Evaluation of Modulo in a Multi-Channel 802.11 Wireless Network

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Abstract - *Since the introduction of the IEEE 802.11 standard, researchers have moved from the concept of deploying a single channel and proposed the utilisation of multiple channels within a wireless network. This new scheme posed a new problem, the ability to coordinate the various channels and the majority of the proposed works focus on mechanisms that would reduce the adjacent channel interference caused by the use of partially overlapping channels. The proposed idea in this paper borrows the concept of network segregation, firstly introduced for security purposes in wired networks, by dividing a wireless network into smaller independent subnetworks and in collaboration with a channel assignment, the Modulo. Modulo defines a set of rules that nodes should obey to when they transmit data. The utilization of multiple channels under the guidance of Modulo for each subnetwork, proves to improve the performance of an ad-hoc network even in noisy environments.*

Keywords: networks, ad-hoc, interference, segregate networks, modulo, throughput.

1 Introduction

Ad-hoc wireless networks provide a means of networking together groups of computing devices without the need for any existing infrastructure. Devices automatically form a network when within range of each other, and also act as routing nodes by forwarding any packets not intended for them.

A single channel for transmission is not always enough and in high traffic routes, a single channel device can create more problems than it can solve. Common problems with wireless networks are interference, multipath and attenuation. All these prevent the wireless networks from performing to their maximum capabilities. Places and environments, which accommodate all the above-mentioned problems, make the existence and deployment of wireless LANs highly restrictive.

In this paper we examine the impact of utilising multi-channel technology within a legacy 802.11g network. Our target is to investigate the performance of segregated multi-channel mesh network and a simple, single channel wireless network - WLAN. The term segregated means that the network is divided into smaller subnetworks and each one operates at different frequencies than others.

2 Literature Review

Node placement and deployment play a crucial role to the network stability and performance. During node placement, variable environment characteristics such as sources of interference and area morphology like physical obstacles and constructions should be taken seriously into consideration. This way it is easier to adjust the deployed wireless network to those needs, achieving maximum operability and performance.

2.1 Channel Assignment Algorithms

To reduce interference, neighbouring nodes should operate in different frequency channels. For example the IEEE 802.11b standard for wireless LANs can operate simultaneously in three non overlapping channels (1, 6 and 11) [1] without each node to interfere with each other. During our testing we used the multi-hop infrastructure which has been proved [2] to overcome many problems of the single-hop networks.

In the multi-hop infrastructure, a node may find many routes to access different access points, potentially operating on different channels. Kyasamur and Vaidya So et al. [3] proposed a routing and channel assignment protocol which is was based on traffic load information.

The proposed protocol successfully adapted to changing traffic conditions and improved performance over a single-channel protocol and one with random channel assignment

Bahl et al. [4] suggested a link-layer protocol called SSCH that increases the capacity of an IEEE 802.11 network by utilizing frequency diversity. Nodes are aware of each other's channel hopping schedules and are also free to change their schedule.

Raniwala et al. [5] developed a wireless mesh network architecture called Hyacinth. This architecture equips each node with multiple IEEE 802.11a NICs supporting distributed channel assignment/routing to increase the overall throughput of the network. Apart from that, there are other proposals [6] and [7] which in fact require proprietary MAC protocols. They propose something like a packet-by-packet channel switching which resulted in an increased time per transmission. More MAC modifications were proposed in [8] to support beamforming, whereas [9] and [10] required a separate radio to communicate firstly with the neighbours and then start transmission. These approaches are under utilizing a channel just for configuration set up whereas it could be used in a more efficient and useful way.

3 Systems Architecture & Evaluation

In the case of an industrial environment, the problems can be more persistent and result in really bad quality of service even of no service. The problem of broken links has been mainly encountered by the deployment of multi-channel networks.

Range is crucial during deployment and operation as it defines and the amount of wireless nodes that should be used for the full coverage of the required area. In wireless networks the number of the devices deployed can have advantages and disadvantages. The main advantage is the best signal coverage throughout the area. On the other hand the main disadvantage is the appearance of interference between the operating wireless nodes. Interference comes into two forms, the co-channel interference (CCI) for devices operating in the same frequency [11] and the adjacent channel interference (ACI) when nodes operate in different frequency spaces [12] but they are close enough to each other

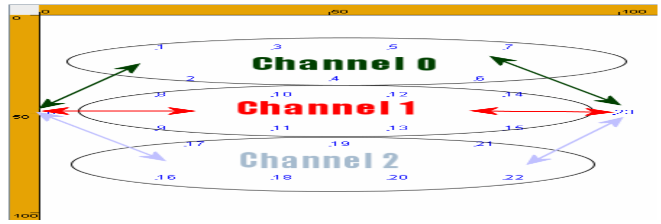

Fig. 1 A sample of a 24 node segregate network using three different channels.

Throughout the experiments that take place we assume that there is no limit to the number of channels that can be used. Although IEEE802.11 sets a limit to the available channels, in our case we emphasize on a more standard independent approach able to operate in all available technologies.

In previous approach [13], we showed that by segregating a network we can achieve better network performance. Current target was to improve further by using more channels inside the segregated network. There are three main steps to achieve that. The first step was to simulate a single channel network, then to divide the network into a variable number of subnetworks and use one different channel for each subnetwork and finally the multichannel approach by using more than one channel within each subnetwork.

3.1 Single channel network

This is the simplest form of a wireless network. A number of nodes able to relay data from one side to the other by using one channel only. This approach is used only for benchmark reasons in order to be able to decide if any improvement has been achieved. Routing protocol used is the Ad hoc On-Demand Distance Vector (AODV) [14] in a standard mode, no multichannel enabled.

3.2 Segregate network using single channel

The approach is the same as explained in figure (1) and figure (2). It should be made clear that nodes don't always follow the configuration given in figure (1) as they are usually placed randomly in the simulated area.

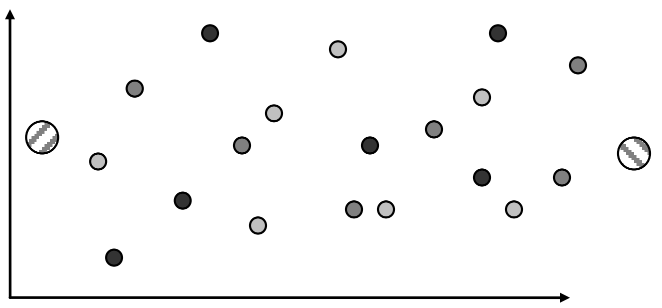

Fig. 2 A segregate network of 21 nodes. The side nodes operate in all the three channels available. All the rest nodes operate in different channels as separated from their colors.

We start dividing the network into smaller subnetworks and watch if there is improvement over this segregation. Channels are randomly chosen during transmission by the edge nodes, whilst inside each subnetwork since there is only one channel operating and the routing is done using AODV multichannel enabled [15] in both cases.

The best way to describe a segregated network is with the help of the parameters that affect it. First, we call S the segregated network, n the total number of nodes, g the number of subnetworks and finally k the number of channels for each subnetwork, which in this scenario is always equal to 1, then S would be expressed as:

$$S\ (n,g,1) \tag{1}$$

3.3 Segregate networks using modulo

In this case, each subnetwork is operating into more than one frequency channel. Again the frequencies in one subnetwork $\{k1,\ k3,\ k5\ \ldots k_n\}$ differ from the frequencies operating in the other $\{k2,\ k4,\ k6\ \ldots k_{n+1}\}$. Again, the number of channels existing in one subnetwork will be the same to all the rest. Based on equation (1), for the current case, the total number of channels T_k equals to,

$$T_k = g * k \tag{2}$$

and the number of available nodes within every subnetwork

$$T_n = n / g \tag{3}$$

The increase rate of the delay is reduced as the network is segregated into more subnetworks due to the smaller density λ of nodes that operate in the same channel. Take a single channel network where all nodes operate on the same frequency, when segregation is applied, the density λ of nodes operating on the same channel within a unit area is decreased. Let T_N be the number of nodes listening to the same channel and α the size of the simulated area then λ would be expressed as in equation (4)

$$\lambda = (T_N/g)/\alpha = T_N/(\alpha * g) \tag{4}$$

The density of a single node network λ_s with transmission range R_{tx} is

$$\lambda_S = 1/\pi R_{tx}^2 \tag{5}$$

From equations (4) and (5) we define the density and the number of segregate networks to maintain connectivity between the nodes of each segregate network

$$\lambda \geq \lambda_S \Rightarrow \lambda \geq 1/\pi R_{tx}^2 \Rightarrow T_N/(\alpha * g) \geq 1/\pi R_{tx}^2 \Rightarrow \Rightarrow g \leq T_N\ \pi\ R_{tx}^2 / \alpha \tag{6}$$

The limitations of density λ are demonstrated in figure (6).

With the introduction of multiple channels inside each subnetwork, modulo was utilised to coordinate the channel assignment decisions of each node. The switching technique is based on modulo algorithm [16] shown in figure (3).

A node, upon receiving a data packet on a channel k, transmits it on the next channel $k+1$, where $k+1$ is next channel greater than the current one in rank. In general, the channel that is in use at hop h, given a starting channel k and e channels available can be expressed as:

$$f n = (n+k) \bmod c \tag{7}$$

A graphical representation of the modulo technique is shown below.

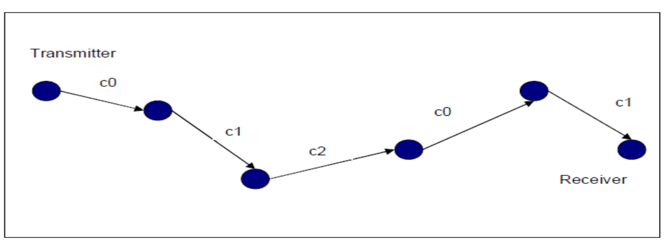

Fig. 3 Modulo channel allocation using three frequency channels.

Modulo adopts a store and forward packet transmission mechanism for every single packet that travels through the multi-hop path defined by AODV [12] and this mechanism is shown in figure (4).

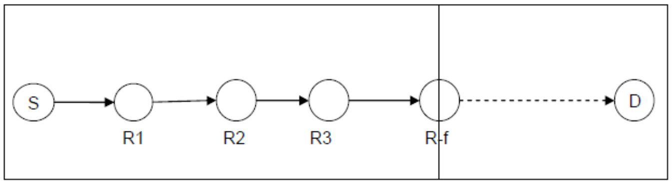

Fig. 4 Modulo channel allocation using four frequency channels.

S is the source node, *D* is the destination node and all the rest are the intermediate nodes between source and destination. *R-f* is the last node that interferes with the transmission of *S* and after the *R-f* node all remaining nodes can transmit using the same frequency with *S* without interfering. The position of *R-f* depends on the transmission range and the location of *S*.

Let denote T_h the transmission time between two adjacent nodes as *R1* and *R2* or *S* and *R1* and let assume that there are *m* chain nodes distributed randomly within the subnetwork of a segregated network $S(n, g, k)$, where g is the number of segregated networks and k the number of channels in each subnetwork. The value of m is a number smaller or equal to the number of member nodes of a single subnetwork.

$$m \leq n / g \quad (8)$$

The source station is sending N_p number of packets of length L (bytes). The packet may be segmented into fragments F with each fragment being acknowledged by an acknowledgement packet A. If no acknowledgment is required, then a fragmentation is not required and L is equal to A. With S being the only injection of traffic source, the end-to-end delay is,

$$T = (m+1) * \mathrm{T_h} \quad (9)$$

The total transmission time T_S of N_p packets will equal to,

$$T_s = m * T_h + (N_p + f(\left\lceil \frac{N_p}{k} \right\rceil - 1)) * (T_h + T_a) \quad (10)$$

where T_h is the transmission delay for one packet within a single hop, T_a is the transmission delay of a single acknowledgment packet (34 bytes), f describes R-f as explained above, k is the number of channels utilised in the subnetwork. Equation (10) shows the dependency between the number of packets that have to be transmitted, the amount of channels utilised within each segregate network and finally the interference range. This equation applies to every segregate network separately and not to the whole network. The upper limit indicator ensures that the outcome of the division between N_p and k is always an integer. Since modulo technique is trying to achieve concurrent transmissions in a chain of nodes, the maximum achievable number of these concurrent transmissions are related to how many packets have to be sent. The number of channels which are available and how many of them will actually be used is related to the interference range *f*. Consider the scenario where four packets have to be transmitted, there are two channels available the interference range is equal to two and the total nodes in the chain equals to eight. Equation (10) shows that once the first two packets are transmitted, they should be two hops away with the aim of achieving another two concurrent transmissions for the next packets in the queue. Having eight nodes in the chain, modulo can achieve four concurrent transmissions of the four packets. If interference range was larger than two, then the concurrent transmissions for the whole length of the chain would be less.

Finally, the capacity $\mathrm{C_s}$ of the transmission measured in packets/second is calculated as,

$$\mathrm{C_s} = \mathrm{N_p} / T_S \quad (11)$$

Each time *S* transmits a packet to node *R1* on channel k, the packet is stored temporarily in the node and an acknowledgment (ACK) is sent to the source node. Once the ACK is received, the packet is transmitted to node *R2* on channel $k+1$ and at the same time node *S* sends the next packet to node *R1*. This way all nodes can transmit simultaneously only if there are enough available channels for utilisation. If there are only two channels available then only two nodes can communicate simultaneously. The transmissions of ACKs don't affect the network's performance as long as multiple channels are used.

4 Methodology

Some of the scenarios presented and investigated in this paper are difficult to investigate and deploy in the real world, thus the best way to gather information is through mathematical analysis simulations performed using one of the network simulators available. The simulator used is

GlomoSim v2.03 [17], a well known widely used and free to use tool able to simulate wireless and wired networks systems. It has been designed using the parallel discrete-event simulating capability provided by Parsec.

5 Results

First of all we start with the simulation results of a wireless network using just one channel, the most basic form of a wireless network, without any segregation. It should be made clear that only delay is presented and evaluated at the moment, due to the big variety of the scenarios. Next, there is a mathematical analysis and evaluation of the modulo approach based on equations (10) and (11). For given scenarios we test the validity of our mathematical model against previously published results that were based on simulations results. The following figures confirm our previous simulations based results [18] [19] [20] and satisfy the design purpose of modulo.

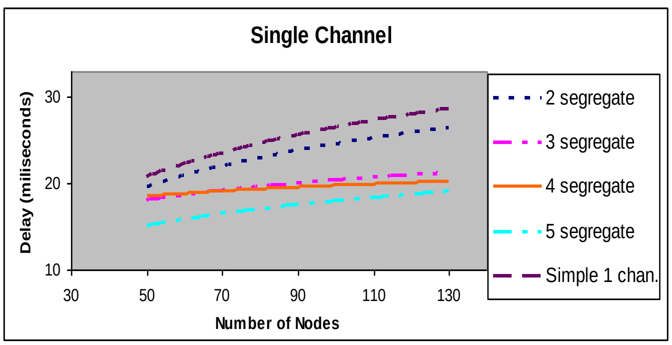

Fig. 5 The average delay of the networks for a variable number of nodes.

As we can see from figure (5), the segregate network operates quite well and overcomes in terms of delay the basic configuration. Something that was expected as it operates in a single channel, thus interference and the luck of multiple routes increases the delay. This first, figure (5), is the base for the comparisons for the segregate network using modulo.

The following results are based on scenarios trying to calculate the transmission time T_S and capacity C_S improvements that modulo offers within a segregated network utilising multiple channels. Consider the scenario where there is a chain of nodes for variable numbers of transmitted packets N_p and variable utilised channels k.

The rate of transmission is set to 11Mbps, and initially m is set to 6 nodes and f equals to 4 nodes, although this values may change for comparison reasons. No ACKs are required and a single packet is 1375 Bytes long, resulting to a T_h of 1 millisecond and finally N_p gets values of 6000, 9500 and 13000 packets respectively.

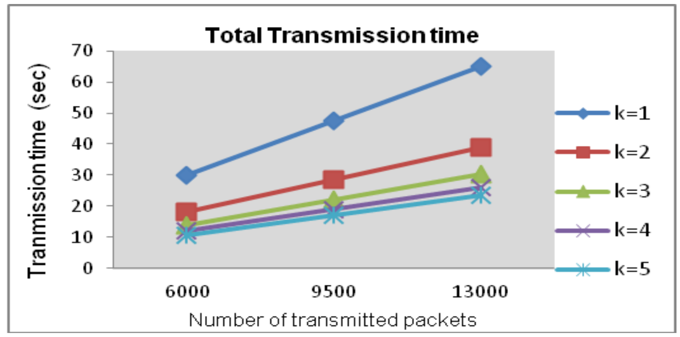

Fig. 6 Transmission time improvement over utilised channels for f=4 and m=6.

Figure (6) presents the improvement of the total transmission time of a single chain of nodes utilising variable numbers of channels while f is equal to 4 nodes and there are 6 nodes in the chain used for the transmission. With the utilisation of a second channel in the chain, the transmission time is improved significantly, and this improvement continues with the addition of extra channels, although with a smaller rate. At the end, with the use of 5 channels, T_S has achieved an improvement of 45 seconds over the single channel scenario when N_p = 13000.

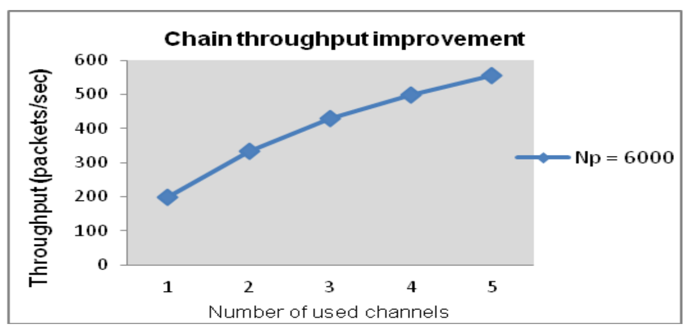

Fig. 7 Chain throughput improvement for f=4 and m=6.

Figure (7) presents the improvement of the throughput of a single chain of nodes utilising variable number of channels while f equals to 4 nodes and there are 6 nodes in the chain used for transmission. By adding extra channels the capacity of the chain is increased following the same rate as the transmission time. For = 6000, there is an increase of 255 packets/sec when 5 channels are utilised within the chain. The same is trend is followed for N_p = 9500 and N_p= 13000

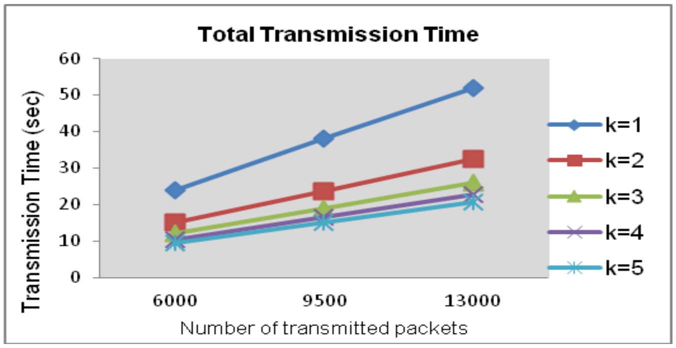

Fig. 8 Transmission time improvement for f=3 and m=6.

Figure (8) presents the improvement of the total transmission time of a single chain of nodes utilising variable numbers of channels while *f* is equal to 3 nodes and there are 6 nodes in the chain used for the transmission. With the utilisation of a second channel in the chain, the transmission time is improved significantly, and this improvement continues with the addition of extra channels, although with a smaller rate. At the end, with the use of 5 channels, T_S has achieved an improvement of 45 seconds over the single channel scenario when N_p = 13000.

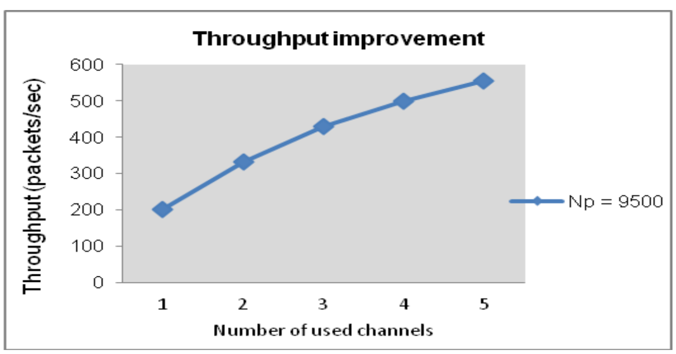

Fig. 9 Chain throughput improvement for f=3 and m=6.

Figure (9) presents the improvement of the throughput of a single chain of nodes utilising variable number of channels while *f* equals to 4 nodes and there are 6 nodes in the chain used for transmission. By adding extra channels the capacity of the chain is increased following the same rate as the transmission time. For N_p = 9500, there is an increase of 255 packets/sec when 5 channels are utilised within the chain. The same trend is followed for N_p = 6000 and N_p = 13000.

The next figure, figure (10) shows the improvement to the transmission time as *f* is further reduced to only two 2 nodes away. The reason behind this is the smaller amount of interference. If we deploy more than 3 channels within the same chain, the rate of improvement is reduced significantly and this indicates that any extra channels do not offer any great benefits.

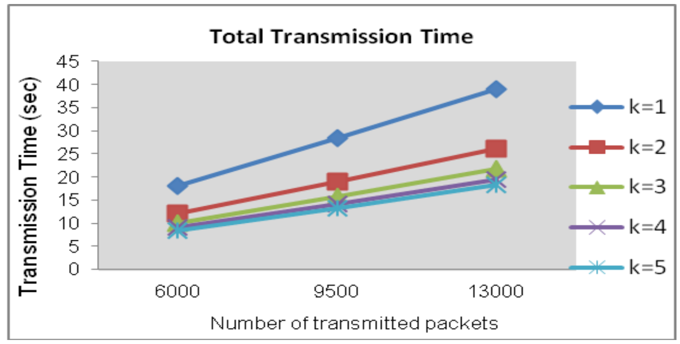

Fig. 10 Transmission time improvement for f=2 and m=6.

Throughput is further improved as it happened in the last two scenarios and modulo now achieves throughput of more than 710 packets/sec. This improvement is shown in figure (11) for N_p = 13000.

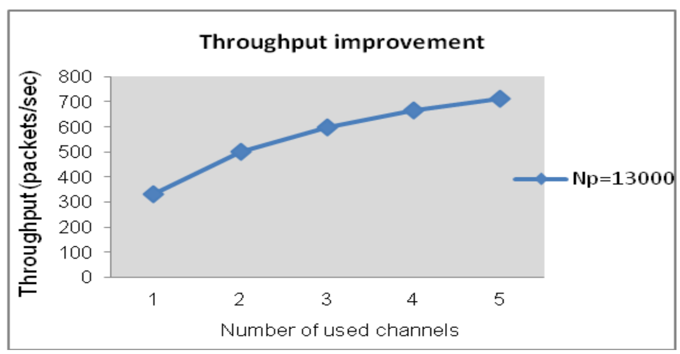

Fig. 11 Chain throughput improvement for f=2 and m=6.

6 Conclusion and Future Work

In this paper we evaluated the performance of a wireless network that is divided into smaller subnetworks and these utilize a variable number of frequency channels. The findings from the proposed theoretical approach show that when nodes are deployed in a chain topology, as it is performed in a segregated network, the use of extra channels for switching from hop to hop reduces the total transmission time for a number of packets N_p and consequently increases the throughput of the chain. When multiple chains are deployed using different channels then the improvement of the throughput is multiple. Apart from the utilised channels, the reduction in the transmission range of the nodes improves significantly the chain’s throughput. This reduction of the transmission range has a double positive impact, as less power is required for transmission and more packets can travel through the chain by using less energy.

Future work plans include the intention to move away from the legacy IEEE802.11 standards such as 802.11b and 8002.11g and start examining the efficient spectrum use of the new IEEE standards such as 802.11n [21] and 802.11ac [22]. When 802.11b/g were introduced there were no plans for any MIMO support by utilising multiple channels within the same network. The future of wireless communications is heavily depending on more competent spectrum management and utilisation of existing available frequencies.

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