The Effect of an Enhanced Channel Assignment Algorithm on an IEEE 802.11 WLAN

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Abstract: - In this paper, a channel-assignment algorithm at the Access Points (APs) of a Wireless Local Area Network (WLAN) is proposed in order to maximize Signal-to-Interference Ratio (SIR) at the user level. We start with an initial channel assignment based on minimizing the total interference between APs. Based on this assignment, we calculate the SIR for each user. Then, another channel assignment is performed based on maximizing the SIR at the users. The algorithm can be applied to any WLAN, irrespective of the users' and load distributions. Simulation results showed that the proposed algorithm is capable of significantly increasing the SIR over the WLAN, which in turn improves throughput. Finally, several scenarios were constructed using OPNET simulation tool to validate our results.

Key-Words: - Signal-to-Interference Ratio; WLAN; Channel Assignment; Access Points;OPNET

1 Introduction

The frequency spectrum available for WLAN operations in North America is limited to eleven frequency channels in the 2.4 GHz band out of which three are non-overlapping and are allocated for 802.11b and 802.11g operations [1]. Due to their limited availability, frequency channels need to be carefully assigned to APs so that the network can maintain an adequate SIR.

Channel assignment in IEEE 802.11 WLAN has received significant attention in the past few years [2]- [12] and [14]. The increase in deployment of APs has led researchers to develop channel assignment algorithms in order to reduce co-channel and adjacent channel interferences from neighboring APs, which cause an overall throughput degradation of the network.

The authors in [2] noted that previous AP placement and channel assignment were always designed sequentially. An integrated model that addresses both issues concurrently is proposed. It is shown that, through an Integer Linear Programming (ILP) formulation, AP placement and channel assignment could be combined with results being superior to the case when both issues are considered separately. The authors tried to minimize overlap between APs using same frequencies, which in turn minimizes contention window (wait time to transmit) for users and subsequently increases the network throughput (data rate per user). The drawback of this study is that in the integrated model user distribution was not taken into consideration. In [3], the authors proposed an approach in hot-spot service areas using an ILP formulation. Their objective was to minimize the maximum channel utilization, thus equalizing the load distribution. This results in a higher throughput by assigning non-overlapping channels among neighboring APs. A dynamic channel-assignment based on ILP formulation that minimizes channel interference between neighboring APs at a reference AP was presented in [4]. The channel assignment was done at the planning stage without taking the users into account. In [5], the authors developed a real-time centralized algorithm to estimate the number of active users and proposed a dynamic radio resource management algorithm that reduces co-channel interference. Channels were assigned to APs that are overloaded with users in order to improve the overall network performance. Each AP is responsible for collecting network status, estimating number of active users and computing the channel utilization. However, it is not always possible to know the exact number of active users. Due to co-channel interference, some users that have messages to send will contend for the same radio channel even if these users may be associated with different APs. Similarly, the authors in [6] used the same approach in [5] and derived an empirical model based on measurements from a university campus environment. On the other hand, the authors in [7] introduced a fully distributed channel assignment algorithm that does not require direct communication between APs. Each AP acts alone based on the feedback of each channel's interference status provided by WLAN protocols such as IEEE 802.11. The authors in [8] applied the concept of channel assignment in the outdoor environment to the indoor environment. They installed three IEEE 802.11 compliant APs in an indoor environment and performed signal measurements to assign channels for the APs. An Integer Linear Programming (ILP) formulation assigns channels to the APs. The authors in [9] proposed a weighted variant of the coloring graph algorithm to improve the usage of wireless spectrum in WLANs. The authors emphasized that a least congested channel assignment is not efficient with the continued growth of WLANs. Due to the coupling between the physical layer (PHY) and the Media Access Control (MAC) layer, the authors in [10] and [11] proposed a Non-Linear Integer Programming (NLIP) model to minimize the maximum effective channel utilization at an AP. Since the Carrier Sense Multiple Access (CSMA) protocol at the MAC layer prohibits APs from transmitting when the channel is sensed busy, an effective channel utilization variable has been defined. Effective channel utilization is the fraction of time at which the channel can be sensed busy or is used from transmission by a particular AP. Therefore, a non-linear model was developed in [10] and [11] to minimize the maximum effective channel utilization at the bottleneck AP. However, only the three non-overlapping channels (1, 6, and 11) were considered for assignment and only AP-AP interference was considered. In [12], the authors proposed an optimization model for selecting the APs' locations and channel assignment while meeting the minimum bandwidth (BW) requirements. In other words, APs are placed and allocated channels such that a minimum BW per user is met, a minimum Signal-to-Noise Ratio (SNR) value is exceeded and a minimum signal power to associate with an AP. The authors in [13] developed a Graphical User Interface (GUI) tool that minimizes interference between APs and consequently maximizes the capacity of the network. Finally, we presented a channel assignment algorithm in [14] that minimizes the interference between neighboring APs after a load-balanced state is reached based on our work published in [15]. Our algorithm showed significant improvements in network performance when channel assignment is applied after load balancing.

In this paper, we extend our research reported in [14] and [15] by proposing a mathematical model to assign channels to the APs based on maximizing the total SIR at the users' level. The improvements achieved by considering the SIR at the users' level as well as on the network will be validated using OPNET simulation tool [16]. Channel assignment is performed in two steps. An initial channel assignment is conducted based on [14] and [12], where channels are assigned to APs after a load-balanced state is achieved [15], then SIR is computed at each user to reassign channels to APs based on maximizing the SIR in the second step. The algorithm in [15] distributes the load more efficiently among APs by reassigning users to different APs while decrementing the transmitted power of the Most Congested AP (MCAP). The current paper goes one step further to reassign channels based on SIR and validates results obtained from the commercial software MATLAB [17] through various OPNET simulation scenarios.

To the best of the authors' knowledge, all related work to date has considered only minimizing the interference between neighboring APs. This could be an efficient channel assignment scheme for small-scale WLANs. However, as the users populate the network, a more suitable channel assignment based on the users' demand is required. The current paper is the first to consider assigning channels to APs based on maximizing the SIR at the users' level, which quantitatively leads to increase in network throughput.

The remainder of this paper is organized as follows: In section 2, we present the load balancing algorithm based on power management. Estimation of the overlapping channel interference is provided in section 3. The channel assignment model and algorithm is described in section 4. Numerical results are presented in section 5. In section 6, OPNET simulation scenarios are presented. Finally, section 7 concludes the paper.

2 Load Balancing Algorithm Based on Power Management

This section describes briefly how the power management algorithm works. The algorithm is based on iteratively decrementing the transmitted power at the MCAPs in discrete steps. The received power at each user's location is evaluated using the No Line of Sight (NLOS) Path Loss model [18]:

$$PL(d) = PL_0 + 29.4\mathrm{Log}_{10}(d) + 6.1x_\alpha \mathrm{Log}_{10}(d) + 2.4y + 1.3x_s y \quad (1)$$

Here, PL_0 is the free-space path-loss in dB, d is the distance between user i and AP_j in meters, and x_α, x_s, and y are mutually independent Gaussian random variables of zero mean and unit variance.

Once the power received at a user from an AP exceeds the receiver's predefined sensitivity threshold, that user becomes a candidate for association with that AP. Thus, a user can be a candidate for association with several APs.

The WLAN under consideration consists of a grid of M APs distributed in a single-floor indoor environment. A set of N randomly distributed users seek to associate with an AP each. A user is defined by its randomly assigned position and data rate. After the initial channel assignment, which is based on minimizing the interference between neighboring APs, we seek to redistribute users' associations in order to minimize the overall congestion in the network. We then assign channels to APs based on the final association of users to APs.

As mentioned, this is achieved by first identifying the MCAP and decrementing its transmitted power in discrete steps. This is done such that each user is associated with one and only one AP. The congestion factor at AP_j, C_j, is defined as:

$$C_j = \frac{\sum_{i=1}^{N_j} R_i}{BW_j}, \quad \text{for } j \in \{1, \ldots, M\}. \quad (2)$$

where N_j is the number of users associated with AP_j , R_i is the data of user i, and BW_j is the maximum bandwidth for each AP (54 Mbps for IEEE 802.11g). The commercial software package LINGO (www.lindo.com) is used to solve the following NLIP [15], model 1.

$$\min_{x_{ij}, 1 \le i \le N, 1 \le j \le M} \max\{C_1(x), C_2(x), \ldots, C_M(x)\}, \quad (3)$$

subject to

$$\sum_{j=1}^{M} x_{ij} = 1, \quad (4)$$

$$C_j(x) = \frac{\sum_{i=1}^{N_j} R_i \bullet x_{ij}}{BW_j}, \quad (5)$$

$$\text{for } j \in \{1, \ldots, M\}.$$

Objective (3) minimizes the congestion at the MCAP in each iteration. Constraint (4) states that each user must be assigned to one and only one AP at any time. The binary variable, x_{ij}, is 1 when user i is assigned to AP_j and 0 otherwise. Constraint (5) defines the congestion factor at the APs as a function of the assignment.

It should be noted that as the users' associations are changing due to the decrease of the transmitted power at the MCAP, the algorithm appropriately relocates the new MCAP at each iteration based on the new bandwidth utilization (C_j's of all APs), and decrements its power assuming no changes are occurring in the channel environment during the course of simulation. In other words, users' data rates suffer minimal fluctuations and the *average* data rate is considered constant over the simulation time, which depends on the variables involved and computer processing time. The final solution provides the power level of the individual APs and the final users' associations such that each user is connected to one AP.

3 Estimation of the Overlapping Channel Interference

Each channel in the 2.4 GHz band spreads over 22 MHz due to the Direct Sequence Spread Spectrum (DSSS) technique employed by the IEEE 802.11b/g. DSSS is a modulation technique that avoids excessive power concentration by spreading the signal over a wider frequency band [19]. For instance, channel 1 ranges from 2.401 GHz to 2.423 GHz and its center frequency is 2.412 GHz. The center frequency of two adjacent channels is separated by 5 MHz. Therefore, there exists a channel bandwidth overlap. The interference-level factor w_{jk} is defined as follows [4]:

$$w_{jk} = \max\ (0, 1 - |Ch_j - Ch_k| \times c) \tag{6}$$

where Ch_j is the channel assigned to AP_j, Ch_k is the channel assigned to AP_k and c is the non-overlapping portion of two adjacent channels, expressed as a fraction of the frequency spectrum of a channel. For instance, channel 1 and channel 2 do not overlap from 2.401 GHz to 2.406 GHz, as shown in Fig. 1. Normalizing the overlap of 5 MHz over the spectrum of 23 MHz, c is equal to 1/5 approximately. When the channels are far apart, as is the case with channels 1 and 6, $w_{jk} = 0$ (i.e., no interference). When the two channels are the same, $Ch_j - Ch_k = 0$, (1) suggests that $w_{jk} = 1$ (i.e., maximum interference). Therefore, channels should be assigned to APs such that overlapping channel interference is minimized. On the other hand, for channels 1 and 6, $|Ch_j - Ch_k| = 5$, $w_{jk} = 0$, suggesting no interference.

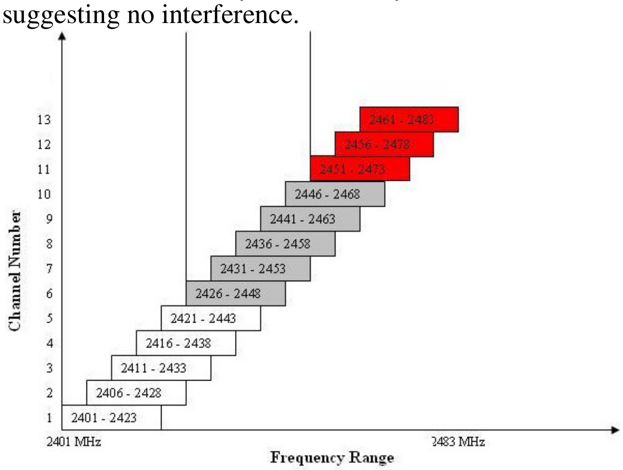

Fig 1 The three non-overlapping channels

4 The Channel Assignment Model

A new channel-assignment algorithm for IEEE 802.11 WLAN systems is presented. Channels are assigned to each AP in such a way to maximize the SIR at the users' level, rather than to minimize interference among APs. By maximizing the SIR over the whole network, the network resources will be utilized more efficiently resulting in higher throughput [20]. Mindful that we only have limited channel resources (11 channels in IEEE 802.11 b/g), some channels need to be reused. If the same channel is to be assigned to two or more APs which are located far enough from each other, the overlapping channel interference detected by each AP should be less than a given threshold.

We now formulate our channel-assignment problem as a NLIP problem using the following variables defined below:

- $\mathbf{A_j}$ is the set of neighboring APs to AP_j.
- K is the total number of available channels, 11 in IEEE 802.11 b/g.
- P_{ik} is the power received by user i associated with AP_k.
- P_{ij} is the power received by user i from the interfering AP_j.
- P_i is the power received by user i from the interfering *users*.
- I_i is the total interference experienced by user i due to all APs j (where $j \neq k$) and neighboring users.

The channel assignment problem, model 2, is modeled as:

$$\max \quad \sum_{i=1}^{N} \sum_{j=1}^{M} SIR_{ij}(k),\ j \neq k \tag{7}$$

subject to

$$w_{jk} = \max\ (0,\ 1 - |Ch_j - Ch_k| \times c) \tag{8}$$

$$I_i = \sum_{j=1}^{M} (P_{ij} \bullet w_{jk}) + \sum_{i=1}^{N-1} P_i, \quad j \neq k \tag{9}$$

$$SIR_{ij}(k) = \frac{P_{ik}}{I_{ij}} \qquad \forall\ i, j, j \neq k \tag{10}$$

$$j, k \in \{1,..,M\}$$

$$i \in \{1,..N\}$$

$$Ch_{j,} Ch_k \in \{1,..,K\}$$

Objective (7) maximizes the total SIR for all users i. Constraint (8) defines the interference overlap factor between AP_j and AP_k, which have been assigned Ch_j and Ch_k, respectively. Based on [12], the overlapping channel factor, c, is 0.2. Constraint (9) defines the interference experienced by user i by all APs except AP_k and all neighboring users. Constraint (10) defines the signal-to-interference ratio for user i due to interfering access points j ($j \neq k$). The NLIP formulation determines the best integer variables Ch_j and Ch_k or channel assignments that lead to the maximum SIR among the entire users. This in turn results in higher throughput. It is observed that the non-linearity in the problem comes from the definition of the w_{jk} variable, as shown in (8).

When executed in real time, it is assumed that each user i updates the serving AP_k with its associated $SIR_i(k) = \sum_j SIR_{ij}(k)$ upon registering with it. Then each AP, synchronized with the other APs, will periodically request SIR from its users. In case of a change in the current user distribution, resulting from users joining or exiting the network, the APs will transfer the $SIR_{ij}(k)$ information to a central server that runs the channel-assignment algorithm to reassign channels to the APs. All APs are assumed to be operated by the same internet service provider. The scenarios in this paper do not involve user mobility. They are set up with a fixed number of APs, a fixed number of users, and assuming constant average data rate over the simulation period. The purpose of the displayed scenarios is to compare between the effects of channel assignment at the initial design stage and a later stage, when users are considered in the network.

It is important to note that user-to-user interference was assumed negligible due to its low transmitted power compared to the AP's transmitted power. The channel assignment algorithm of the NLIP model is divided into a number of computational steps. Our channel-assignment algorithm can be stated as follows:

1. Assign channels to the M APs based on the NLIP model proposed in reference [14] which is based on minimizing the total interference between APs (users are not taken into consideration at this level).
2. Input the positions of N randomly distributed users.
3. Perform load balancing based on the power-management algorithm proposed in section 2.
4. The output from model 1, the final transmitted power at each AP, helps us calculate the received power at each user.
5. Compute interference caused by neighboring APs at each user based on distance between AP and user (path loss model in (1)), and the interference overlap factor presented in (6).
6. Compute SIR for each user.
7. Input the values, the final transmitted power at each AP and the association matrix x_{ij}, and run model 2.

The above algorithm is executed on a static environment, i.e, at one time slice. If we were to assume continuity among time slices and that states transition smoothly from one time slice to another, then an additional step could be added to the channel assignment algorithm that involves repeating steps 2-7 in every new time slice. To test this hypothesis, a simulation is run continuously until the balanced load state discussed in [15] is achieved among data based on existing user patterns. The OPNET simulation tool was used to run real-time scenarios to affirm our simulation results. Because of the random distribution of the users, we ran more than 200 simulation replications for each scenario. It was judged that 200 replication cycles were sufficient to reach a steady state. During each replication cycle of the simulation, the association of user location i to AP_j remain fixed—until a new association is obtained in step 3. We show the average results of each scenario below followed by OPNET simulation results.

Instead of an optimization solver, the authors solved model 2 by enumeration using Matlab software tool. The purpose of using an enumeration method is to gain some insight on the SIR value for each iteration. SIR values were examined until a maximum was obtained. The exercise will pave the way for a more formal optimization routine in the future.

5 Numerical Results

The simulations were carried out with service areas consisting of 4, 6, 9 and 12 APs and 20, 30, 40 and 50 users, respectively, forming a WLAN. APs are placed 60 meters from each others, 20 meters from adjacent walls and the service area's lengths and widths vary with the number of APs. The purpose of the presented scenarios is to show the effectiveness of the proposed algorithm on different network scales.

The following assumptions were taken into consideration during the simulation:

- All users and APs are stationary.
- All APs are distributed in a homogeneous environment.
- The locations of the users and APs are known.
- All APs are assumed to be operated by the same internet service provider.

- All users are continuously active.
- Users associate to APs based on the highest RSSI.
- Data rate represents the average data rate over the simulation period since it is hard to capture instantaneous data rate fluctuations.
- All simulations were run based on the IEEE 802.11g technology, i.e., 54 Mbps.
- APs transmitted power levels are set equally at 20 dBm before power management algorithm is invoked.
- User sensitivity is set at -90 dBm. Any signal level above this threshold will be a potential association.
- The receiver detection threshold is assumed to be -110 dBm. If the user is receiving a signal from an AP that falls below the detection threshold, then this signal is assumed to cause no interference at the receiver. Where as if the signal falls between receiver sensitivity and detection threshold that means the AP causes interference.

5.1 Scenario 1

In scenario 1, we consider a grid of 4 APs over a 100 m × 100 m area and 20 randomly distributed users. We run the load balancing algorithm in section 2 to get the final transmitted power level at each AP, which in turn leads to the final received power at the user, and the final association matrix. The final association matrix is the user to AP assignment that leads to the best load distribution. Fig. 2 shows the final user-to-AP association for the scenario under consideration.

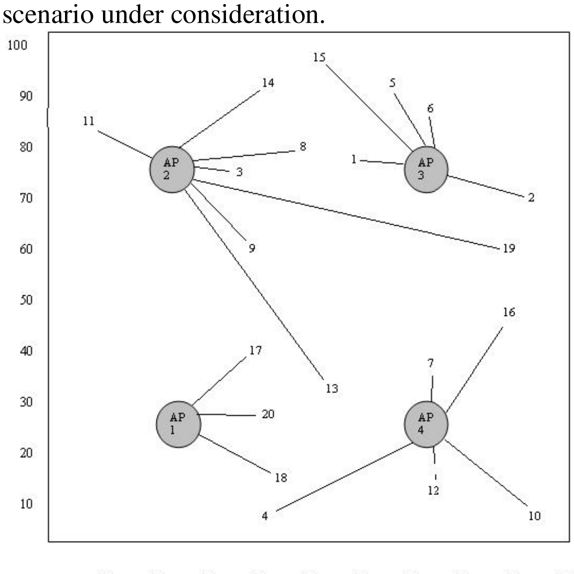

Fig. 2 User-to-AP association

Taking a close look at Fig. 2, we notice that the circled user between AP1 and AP4 is associated with AP2 although it is closer to either AP1 or AP4. However, this association represents the final association after the power has been decremented on the MCAPs iteratively. The final transmitted power at AP1, AP2, AP3 and AP4 is 11 dBm, 9 dBm, 4 dBm, and 3 dBm respectively, and that particular user ended up associating with AP2 leading to a better load distribution. The decision has been made based on the power-management algorithm presented in section 2.

Next, an initial channel assignment is obtained based on minimizing the interference between APs, [4] and [14]. Then, the model 2 is invoked to find the best channel assignment that leads to the maximum SIR at the users. To provide a fair comparison between the proposed algorithm and previous work, we apply the initial channel assignment condition (based on minimizing interference between APs) at the balanced network with the same power levels achieved by the APs along the corresponding user-to-AP association (based on power load balancing algorithm in section 2 [15]) and then apply the channels assigned by our proposed algorithm (based on maximizing SIR at the users under same conditions). Results are shown in Table 1. This procedure is followed throughout the remaining scenarios.

Table 1 – Comparison between Our Model and Models Based On Minimizing Interference between APs (SCENARIO 1)

	Initial Channel Assignment (previous work [4], [14])	Final Channel Assignment (current work)
AP1	11	1
AP2	1	6
AP3	8	11
AP4	3	2
Average SIR	4.48	5.83

Table 1 shows that if we were to start with a channel assignment in the initial design stage and keep that channel assignment unchanged after users are entered into the network, the average SIR per user would be 4.48. However, by applying our algorithm at the balanced state, the average SIR was improved by almost 30% (to 5.83).

5.2 Scenario 2

In scenario 2, we constructed 6 APs over 160 m × 100 m and 30 randomly distributed users. We run our model in [15] to get the final transmitted power levels at each AP and the final users' association matrix. Then, similar steps are followed as in scenario 1 to provide ground for comparison. Table 2 shows the results for the 6-AP scenario.

Table 2- Comparison between Our Model and Models Based On Minimizing Interference between APs (SCENARIO 2)

	Initial Channel Assignment (previous work [4], [14])	**Final Channel Assignment (current work)**
AP1	6	2
AP2	1	11
AP3	6	6
AP4	11	6
AP5	1	8
AP6	11	1
Average SIR	2.64	3.15

From the results in Table 2, we again notice the improvement in the average SIR over all users. The average SIR per user was improved by almost 19%. In this case, even though both AP3 and AP4 used channel 6, it still led to a better SIR at the users.

5.3 Scenario 3

In this scenario, we deployed 9 APs with 50 users randomly distributed over 160 m × 160 m area, where they are distributed in a 3 × 3 grid. Similar procedure is followed as before. Results for this scenario are depicted in Table 3.

Table 3- Comparison between Our Model and Models Based On Minimizing Interference between APs (SCENARIO 3)

	Initial Channel Assignment (previous work [4], [14])	**Final Channel Assignment (current work)**
AP1	4	6
AP2	9	1
AP3	1	11
AP4	11	8
AP5	1	11
AP6	11	4
AP7	6	6
AP8	11	8
AP9	6	11
Average SIR	1.11	1.93

The average SIR per user was improved by almost 74%. This improvement can be related to the fact that after load balancing, some users that were close in association to their original AP are now redirected to a farther AP that provides a better load distribution. Although these particular users might suffer higher interferences from neighboring APs, yet they had enough RSSI to associate with a farther AP.

5.4 Scenario 4

Finally, our algorithm is applied on a 12-AP with 60 randomly distributed users service area. The 12 APs are located on a 3 × 4 grid. Following the same procedures mentioned earlier. Comparison of results is depicted in Table 4.

Table 4- Comparison between Our Model and Models Based On Minimizing Interference between APs (SCENARIO 4)

	Initial Channel Assignment (previous work [4], [14])	**Final Channel Assignment (current work)**
AP1	1	1
AP2	11	1
AP3	1	6
AP4	6	1
AP5	11	6
AP6	6	1
AP7	1	11
AP8	6	1
AP9	11	5
AP10	1	1
AP11	9	8
AP12	4	1
Average SIR	4.74	7.23

It is noticed from the results that our algorithm was efficient in assigning the same channels to APs where there was no overlapping or where overlapping in AP coverage had no significant impact on the SIR of the users, which caused the average SIR over all users to improve greatly (almost 53%).

In conclusion, the NLIP algorithm showed significant improvement in the average SIR when channel assignment was conducted again at the end of the balanced state. It is important to note, however, that users were distributed randomly in every scenario and it is very hard sometimes to arrange, a priori, the users to be in the overlapping region of all APs.

While the results look promising, we recognize some limitation to our analysis. First, NLIP is computationally intensive. Most optimization solvers, such as LINGO, may not reach optimal assignments. Our computational results to date suggest that the assignment can be significantly improved by considering interference at the user level simultaneously with interference between APs. The generality of these results can only be established by examining the properties of the NLIP, which is beyond the scope of the current investigation. By definition, NLIP such as our assignment model is not a convex program. No global optimum can be guaranteed in the solution. As a result, little can be stated on the "duality gap," or the error bounds on the solution so obtained.

6 Validation Using OPNET

This section covers the channel assignment simulation in a WLAN to study the effect of different channel assignments at the user level. Several 4-AP with 20 users WLANs were constructed using OPNET simulation tool. Fig. 3 shows the configuration of the WLAN under study.

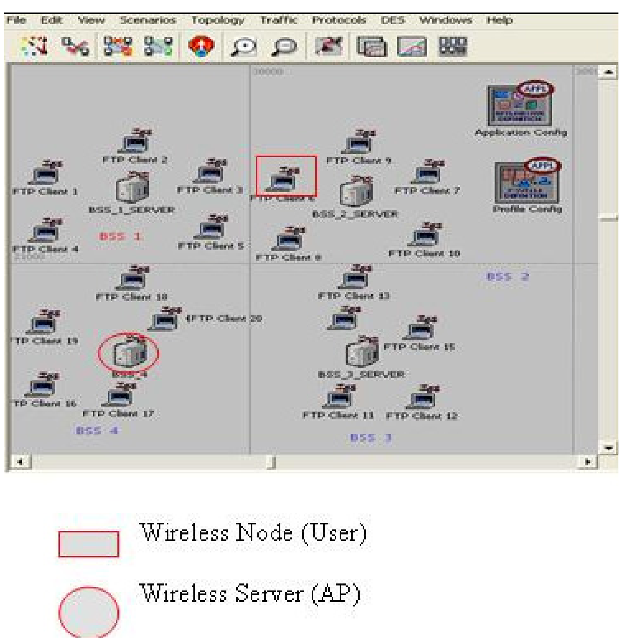

Fig. 3 4-AP and 20-User WLAN in OPNET

The following assumptions were taken into consideration:

- All users are stationary.
- Power transmitted from each AP is 20 dBm.
- Receiver's threshold power is -90 dBm.
- All APs' data rates are set to 54 Mbps.
- Each AP has 5 users that are uploading a 400 Kbytes file simultaneously to their respective wireless servers (APs).
- Simulation time is 1000 seconds (16 minutes and 40 seconds).

Four scenarios were conducted to study the effect of interference on the application level and the network level. In scenario 1, channels 1, 2, 3, and 4 were assigned to AP1 to AP4, respectively. In Scenario 2, non-overlapping channels 1, 6, 1, 11 were assigned to AP1 to AP4, respectively, where the same channel, 1, was assigned to the diagonal APs. Optimal channel assignment, based on minimizing interference among neighboring APs, assigned 1, 8, 3, and 11, for AP1 to AP4, respectively in scenario 3. Finally, channels 6, 11, 2, and 1, were assigned to AP1 to AP4 in scenario 4 based on maximizing the SIR at all user. One scenario was constructed and all other scenarios were duplicated while modifying the channel in each AP. Table 5 summarizes the channel assignment scenarios.

Table 5- Summary of Channels Assigned to Each AP in Each Scenario

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
AP1	1	1	1	6
AP2	2	6	8	11
AP3	3	1	3	2
AP4	4	11	11	1

6.1 Results

Analysis of the different channel assignments is presented in this section. Results are intended to show the effect of channel assignment on the FTP upload response time at the application level and network level, as well as other network statistics.

Fig. 4 shows a comparison between the 4 channel assignment schemes in terms of global upload response time.

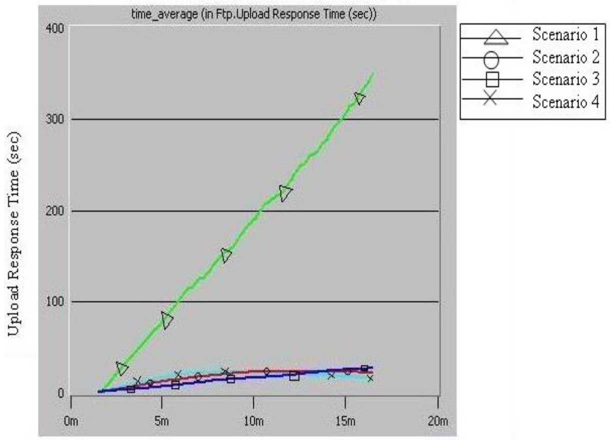

Fig. 4 Global FTP Upload Response Time (sec)

It is clear that the one-channel distance assignment causes the network's upload response time to increase linearly with simulation time. This is because all FTP clients associated with their respective AP are suffering from large interference from their neighboring APs which causes the Medium Access Control (MAC), of each FTP client, to continuously transmit packets but arriving to the intended AP with high bit error rates causing end to end delay. On the other hand, the remaining 3 channel assignment schemes perform very closely with the exception of scenario 4 (light blue), as shown in Fig. 5, where response time after the 12th minute starts falling below the other two competing channel assignments (red and dark blue). Therefore, in the long run, employing the channels assignment algorithm based on SIR provided better upload response time than the other approaches.

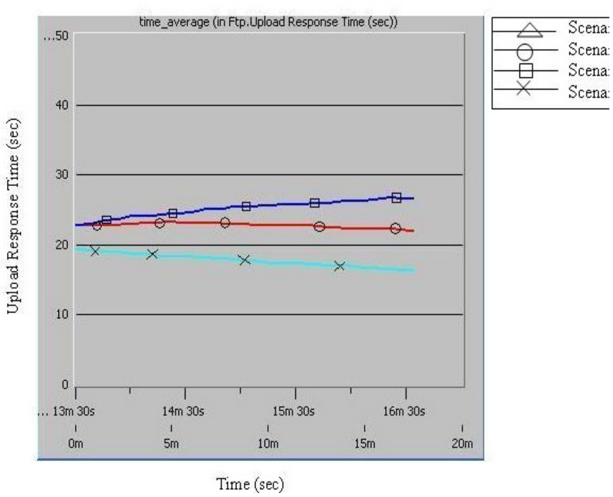

Fig. 5 Zoomed in view of scenarios 2, 3, and 4.

It is important to note that the channel assignment provided by scenario 4 is based on maximizing the SIR of the users. A different user distribution might lead to a different channel assignment. Whereas, the channel assignment based on minimizing the interference between APs will remain the same as long as the AP distances are fixed.

Consequently, improving delay and response time of the network leads to a better network throughput, as shown in Fig. 6.

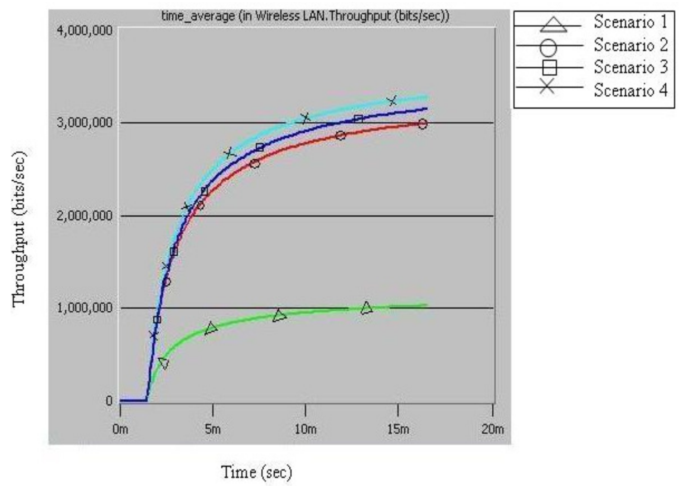

Fig. 6 Global throughput of the 4-BSS WLAN.

Furthermore, the delay at AP1, AP2, AP3, and AP4 are displayed in Fig. 7 through Fig. 10, respectively.

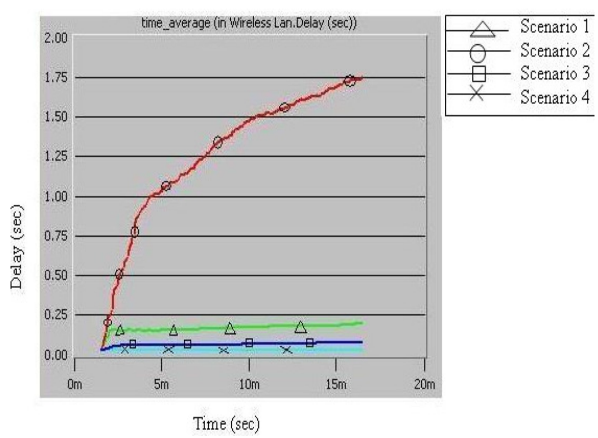

Fig. 7 Delay at AP1 (sec)

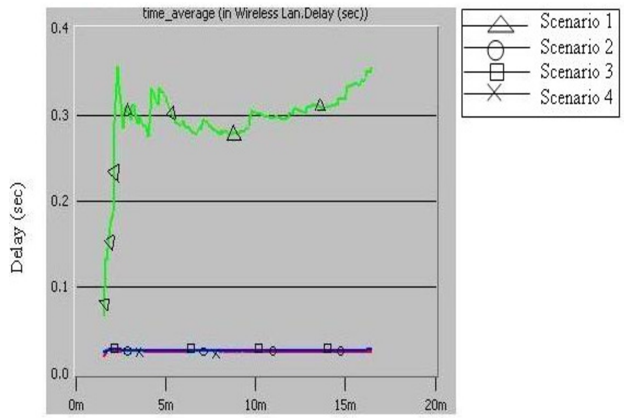

Fig. 8. Delay at AP2 (sec)

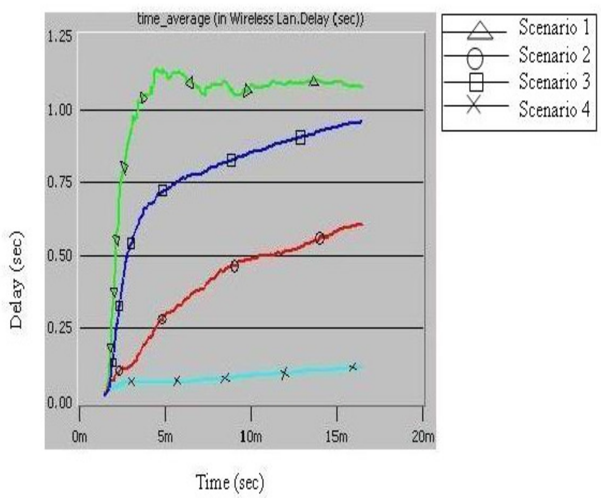

Fig. 9. Delay at AP3 (sec)

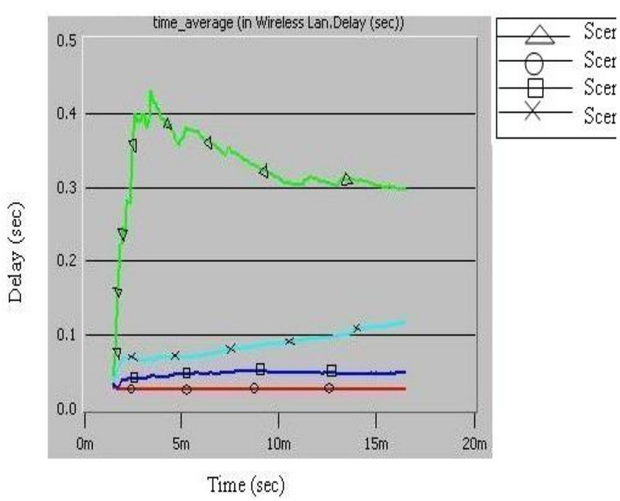

Fig. 10. Delay at AP4 (sec)

It is noticed from the above figures that the one-channel distance scenario has the highest delay on AP2, AP3, and AP4. This is because the MAC transmits a packet and due to the high interference overlap in the channel assignment a collision takes place and the MAC has to defer transmission to another time interval, causing delay (after several collisions on the same packet). However, since AP1 and AP3 share the same channel "1" in scenario 2, the delay at AP1 from scenario 2 exceeds the other scenarios by far, since collisions occur more frequently because the same channel is reused.

As for the other three scenarios, it is determined that the channel assignment based on SIR has less delay at AP1 and AP3 than the other two scenarios. This is because under this user distribution, the channels that lead to the maximum SIR are assigned. However, for AP2, it provides almost the same amount of delay as the other scenarios. Finally, the delay at AP4 is more than the other two algorithms. This can be explained by the fact that AP3 and AP4 have non-overlapping channels in the other competing scenarios: scenario 2 (channel 3 and channel 11 to AP3 and AP4, respectively) and scenario 3 (channel 1 and channel 11 to AP3 and AP4, respectively). Therefore, it is expected to have more delay than the others, whereas, AP3 and AP4 are assigned channels 2 and 1, respectively, in scenario 4 leading to high interference on users.

In summary, the proposed channel assignment algorithm based on maximizing SIR (scenario 4) chooses the assignment of channels that leads to the best throughput on the network as shown in Fig. 6. We recognize that the results of the validation experiments, while promising, cannot be generalized. Our literature review to date suggests that, to be best of our knowledge, there are no other optimization models that perform the same function as we report here in this paper. Accordingly, the numerical validation is the best we can do until results from other optimization models can be found.

7 Conclusions

In this paper, a channel assignment algorithm has been proposed based on maximizing the SIR at the users. The algorithm extends the models presented in [14] and [15], where a channel assignment algorithm based on minimizing interference between neighboring APs was applied to include a channel reassignment at the balanced state by considering the SIR of the users. The algorithm has shown to provide better results compared to previous work where channel assignment was made at an initial stage with no consideration given to users, taking into account only interference between APs rather than SIR at the users. To support our findings recorded in MATLAB, a real-time model was constructed in OPNET. Different channel assignment scenarios were implemented and results have shown the expected improvement in network throughput and delay if our algorithm is to be applied when users enter the network.

The problem discussed in this paper was developed for research development purposes and not for real-time applications, due to numerous existing complications. Model 2 has proven to perform well for small networks. But due to its computational complexity, future work could involve solving the NLIP by linearizing it by optimization solvers. Interested researchers could be guided to a multicriteria optimization formulation after the linearization procedure is executed. This could lead to solving larger size networks efficiently. Upon solving the NLIP on a real time basis, one can include dynamic changes in the user's locations and mobility. In other words, the 7-step algorithm described in Section 3 would include optimizing over all instances when a user leaves or join a network. This would lead toward operational application of the NLIP model in the long run.

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