CHANNEL ALLOCATION SYSTEM FOR WIRELESS VIDEO COMMUNICATION IN 802.11n MESH NETWORKS

by

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ABSTRACT

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With the latest technological achievements, wireless communication is spreading all around the world and entering into the daily life of individuals more. Especially with the development of 802.11n standard, high data rate communication is becoming available, which is beneficial for multimedia applications like real-time video communication. However, increased number of wireless communication users occupy the limited channel spectrum and prevent other users from accessing the channel as they desire. This issue requires proper channel allocation for access points (AP) essential.

This thesis presents a complete solution for an effective channel allocation system in order to minimize the channel usage experienced by the APs. Our objective is to realize video communication for a mesh of access points operating on the same frequency. Therefore, minimizing channel switchings is very important in order not to interrupt the video communication frequently. The main steps of the proposed solution include measurement collection and processing techniques, channel switching decision and determining the optimal channel. Our proposed adaptive measurement processing method using Kalman and Median Filters can estimate channel usages accurately for both high-variance and low-variance data. By using multiple thresholding mechanisms, the proposed channel allocation algorithm not only minimizes the number of interfering APs, but it also strives to avoid unnecessary switching of the operating channel.

ÖZET

KABLOSUZ VİDEO İLETİŞİMİ İÇİN 802.11n ÖRGÜ AĞLARINDA KANAL BELİRLEME MEKANİZMASI

Teknolojinin gelişmesiyle birlikte ve özellikle de 802.11n gibi haberleşme standartlarının yüksek veri hızlarına erişmesiyle kablosuz iletişim, bütün dünyada insanların hayatına daha çok girmeye başlamıiştıir. Yüksek hızlarda veri iletişimi en çok video haberleşmesi gibi çoklu haberleşme uygulamalarında kendisini göstermektedir. Fakat kablosuz haberleşmenin her geçen gün daha fazla kullanıcı tarafından tercih edilmesiyle birlikte kısıtlı kanal kapasitesi bir sorun olarak ortaya çıkmaktadıir. Bu yüzden de erişim noktaları için doğru kanal seçimi daha önemli bir hal almaktadıir.

Bu çalışmada, kullanıcıların maruz kaldıkları kanal doluluğunu en aza indirgemek için baştan sona bir kanal belirleme sistemi önerilmiştir. Burada ana amaç aynı kanalı kullanan ve video iletişimi gerçekleştiren, örgü ağlarındaki erişim noktaları için bir sistem geliştirmektir. Bu yüzden de video iletişiminin kanal değişimiyle sık sık rahatsız edilmemesi çok önemlidir. Ölçümlerin toplanması, işlenmesi, kanal değişim kararının alınması ve geçilecek doğru kanalın belirlenmesi sistemin ana bileşenlerini oluşturmaktadır. Önerilen Kalman ve Median Filtrelerini kullanan uyarlamalı ölçüm işleme tekniği hem düşük hem de yüksek varyanslı ölçümler için iyi bir tahmin sonucu verebilmektedir. Önerilen algoritmaysa gereksiz kanal geçişlerini engellerken yüksek kanal kullanımı yüzünden düzgün çalışamayan erişim noktası sayısını da en aza indirgemeyi hedeflemektedir. Bunu yaparken de kanal değişim kararının alınması ve gerçekleştirilmesi için çeşitli eşik değerleri kullanıır.

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LIST OF SYMBOLS/ABBREVIATIONS

a	Correlation coefficient used in Kalman filtering
a_j	Binary variable stating if AP j is selected
B_j	Maximum bandwidth provided by AP j
b	Scaling factor of Random Channel Allocation method
C	Number of possible channels
$\tilde{C}$	Selected channel
C_i	Ratio of time spent for successful transmissions of one station
C_{rate}	Rate of channel switch for a time period
C_{total}	Ratio of time spent for successful transmissions
c_{kj}	Binary variable stating if channel k is assigned to AP j
D_i	Average traffic demand of point i
G_a	Channel assignment graph
G_{ij}	Channel gain from node i to node j
I	Interference level
I_{av}	Average channel usage value for a time period
I_m	Median filtered interference
$\hat{I}$	Interference estimation
k	Kalman gain
n	Number of stations in the medium
N	Measurement window size
N_{AP}	Number of detected APs
$N_{AP_{av}}$	Average number of APs in the medium for a time period
N_a	Number of candidate AP points
N_d	Number of clients
N_{succ}	Total number of slots needed for a successful transmisison
N_{total}	Total number of slots in the time period of interest
P	Error variance in Kalman filtering
$\hat{P}$	Error variance estimation in Kalman filtering
P_{ext_int}	Power representation of the potential interference

P_i	Transmission power of station i
P_{int_bound}	Assigned power for a station
P_{max_int}	Maximum possible transmission power level
P_{req}	Number of packets a station needs to transmit
P_{sent}	Number of packets a station can send
P_{sum_int}	Power representation of sum of all interferences
$P_{thermal}$	Power noise
p_{coll}	Probability that a collision occurs
p_{idle}	Probability that no station transmits a packet in a slot
p_s	Probability that a transmission seizes the channel
p_{succ}	Probability that only one station transmits a packet in a slot
p_{tr}	Probability that at least one station transmits in a slot
Q	Channel quality scala
S	Signal value
$\hat{S}$	Signal Prediction
T_{coll}	Duration spent on a collision
T_{high}	Channel usage threshold to start channel switching algorithm
T_{hys}	Hysteresis threshold for the current and candidate channels
T_{idle}	Duration of an idle slot
T_p	Throughput
T_{succ}	Duration of a successful transmission
v	Measurement noise of Kalman filtering system
$\bar{v}$	Mean of the measurement noise v
W	Noise driving sequence / Process noise for Kalman filter
$\bar{W}$	Mean of the process noise W
X	Signal measurement
x_{ij}	The binary variable stating if client i is assigned to AP j
Z	Interference measurement
$\bar{Z}$	Mean of the interference measurements
α	Smoothing factor of EMA

β	Scaling Factor of the cost function
γ	Scaling coefficient of STLT algorithm
ζ	Factor between process variance and measurement variance
η	Load factor of the power control scheme
ξ	Maximum traffic load assigned to APs
σ_v^2	Variance of the measurement noise v
σ_W^2	Variance of the process noise W
τ	Probability that a station transmits a packet in a slot
ψ	Unit Step Function shifted for T_{high} units

ACK	Acknowledgement
AP	Access Point
BPSK	Binary Phase Shift Keying
BS	Base Station
CCA	Clear Channel Assessment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Spacing
EMA	Exponential Moving Average
HCA	Hybrid Channel Allocation Algorithm
HDTV	High Definition Television
IEEE	Institute of Electrical and Electronics Engineering
IP	Internet Protocol
IPTV	Internet Protocol Television
ISI	Inter Symbol Interference
LAN	Local Area Network
MAC	Medium Access Control
MAN	Metropolitan Area Network
MIMO	Multiple Input Multiple Output
MWM	Maximum Weight Minimization Algorithm

OFDM	Orthogonal Frequency Division Multiplexing
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RSSI	Received Signal Strength Indicator
SGI	Short Guard Interval
SINR	Signal to Interference plus Noise Ratio
STBC	Space Time Block Coding
STLT	Short Term - Long Term Algorithm
TWM	Total Weight Minimization Algorithm
WLAN	Wireless Local Area Network

1. INTRODUCTION

With the latest technological achievements, communication between people and access to information have become easier. In addition to the classical wired media, communicating via wireless media has become quite popular. In particular, the use of Wireless Local Area Networks (WLAN) has been increasing immensely especially in urban environments.

Considering the internet usage, as more people are sharing the same wireless medium, interference amongst the Access Points (AP) has started to grow due to the limited frequency spectrum. Interference results in a degradation in network performance by reducing capacity. Increased number of users also makes the channel busier and makes it harder for other stations to reach the medium. High channel usage increases the delay and packet losses, which decreases the throughput. As a result, minimizing the interference between APs and the exposed channel usage are becoming more important. There are several possible solutions for this problem [1]:

- Effective AP placement
- Transmission power control
- Intelligent channel allocation

Effective AP placement and transmission power control methods are not applicable for home users in urban environments, because they are quite restrictive. Therefore, intelligent channel allocation turns out to be the most suitable solution in order to minimize interference and hence avoid busy channels.

802.11n WLAN standard operates mainly in the 5 GHz band and due to the improvements such as MIMO technology, optional 40 MHz channels and the block acknowledgement support, it offers much higher throughput for the end users compared to existing 802.11b/g/a standards [2]. Today, although most of the users operate in the 2.4 GHz band, the number of the users in the 5 GHz band using 802.11n standard will increase in the near future. This situation will result in increased interference and channel usage. Compared to the 2.4 GHz band, the 5GHz band offers more possible channels on which APs can operate. For this reason, resolving the channel selection problem in the 5 GHz band has great importance.

Demands of the users also change with the technological improvements and higher speeds are required especially for real-time video transmission applications. Therefore, the frequency planning system should consider real-time video communication with quick-response and seamless channel switching.

For example, IPTV is considered to be a developing application for home entertainment by providing QoS, value, service differentiation and convenience [3]. 802.11n standard is one of the possible solutions for IPTV with its raw data rate of up to 540 / 600 Mbps. For in-home IPTV distribution, usage of mesh networks is a possible option. Wireless mesh networks can eliminate wires and can reach all points inside houses and large offices.

In this thesis, intelligent frequency assignment for home mesh networks is our main objective, where all nodes in the network operate on the same frequency and where there may be multiple clients which are making video communication on the mesh. In order to realize this aim, there are several steps to be considered:

- Decision of taking measurements on various channels
- Processing these measurements.
- Decision of sharing these processed measurements.
- Decision of channel switching.
- Choosing the optimal channel.
- Changing the channel in a coordinated fashion.

In the following section, related work on channel allocation algorithms and channel switching mechanisms in the literature are presented.

1.1. Related Work on Channel Allocation and Switching

There is a vast amount of literature on the channel selection problem and many techniques have been studied. There are two main categories of algorithms, namely centralized and distributed.

1.1.1. Centralized Channel Assignment

In centralized techniques, a central unit decides on the operating channel of each wireless unit, using the information collected from all APs and/or clients.

In some centralized techniques [4], [5], the frequency assignment problem is handled jointly with the AP placement problem by a central processor. After forming the objective function, APs are placed and frequencies are selected for either maximizing the objective function [4], or minimizing the fitness function [5]. However, fixing the places of the APs is neither suitable nor applicable in urban home environments.

Graph coloring is another widely used centralized channel allocation mechanism. A central unit assigns channels to all of the stations one by one, in order to maximize the channel distance of the stations to each other. Channel re-use is maximized in this method [6]. However, the central unit can only assign channels to the stations in its own command and has to ignore the outer interference and channel usage.

A client-driven approach is proposed in [7]. Measurement information is received from both clients and APs in order to realize the channel assignment that minimizes the conflicts in the system, which is a version of coloring method. The method tries to solve the frequency assignment problem along with the load balancing problem which aims to minimize intra-AP load by organizing the associations of clients with the APs. Including the measurement or data from the clients to the decision making process can give better results. However, a major drawback of these types of algorithms is the binary interference model, which does not take the load of outer traffic into account, but only counts the interfering stations.

1.1.2. Distributed Channel Assignment

In distributed techniques, each AP decides on the operating frequency independently [1]. Some of the distributed algorithms are communication free where each AP makes its decision independent of its neighboring APs. There are also some distributed algorithms with communication, where APs share their interference, channel usage or throughput measurements. Then, each AP chooses its optimum channel based on this information.

The basic mechanism for an AP in distributed, communication-free algorithms is estimating the throughput for each possible channel, and subsequently selecting the channel with the highest throughput [1], or the channel with the least interference [8]. There are also algorithms, such as the Hminmax algorithm presented in [9], where each AP forms an objective function and tries to choose the most suitable channel accordingly. Channel assignment through objective functions is a clever idea. However, in varying channel conditions, these techniques result in frequent channel switches, which is undesirable for video communication, therefore additional precautions are required.

In [10], a communication-free algorithm is presented. This is a probabilistic approach, where channels are being selected randomly, decreasing the probability of unsuccessful channels (i.e., target throughput or packet error rate is not achieved) and sticking to the successful channels for each AP based on trials. Since our intended application is video communication, this method of trying each channel with certain probabilities until finding a suitable one will not be an effective solution in our case.

In distributed algorithms with communication, each AP decides on its operating frequency based on, not only the information it collects locally, but also the information it gathers from the other APs. The Hsum algorithm in [9] makes its frequency decision based on the channel conflict information of its neighbors. As another example, an AP using Local-Coord Algorithm in [8] decides on its operating frequency on the basis of the interference information for a channel received from the neighboring APs, which are using the same frequency channel. Although using the information of neighbors increases the effectiveness, the same issue of frequent channel switching in high-variance channel conditions is also valid here.

In [11], the channel assignment problem is solved in order to increase the fairness of the system at the same time. To this end, channel hopping method is used. Each AP determines a channel hopping sequence, which is the least conflicting sequence with its neighbors, and changes its operating frequency with intervals of few seconds. Channel hopping will not be suitable for our system of video communication, since all of the mesh nodes are required to operate on the same frequency. Therefore, channel hopping will decrease the throughput of the system.

A cellular neuron networks model is applied for frequency assignment in [12]. Each AP determines the best channel it should use in the next time slot on the basis of the traffic load and channel usage information gathered from its neighbors. The system converges to an equilibrium state in a short time. Changing the channel used is also realized with a certain probability. However, in our system, instead of iterations, the optimal channel should be determined and chosen in one step not to lose too much time to change channel during video transmission.

Channel allocation techniques of mesh networks in the literature are mainly focused on mesh networks of multi-radio wireless nodes [13], [14]. Multi-radio nodes can operate on more than one channel with different nodes at the same time. However, the cost of multi-radio network elements is high. Therefore, a channel allocation scheme for mesh stations, that are all operating on the same channel, should also be designed.

1.1.3. Channel Switching

Frequent channel switching brings a cost of packet losses during video communication. Therefore, there is a trade-off between channel switching and throughput. To address this problem of frequent and unnecessary channel switching, it is useful to investigate related work in cellular communication systems.

In cellular systems, users change their base stations (BS) while the service continues to operate. This procedure is called the handoff between BSs. One of the possible solutions of handoff is switching to the BS with strongest received signal power level. However unnecessary handoffs can be observed with an uncontrolled mechanism [15]. In [16], an algorithm based on hysteresis levels is used to control and prevent unnecessary channel handoffs to increase the performance. After this work is developed, BS switching is realized only when the current BS's signal power is lower than a certain threshold and the signal power difference between the current BS and candidate BS is over a hysteresis level [17].

There are hard handoff techniques [15], [16], [17] where there can only be one associated BS at a time. There are also soft handoff techniques [18], [19], [20] where a candidate set of BSs are chosen and communication can be realized with more than one BSs at the same time.

Just as mobile terminals can change their associated BSs, APs may require to change the frequency channel they operate on. For BSs, criteria like signal power or SINR can be included in the decision mechanism, where for channel switching interference, channel usage or throughput can be the thresholding criteria. As in BS switching mechanism, channel switching can be realized when current measurement passes a certain threshold and the difference between the current and candidate channels is over a hysteresis level.

1.2. Motivation & Outline of the Thesis

This thesis addresses the problem of channel assignment for IEEE 802.11n networks in order to realize seamless video communication for home environment applications. While there is a vast amount of related work discussed as above, there are several novelties introduced in this thesis. Channel allocation is not taken as a single step, but the complete channel allocation system is designed. This system is specialized for video communication, where packet losses and delay are critical parameters. Another important contribution is the design of channel allocation system for single-radio mesh networks where all the elements of the mesh operate on the same frequency channel.

The organization of the rest of the thesis is as follows: Chapter 2 explains the improvements of 802.11n standard, its benefits on video communication and information about mesh networks. The proposed measurement taking and processing techniques are described in Chapter 3. The mechanism that decides on channel switching and the algorithm that chooses the optimal channel are discussed in Chapter 4. Finally, Chapter 5 concludes the thesis.

2. 802.11n PROTOCOL STRUCTURE

802.11 is a set of standards developed by IEEE LAN/MAN Standards Committee (IEEE 802) for WLAN communication. 802.11a, 802.11b and 802.11g standards are the most common and widely used protocols. However as needs and demands of people have increased, more advanced systems with higher speed and reliability are required. 802.11n standard has been developed to satisfy these requirements.

2.1. Improvements of 802.11n

802.11n protocol is being standardized with many advantages and enhancements compared to its predecessors. First of all, 802.11b/g systems operate on the 2.4GHz band and 802.11a system operates on the 5GHz band [21]. The 802.11n protocol combines these two bands and is able to operate on both bands, increasing the number of available channels. There are 11 or 13 channels in the 2.4GHz band, but only 3 of these channels do not overlap, which can be seen in Figure 2.1. On the other hand, the 5GHz band provides 12 to 20 channels which are all non-overlapping as shown in Figure 2.2, which provides more channel options to choose from. Moreover, in the 5 GHz band, channels are divided into 52 subcarriers and bits are distributed over these subcarriers to create a symbol, which is called an OFDM symbol, as shown in Figure 2.3.

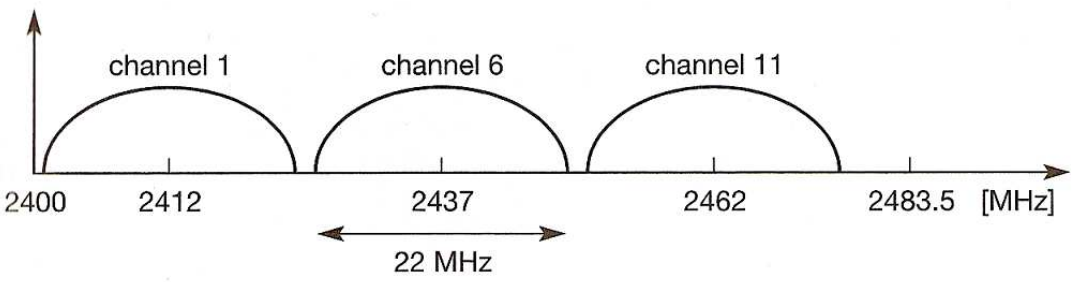

Figure 2.1. Non-overlapping channels (1,6 and 11) in 2.4 GHz band used by 802.11b/g/n [21].

The protocol also provides users with improved bandwidth by applying channel

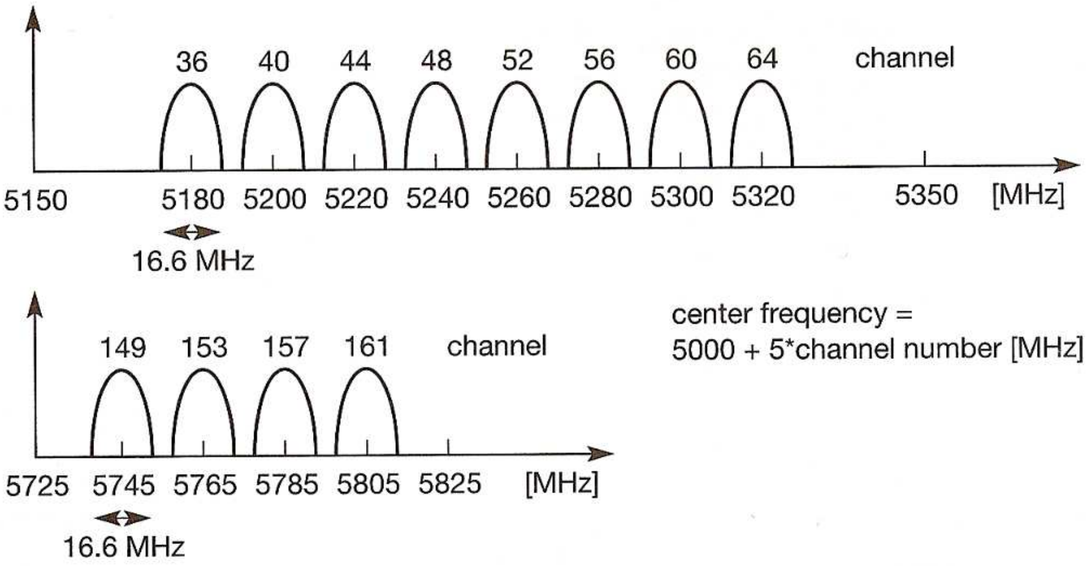

Figure 2.2. Non-overlapping channels in 5 GHz band used by 802.11a/n [21].

bonding property [22]. Other systems are limited by the use of a single channel which provides a 20 MHz bandwidth. The 802.11n protocol can combine two adjacent 20MHz channels into one 40MHz channel, which, in turn, enlarges the bandwidth to provide higher data rates. Since the 5 GHz band contains many non-overlapping channels, channel bonding can be applied with higher performance in the 5 GHz band.

Another major contribution of the 802.11n protocol is the introduction of Multiple Input Multiple Output (MIMO) technology, which is realized by the use of multiple antennas [23]. Instead of a single data stream transmitting from a single antenna, two or more data streams can be transmitted from two or more antennas. This technology, which results in an important increase in data rate, is called spatial multiplexing.

MIMO technology can also increase the reliability of the system with the space-time block coding (STBC) scheme [2]. Here, multiple antennas add diversity to the system by sending the same data in multiple streams with special coding systems. In the receiver side, multiple receiver antennas decode these special coded streams, therefore a redundancy is created and the system becomes more reliable.

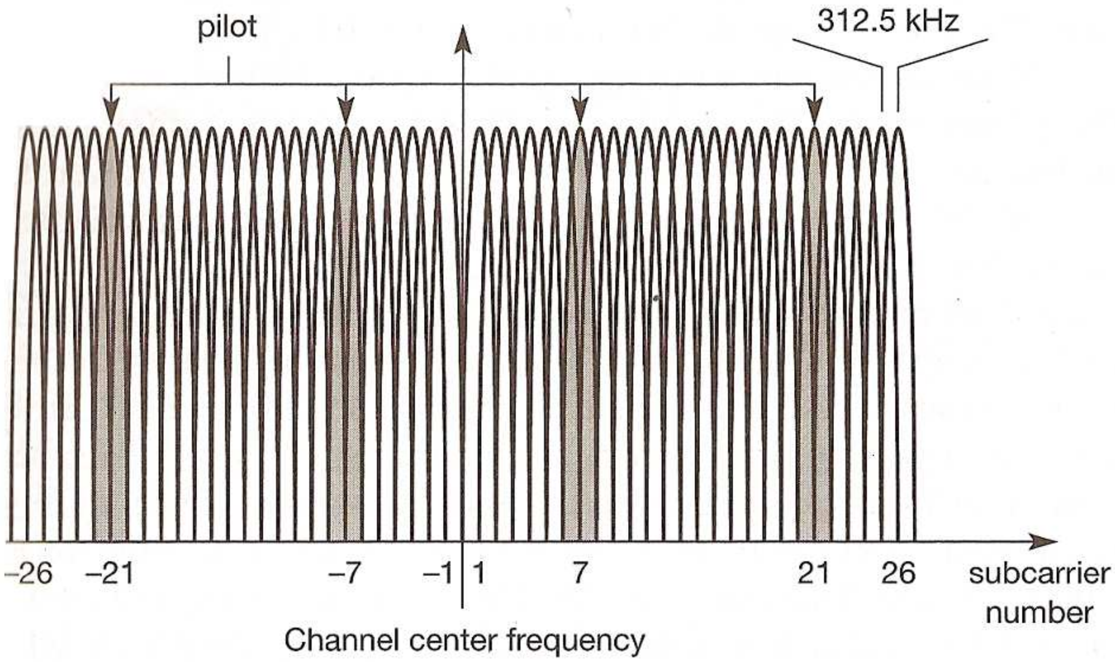

Figure 2.3. Usage of OFDM in one of the channels with subcarriers in 5GHz band [21].

With additional antennas, modulation and coding schemes, 802.11n systems can operate on several modes (16 modes for 2 antennas) [24]. In Table 2.1, these antenna usages, modulation and coding schemes and the corresponding data rates can be seen. With four antennas, these data rates will be doubled enabling 600 Mbps raw data rate. This is a huge improvement compared to 54 Mbps raw data rate provided by 802.11g systems.

Short Guard Interval (SGI) is an optional structure in 802.11n standard [24]. Guard intervals are the time gaps between transmitted symbols, that are necessary to prevent Inter Symbol Interference (ISI). Halving the 800ns guard interval to 400ns with the SGI option can be used, which leads to an increase in interference, while reducing the unused idle time. In appropriate environments, use of SGI can increase the system data rate.

Packet aggregation is another improvement of 802.11n protocol [23]. This technology allows the aggregation of multiple data packets into single frame with fixed

Table 2.1. Modulation and Coding Scheme Table [24]

MCS Index	Type	Coding Rate	Spatial Streams	Data Rate (Mbps) with 20 MHz CH		Data Rate (Mbps) with 40 MHz CH	
				800 ns	400 ns (SGI)	800 ns	400 ns (SGI)
0	BPSK	1 / 2	1	6.50	7.20	13.50	15.00
1	QPSK	1 / 2	1	13.00	14.40	27.00	30.00
2	QPSK	3 / 4	1	19.50	21.70	40.50	45.00
3	16-QAM	1 / 2	1	26.00	28.90	54.00	60.00
4	16-QAM	3 / 4	1	39.00	43.30	81.00	90.00
5	64-QAM	2 / 3	1	52.00	57.80	108.00	120.00
6	64-QAM	3 / 4	1	58.50	65.00	121.50	135.00
7	64-QAM	5 / 6	1	65.00	72.20	135.00	150.00
8	BPSK	1 / 2	2	13.00	14.40	27.00	30.00
9	QPSK	1 / 2	2	26.00	28.90	54.00	60.00
10	QPSK	3 / 4	2	39.00	43.30	81.00	90.00
11	16-QAM	1 / 2	2	52.00	57.80	108.00	120.00
12	16-QAM	3 / 4	2	78.00	86.70	162.00	180.00
13	64-QAM	2 / 3	2	104.00	115.60	216.00	240.00
14	64-QAM	3 / 4	2	117.00	130.00	243.00	270.00
15	64-QAM	5 / 6	2	130.00	144.40	270.00	300.00
16	BPSK	1 / 2	3	19.50	21.70	40.50	45.00
...	...	...	...	...	...	...	...
31	64-QAM	5 / 6	4	260.00	288.90	540.00	600.00

overhead. Therefore overhead cost is reduced and efficiency is increased.

With the same logic and purpose, some form of block acknowledgements (ACK) called frame bursting is also adapted in this standard [23]. One ACK for each packet is sent in 802.11g and 802.11a standards. Block ACK option in 802.11n standard sends one ACK for more than one data packets. By removing the need for one acknowledgment frame for every data frame, the amount of overhead required for the ACK frames, as well as preamble and framing, is hence reduced.

2.2. Video Communication and 802.11n

With the improvements of 802.11n protocol mentioned above, more reliable communication with higher throughput becomes possible. Clearly, applications that require reliability and throughput will benefit from the 802.11n protocol. Video communication is one such application that requires reliability, high quality and throughput. The data rates sent on wireless links are limited and are not reliable with the existing WLAN protocols. Therefore, with additional antennas, increased number of available channels and greater bandwidth, 802.11n protocol provides users with a better solution for video communication.

An example application of video communication that can benefit from 802.11n is IPTV [3]. IPTV enables digital television service through the internet network using IP protocol. When this IPTV traffic arrives the home gateway, it should be distributed to multiple televisions in the house. Data communication from internet should also be not affected.

Distributing the IPTV through wireless mesh networks can be considered a preferable solution by eliminating the wires [3]. Wireless mesh networks consist of a bunch of wireless APs communicating with each other as shown in Figure 2.4. There can be a centralized station that controls the medium access, or alternatively random-access mechanisms may also be used. The mesh structure is a reliable, error resilient and easily installed one. Considering wireless mesh network solutions, 802.11n might be a suitable option, which can realize video and data communication with a high performance.

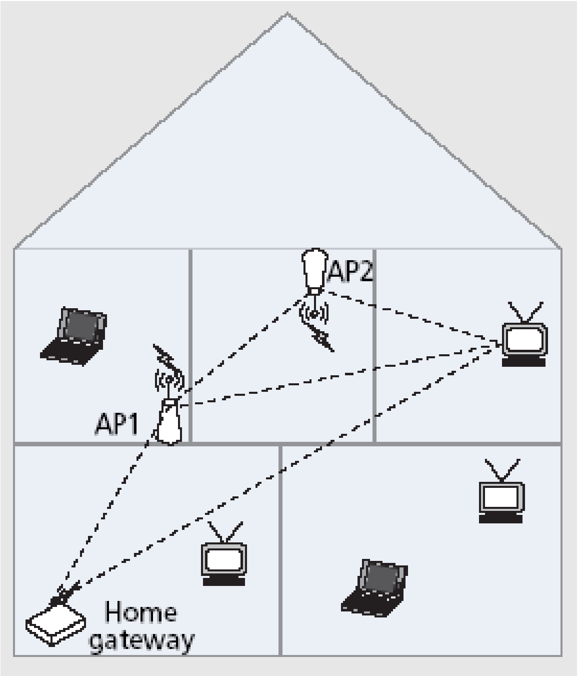

Figure 2.4. Home mesh network architecture [3].

3. MEASUREMENT PROCESSING

The channel allocation system consists of several steps as discussed in Chapter 1. This channel decision mechanism can be summarized by the flow chart shown in Figure 3.1.

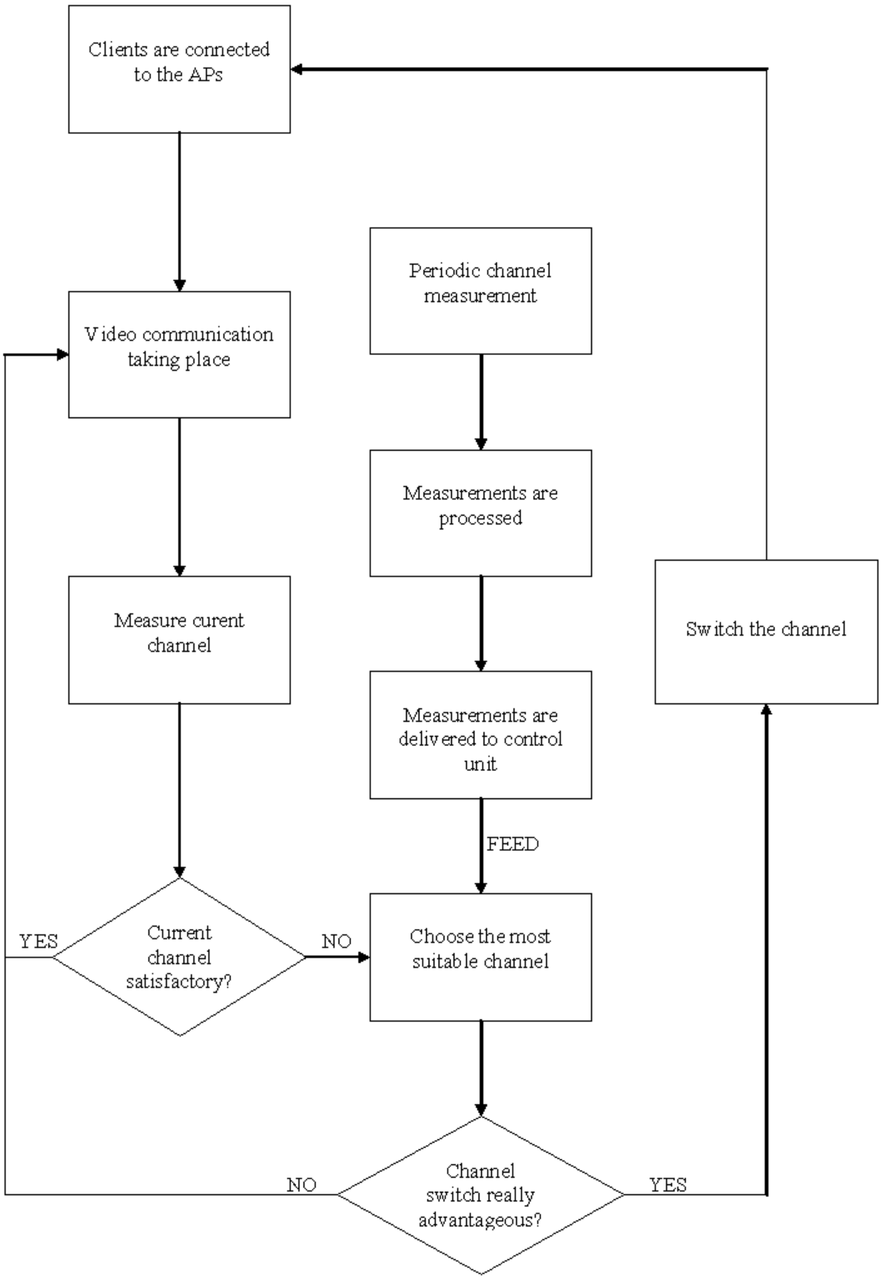

Figure 3.1. Flow chart of the channel allocation mechanism.

The first two steps of this mechanism are collecting the necessary measurements and processing them to get information about the potential channels to be switched to. Although some of the related studies in the literature solve the channel allocation problem without taking any measurements, the solution for continuous video transmission applications should be quick, effective and non-iterative, which forces us to build our channel allocation system based on channel measurements.

3.1. Collecting the Measurements

There are many possible measurement parameters that can be utilized in our proposed framework, such as, received signal strength indication (RSSI), transmission power, path loss, number of APs, data rate, throughput, etc. Since our main objective is to minimize the interference and channel usage, building the system on these measurements can be a preferable solution. We take the measurements by means of channel usage ratio value and refer to them as CCA (clear channel assessment). These measurements are taken by polling each candidate channel periodically and staying there for a short time to get the necessary information about channel usage without disturbing the video communication. These measurements are quantized and scaled to get a final channel information between 0 and 255.

After taking the measurement of a specific channel, along with past measurements of the channel, they are processed, smoothed and a final channel usage score for the channel is obtained.

3.2. Processing Methods

Filtering and smoothing the measurements to predict the channel usage level in the channels and to react accordingly are important in proper channel allocation. In order to have a better performance, the system should adapt itself to changes and should not be affected from the erroneous measurements and short term changes. We first investigate the existing filtering methods in the literature.

3.2.1. Mean Time Window

One of the simple smoothing mechanisms is based on averaging measurements [25]. The last N measurements of a specific channel are kept in the memory and the mean of the measurements is interpreted as the prediction of the measurement in the future, i.e.,

$$I(n) = \sum_{i=1}^{N} Z(n-i) \tag{3.1}$$

where I(n) is the prediction and Z(n)'s are the measurements.

Although this method is a simple one, it does not take the tendency of the measurements into account. Moreover, the erroneous measurements affect the results for a longer time. A smaller time window results in a quicker adaptation to changes, but is affected by the errors more seriously for a short period of time. A larger window, on the other hand, cannot adapt to changes quickly, however it is not affected from the instantaneous errors that seriously.

3.2.2. Exponential Moving Average (EMA)

Exponential Moving Average (EMA) is another method used for smoothing [25]. Here, past measurements are weighted with exponentially decreasing coefficients. Therefore, recent measurements are given higher importance without totally ignoring old measurements, i.e.,

$$I(n) = \alpha Z(n-1) + (1-\alpha) I(n-1) \tag{3.2}$$

The variable α in the above equation determines the weight of the new measurements. Small α values give past measurements more importance, whereas high α values give more importance to recent measurements.

3.2.3. Median Filter

Median filter, which is mainly used for signal processing, is a simple but effective filtering mechanism that helps the elimination of errors. Basically, it takes the middle value for a sequence of values in a predetermined length of window [26]. As a result, extraordinary high or low values are eliminated from the data sequence. We can formulate the median filtering for 2k+1 window size as

$$I_m(n) = median[I(n-k), ..., I(n-1), I(n), I(n+1), ..., I(n+k)] \tag{3.3}$$

In our case, median filtering can help us eliminate short noise errors. On the other hand, using median filters delays the reaction time of the system to changes.

3.2.4. Kalman Filter

Kalman Filters are easy to implement recursive filters that can give good estimates for noisy measurements.

3.2.4.1. Kalman Filter Equations. In [27], an explanatory Kalman Filter derivation is presented, that will be used here as well. Kalman Filters assume that the signal is a zero-mean Gaussian sequence of the form

$$S(n) = a(n)S(n-1) + W(n) \tag{3.4}$$

Here, $S(n)$ is the signal sequence, $a(n)$ is a constant series and $W(n)$ is zero-mean, additive, white, Gaussian noise, which can be called “noise driving sequence” or “process noise”.

The observations $X(n)$ are assumed to be corrupted with noise $v(n)$, which is also zero-mean, additive, white Gaussian noise independent from $W(n)$ and $S(n)$. $v(n)$ is called the “measurement noise” of the system. The observations can be formulated as

$$X(n) = S(n) + v(n) \tag{3.5}$$

where the variances of process noise $W(n)$ and measurement noise $v(n)$ are assumed to be known and equal to σ_W^2 and σ_v^2, respectively. Based on these two assumptions, the Kalman Filter equations can be summarized as follows:

$$\hat{S}(n+1) = a(n+1)[\hat{S}(n) + k(n)(X(n) - \hat{S}(n))] \tag{3.6}$$

$$k(n) = P(n)/[P(n) + \sigma_v^2(n)] \tag{3.7}$$

$$\hat{P}(n+1) = a^2(n+1)[1 - k(n)]P(n) + \sigma_W^2(n+1) \tag{3.8}$$

The 5 equations from (3.4) to (3.8) provide the estimation of the signal, which is denoted as $\hat{S}(n)$. $k(n)$ is the Kalman gain, $P(n)$ is the error variance and $\hat{P}(n)$ is the estimate of the error variance.

In our channel usage estimation case, we can use the above equations by replacing $I(n)$ with $S(n)$ to denote the channel usage value and by replacing $X(n)$ with $Z(n)$ to denote channel usage measurements. Additionally, we can neglect the factor $a(n)$ in (3.4), since the mean of the possible channel usage values does not change. In summary, the 3 equations for the estimation are formed as

$$\hat{I}(n+1) = \hat{I}(n) + k(n)[Z(n) - \hat{I}(n)] \tag{3.9}$$

$$k(n) = P(n)/[P(n) + \sigma_v^2(n)] \tag{3.10}$$

$$\hat{P}(n+1) = [1-k(n)]P(n) + \sigma_W^2(n+1) \tag{3.11}$$

Here, the important problem that remains is estimating σ_W^2 and σ_v^2 based on the measurements $Z(n)$. Our system should be adaptive, because measurements change in time and variance of these changes and measurement errors are not fixed, either. These variances are going to be handled in the upcoming sections.

3.2.4.2. Determination of Filter Parameters. The Kalman filter assumes the process noise and measurement noise variances to be known. However, in our application neither of them is unknown, moreover they change in time. Therefore an adaptive estimation of these parameters should be realized. An adaptive system is presented in [28] however, estimations of filter variances are not presented.

Since we only have measurements, the real channel usage levels and measurement noise are not present. The process noise is also unknown, since the real sequence of channel usage levels is unknown. However, we can assume zero-mean Gaussian process noise.

To estimate the measurement noise, somehow we have to estimate real channel usage sequence. Here, median filtering can work, because the main function of the median filter is the elimination of step errors. [29] gives an example usage of Median Filter together with Kalman Filter, but once again parameter derivations are missing in [29].

In the following, we develop an approach for estimating these variances. After the median filtering, the difference of the sequence between the input and the output of the median filter can be interpreted as the measurement error sequence. $v(n)$, the measurement error sequence becomes

$$v(n) = I_m(n) - I(n) \tag{3.12}$$

where, assuming the window length of the median filter to be equal to 3, the median filter output which is denoted as $I_m(n)$ becomes

$$I_m(n) = median[Z(n-1), Z(n), Z(n+1)] \tag{3.13}$$

Taking the variance of the measurement error sequence $v(n)$ provides an estimate for σ_v^2 that we can use in Kalman equations. Below, past N measurements are assumed to be used for the variance calculations:

$$\bar{v}(n) = \frac{1}{N} \sum_{i=0}^{N-1} v(n-i) \tag{3.14}$$

$$\sigma_v^2 = \frac{1}{N-1} \sum_{i=0}^{N-1} [v(n) - \bar{v}(n)]^2 \tag{3.15}$$

Since we assume that we eliminate the errors with median filtering, the output can be interpreted as the original channel usage sequence $I(n)$. Therefore, the process noise W(N) can be extracted from $I_m(n)$ as

$$W(n) = I_m(n) - I_m(n-1) \tag{3.16}$$

Then, taking the variance of the process noise sequence $W(n)$ gives σ_W^2 that we can use in Kalman equations, i.e.,

$$\bar{W}(n) = \frac{1}{N} \sum_{i=0}^{N-1} W(n-i) \tag{3.17}$$

$$\sigma_W^2 = \frac{1}{N-1} \sum_{i=0}^{N-1} [W(n) - \bar{W}(n)]^2 \tag{3.18}$$

However, an alternate estimation method for the process and measurement noise variances is needed for situations where Median Filtering is not preferred. For such cases, [30] proposes to estimate the process noise directly from the measurements as

$$\bar{Z}(n) = \frac{1}{N} \sum_{i=0}^{N-1} Z(n-i) \tag{3.19}$$

$$\sigma_W^2 = \frac{1}{N-1} \sum_{i=0}^{N-1} [Z(n) - \bar{Z}(n)]^2 \tag{3.20}$$

The variance of past N measurements $X(n)$ is considered as σ_W^2. Because, variance of measurements $X(n)$ is the variance of real channel usage level $I(n)$ plus measurement noise $v(n)$

$$var[Z(n)] = var[I(n) + v(n)] \tag{3.21}$$

Since $I(n)$ and $v(n)$ are independent, Equation (3.21) results in

$$var[Z(n)] = var[I(n)] + var[v(n)] \tag{3.22}$$

Here, the variance of $v(n)$ is assumed to be negligible compared to the variance of $I(n)$. Therefore, the variance of the measurements $X(n)$ can be taken to be equal to the variance of the actual channel usage levels σ_W^2.

The authors of [30] provides additional insights on σ_v^2. Although it is stated in [30] that basically Q(n) and R(n) are independent of each other, R(n) is estimated as

$$\sigma_v^2 = \zeta \sigma_W^2 \tag{3.23}$$

This assumption is reasoned on the fact that σ_W^2 also includes the variance of measurement noise. Although it is a weak assumption, it can be tested with real measurements and used in Kalman Filter estimations.

3.3. Numerical Evaluation of Filtering Mechanisms

A comparison of the filtering mechanisms for channel usage measurements using real and controlled data can be useful to decide which mechanisms to be used. In this section, mean time windowing, EMA and Kalman filtering methods are compared and Median Filter is used in Kalman Filter parameter estimation.

Real measurements taken with Broadcom 4323 wireless driver with 802.11n support are used in our comparison simulations. We create a controlled channel usage level and apply various filtering mechanisms to see which one is more suitable for our measurements.

First, a steady channel usage value is generated, occupying a specific ratio of the channel, which creates a CCA value of about 165. After measuring 1000 samples of this channel usage level, we observe the measurement scheme seen in Figure 3.2. The estimation errors of the methods are shown in Figure 3.3, where the x-axis for time window method is the averaging window size; for Kalman Filter, it is the window size of variance estimation; and for EMA, it is the α value varied from 0 to 1.

As can be observed from the graph, time window gives the least successful prediction, because it is affected from erroneous measurements the most. EMA and Kalman give somewhat stable results, because the measurements are stable and the filters are designed to prevent from the effects of step errors. The effect of the median filter, which eliminates the unit step errors can be observed here in Figure 3.4, which is a closer look to a segment of Figure 3.2.

Subsequently, we apply these filtering methods on measurements of varying CCA levels between 6 (minimum measured value) and 241 (maximum measured value) shown in Figure 3.5. Once again, the x-axis for time window method is the averaging window

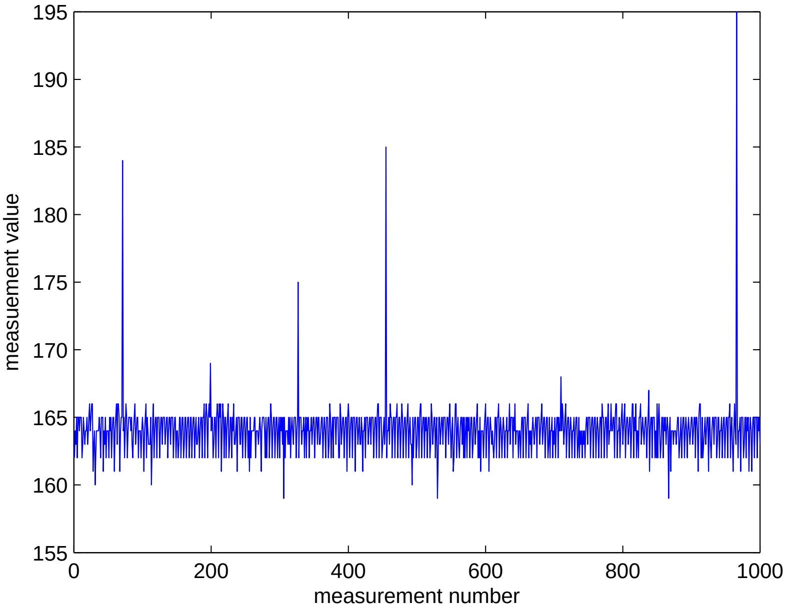

Figure 3.2. Measurement sequence of a controlled stable, low-variance CCA value

size; for Kalman Filter, it is the window size of variance estimation; and for EMA, it is the α value varied from 0 to 1.

The graph in Figure 3.6 provides similar results, however moving average filter can give better estimation results for some α values this time. The reason is that, estimates obtained with Median Filtered measurements react one step later to changes. This situation can be observed in Figure 3.7 which shows a segment of the measurements in Figure 3.5 with median filter outputs. While still eliminating errors, late reaction to changes occurs.

In conclusion, we will choose either the Exponential Moving Average or Kalman Filtering to estimate and smooth the measurements. But first, it is useful to investigate the advantages and disadvantages of Median Filtering in high variance and low variance measurements. As described before, Median Filtering eliminates unit-step errors or temporary increases in the measurements. On the other hand, Median Filtering creates a delay for the system to adapt changes. Therefore, it is expected that for highly varying channel usage levels, Median Filtering is a disadvantage, while for stable channel usage levels Median Filtering improves the performance of the system. Performances of

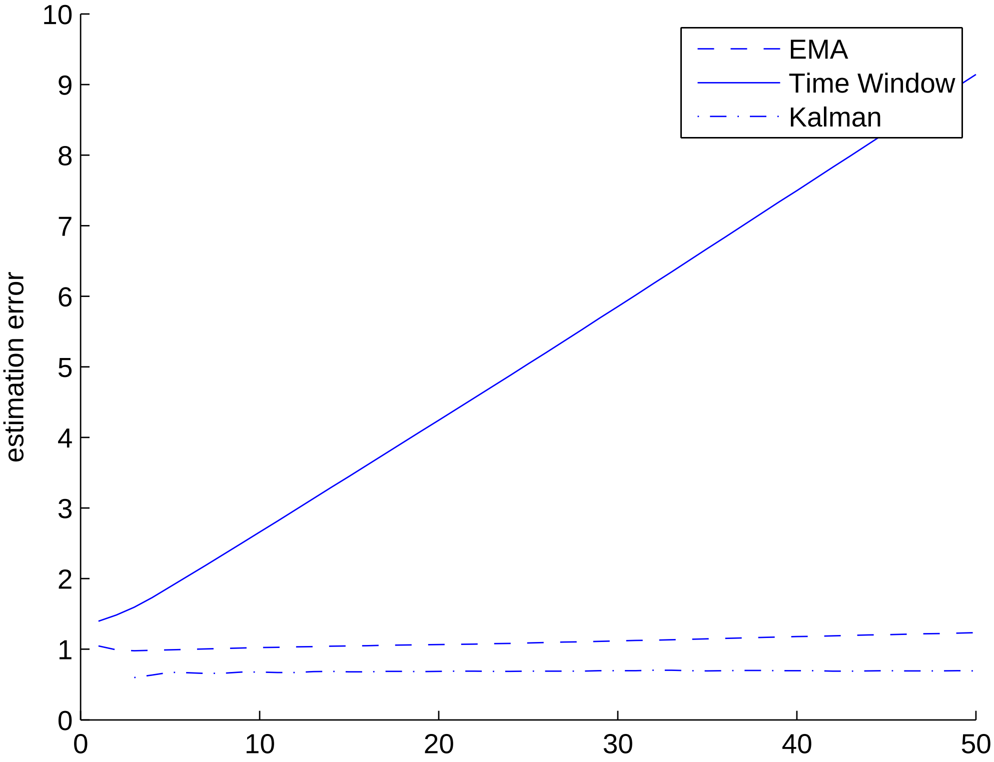

Figure 3.3. Estimation error of estimation algorithms for a low variance data. Results of Averaging Window, EMA and Kalman Filter are shown in the graph.

Kalman Filter with and without Median Filter along with EMA are shown in Figures 3.8 and 3.9 for stable and varying channel usage levels respectively. Again the x-axis for Kalman is the window size of variance estimation; and for EMA, it is the α value varied from 0 to 1.

While the noise variance is being estimated, the technique developed above in equations from (3.12) to (3.18) is used for Kalman Filtering with Median Filtering. For Kalman Filtering without Median Filtering, the parameter estimation method described in [30] is used. ζ value, which is the ratio between measurement noise variance and process noise variance is chosen a small value like 0.1 for high variance data and chosen a greater one like 0.9 for low variance data, to achieve the highest performance from Kalman filtering.

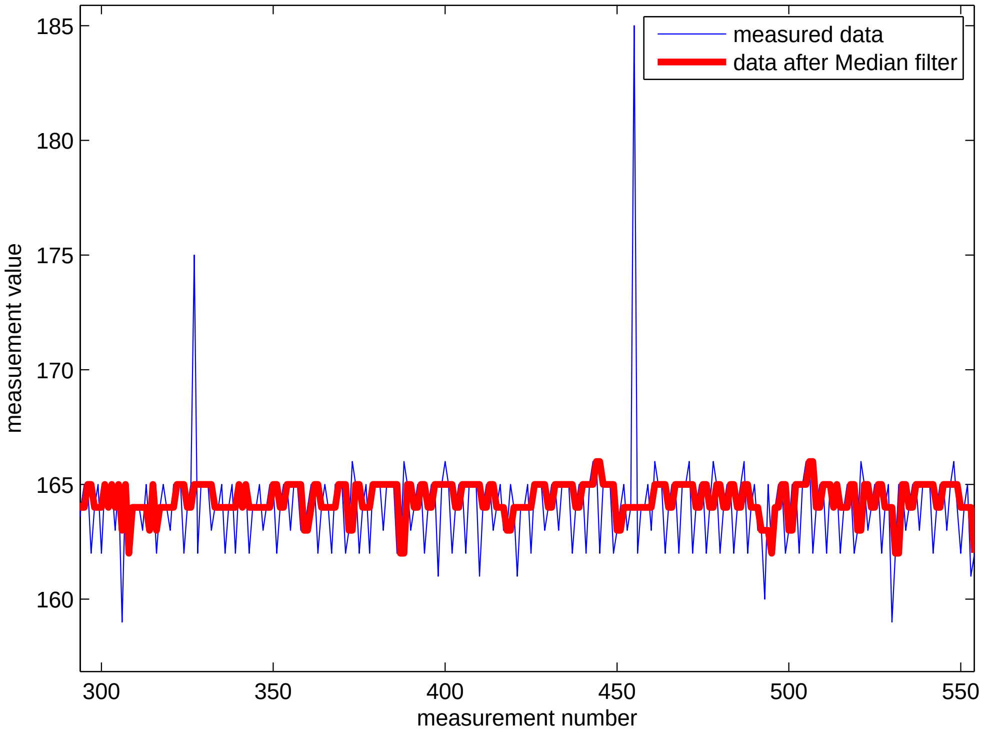

Figure 3.4. Effect of Median Filter on measurement smoothing. Measurement sequence at the input and output of the Median Filter for a stable CCA value.

For low-variance data, using Median Filter gives better estimation results. On the other hand, for high-variance data, usage of Median Filter gives a worse performance and therefore, it is not preferred. Based on these results, EMA cannot be considered to be a viable option, because it performs worse than or equal to the Kalman Filter for each situation, either with low or high-variance data.

3.4. Proposed Processing Algorithm

Since Median Filtering is advantageous for low-variance and disadvantageous for high-variance data, we propose to develop a method to optimize the measurement processing for both types of data.

Since we have the last N measurements, we can calculate the variance of this measurement sequence and decide whether to use Median Filter or not. If the history

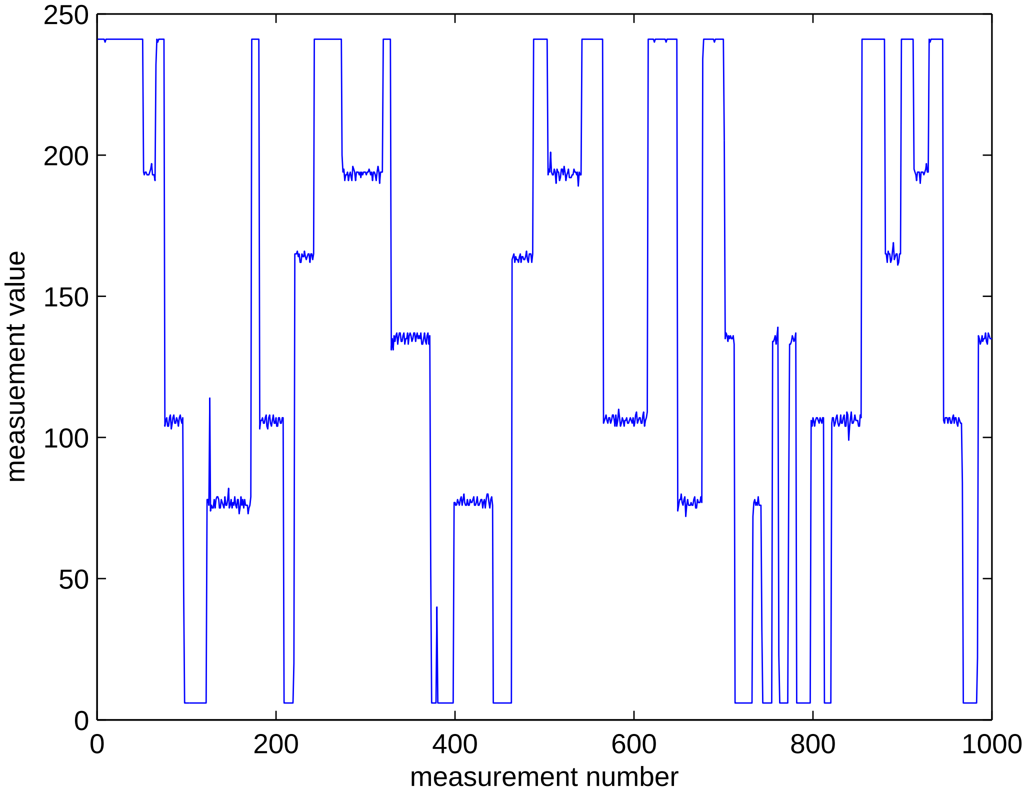

Figure 3.5. Measurement sequence of a controlled high-variance CCA value

of the measurements tells us that the channel usage levels are somewhat stable, we can use the Median filter. On the other hand, if the past measurements tell us that channel usage levels are highly varying, we do not apply Median filter before Kalman Filtering. The threshold value for variance comparison can be acquired through simulations by varying the threshold, here this step will not be discussed in detail. The flow chart of this hybrid method of processing can be seen in Figure 3.10.

Figures 3.11 and 3.12 show the performances of the Kalman Filter with and without Median Filter along with the proposed processing technique. The plots verify that our processing technique works well for both low and high-variance data and the proposed measurement processing techniques give the best output for both cases.

From now on, processed measurements with the proposed technique will be used for CCA values to select the appropriate channel for the APs to operate on.

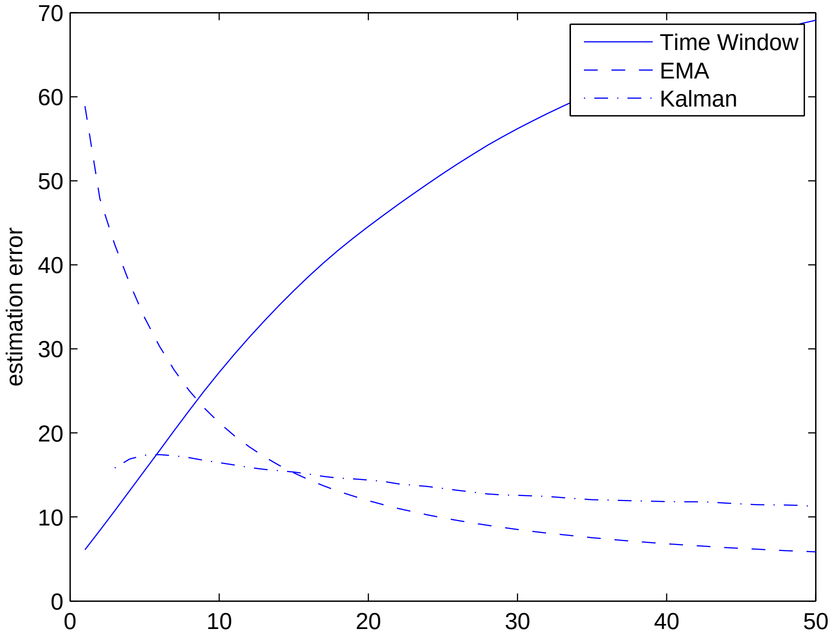

Figure 3.6. Estimation error for high variance data.

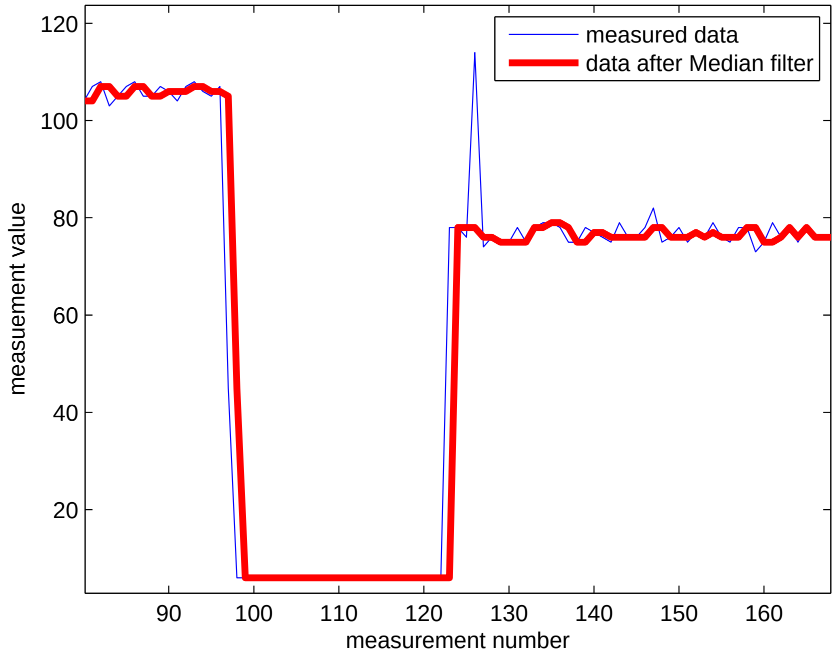

Figure 3.7. Effect of Median Filter on measurement smoothing. Measurement sequence at the input and output of the Median Filter for a high-variance CCA value.

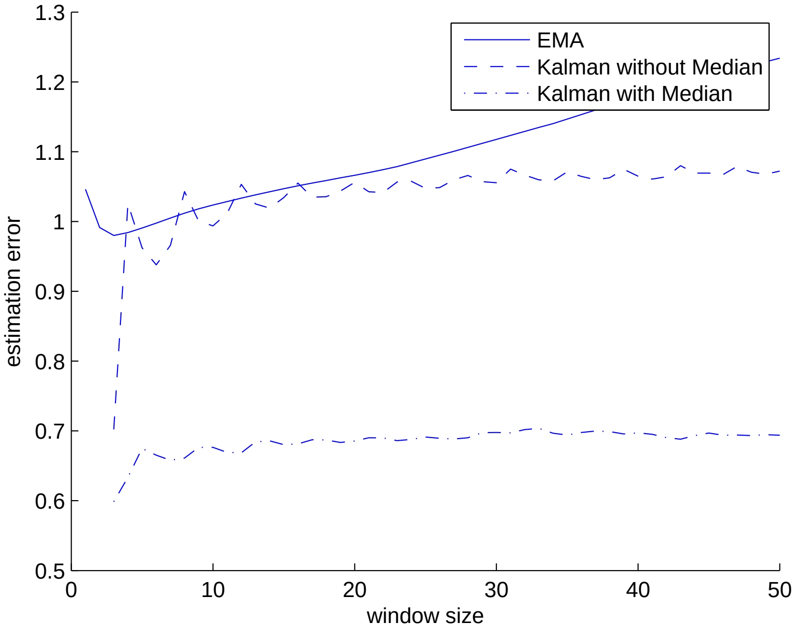

Figure 3.8. Estimation errors of various algorithms to observe the effect of Median Filter for low variance channel usage.

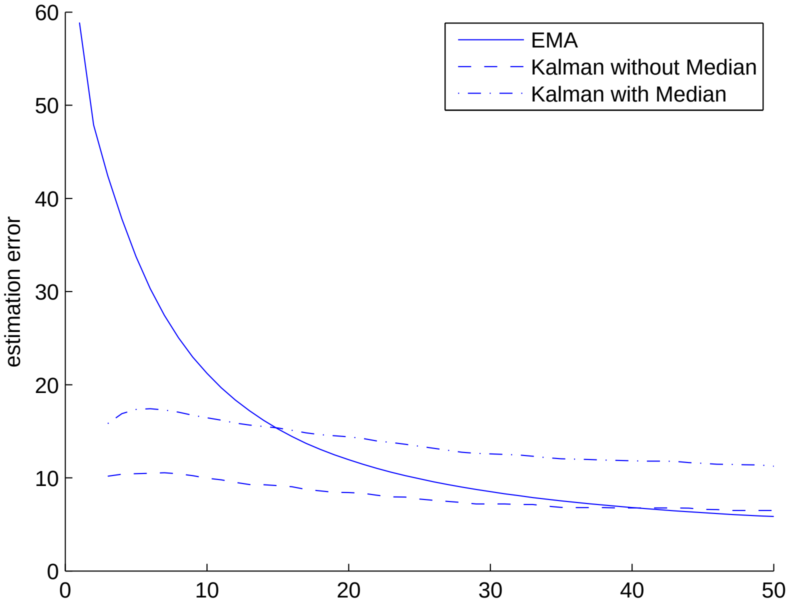

Figure 3.9. Estimation errors of various algorithms to observe the effect of Median Filter for highly varying channel usage.

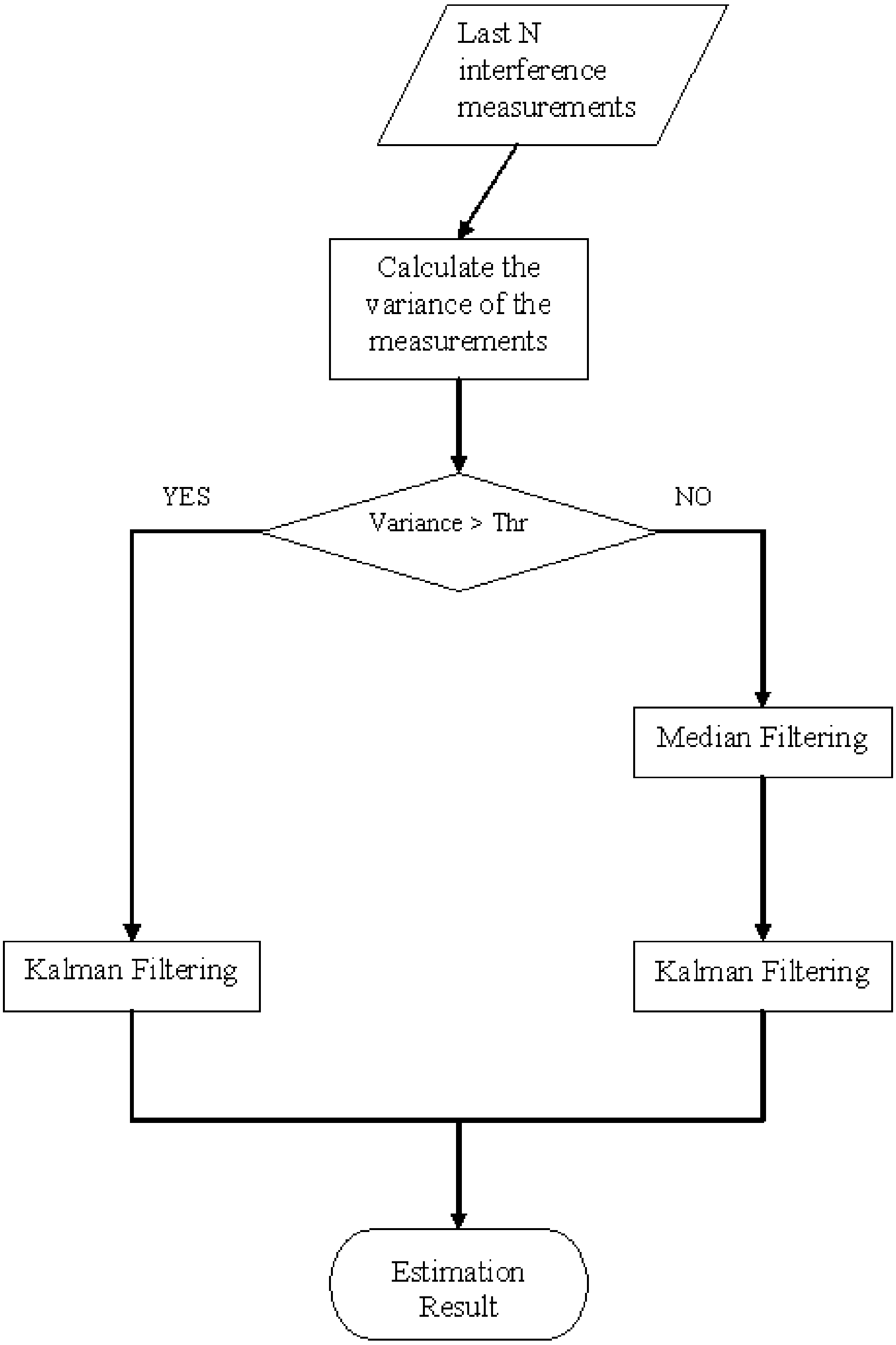

Figure 3.10. Flow chart of the proposed hybrid measurement processing mechanism

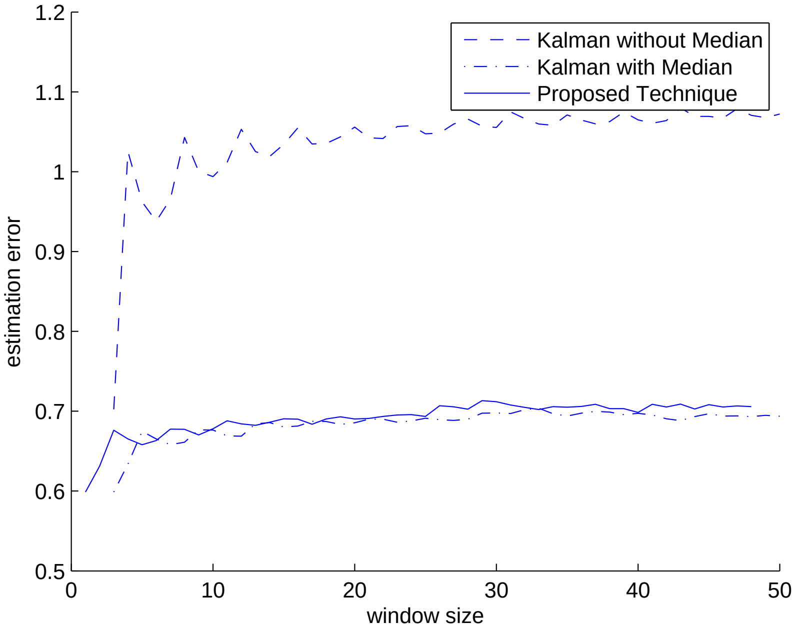

Figure 3.11. Estimation errors for low-variance data.

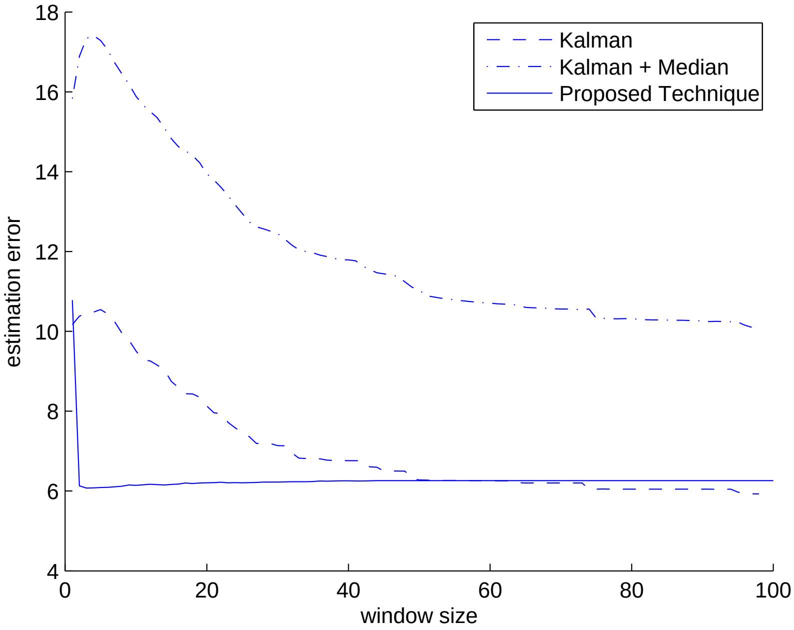

Figure 3.12. Estimation errors for highly varying data.

4. INTELLIGENT CHANNEL ALLOCATION

Now that we have the processed channel measurements obtained by the proposed method in Chapter 3, we can present the channel allocation algorithm. However, we will first investigate alternative interference avoidance techniques to get a better understanding of the problem. After we describe what is meant by CCA, we will derive the cost function, that will be used to decide on the most suitable channel assignment algorithm. Subsequently, channel switching using thresholds and hysteresis levels will be studied. Finally, we will present the possible channel allocation algorithms. Four of these algorithms are already available in the literature and the other two are the ones that are propose in this thesis. We will also evaluate the performance of these algorithms in order to determine the most suitable one for a single AP and client network; and the one for a mesh network.

4.1. Interference Avoidance on Mesh Networks

As stated in Chapter 1, there are three main interference avoidance techniques:

- Effective AP placement
- Transmission power control
- Intelligent channel allocation

Intelligent channel allocation is the one we will concentrate on in upcoming sections; however, it may be useful to provide information about the other two.

4.1.1. Transmission Power Control

There are many power control schemes in the literature. A typical one is investigated here [31]. The main idea is that if the mesh APs choose their transmit powers appropriately, the transmissions of the elements of the mesh network will not interfere with each other.

Consider a mesh network with n nodes where the transmission power of node i is P_i. If the channel gain from node i to node j is G_{ij} and the noise is $P_{thermal}$, the SINR of node j is

$$SINR(i,j) = \frac{P_i G_{ij}}{\sum_{m \neq j} P_m G_{mj} + P_{thermal}} \tag{4.1}$$

assuming the transmission power is fixed. If this value is higher than a threshold value $SINR_{thr}$, then node j can receive data from node i successfully.

To realize power control, a load factor, η, is defined as

$$\eta = 1 - \frac{P_{thermal}}{P_{sum\_int}} \tag{4.2}$$

where

$$P_{sum\_int} = \sum_{m \neq j} P_m G_{mj} + P_{ext\_int} \tag{4.3}$$

Here, P_{ext_int} is the potential interference and P_{sum_int} is the sum of all interferences. Then the threshold SINR is calculated as

$$SINR_{thr} = \frac{P_i G_{ij}}{\sum_{m \neq j} P_m G_{mj} + P_{ext\_int} + P_{thermal}} = \frac{P_i G_{ij}}{\frac{2-\eta}{1-\eta} P_{thermal}} \tag{4.4}$$

which results in the transmission power of node i:

$$P_i = \frac{\frac{2-\eta}{1-\eta} P_{thermal} SINR_{thr}}{G_{ij}} \tag{4.5}$$

Now it is assumed that node B calculates the transmission power of node A using the equation above. The potential interference P_{ext_int} in the network is calculated and distributed among all n nodes in the network:

$$P_{ext\_int} = P_{sum\_int} - \sum_{j \neq B} P_j G_{jB} = \frac{1}{1-\eta} P_{thermal} - \sum_{j \neq B} P_j G_{jB} \tag{4.6}$$

$$P_{int\_bound} = \frac{P_{ext\_int}}{n} \tag{4.7}$$

The values P_A and $P_{int\_bound}(B)$ are sent to the medium by node B, and the other nodes that can hear the node B can retrieve this information to calculate the transmission interference of node A and their maximum transmission powers:

$$P_{max\_int}(i) = \min_{j \epsilon Nei(i)} \{ \frac{P_{int\_bound(j)}}{G_{ji}} \} \tag{4.8}$$

where Nei(i) denotes the set of the neighbors of the node i. Node i can send only if $P_C < P_{max\_int}(i)$. The value of n is adjusted for each node as

$$n(t+1) = \begin{cases} n(t) & P_{sum\_int} \ \epsilon \ (\frac{1}{1-\eta} P_{thermal} 70\%, \ \frac{1}{1-\eta} P_{thermal} 90\%), \\ n(t) - 1 & P_{sum\_int} < \frac{1}{1-\eta} P_{thermal} 70\%, \\ n(t) + 1 & P_{sum\_int} > \frac{1}{1-\eta} P_{thermal} 90\%. \end{cases}$$

There are other studies on power control [30], some of which handle the power control problem along with channel allocation problem [32]. There are also power control techniques proposed for cellular systems, which handle the problem with cell-site selection [33] or BS assignment [34].

Adaptive power control is not very practical for WLAN applications at home, because there are also many non-mesh neighboring APs in the environment with high level power transmissions. Therefore, decreasing the power levels of the mesh APs in order to decrease the interference may reduce the performance of the network.

4.1.2. Effective AP Placement

AP placement is another way of interference minimization [4], [35], [36]. Placing the APs as distant from each other as possible, without leaving an uncovered spot in the region of interest is the main idea in intelligent AP placement. Essentially, candidate AP locations are determined and throughput is maximized by trying out each combination of these candidate AP locations for a fixed number of APs.

In general, the AP placement problem is solved along with channel allocation problem by fixing the transmission power. Non-overlapping channels (such as channels 1, 6 and 11 in the 2.4 GHz band) are assigned for the APs in determining their locations. As an example, the simple AP placement and channel allocation solution in [35] is described here. It is assumed that there are C possible channels, N_a candidate AP points and N_d demand points (clients). Average traffic demand of point i is denoted by D_i, where maximum bandwidth provided by AP j is denoted by B_j. The binary variable x_{ij} is 1 if and only if the point i is assigned to AP j, c_{kj} is 1 if and only if the channel k is assigned to AP j and a_j is 1 if and only if AP location j is selected. G_a is the channel assignment graph. Finally the minimization variable ξ is the maximum of traffic loads assigned to APs.

The variable ξ is to be minimized subject to the following conditions:

(i) Each client should be assigned to an AP:

$$\sum_{j \epsilon N_a} x_{ij} = 1, \quad \forall i \; \epsilon \; N_d \tag{4.9}$$

(ii)The traffic demand should be no more than the bandwidth provided:

$$\sum_{i \epsilon N_d} D_i \; x_{ij} \leq \xi \; B_j, \quad \forall j \; \epsilon \; N_a \tag{4.10}$$

(iii) An AP is selected if and only if at least one client is associated with it:

$$x_{ij} \leq a_j \quad \forall i, j \tag{4.11}$$

(iv) A channel should be set for each selected AP:

$$a_j \leq \sum_{k \epsilon K} c_{kj} \quad \forall j \; \epsilon \; N_a \tag{4.12}$$

(v) The non-overlapping channel condition with the minimum channel distance:

$$c_{ki} \sum_{l \epsilon [(k-d+1,\ldots,k+d-1)|(k-d+1 \geq 1) \wedge (k+d-1 \leq |K|)]} c_{lj} \leq 1 \quad \forall k \; \epsilon \; C, \; \forall i \; \epsilon \; N_a, \; \forall (i,j) \; \epsilon \; G_a \tag{4.13}$$

Under the above constraints, minimizing ξ will give the best candidate AP locations. Alternatively, with the same set of constraints, the number of selected APs (cost) or signal power can be minimized.

Video communication for IPTV will mostly be used in urban home environments. It is not very practical to determine and fix the locations of APs and clients in home environments but it may be applied in big office environments. However, it may be useful to simulate and evaluate the performance of effective AP placement.

We create a sample situation where there are 10 candidate points for AP locations, 5 of which can be selected to place an AP. There are 16 neighboring APs, each affecting some of the AP candidate locations. The neighboring APs are assigned channels and traffic loads randomly.

After taking long-term data, the channel and candidate AP locations that minimize the channel usage are selected for installation. On the other hand, 5 candidate locations are chosen randomly and the final channel usage levels are compared. As can be seen in Figure 4.1, proper selection of the locations of the APs makes a considerable contribution.

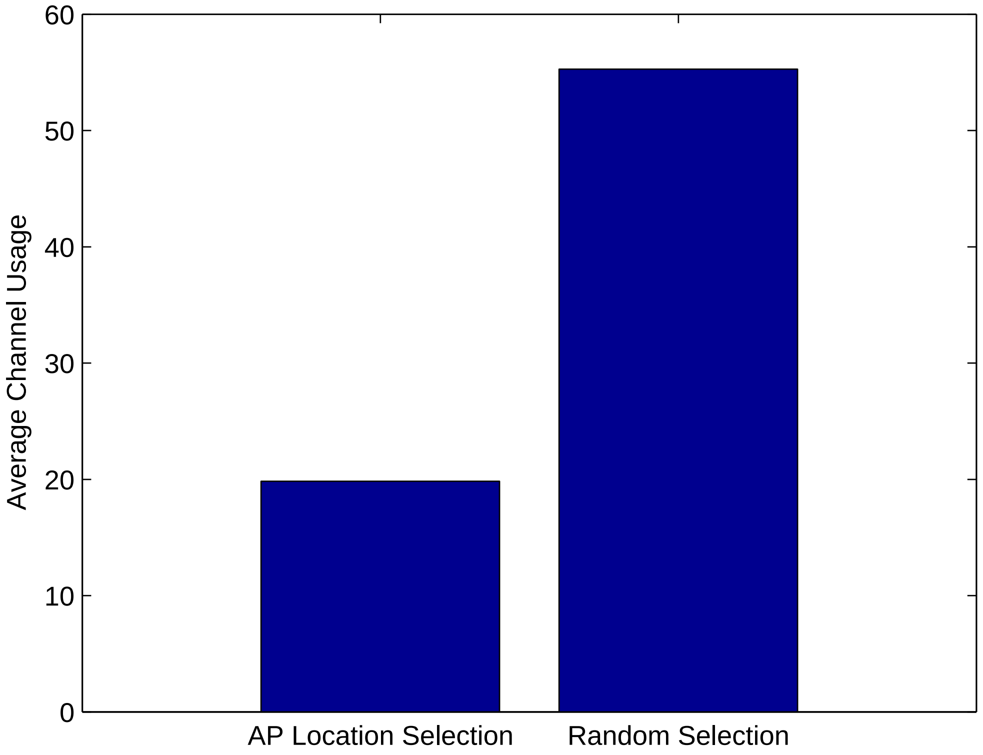

Figure 4.1. Average channel usage levels achieved with AP placement algorithm and random selection

4.1.3. Channel Allocation

In this thesis, we focus on intelligent channel allocation, as this control mechanism is the most appropriate for urban home users. The main idea behind is to avoid interference by switching to a channel with less users and less traffic. While we apply this technique, we will not deal with power control nor will we fix the locations of the APs. Throughout the rest of this chapter, the proposed channel allocation scheme will be explained in detail.

4.2. Channel Usage

The metric we use is the Clear Channel Assessment (CCA) value that is measured and processed for each channel. CCA indicates the scaled value of channel usage between 0 and 255.

What do we mean by channel usage? The mandatory medium access mechanism in 802.11 systems, which is a version of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), is the Distributed Coordination Function (DCF) [21]. In Figure 4.2, we can see the basic mechanism of this technique.

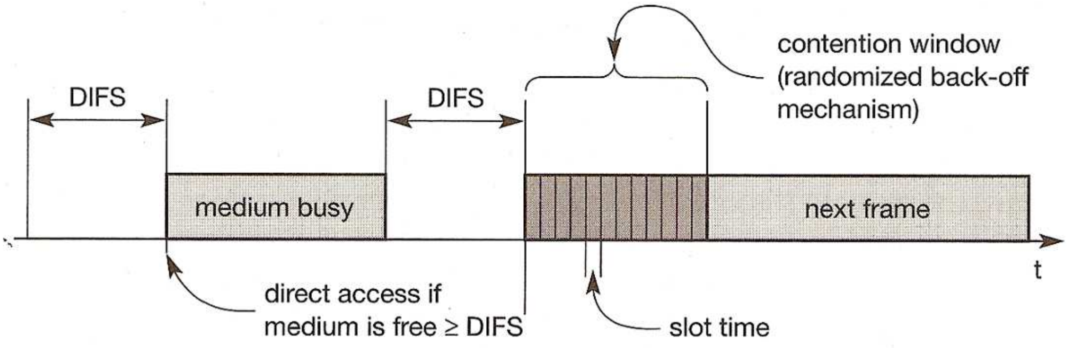

Figure 4.2. DCF mechanism for a single station showing the DIFS and contention window waiting times [21].

If the medium is sensed idle for the duration of DCF Inter-Frame Spacing (DIFS), which is about 50 μs, the station accesses the medium; if sensed busy, the station enters the contention phase. When the medium is sensed busy by the station, no transmission occurs and the station waits for the medium to be idle again. When the medium is idle, the station waits for the duration of DIFS, then chooses a random backoff time within a contention window size. This contention window may take values such as 32, 64, 128, etc. Hence, the medium access is delayed this amount of slot times. If the

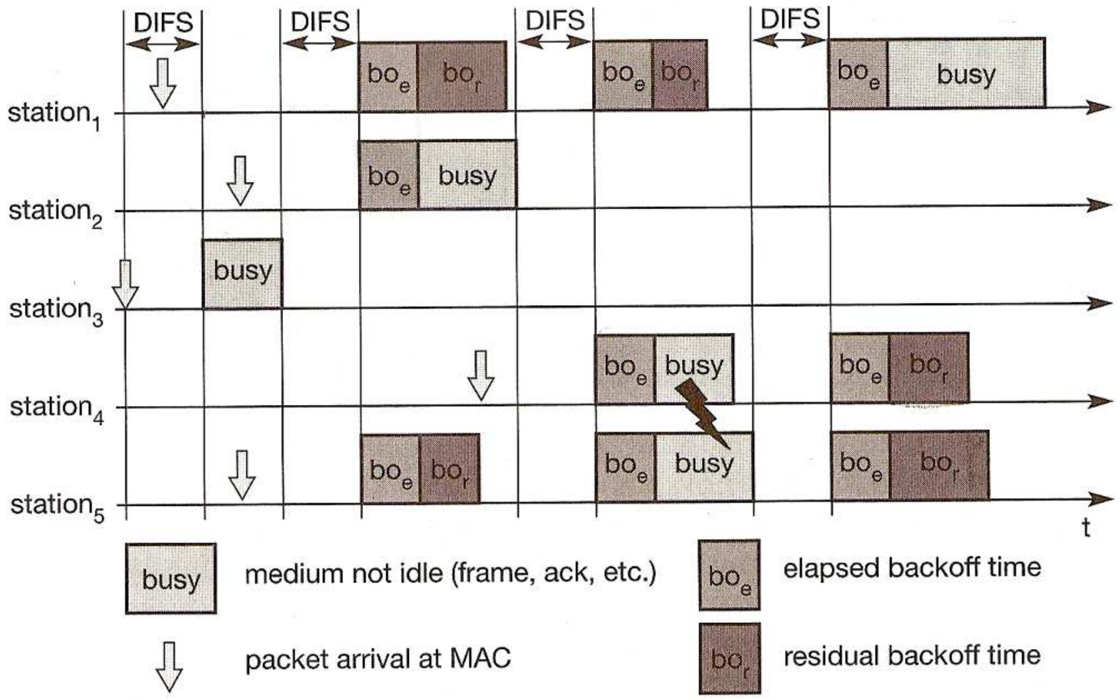

Figure 4.3. DCF mechanism for more than one competing stations showing the waiting times, collisions and transmissions [21].

medium is sensed busy while counting down, the station freezes its timer and in the next turn, it continues counting down again from its residual backoff timer. If this backoff timer expires and the medium is idle, the station can now begin transmission.

We can understand this mechanism better by analyzing Figure 4.3, which shows the DCF mechanism for 5 competing stations. As can be observed, after busy period caused by Station 3 ends, stations which have packets to send wait for a period of DIFS and then choose a random backoff timer within the contention window. The station, which chooses the smallest timer (in this case, Station 2) reaches 0 and starts transmitting its packets, which leads to another busy period for other stations. When its transmission ends, other stations continue to count down from their residual backoff time from the previous turn.

It may happen that more than one station chooses the same random backoff timer. In this case, they will try to reach the medium at the same time, resulting in a collision of packets. Collisions destroy the packets by making them meaningless for their destinations. If collisions occur, retransmissions are required in order to compensate for the destroyed packets. Therefore, the stations, which send those collided packets, choose a new random backoff timer.

Here the idle period of the channel can be described as the period without data communication, including DIFS periods, backoff timer countdown periods and the periods where no station wants to transmit a packet. Busy periods are described as the periods when there is a transmission, that ends either with success or with collision.

The CCA value that is measured by entering each channel is the channel usage value, which can also be defined as the ratio of the busy period described above to whole measuring period of the channel.

4.3. The Cost Function

The focus of this thesis is to develop an algorithm in order to determine the optimal channel allocation for a network while realizing video communication. Since our purpose is not to disturb the wireless real-time video communication, our cost metrics should be chosen accordingly.

As measured CCA, channel usage, or the ratio of the busy period increases, it will be harder for a station to handle the medium, that will result in decreased throughput. Therefore, the measured CCA value should be included in the cost function. As explained in the previous section, the stations that are trying to reach the channel compete with each other. As a result, as the number of stations increases, reaching the medium becomes more difficult for each station.

Channel switching in order to increase the chance of reaching the medium brings a cost itself. Since single-radio stations can only operate on a single channel, the hard handoff procedure results in packet losses that disturbs the video communication, which is undesirable. Therefore, we can enumerate the following three factors that bring cost to our system:

- Channel Usage (CCA)
- Number of AP
- Channel Switching

We should combine the above factors in our cost function in a meaningful way. There is a tradeoff between the first two factors and the third one; as we change the channel to avoid the first two, we add cost through the third factor. Therefore, we can divide the cost function in two parts; the first part is the channel usage cost that includes the CCA measurements and number of neighboring APs. The second part is the channel switching cost, i.e.,

$$cost = cost(Channel\ Usage) + \beta cost(Channel\ Switch) \tag{4.14}$$

Here, β is the scaling factor, which determines the relation between the packet losses caused by high channel usage and the packet losses caused by channel switching. In the sequel, we will investigate the effect of each of these factors individually.

4.3.1. CCA vs. Throughput

We described the medium access mechanism of the 802.11 standard in Chapter 2. Now we investigate the effect of this mechanism on throughput. [4] and [37] analyzed this situation and reached similar results. Assuming there are n stations in the medium, the probability that at least one station transmits in a time slot (p_{tr}) is

$$p_{tr} = 1 - (1 - \tau)^n \tag{4.15}$$

Here, τ is the probability that a station transmits a packet, which means that its random backoff timer decreases to 0. Therefore, if stations take random backoff timers within a contention window with size CW, τ, becomes [38] :

$$\tau = \frac{2}{CW + 1} \tag{4.16}$$

p_s is the probability that a transmission seizes the channel, meaning that exactly one station transmits, given that at least one transmits:

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{tr}} \tag{4.17}$$

Using p_{tr} and p_s, we can derive other probabilities that are useful in our throughput calculations. The probability that a channel is idle, p_{idle}, is the situation where no station wants to transmit a packet:

$$p_{idle} = 1 - p_{tr} \tag{4.18}$$

The probability that a successful transmission occurs, p_{succ}, is the situation where there is only one station that wants to transmit a packet:

$$p_{succ} = p_{tr} p_s \tag{4.19}$$

The probability that a collision occurs, p_{coll}, is the situation where more than one station wants to transmit a packet in a time slot:

$$p_{coll} = p_{tr}(1 - p_s) \tag{4.20}$$

Now we can create our throughput function. The possible scenarios that can be encountered are,

- No transmission in a slot time

- A successful transmission takes place
- A collision takes place

Normalized throughput, denoted as C_{total} is the ratio of time spent on successful transmissions to the total time spent:

$$C_{total} = \frac{p_{succ}T_{succ}}{p_{idle}T_{idle} + p_{succ}T_{succ} + p_{coll}T_{coll}} \tag{4.21}$$

In (4.21), T_{succ} is the duration of a successful transmission, T_{idle} is the length of a slot time and T_{coll} is the duration of a collision. Channel is sensed busy during a collision or a successful transmission.

The assumption here is that all the stations have the same collision window size CW and have the same τ. If we divide the throughput value out between all the stations to find the throughput, C_i, of a single station i, we get

$$C_i = \frac{\frac{p_{succ}T_{succ}}{n}}{p_{idle}T_{idle} + p_{succ}T_{succ} + p_{coll}T_{coll}} \tag{4.22}$$

As can be observed, C_i is the ratio of the successful transmissions of a single station i to the whole time spent on transmissions, collisions and backoff timer durations.

There is another assumption above that all of the stations always have packets to transmit. However, this is not always true. Therefore, we can relax this assumption and limit the packet count of each station to transmit in unit time. We also limit the total slot times and see if a station can send all of its packets during that time period, and if not, what percent of the required packets can be transmitted in that period of time. This ratio can be interpreted as normalized throughput of a station.

One other reason of this extension is that only the number of APs, n, affects the throughput received from a channel. However, it may happen that some APs have many packets to send, while some others do not transmit packets at all. Therefore, conditioning channel usage only on AP number is not always a reliable solution.

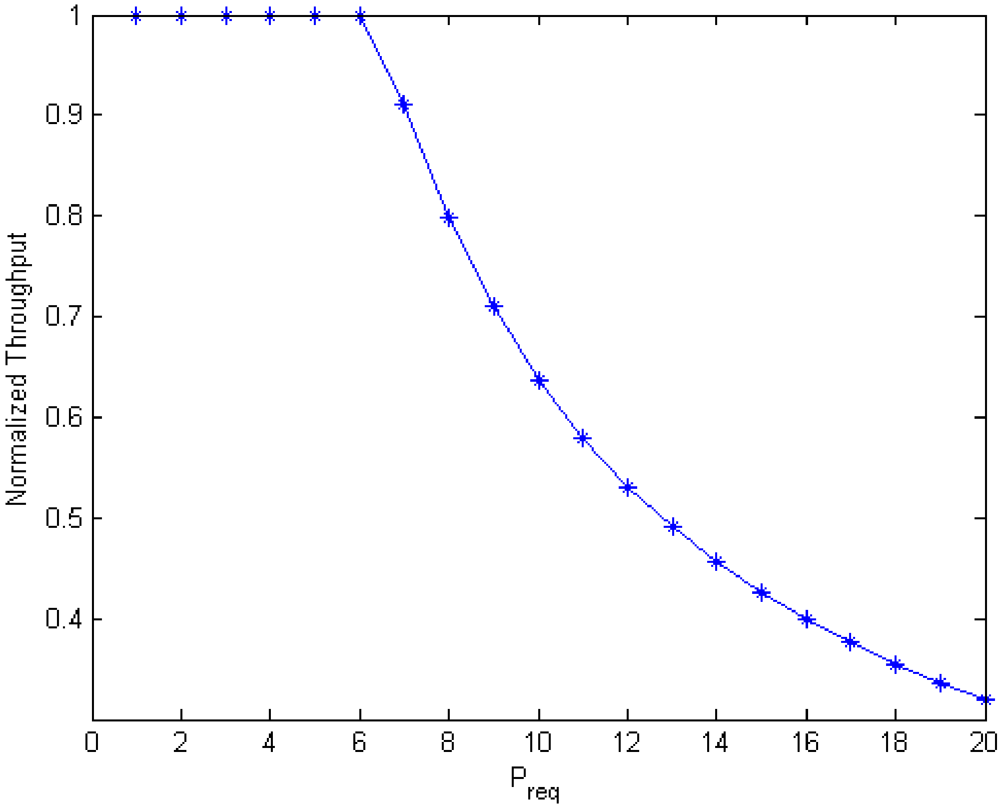

Figure 4.4. Required packet count P_{req} of the stations vs Normalized throughput.

Now we define N_{total} as the total number of time slots in our time period of measurement. P_{req} is the number of packets that a station needs to transmit in N_{total} slots. If we say a packet can be transmitted in N_{succ} time slots, the total number of packets a station is able to send in N_{total} slots is

$$P_{sent} = \frac{N_{total} C_i}{N_{succ}} \tag{4.23}$$

since it can only use C_i percent of the time for its transmissions. P_{sent} is the total number of packets that could be sent and P_{req} is the number of packets that are required to be sent. We can describe throughput, Tp, as the ratio of P_{sent} to P_{req}:

$$Tp = \frac{P_{sent}}{P_{req}} = \frac{N_{total} C_i}{N_{succ} P_{req}} \tag{4.24}$$

If it can transmit all P_{req} of its packets, we say that the normalized throughput is 1.

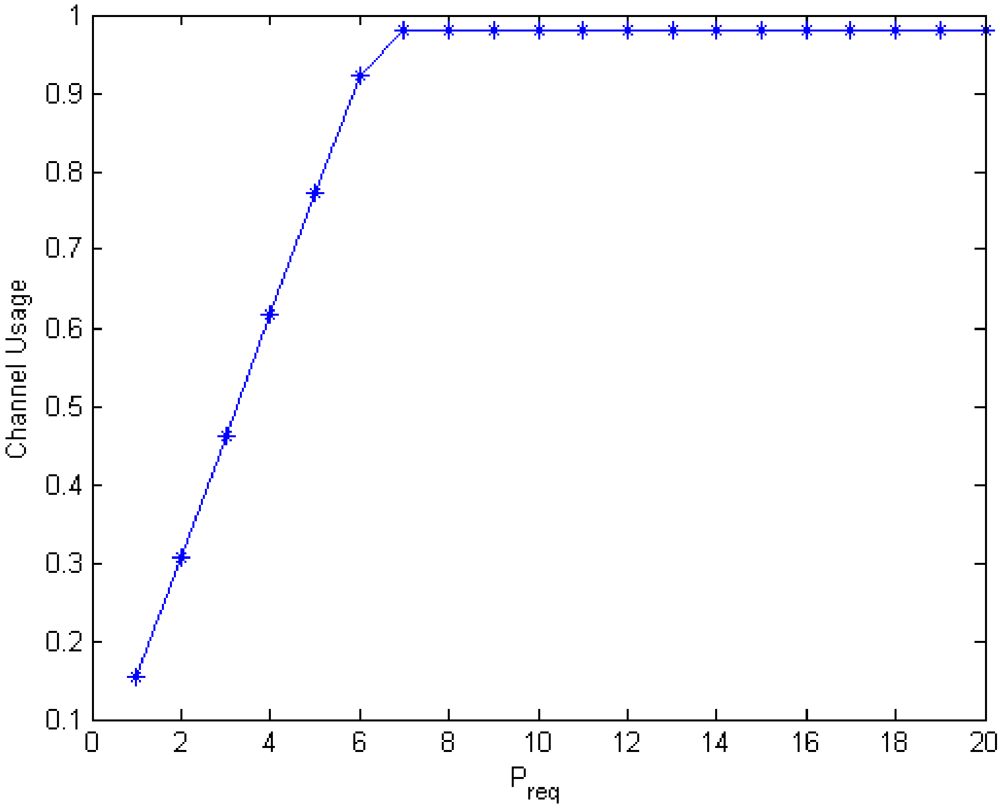

Figure 4.5. Required packet count P_{req} of the stations vs Channel Usage (channel busy probability).

If it cannot, the throughput can be computed as in the above equation. Hence, the throughput is

$$Tp = \min\{\frac{P_{sent}}{P_{req}}, 1\} \tag{4.25}$$

Lastly, when we simulate this mechanism for a fixed number of APs, we get the curve in Figure 4.4. The graph shows that unless the channel is completely full with packets, (i.e., the normalized throughput is 1), stations can transmit all the packets required. However, when the channel is completely full, stations cannot send all the packets they need and they start dropping packets, which decreases the throughput.

The corresponding channel usage is shown in Figure 4.5. Until the channel be-

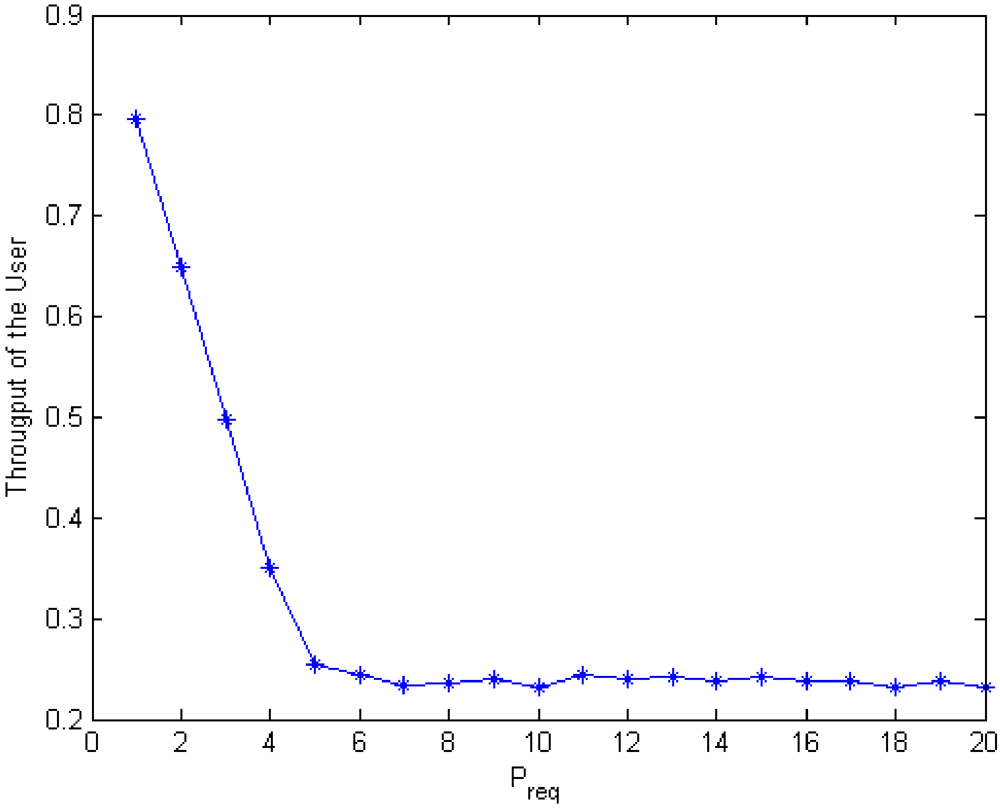

Figure 4.6. Required packet count P_{req} of the stations vs Throughput of additional station.

comes full, channel usage increases as packet count increases. When the channel is full, channel usage is fixed at a value near 255. It does not reach the maximum value of 255, even when the channel is full, because DIFS and contention window waiting times are not included in the channel usage rate; they are treated as idle channel slots.

At this point, we add another station to the channel, which will be exposed to the channel usage levels in Figure 4.5. We give the new station a certain amount of packet load to fill the channel completely and increase the packet loads of the other stations to get the graph of the normalized throughput of the new station as in Figure 4.6. The throughput of the user decreases as other stations have more packets to send, until the throughput comes to an equilibrium with other users at some level, where they all share the medium equally.

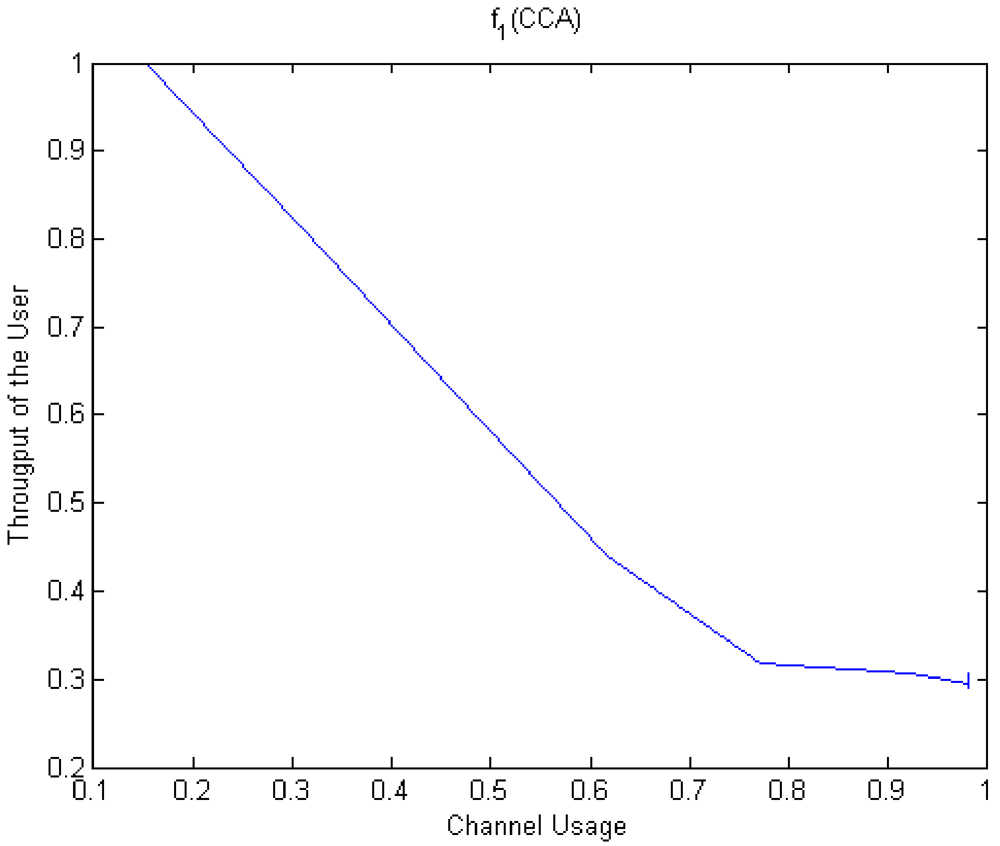

Figure 4.7. Channel usage probability vs Throughput of the additional user. $(f_1(CCA))$

Taking the above points into consideration, we can construct our first function $f_1(CCA)$ as in Figure 4.7. The graph is normalized between 0-1. There is somewhat linear trend at first, which settles down to a value at the end. This final value depends on the number of APs which will be investigated in the next section.

4.3.2. AP count vs. Throughput

In the previous section, we fixed the number of APs; however the number of APs also affects the throughput. As the number of APs increases, there will be more stations to compete for the medium and the probability of collisions, as well as the busy period and the channel usage will increase. Therefore, the function we have in Figure 4.7 can be scaled with a function that depends on the number of APs. By plotting the throughput function acquired above with respect to number of APs, fixing

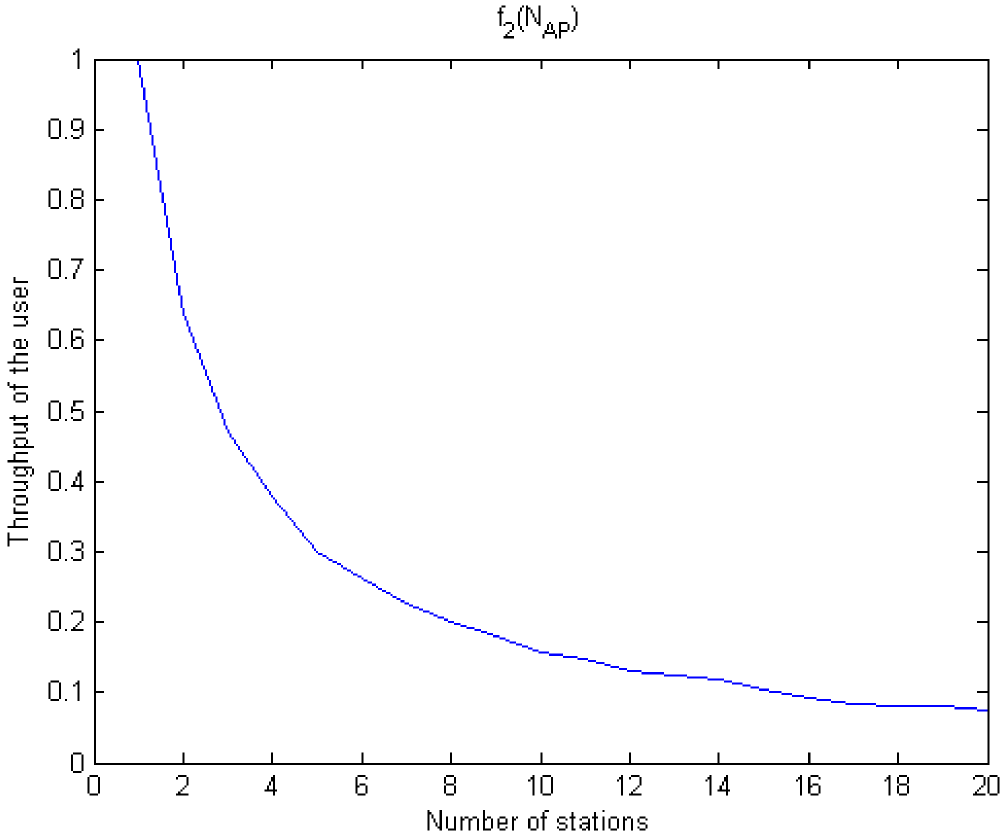

Figure 4.8. Number of competing stations vs Throughput of the additional user. ($f_2(N_{AP})$)

the number of packets, P_{req}, we can get this second scaling function. The graph, which is the second element of the cost function, $f_2(N_{AP})$, can be seen in Figure 4.8. Again the plot is the normalized between 0-1.

4.3.3. Channel Switching vs. Throughput

While an AP is streaming a real-time video to its clients, even small disturbances, pauses or delays can create packet losses. Since, real-time applications are time-sensitive, delayed packets become meaningless for the clients.

Our objective is to develop a channel allocation system for seamless video communication while avoiding the channels with high traffic. However, channel switching itself also brings cost to the system. While APs and clients are operating on a channel and streaming videos, channel switch is not instantaneous, but it takes some time for the APs to warn its clients and switch to the desired channel collectively. This required time results in packet losses especially in high-data rate streams, because the buffer size is limited and there is a small interval where no transmission occurs between the AP and clients. Burst packet losses occur in these intervals without a transmission and because of the characteristics of video communication, the effects of these burst video packet losses last longer. Therefore, frequent channel switches are not desirable and should be included in the cost function as a tradeoff metric.

Packet losses with respect to the channel switching rate in a time period can be assumed linear, as the packet loss rate increases with the channel switching rate. For example, if 5% channel switching causes 1% packet loss, then 10% channel switching will cause 2% packet loss. Experimental results support this conclusion as can be observed in Figure 4.9. This normalized graph will be our third function to be used in the cost function, $f_3(C_{rate})$, where C_{rate} is the channel switching rate in a certain time period.

4.3.4. The Cost Function

We have defined, categorized and combined the cost factors as,

$$cost = cost(Channel\ Usage) + \beta cost(Channel\ Switch) \tag{4.26}$$

As we have observed, an increase in the channel switching ratio, the channel usage ratio and the number of APs all decrease the throughput. However, channel switching is an action performed to move to a channel with lower channel usage and less AP count. Hence, there is a tradeoff between channel switching ratio and channel usage along with AP count.

Ignoring the channel switches, the normalized throughput, $\bar{T_p}$, can be formulated

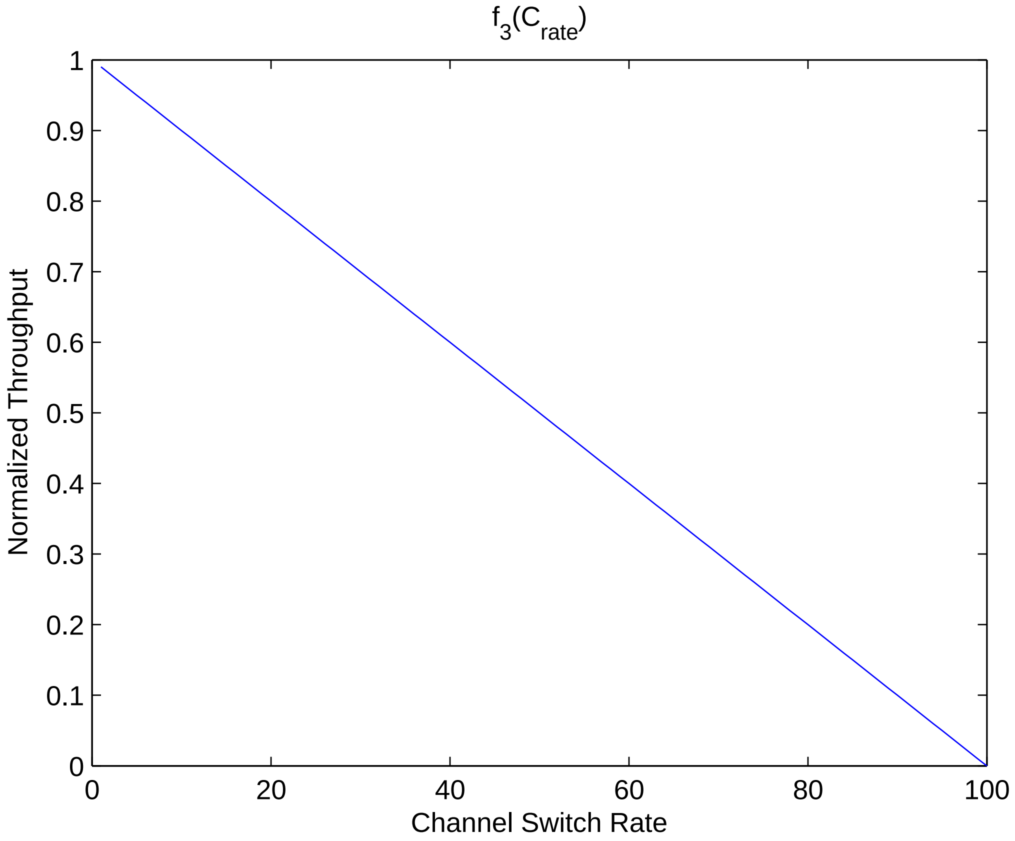

Figure 4.9. Channel Switching Rate C_{rate} vs Throughput of the additional user. ($f_3(C_{rate})$)

as

$$\bar{T_p} = f_1(I_{av})f_2(N_{AP_{av}}) \tag{4.27}$$

where I_{av} is the average measured CCA in a time period and $N_{AP_{av}}$ is the average AP count in a time period. When we subtract the scaled throughput loss caused by channel switching, the normalized throughput becomes

$$\bar{T_p} = f_1(I_{av})f_2(N_{AP_{av}}) - \beta(1 - f_3(C_{rate})) \tag{4.28}$$

The corresponding cost function, CF, is obtained by the throughput losses created by the cost factors. When we subtract Equation (4.28) from 1, the normalized throughput level with no losses, we get the CF as

$$CF = (1 - f_1(I_{av})f_2(N_{AP_{av}})) + \beta(1 - f_3(C_{rate})) \tag{4.29}$$

The first term of CF is the $cost(Channel\ Usage)$ part in Equation (4.26), while the second term is the $cost(Channel\ Switch)$ part.

Estimation of the variable β is important here. The packet losses due to channel switches should be compensated by channel usage levels. We cannot know exactly in advance how much channel usage gain will be provided by channel switching; we can only make a logical deduction. Frequent channel switching, even when the channel does not cause any losses, creates unnecessary and bursty packet losses. However, not switching the channel when needed results in even more and continuous packet losses.

When the channel is completely full, packet losses occur and switching the channel becomes vital. However, the stations cannot know how much channel usage space will be required, so detecting that the channel that is not completely used, does not always mean that the station will not experience any packet losses. If the channel is detected 80% used but the user needs to use 30 % of the channel for its transmissions, operating on that channel will cause packet losses and the channel should be switched.

We cannot know how much traffic a station will require. Our experiments show that 30 Mbps data rate, which is required for three HDTV streams, creates a CCA level of 123 to 171 over 255 channel usage depending on the modulation level, which leaves an idle channel between 33% and 52%. We will keep the worst case channel usage level as our target and set the β value to $f_1(I = 0.33)$.

4.4. Decision to Change the Channel

The channel, that minimizes the cost function, will be chosen as the optimal channel to be operated on. However, this channel may change frequently. As we have discussed before, frequent channel switching, which creates packet losses, is not desirable. Therefore, we should use some check mechanisms to control channel switching system to decide when to switch.

First of all, if the current channel measurement levels are sufficient, channel switching algorithm should not start and create unnecessary channel switching cost. We will call this channel usage threshold T_{high} and determine its value as we have decided on β value before. If there are no packet losses, channel switching is not needed, so T_{high} can be taken as 0.33 also. Since our CCA values are scaled between 0 and 255, T_{high} is equal to 85.

Next, we assume that we are over T_{high} and have found a new channel. Will it be worth changing the channel? Is the new channel really better than our current channel or is there only a slight difference? We create a new threshold T_{hys}, which is the hysteresis level after the channel switching, the difference between the measurements of the current channel and the candidate channel. The gain of the channel switching should compensate the channel switching packet loss. According to our experiments, one channel switch can result in up to 5% packet loss. Therefore, we can set

$$T_{hys} = f_1^{-1}(x - 0.5) - f_1^{-1}(x) \tag{4.30}$$

where, x can be a throughput value chosen from the linear range of $f_1(CCA)$. This equation results T_{hys} will be taken 0.062, which will be equal to 16 when scaled between 0 and 255.

4.5. Potential Algorithms

In this section, some algorithms for channel allocation are described. Four of these algorithms can be found in the literature. The other two algorithms are more intelligent solutions and developed by us. These algorithms that will be described are:

(i) Random Method

(ii) AP minimization

(iii) Total Weight Minimization (TWM)

(iv) Maximum Weight Minimization (MWM)

(v) Short Term - Long Term (STLT) algorithm

(vi) Hybrid Channel Allocation (HCA) algorithm

4.5.1. Random Method

The algorithm described in [10] randomly chooses the channel i from C possible channels. Each possible channel has a selection probability p_c. When selected, it is checked if the channel satisfies certain criteria. The criterion can be factors such as throughput or packet loss. For us, the criteria will be the comparison of the channel usage of the operating channel with T_{high} value. If it does satisfy the comparison, the algorithm sticks to that channel and starts to operate on it:

$$p_i = 1, p_j = 0 \forall j \neq i \tag{4.31}$$

If the randomly selected channel does not satisfy the condition, the selection probability of that channel is decreased and the selection probability of other channels is increased:

$$p_i = (1-b)p_i \tag{4.32}$$

$$p_j = (1-b)p_j + \frac{b}{C-1} \forall j \neq i \tag{4.33}$$

where, b is a scaling factor that determines how much the selection probability of an unsuccessful channel will degrade.

This Random Method is an iterative algorithm that cannot reach the result quickly, which is undesirable for video communication applications. Although in the final selection it can reach a suitable level, frequent channel switches is another disadvantage.

4.5.2. AP Minimization

In AP minimization, the AP chooses the channel with the least number of APs:

$$\tilde{C} = \arg \min_{c=1...C} N_{AP}(c) \tag{4.34}$$

If the number of APs stays constant, the selected channel will not be changed, no matter how much the amount of traffic in each channel is. This situation shows that the algorithm is independent of the channel usage. Therefore, the decision cannot be an optimal one. Some APs may be realizing high video or data communication, while some may not be transmitting a single packet.

4.5.3. Total Weight Minimization (TWM)

In this method the APs and clients take measurements, process them and choose the channel with the least channel usage level.

$$\tilde{C} = \arg \min_{c=1...C} I(c) \tag{4.35}$$

If there is only one AP, it makes the decision using the measurements of its clients and itself. If there is a mesh, a central unit makes the decision. A similar approach is also described in [8] and [9]. $\tilde{C}$ denotes the selected channel, where $I(c)$ denotes the average channel usages of all APs and clients.

This method is the most obvious one, considering the channel usage minimization, however conditions may vary quickly, which results in frequent channel switching, which is again undesirable for real-time video communication.

4.5.4. Maximum Weight Minimization(MWM)

This technique chooses the channel which minimizes the measured CCA on the bottleneck station. Bottleneck station is the station with highest CCA measurements. This highest value is minimized with this channel selection:

$$\tilde{C} = \arg \min_{c=1 \ldots C} \max_{i=1 \ldots n} I(i,c) \tag{4.36}$$

where $I(i,c)$ denotes the channel usage measurement of the channel c by the station i. For single AP and single client case, this station can either be the AP or the client. A similar approach is also described in [8] and [9].

This technique does not guarantee to find the channel with minimal channel usage, but it minimizes the channel usage of the most suffering stations in the mesh network. Quickly varying channel usage levels cause undesirable, frequent channel switches in this technique as well.

4.5.5. Short Term - Long Term (STLT) Algorithm

Choosing the channel with only the recent measurement values, even if they are smoothed and processed, can be misleading. There can be a temporary increase or decrease in the channel conditions. This is why, observing and including the long term data can give better results besides the recent data.

Short term data is the recent processed CCA measurement. Long term data can also be called as the channel availability scala. This scala can be extracted from the history of the measurements. Past N measurements are observed and the percentage of measurements over the threshold T_{high} is determined as channel quality scala, which we call Q. Finally these measurements are combined and minimized to determine the candidate channel, $\tilde{C}$. Channel usage measurements I are also assumed to be scaled between 0-1.

$$\tilde{C} = \arg \min_{c=1\ldots C} [\gamma I(c) + (1-\gamma)Q(c)] \tag{4.37}$$

where γ is a scaling coefficient and can take values between 0 and 1. γ factor determines which measurement type, long term or short term, will be given higher priority. Here, we will give equal priority to both setting the γ 0.5.

For STLT Algorithm, current processed CCA measurements are important to determine the switching channel. If the usage of a channel is high, that channel should not be chosen. But also if the usage of a channel has increased frequently in the past, the probability that it will increase again is higher, even if the usage is low at the decision moment. Hence, choosing a channel with a stable, low historical record prevents future channel switches. Therefore the purpose of STLT Algorithm is to find a channel whose historical records do not show frequent channel usage increases along with relatively low current channel usage. Here, if the thresholding mechanisms are added to the algorithm, frequent channel switches are prevented and a more stable channel allocation can be achieved.

4.5.6. Hybrid Channel Allocation (HCA) Algorithm

This algorithm proceeds step by step and combines Total Weight Minimization (TWM) and Maximum Weight Minimization (MWM) algorithms. Thresholding mechanisms are also used for the decision making process.

If the channel usage of a station is over T_{high}, we call that it suffers packet drops. Our first purpose here is to decrease the stations suffering packet drops; then to minimize the overall channel usage. The procedure can be described with the following steps:

(i) Determine the channel or channels with the least number of stations with channel usage over T_{high}.

(ii) If there is only one channel found, choose that channel.

$$\tilde{C} = \arg \min_{c=1 \ldots C} \sum_{i=0}^{N-1} \psi(i,c) \tag{4.38}$$

where,

$$\psi(i,c) = \begin{cases} 1 & I(i,c) > T_{high}, \\ 0 & I(i,c) <= T_{high}. \end{cases}$$

(iii) If there are more then one channels found, and if there is at least one suffering station in these channels, choose the channel that minimizes the maximum channel usage.

$$\tilde{C} = \arg \min_{c=1 \ldots C} \max_{i=1 \ldots n} I(i,c) \tag{4.39}$$

(iv) If there are more than one channels found, and if there are no suffering stations in these channels, minimize the total channel usage. Switch the channel if the difference between the current channel and candidate channel is over T_{hys}.

$$\tilde{C} = \arg \min_{c=1 \ldots C} I(c) \tag{4.40}$$

This algorithm's initial concern is the number of individual APs with measured channel usage levels over the determined threshold level T_{high}. The purpose is to make each device work well to keep the video communication going. Maximum Weight Minimization (MWM) is used for this purpose. Secondary concern is to minimize the overall channel usage measurements as in Total Weight Minimization (TWM). Thresholding mechanisms prevent the system from making frequent channel switches and make it a more stable channel allocation system.

4.6. Simulation Results

4.6.1. Algorithm for Single AP - Single Client Case

First, we will test these algorithms for a single AP case, which is commonly used in home environments. There is an AP, which takes channel usage measurements and there is a client connected to the AP which also takes channel usage measurements and passes these measurements to the AP. Naturally, these two devices operate on the same channel.

Table 4.1. Comparison of different algorithms for a single AP and client.

Single AP	Avg. Usage	Max. Usage	%change	%overflow	Cost
Random Method	57.72	83.41	16.77	18.56	0.2459
AP Minimization	68.61	102.14	0	35.38	0.1429
TWM	44.29	68.41	4.23	16.02	0.0447
TWM + Threshold	45.45	72.22	1.35	16.32	0.0342
MWM	46.58	64.18	4.47	19.15	0.0637
MWM + Threshold	47.27	65.19	1.71	19.29	0.0437
STLT	45.98	72.83	1.12	17.06	0.0290
HCA	45.06	70.87	1.19	16.18	0.0242

In the simulation environment, there are 10 neighboring stations, some of which affect both the client and the AP. Some of the stations only affect the client and some of them affect only the AP. Each of these stations is assigned channel usages randomly with mean 30 Mbps. After each turn, the channel usage levels of these stations are increased or decreased again randomly with a Gaussian-like random variable with mean 0, which means that small changes are more probable than large ones. The AP checks the channel switching need after each turn. The simulations are run for 100 turns and repeated for 10000 times to get an average.

Comparison criteria are average channel usage measurements, maximum channel usage measurement of each single stations, channel switching rate, rate of overflows (if the average of channel usages are over T_{high}, an overflow is assumed to be occured) and finally value of the cost function. After simulations, the values in Table 4.1 are obtained. The six described algorithms are simulated. TWM and MWM are simulated two times both with thresholding and without thresholding mechanisms.

If we compare the results, we can see from the bar graph in Figure 4.10 that TWM minimizes the total channel usage and MWM minimizes the channel usage on bottleneck station better than the other algorithms, as expected. Random method achieves to be under the threshold level, while AP minimization cannot succeed at all. Our two algorithms could minimize the channel usages somewhere between MWM and TWM, however HCA could do a little better than STLT.

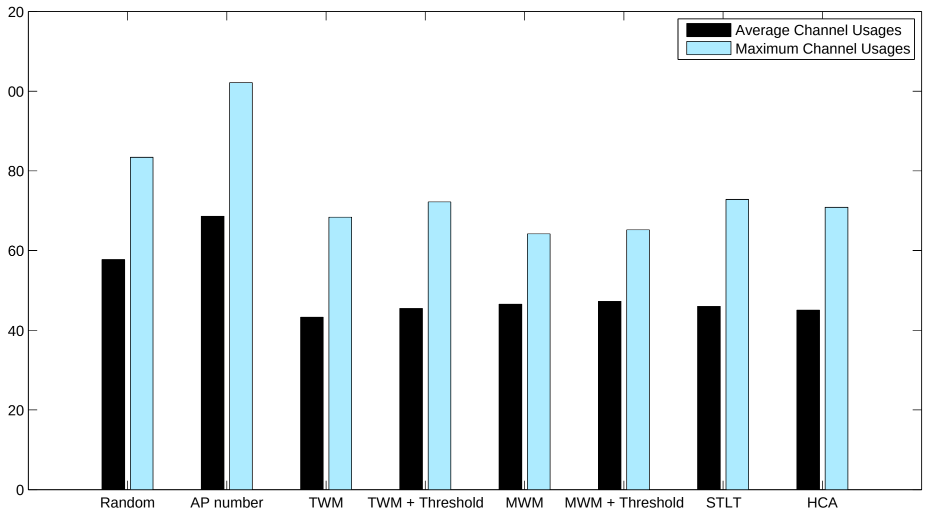

Figure 4.10. Average and Maximum channel usages for a single AP-Client pair with respect to the algorithms

We can see the real benefit of our algorithms in the channel switching rate graph in Figure 4.11. Random method switches the most, while AP minimization does not switch channels because of the fixed number of stations assumption. The benefits of the thresholding mechanisms can also be observed in the graph. MWM and TWM's channel switching rates are three times more if they do not use thresholds for performance checks. HCA could do as well as MWM, while STLT achieves the least channel switching rate, because it also checks the long term information about the channel and chooses the channel with the least used in the past. Figure 4.12 shows the percent of

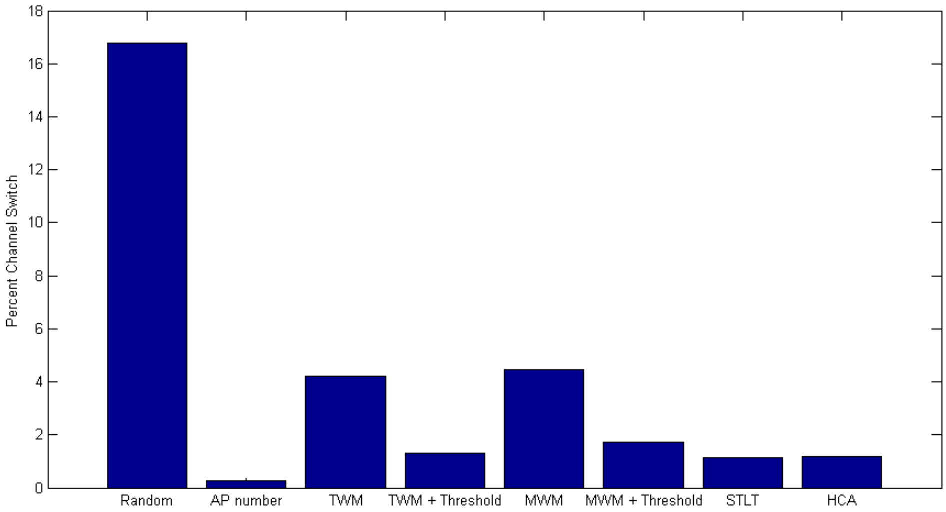

Figure 4.11. Channel Switching requirement percentage for a single AP-Client pair with respect to the algorithms

turns, that the average channel usage is over the threshold value. Random method has done relatively well, with the cost of frequent channel switching. TWM and HCA gave better results compared to the others.

Finally, when we apply our cost function on the simulation results, and observe the bar graph in Figure 4.13, we can examine that our two algorithms minimizes the cost function better than the other algorithms. STLT uses the past information and can choose a channel in which there will be less need for channel switching. HCA has done slightly better and with thresholds, channel switching is minimized and with the combination of TWM and MWM, minimum channel usages are obtained.

4.6.2. Algorithm for Mesh Network

Now the same algorithms will be applied on mesh networks of more than one APs and clients. All the elements of the single-radio mesh networks operate on the same channel. Therefore, measurements of all stations are needed to be transmitted to a central AP and the channel is selected there.

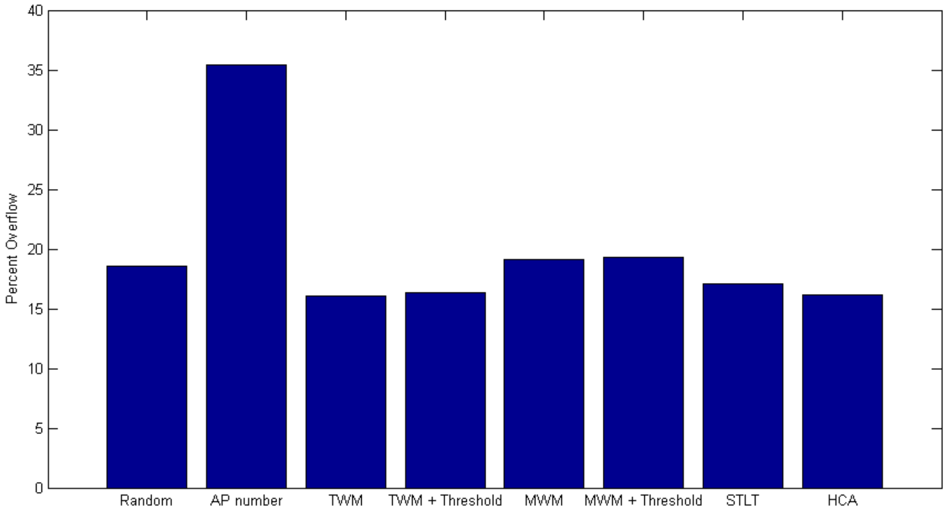

Figure 4.12. Occurrence percentage of overflow channel usage for a single AP-Client pair with respect to the algorithms

In the simulations, 8 mesh stations take measurements and combine them. This time there are 14 neighbors that create traffic and result in increased channel usage. Again each mesh station is affected from a specific part of the neighbors and the channel usages of neighbors change after each turn. The central AP checks the channel switching need after each turn and all the mesh elements switch to the determined channel together. The simulations are run for 100 turns and repeated for 10000 times to get an average. The same comparison criteria are applied and results are shown in Table 4.2.

When compared, it can be observed from the Figure 4.14 that TWM minimizes the total channel usage and MWM minimizes the maximum channel usage better than other algorithms. Again our algorithms have achieved between the two, while STLT has done slightly better than HCA. For the single AP case, HCA was better than STLT, while here STLT can minimize the channel usage better than HCA.

Similar results are achieved for channel switching rates, which are shown in Figure 4.15. Thresholding mechanisms are again beneficial, they cause less channel switches for TWM and MWM. Our two algorithms perform better than the others considering

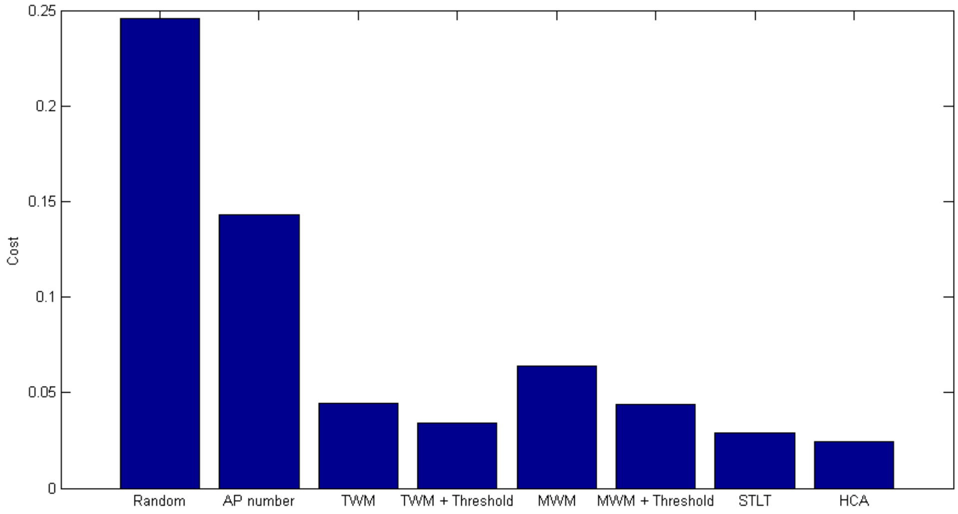

Figure 4.13. Cost value for a single AP-Client pair with respect to the algorithms

the channel switching rates, STLT causing the least number of channel switches. Again this is because STLT makes its decision based on both the recent measurements and the historical behavior of the measurements. STLT and HCA could also decrease the overflows nearly as well as TWM as can be observed in Figure 4.16. Random allocation also performs well considering the overflows, because its ultimate purpose is to hold the channel usage under the threshold.

Finally, if the cost function results are compared as in Figure 4.17, it can be seen that STLT and HCA could minimize the cost function better than the others. STLT is the best performing algorithm for mesh networks. For the single AP case, it was the HCA algorithm. Therefore, we can conclude that for a single AP, HCA algorithm can be chosen, while for mesh networks, STLT is the algorithm that should be preferred.

Table 4.2. Comparison of different algorithms for a mesh network

Mesh	Avg. Usage	Max. Usage	%change	%overflow	Cost
Random Method	68.15	130.31	10.86	11.88	0.2334
AP Minimization	65.12	133.68	0	32.04	0.1239
TWM	53.63	118.74	4.35	21.51	0.097
TWM + Threshold	55.64	122.67	1.31	22.28	0.0864
MWM	61.95	109.75	4.99	29.14	0.1449
MWM + Threshold	60.73	108.75	1.98	28.17	0.1102
STLT	54.58	120.22	1.14	21.85	0.0717
HCA	56.25	123.6	1.22	22.54	0.0764

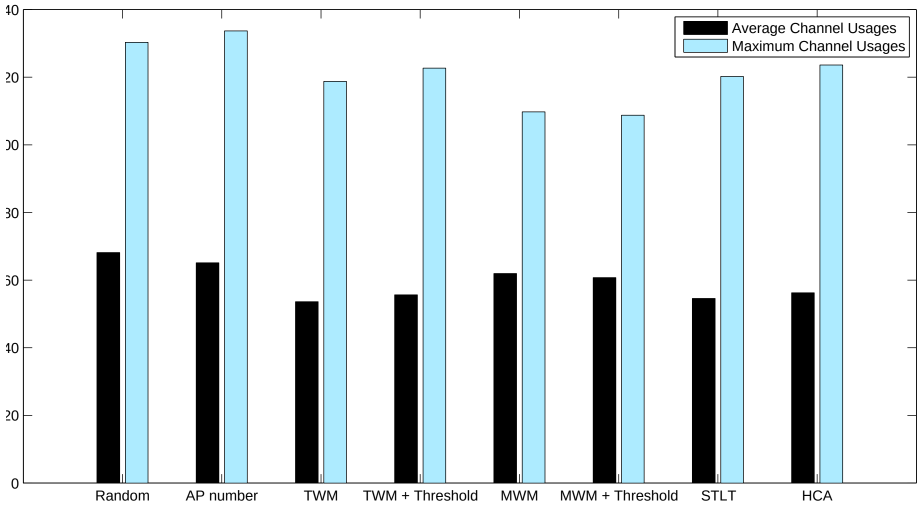

Figure 4.14. Average and Maximum channel usages for a mesh network with respect to the algorithms

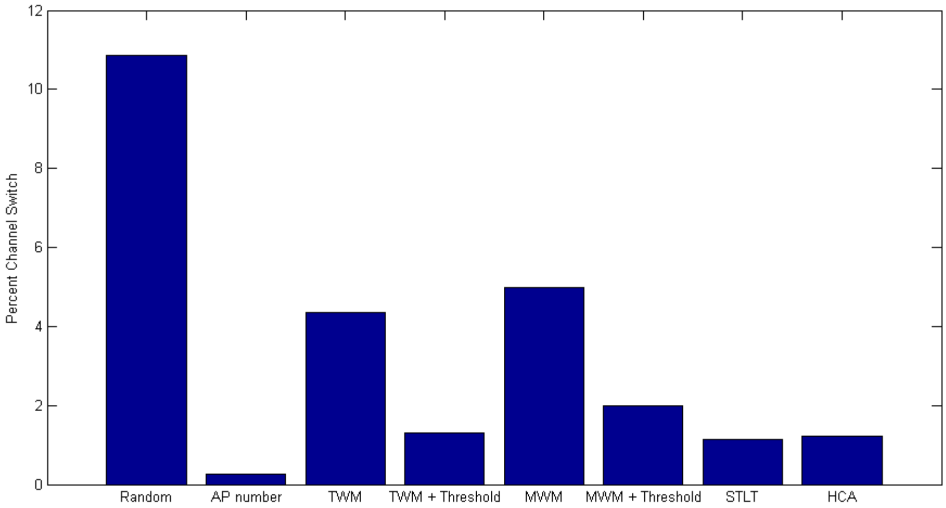

Figure 4.15. Channel Switching requirement percentage for a mesh network with respect to the algorithms

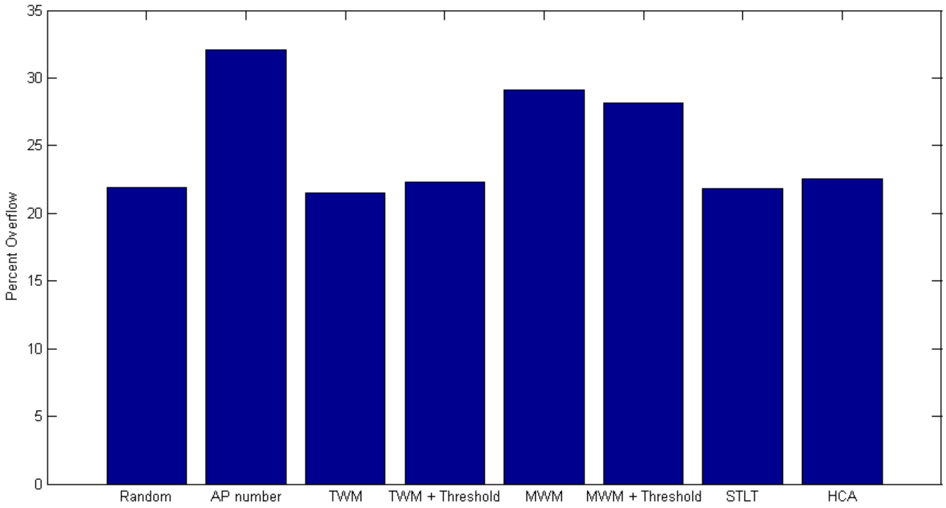

Figure 4.16. Occurrence percentage of overflow channel usage for a mesh network with respect to the algorithms

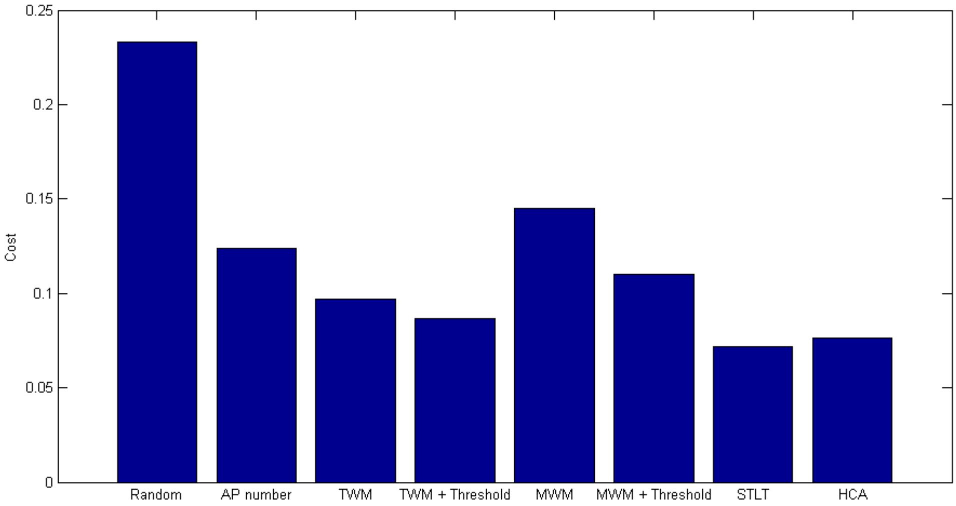

Figure 4.17. Cost value for a mesh network with respect to the algorithms

5. CONCLUSION

In this thesis, we have developed a channel allocation system for mesh networks realizing video communication. Our system is built on 802.11n standard, which provides more available channels both in the 2.4GHz and the 5GHz band. Although the proposed system is composed of several steps, we have focused mainly on three steps: measurement processing, decision to change the channel and determining the optimal channel.

Measurements used in the system are channel usage values, scaled between 0-255, that determine the percentage of the channel that is busy. In our system, these measurements are taken for each channel and processed using Kalman Filter. For low-variance measurements, Median Filter increases the performance of the system. Therefore, an adaptive version of the Median Filter is applied.

Determining the most suitable channel to be switched to is handled by two proposed algorithms. Hybrid Channel Allocation (HCA) algorithm proceeds step by step: First, it minimizes the number of stations over a certain threshold T_{high}, then the maximum channel usage measurement and finally the total channel usage measurements in order to eliminate packet losses. The Short Term - Long Term (STLT) Algorithm accounts both recent channel usage levels and the situation of the channel in the long run, thus tries to eliminate the need of channel switches in the future. We compared these two proposed mechanisms with the channel allocation solutions in the literature and showed that our algorithms can minimize both channel usage measurements and the number of required channel switches.

Frequent channel switches degrades the throughput, because the central AP has to achieve the coordinated channel switching with the other APs and clients, which creates a time interval without a transmission. Therefore, channel switching should be controlled by the use of some thresholding mechanisms. In our system, channel switching decision is taken only if the channel usage measurements in the current channel are over a certain threshold and if the difference of channel usage measurements between the candidate channel and the current channel is over a specific hysteresis level. The positive effect of these thresholding mechanisms has been demonstrated via the simulation results.

The proposed channel allocation system can be combined with power control schemes and/or efficient AP placement algorithm in order to achieve more intelligent systems. This joint optimization problem and its application in WLAN networks transmitting video is open to investigation.

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