power can be different. Based on regulatory power limits for different regions, different transmitted power are allowed for different frequency channels [12]. In next section, we explain how the SINR factor is incorporated into channel selection.

IV. Metric Derivation

Non-Utilized Outage Capacity (*NUOC*) is the metric we use which includes both channel utilization and quality. *NUOC* formulation exactly shows how these two performance factors are combined in channel quality assessment.

Outage capacity is well-known as an appropriate design criteria for wireless fading channels [13]. Outage capacity concept is a pure physical layer concept which shows how SINR of a channel can impact its performance. But channel utilization concept, which is a layer 2 concept, is not included in outage capacity definition.

Assuming a constant bit rate transmission, the minimum SINR required at the receiver to be able to decode packets is:

$$\gamma_{min} = 2^{R/B} - 1, \tag{3}$$

where γ_{min} is minimum required receiver SINR, R is transmission rate and *B* is the bandwidth.

For any SINR γ less than γ_{min} outage will occur and transmitted packets will be dropped. The possibility γ to be less than γ_{min} is called *outage probability* which is important in definition of *outage capacity*.

$$C_{out} = B \times (1 - P_{out}) \times log_2(1 + \gamma_{min}) \tag{4}$$

C_{out} is the outage capacity and P_{out} is the outage probability. With assumption of Rayleigh fading channel, outage probability will be

$$P_{out} = P(\gamma < \gamma_{min}) = 1 - e^{-\frac{\gamma_{min}}{\gamma}}, \tag{5}$$

and outage capacity will be

$$C_{out} = B \times e^{-\frac{\gamma_{min}}{\gamma}} \times log_2(1 + \gamma_{min}). \tag{6}$$

Adding utilization concept to the outage capacity, *non-utilized Outage Capacity* is defined as [14]

$$NUOC^{m,n} = B \times (1 - U_{m,n}) \times e^{-\frac{\gamma_{min}}{\gamma}} \times log_2(1 + \gamma_{min}), \tag{7}$$

where $U_{m,n}$ and $NUOC^{m,n}$ are the utilization ratio and non-utilized outage capacity of the link between nodes m and n.

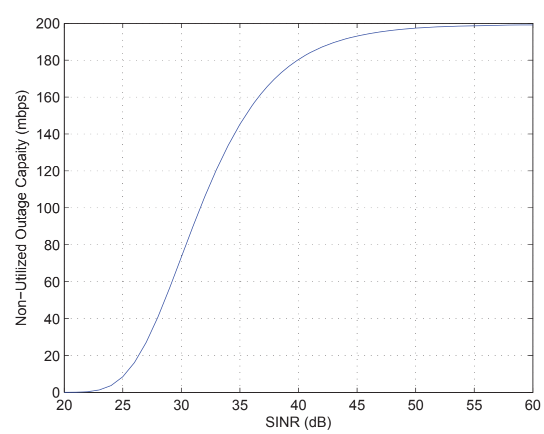

Fig. 1. Outage capacity vs. SINR for $\gamma_{min} = 30db$

Figure 1 shows the non-utilized outage capacity versus SINR γ, for a particular transmit data rate ($\gamma_{min} = 30db$) and bandwidth ($B = 20MHz$). From this figure, it can be seen that for an *SINR limited regime* ($\gamma \ll \gamma_{min}$), the outage capacity increases exponentially with any SINR increase. While for *high SINR regime* ($\gamma \gg \gamma_{min}$), any increase in SINR results in a very small performance improvement. One the other hand, non-utilized outage capacity is linearly proportional to channel utilization (U). Therefore, from performance point of view in a low SINR regime, SINR improvement is more important while for high SINR regime utilization is the dominant factor. *NUOC* is the metric which can autonomously determine which of the two factors, channel utilization and channel quality, is more critical for a specific deployment case.

For example, in dense wireless deployment scenarios such as small apartment buildings in urban areas, the link between wireless Access Point (AP) and its clients will be short and the RSSI will be fairly good. But in these deployments, interference from neighboring networks will be severe. As a result, *NUOC* will depend more on utilization factor than quality factor. On the other hand, in suburb and rural areas with lower network density and larger residential units, interference will be less severe and a fairly low channel utilization is expected for most wireless channels. But, link quality will be worse due to more stretched links. Therefore, channels with higher transmit power, equivalently higher RSSI and SINR, are more desirable. In these cases, channel quality factor is more critical than channel utilization factor.

Therefore, it is critical to understand that channel quality or channel utilization alone cannot be a good metric for all deployment scenarios. Also, a combined metric of the two factors without an intelligent adaptivity is not effective. *NUOC* is the metric which includes both these factors and can inherently adjust their importance based on realtime environment condition.

V. Implementation

Implementation of this channel selection metric includes three modules of *measurement*, *decision* and *execution*.Further for implementation purposes, we need to consider two separate phases of channel selection. First phase is *initial channel selection* by AP and seconds phase is *dynamic channel switching* during operation which is managed by AP and followed by all its clients.

A. Measurement

The measurement module involves measuring different parameters required for *NUOC* calculation. As we explained earlier, *NUOC* includes SINR and utilization calculation. SINR is an essential parameter which is calculated by most communication devices either in per packet basis or in some unit of time. Details of SINR calculation methods in wireless devices is beyond the scope of this paper.

Channel utilization requires a more complex calculation which is usually not available in basic wireless cards, but underlying parameters required to calculate utilization is usually available or easy to implement. To understand the channel utilization concept, we divide a time unit to four separate parts. These four parts are called transmission time (TX_{time}), reception time (RX_{time}), interference time (Int_{time}) and free time ($Free_{time}$).

$$TimeUnit = TX_{time} + RX_{time} + Int_{time} + Free_{time} \quad (8)$$

During initial channel selection phase, there is no data transmission by AP, therefore TX_{time} and RX_{time} are approximately zero. For this case, total channel time is either Int_{time} or $Free_{time}$. This means by periodic carrier sensing with short intervals, AP can estimate the time when channel is occupied by interfering traffic (utilized ratio) and the time when channel is free (non-utilized ratio). Even during normal operation when AP is transmitting or receiving data, it can calculate the total time spent from its own transmission and reception and derive utilized and non-utilized ratio of the channel from equation (8). Therefore, since carrier sensing is a mandatory feature in IEEE 802.11 standard, measuring utilization ratio of a wireless channel is easily feasible by already existing mechanisms in standard compliant devices.

SINR and utilization ratio measurement has to be done for all available channels to have a comprehensive channel comparison. Then, *NUOC* can be derived easily. One problem is that SINR can only be calculated knowing the channel attenuation between AP and client. During initial channel selection by AP, there is no client associated. Therefore, SINR can not be calculated during initial channel selection. Same problem exists with current network traffic which is required for *NUOC* calculation. As a result, computation of *NUOC* is different during initial channel selection and during dynamic channel selection. The initial channel selection will be explained in the decision module section. For dynamic channel selection, AP can measure SINR, transmit rate and utilization ratio to calculate the *NUOC* of current channel.

Since AP and clients are located at different location, the interference environment can be different for each one of them. Therefore, to have a channel which can perform well for AP and all its clients, the interference environment around all devices should be considered. This means either AP has to estimate the interference around clients by itself or it should receive some information from them about their neighborhood's interference. For the first approach, AP can use some logic based on retransmission, packet errors and delivery rates to have an estimate of clients' environment. But in general the second approach is more accurate. Having clients measure the interference in their neighborhood will take advantage of geographical distribution of devices. More details and implementation of this client side improvement is beyond the scope of this paper.

B. Decision

For our scheme, we use an AP centric decision engine where AP makes decision based on all available information. The advantage of this method is that AP can make a comparison of all channels locally and determine the best channel by a data driven decision.

For initial channel selection phase, AP has to select channel before any client association. In this case, since AP does not know the location of future associating clients, it has to select channels with higher allowable transmit power to provide better transmission range. In majority of wireless systems, there are multiple channels with the same transmit power. Therefore, we narrow down our initial channel selection to selecting the best channel among all channels with highest allowable transmit power. In this case, after AP measures utilization of all these channels, it will pick the channel with minimum utilization for operation. After this initialization, clients can start associating to AP and data transmission can start.

For dynamic channel switching phase AP calculates *NUOC* of current channel and compare it to all other channels. In this case, since AP knows the exact SINR and traffic at current channel, it can calculate *NUOC* for current channel and estimate it for all other channels including channels with lower transmit power. After *NUOC* is calculated for all channels, AP picks the best channel. If the current channel was not the best channel, AP will go to execution module.

Unnecessary channel changes may result in system instability. Therefore, having a mechanism to provide a good balance between unnecessary and necessary channel switches is important. For this purpose, we have added some channel switching preconditions into decision module. Only if these preconditions are met during measurement module, AP will move to decision module to see if better channels are available. These conditions are designed to make sure that current channel is no longer a good choice for operation. This will usually happen when a new interfering source is added to the channel. Therefore, we assign the precondition to be deterioration of current channel *NUOC*. During initial channel selection, AP picks a channel and clients are associating to this channel, AP measures initial *NUOC* which is called $NUOC_{init}$. Any time measurement module reports new measurement, AP will compare the new calculated *NUOC* which is called $NUOC_{new}$ with $NUOC_{init}$. Only If there was a significant deterioration, AP starts looking for a better channel. Otherwise, It will wait for next measurement interval. This mechanism will avoid unnecessary channel switching.

Note that calculated utilization for other channels our basically based on measurement done during initial channel selection. This will work well for static environments but may not be an accurate indicator of current channel conditions in dynamic environments. To address this problem, a real-time off-channel evaluation mechanism for non-operating channels can be implemented. This implementation can improve the performance of decision module. This implementation is beyond the scope of this paper.

C. Execution

This module is only used for dynamic channel switching and is not required for initial channel selection. After AP decided that a channel switch is required, it has two choices. One is to immediately switch to a new channel. This will result in a disassociation between AP and clients and service interruption which is not desirable. Alternative, AP can announce this channel switch to its clients. In an IEEE 802.11 compliant system, AP can use Channel Switch Announcement (CSA) message to inform all clients about its decision on channel switching. This message includes the next channel and the timing of the channel switch. Using this mechanism, AP and clients can stay associated during the channel switch. This will minimize the impact of channel switch on the performance and makes it seamless for the end user.

Therefore, after initial channel selection and association of clients to AP, whenever AP decides that the current channel is not in good condition and there is a better channel available, it can use CSA to execute a concurrent channel switching for all device in the service set. CSA can be implemented as part of Beacon broadcasted by AP.

VI. Simulation

We use OPNET [15] as the simulation environment to evaluate the performance of our new channel selection scheme. We compare our scheme with two other well-known channel selection methods introduced in [10] and [8] along with random channel and fixed channel selection which are two basic commonly used channel selection methods. We also compare our scheme with optimal manual channel selection.

For comparison purposes, we first evaluate the maximum achievable *throughput* of each technique. This will represent an application where user is interested to transfer a large data file with maximum possible rate. In another comparison, we consider fixed rate applications such as video. In this case, data is transferred at a limited rate and the *delivery ratio* of each scheme is evaluated. This comparison will show the reliability of channels selected by each one of these schemes.

To represent a real deployment scenario in a residential neighborhood, a simulation area of $300m \times 300m$ is considered. Depending on the test case, different number of APs and clients are randomly distributed in this area with a ratio of two clients for each AP. For each test, we have conducted cases with different network density to evaluate scalability of different techniques. IEEE 802.11g is the phy model used in 2.4 GHz unlicensed band and transmit power for all nodes (AP and client) in all channels are considered to be 200mW. The transmission range of each node is 115 meter which means that only close nodes can see and impact each other in this network.

For the comparison of all five techniques, we run this test on three different random distribution of nodes and take the average result as indicator of performance for that particular method. For each distribution, we run each test case for six minutes. When we start the test, there will be some time required for channel stabilization. This is a ramp up time for APs to select the best channel. Therefore, we ignore the first minute of each test and consider the performance over the remaining 5 minutes as an indicator for the long term performance of each technique.

For the first test, we transmit a Downlink TCP traffic from AP to each associated client. Basically, by selecting TCP traffic, with congestion control, each AP will adjust its transmit rate based on the available bandwidth and channel resources. Therefore, the bottleneck in these tests will be link capability not data availability at AP.

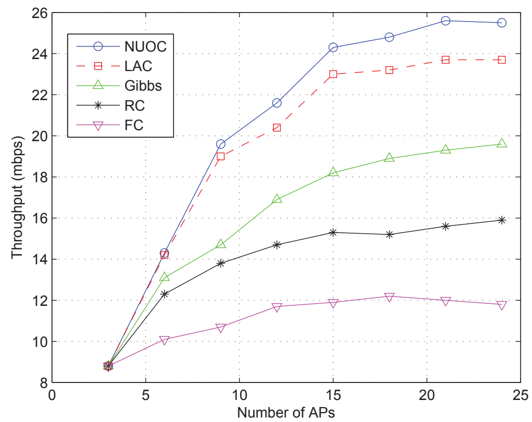

Fig. 2. Throughput Comparison

Figure 2, shows the throughput comparison with different AP densities for all five techniques. As it is shown, for a very low density case, where only 3 APs are located in the $300m \times 300m$ area, all techniques perform similarly. The reason is that because of distance between them, these APs do not impact each others performance. So, any channel selection method is fine. But as we increase the density by adding more APs, performance of different techniques are diverging. The Fix Channel method (FC) and Random Channel (RC) are showing the worst performance while $NUOC$ shows the best performance.

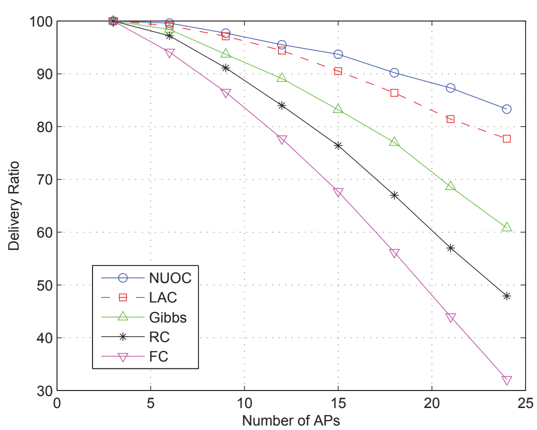

Fig. 3. Delivery Ratio Comparison

Second test is designed to represent a video type application where real-time data is transmitted with a fix data rate and system reliability is evaluated. Figure 3 shows delivery ratio performance of each technique in a this fix data rate test. A UDP traffic with a total transmission rate of 1.5 mbps per AP is considered. Our results show that performance order of five evaluated techniques are similar to previous test.

VII. Conclusion

We introduced a new metric for wireless channel selection in this paper. Our technique considers both channel utilization and channel quality for optimal channel selection performance. Based on these two factor, we introduce Non-Utilized Outage Capacity (NUOC) as a channel metric which can adaptively provide a balance between these two factors based on the environment. We also showed how our metric can be implemented in two phases of initial channel selection and dynamic channel switching by developing three modules for measurement, decision and execution. Simulation result provided show that our metric outperforms other well-known and widely used channel selection methods.

References

[1] K. K. Leung and B. J. Kim, *Frequency assignment for IEEE 802.11 wireless networks*, in Proceedings of IEEE Vehicular Technology Conference (VTC), vol. 3, pp. 1422-1426, October 2003.

[2] A.Mishra, V. Brik, S. Banerjee, A. Srinivasan, and W. Arbaugh, *A client-driven approach for channelmanagement in wireless LANs*, in Proceedings of IEEE International Conference on Computer Communications (INFOCOM), April 2006.

[3] S. J. Han, Y. Bejerano and M. Smith, *A novel frequency planning algorithm for mitigating unfairness in wireless LANs*, Computer Networks, vol. 54, no. 15, pp. 2575-2590, 2010.

[4] D. J. Leith and P. Clifford. *A self-managed distributed channel selection algorithm for WLANs*, IEEE 4th International Symposium on in Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, pp. 1-9, 2006.

[5] A. Mishra, V. Shrivastava, D. Agarwal, S. Banerjee and S. Ganguly, *Distributed Channel Management in Uncoordinated Wireless Environments*, International Conference on Mobile computing and networking (MOBICOM), September 2006.

[6] M. Silva and J. Rezende, *A Dynamic Channel Allocation Mechanism for IEEE 802.11 Networks*, In Proceedings of IEEE International Telecommunications Symposium (ITS), September 2006, pp. 225-230.

[7] M. Silva and J. Rezende, *TDCS: A New Mechanism for Automatic Channel Assignment for Independent IEEE 802.11 Networks*, The 8th IFIP Annual Mediterranean Ad Hoc Networking Workshop, 2009.

[8] B. Kauffmann, F. Baccelli, A. Chainteau, V. Mhatre, K. Papagiannaki,and C. Diot. *Measurement-Based Self Organization of Interfering 802.11 Wireless Access Networks*, IEEE INFOCOM, 2007.

[9] M. Ihmig and P. Steenkiste, *Distributed dynamic channel selection in chaotic wireless networks*, In 13th European Wireless Conference, Paris, France. 2007.

[10] G. Athanasiou, I. Broustis, T. Korakis, and L. Tassiulas, *LAC: Load-Aware Channel selection in 802.11 WLANs*, In Proceedings of PIMRC, 2008.

[11] G. Kazdaridis, S. Keranidis, A. Fiamegkos, T. Korakis, I. Koutsopoulos and L. Tassiulas, *Novel Metrics and Experimentation Insights for Dynamic Frequency Selection in Wireless LANs*, in the proceedings of WiNTECH 2011, MobiCom 2011, Las Vegas, Nevada, USA, September 2011

[12] E. Perahia and R. Stacey, *Next generation wireless LANs: throughput, robustness, and reliability in 802.11n*, Cambridge University Press, 2008.

[13] A. Goldsmith, *Wireless Communications*, Cambridge University Press, New York, pp. 69–72, 2005.

[14] B. Amiri and H. R. Sadjadpour, *QUIT: A Cross-Layer Routing Metric Based on Non-Utilized Outage Capacity*, Proceddings of IEEE ICNC, San Diego, USA, 2013.

[15] OPNET Technologies, Inc. http://www.opnet.com/, Radio/Wireless Models.