A multiple channel selection and coordination MAC Scheme

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Abstract - **The realization that single channel MAC protocols do not offer adequate end-to-end throughput has prompted researchers to explore more scalable approaches such as multi-channel MAC protocols. Multi-channel MAC protocols implementing a dedicated control channel offer promising solutions. However, it has been suggested that the use of a single control channel may lead to saturation problems. The saturation problem needs to be investigated. The paper proposes a cyclic scheduling algorithm, which schedules data transmission in phases. The scheme reduces the signalling overhead of the control channel and improves its capacity by reducing the effects of the channel switching delay and the idleness of the control channel. The scheme is connection oriented and implements the services of a network support systems, which provides the network with the required intelligence for data channels reservation. The scheme takes advantage of the integration of mesh routers and mesh clients in an overlaid wireless mesh networks (WMN). Mesh routers are also deployed in the ad hoc network of mesh clients to act as a network support backbone. The mesh routers forming the network support backbone are assumed to be within the communication range. We first analyze the control bottleneck problem of the proposed scheme as a channel selection and coordination problem requiring an effective channel scheduling technique. The scheduling techniques should be designed to minimize the effects of channel switching penalty on the control channel. The techniques should also increase the scheduling capacity of control channel. A single dedicated channel with at least two data channels and one transceiver system was considered in the analyses. The capacity of a single control channel is investigated as the number of data channels is increased from two to fourteen. Channel saturation is observed on data channels. Analytical results show that a single dedicated control channel causes no bottlenecks. Its capacity is affected by the saturation of data channels. The proposed scheme was also evaluated through NS 2 simulations. The numerical results show that the scheme is effective in reducing the signalling overhead.**

Keywords-Channel bottleneck, Channel coordination, Channel saturation, Channel selection, Connectivity, Multiple Channel MAC

I. INTRODUCTION

The paper analyzes multi-channel MAC protocols, which implement a dedicated control channel. The motivation is to establish the effects of channel saturation on the performance of the network and the causes of the saturation problem. The choice of multichannel schemes, which employ a dedicated control channel as a single signalling channel was motivated by the ability of these schemes in ensuring total network connectivity. The schemes under this category do not segment a network into logical segments.

A scheme, which implements one transceiver, a dedicated control channel, and at least two data channels is proposed. The proposed scheme facilitates network connectivity and is designed to use network resources efficiently. The saturation levels of channels are first investigated including the capacity of the control channel. The study seeks to establish through analytical means whether a dedicated control channel is a bottleneck in multi-channel systems. It also investigates how channel switching penalty can be employed effectively in improving the capacity of a control channel. The proposed scheme also attempts to reduce the idle periods of the control channel with a view of increasing its scheduling capacity.

The proposed a multi-channel scheme schedules flows on data channels in cycles. The scheme incorporates channel switching delay. Thereafter, through analytical means, the paper studies the effect of the saturation problem on both control and data channels. Key to the analysis is the capacity of the control channel as the number of data channels is increased steadily from two to fourteen. The paper tries to establish the soundness of this approach through analytical and simulations.

The rest of the paper is organized as follows: the need for a new multi-channel MAC scheme is discussed in Section II and related works are highlighted in Section III. The model is presented in Section IV and Section V presents the analytical results. The effectiveness of the proposed scheme is evaluated in Section VI. The simulation model and the numerical results are presented and discussed in Section VII. Section VIII then concludes the paper.

II. MOTIVATION

Multi-channel MAC schemes have a potential of increasing the capacity of current wireless access technologies. A number of multi-channel MAC protocols show that this increase in capacity is possible. However, channel selection and coordination needs to be addressed if the full potential of multi-channel schemes is to be realized. The multi-channel MAC protocols, which implement a dedicated control channel architecture, are promising as they facilitate total network connectivity.

Furthermore, a single transceiver system employing two data channels and one dedicated control channel has been investigated elsewhere. The saturation of the control channel did not impact severely on the performance. It was established that the control channel can support a reasonable number of data channels. However, channel switching penalty has not been adequately considered in channel coordination and in multi-channel selection. Its effect has not been considered in the context of data channels degradation and how it increases the scheduling capacity of a dedicated control channel. When data transmission is scheduled in cycles, it is possible to minimize the effect of channel switching delay and to improve the capacity of the control channel.

III. RELATED WORK

In this Section, multi-channel MAC protocols, which employ either a temporary or a dedicated common control channel, are reviewed. The evaluation focuses on the efficiency of MAC protocols in reducing the signalling overhead of the control channel and how they improve the scheduling capacity of the control channel.

In [1] a temporary signalling channel called a default channel is implemented. Nodes reserve data channels during the ATIM window through the default channel. The reservation of the data channels is done through a data structure called the Preferable Channel List (PCL). Nodes exchange the ATIM/ATIM-RES/ATIM-ACK packets during the ATIM window and then the RTS/CTS packets during the data window to reserve one of the data channels. The signalling duration is long and its overhead cost is too high. All the signalling packets have been increased in size. These challenges impact negatively on the efficiency of the control channel and its scheduling capacity is reduced. During the ATIM window, only the default channel is used while all the data channels lie idle. The bandwidth of the data channels is therefore, wasted during the ATIM window.

In [2] a temporary common signalling channel is implemented during the control window. One data channel is selected by a number of pairs thereby increasing the probability of data collisions. The sizes of all the control packets have been increased, which degrades the performance of the control channel and reduce its capacity to support many data channels. There is also an additional signalling packet called the reserve (RES) packet, which increases the signalling payload of the scheme. The protocol is similar to [1] and it suffers from similar constraints. The bandwidth of data channels is also wasted during the control window.

A multi-channel MAC scheme employing a dedicated control channel is proposed in [3]. The reservation of data channels is done through the control channel with an aid of the local channel tables. If a pair fails to reserve a data channel, they are given a second chance to reserve a free data channel. Assuming that all pairs succeed in their second attempts, a significant control channel overhead will be incurred. The nodes also defer for a DIFS and for the multi-channel switching durations, which erodes the capacity of the control channel. The reservation of data channels is done when the current transmissions have ended. Unfortunately, the control channel lies idle for fairly long durations, which can be reduced to improve its capacity. The bandwidth of the control channel is wasted when data frames are being transmitted on the data channels. On the other hand, the bandwidth of data channels is wasted as they are queued at the control channel waiting for their next transmissions.

The feasibility and functionality of the scheme is challenged in newly deployed networks and by the joining terminals. Joining nodes have to first set all the channels unavailable until they have updated their local channel tables. With inadequate network information, nodes will defer indefinitely their next transmissions. Nodes returning to the control channel are also equally affected as they have to set all the channels unavailable except the ones they have just visited. Nodes have to defer their transmission until they have acquired adequate information about the status of the network. This is not possible with a newly deployed network where all nodes have no knowledge of the network. In such a situation nodes will defer indefinitely their transmission resulting in a blocked network state. There will be no transmission that will take place, until nodes acquire adequate network information.

CTS packets reserves a data channel, unfortunately they fail to calm hidden nodes, which are in the sender neighbourhood. The probability of collisions and destroyed packets will increase forcing the scheme to retransmit a substantial amount of packets, which will further degrade the capacity of the control channel. Furthermore, nodes have limited processing power and storage capability and cannot process efficiently the local node tables and store the processed information.

The Dynamic Channel Assignment (DCA) [4] uses two transceivers, the control channel and the data channels transceivers. The use of two transceivers is expensive in terms of hardware costs. It also comes with increased design complexity. There is also a signal linkage problem where signals from the adjacent transceivers interfere with each other.

Each node keeps two data structures called the channel usage list (CUL) and the free channel list (FUL). Their use is similar to the three schemes above. The introduction of the RES packet also causes further delays. The control channel and the control channel transceiver will be idle when all data channel transceivers are busy on the data channels. The capacity of the control channel is therefore degraded. The bandwidth of the data channels is equally wasted when they lie idle waiting for the control channel to schedule data transmissions.

The scheme proposed in [5] also exploits the common control channel approach. Nodes listen on the common channel to synchronize their hopping sequences. Long signalling durations are experienced by nodes when they negotiate and share hoping sequences. Furthermore, nodes send RTR packets without sensing channels, which may results in RTR collisions. Frequent hopping involves a sizeable amount of channel switching delays, which may significantly degrade the performance of the proposed scheme.

In [6] a dedicated signalling channel is employed. The dedicated channel is also used as a data channel after the contention period. The protocol is divided into contention reservation interval (CRI) and the contention free interval (CFI). Nodes contend for network resources and data channels during the CRI and they all defer their transmissions until the beginning of the CFI. The deferment wastes resources and degrades the capacity of the signalling channel. The protocol requires global synchronization a challenge in wireless networks.

In [7] a system employing busy signals is proposed. A single channel is divided into a control and a data channel. Busy signals are sent on the control channel while data frames are being transmitted on the data channels. The scheme assumes that a node can send and listen at the same time. It also assumes that a node can transmit on two channels simultaneously. The major shortcoming of this scheme is the wastage of bandwidth of the control channel – the busy signal channel.

Nodes in [8] [9] randomly select independent home channels to listen on when they are idle. This approach segments a network and does not facilitate network connectivity for effective communication. The idea of data structures is also employed.

To address the problem of synchronization a guard time is implemented unfortunately the guard time degrades the performance of the protocol. On the other hand every packet sent should include a 32 bit current time and seed. The time stamp increases the payload of the protocol.

A new node, which has just joined a network, has to first wait for ten seconds before it establishes and follows its own hoping sequence. This waiting time increases the signaling overhead cost. Courtesy HELLO packets are also sent to newly discovered neighbours. The HELLO messages do degrade the performance of the protocol and may fail to reach all the nodes on different channels.

A scheme implementing a separate control channel and N traffic channels is proposed in [10] and in [11]. A CTS selects the clearest channel, unfortunately a CTS based data channel selection scheme fails to calm hidden nodes at the sender's neighbourhood as a result there will be numerous retransmissions, which will degrade the control channel. The size of the control packets has been increased. The enlarged packets will further degrade the capacity of the control channel.

The protocol assumes that nodes can sense all the channels and receive on all the channels simultaneously. Nodes can sense only one channel at a time and thereafter can switch to the next channel incurring very high overhead costs in both channel switching and channel sensing.

A multi-channel MAC protocol called dynamic channel assignment with power control (DCA-PC) is proposed [12]. However, it uses the same channel access and reservation mechanisms discussed in [4]. The proposed protocol therefore suffers from the same challenges.

The paper in [13] proposed a Distributed Queue Dual Channel (DQDC) scheme, which seeks to increase the utilization of the data channels and to increase the achieved throughput. The scheme implements the notion of a control channel however; the DQDC introduces a four way packet handshake negotiation scheme. The following packets are exchanged before a data channel is reserved: Mesh Transmission Opportunity Request (MTXOP REQ), Mesh Transmission Opportunity Response (MTXOP RSP), Mesh Transmission Opportunity Acknowledgment (MTXOP ACK) and Agreement Indicator (AID). A three way handshake is also possible when the receiver accepts the MTXOP REQ.

When the channel has been reserved, neighbouring nodes are notified through the AID, which is sent by the node receiving the MTXOP ACK. The AID is a broadcast message, which fails to reach nodes, which are currently transmitting on data channels and those, which are hidden from the AID broadcasting node. Returning nodes assume that the data channels are busy until they receive the reservation messages or after the expiry of a set threshold. This delays the next transmissions of the returning nodes and forces the control channel to be idle for longer time frames. Furthermore the signaling overhead is significant and it degrades the performance of the control channel. Nodes have to update their DQ each time they receive an AID or MTXOP ACK message. The DQ processing requires a node with unlimited processing power and storage capacity.

The signalling delay should be reduced further. As noted above, most multi-channel protocols suffer from high control channel overhead and wastage of bandwidth of both the control and data channels. These should be reduced to improve the scheduling power of the control channel and to increase its capacity. The idle durations of the control channel should also be reduced for improved control channel performance. The processing and storage constraints of mobile nodes should also be considered. A number of other multi-channel MAC protocols are discussed in [14] to [22]. The scheme proposed in [26] seeks to address these and other challenges of multi-channel MAC protocols, which employ the services of a control channel. A common control channel is presented as a driver that can increase the capacity of multi-channel MAC protocols.

IV. The Model

A Cyclic Scheduling algorithm (CSA), which is equipped with network support infrastructure, is proposed. The network infrastructure is designed to provide terminals with adequate network information, which is required for the reservation of data channels through the control channel. The main objective is to reduce the signalling overhead of the control channel and increase its scheduling capacity. The network support infrastructure is made up of a network of mesh routers overlaid in the ad hoc network of mesh clients. The mesh routers forming a network support infrastructure are called the NST nodes. Every NST node is within the communication range of the next NST node. The mesh routers are powerful and intelligent. Their communication ranges are wider and do cover as many mesh clients as possible.

The proposed scheme requires the services of a single transceiver and it divides the channels into one dedicated control channel and *n* data channels. The number of data channels should be at least two. The control packets, the Request To Send (RTS) and the Clear To Send (CTS) will be transmitted on the control channels. The data frames and the Acknowledgement (ACK) packets will the transmitted on the data channels.

Data transmission on data channels is scheduled in cycles when data channels are about to be free to improve the scheduling capacity of the control channel. The sending nodes will start contending for the control channel when the first channel is about to be free. A communicating pair reserves the next available data channel through the control channel. However the reservation and the handshake of control packets will be done before the data channel to be reserved becomes idle. Data channel reservation starts when the remaining transmission time of the current transmission on the data channel is exactly equal to the duration of the control channel handshake. The data channel will only become free as the new pair is switching onto the reserved data channel. The switching will be completed when the data channel is free. To ensure that the timing is perfect, an inter-cycle duration, which is a function of the number of data channels, is designed.

The switching penalty is considered in the design of our scheme. The nodes switch to the reserved data channel after the exchange of RTS/CTS. They do not defer for the summation of DIFS and the channel switching duration. When the acknowledgement has been sent, the nodes will switch back onto the control channel. Given this double effect of switching delay on data channels, a control channel is unlikely to result in a bottleneck. The scheduling capacity of the control channel is likely to improve as nodes take longer to return to it. The control channel will have more capacity to service the sender-receiver pairs, which are currently in the queue. The data channels may instead create a bottleneck in the system. The scheme takes advantage of switching penalty to improve scheduling capacity of a control channel. Carrier sensing and channel contention are limited to the control channel to improve the capacity of the protocol. Data channels are reserved thorough the network support infrastructure.

The inter-cycle duration will separate data transmission cycles and indicate when control channel reservation should start. Given the inter-cycle duration, the next pair will initiate communication on the control channel, exchange control packages and then switch onto the data channel while it is still busy sending data. The inter-cycle duration is the duration that separate two consecutive cycles. Its value varies with the number of data channels. It is an inter-cycle hold off duration whose value is determined by (3). The busy data channel will be expected to be free just before the next pair arrives on the data channel. The implementation of the network support infrastructure ensures that there are no retransmissions on the data channels. Retransmissions are possible on the control channel which implements the IEEE 802.11 channel reservation mechanisms.

In a given cycle the first pair to reserve the control channel will automatically reserve the first data channel; the second pair will reserve the next data channel while the last pair in a cycle by default will reserve the last data channel. There will be no contention required for the data channels however; the nodes have to contend for the access of the control channel. The cyclical scheduling algorithm will tie access to data channels to phases in a cycle to reduce the reservation duration and signalling overheard. Access to data channels will be linked to the reservation of the control channel. The access to data channels will be in phases within a cycle.

The pair, which wins the control channel in phase one will access the first data channel and in the N^{th} phase the N^{th} data channel will be reserved by the N^{th} pair. The cyclic scheduling algorithm will be memory based (network support) keeping track of all the activities of the data channels, cycles and phases within cycles. These details will be stored on the network support infrastructure of multitasking mesh routers in a hybrid Mesh network.

To explain further the concept behind the cyclic scheduling algorithm Figure 1 is employed. The diagram though not in scale is based on the length of control packets, channel switching duration of 224µs and the length of data packets as stipulated in the standard. The durations however, were changed to make them more manageable and easy to work with. For example short durations were scaled up while longer ones were scaled down. This manipulation of the durations only reduces the duration of the inter-cycle hold off time. However, the idea the paper conveys can still be appreciated.

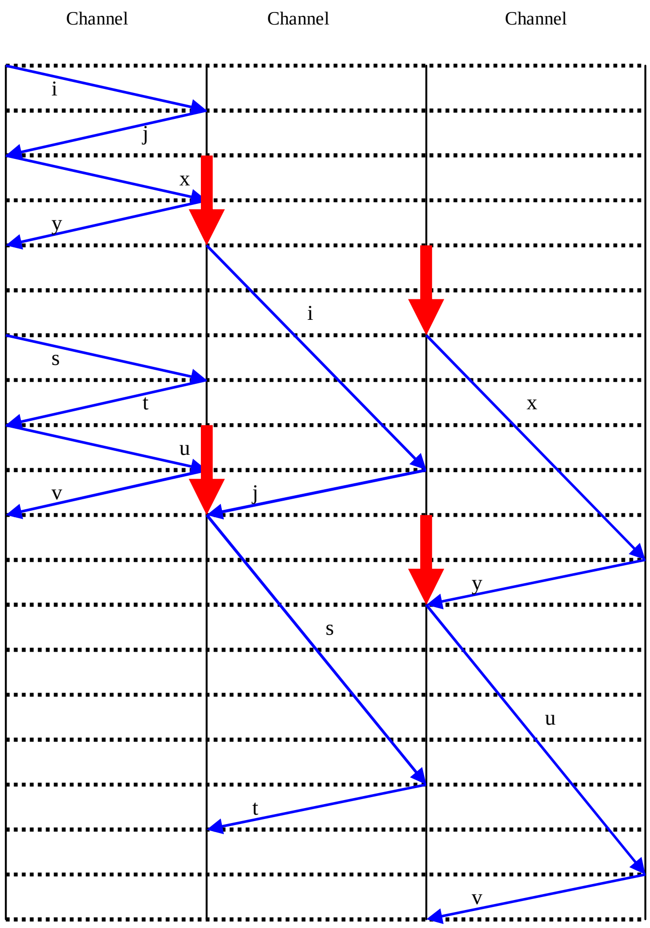

Figure 1. Packet switching analytical diagram.

Channel 0 denotes the control channel, while channels 1 and 2 are the two data channels. The red arrow depicts the channel switching delay. Lastly, the blue arrows represent data and control packets durations.

In Figure 1 the two communicating pairs (ij) and (xy) will automatically reserve data channels one and two respectively during the first cycle. After the first cycle terminals will back off for an inter-cycle duration to accommodate the switching delay and to properly mark the beginning of the next cycle. For a three channel system, the inter-cycle duration will be equal to the total transmission duration of a data packet plus two switching durations minus the summation of three control packets handshakes. The inter-cycle is computed using equation (3). During the inter-cycle duration, the control channel lies idle until the onset of the next cycle. The inter-cycle duration will reduce as more data channels are implemented, which improves the capacity of the control channel.

In the next cycle, the next pairs (st) and (uv) will reserve the two data channels while the previous two pairs are still communicating on the same two data channels. As the next pairs are switching to data channels, the first pairs will complete their transmission. The first pairs will then switch back to the control channel to wait for the next cycle if they still have data to send. The first pair in each cycle must reserve the first data channel. This rule ensures a collision free data exchange on data channels.

The design of the hold off duration and the channel coordination scheme is fundamental to the success of this scheme. In Figure 1 only channel switching delay to a data channel is depicted. The reverse channel switching delay is not shown in the diagram.

In Figure 2, RTS, CTS, DATA and ACK packets are presented in a form of a block diagram. It can be seen that this approach waste bandwidth in the data channels during the first cycle. This is caused by the switching delay and the use of multiple channels. We call this bandwidth wastage; the multi-channel scheduling cost (MSC). This degradation is not avoidable, but can be limited to the first cycle like in our case. The MSC has been eliminated in the subsequent cycles by our scheme. In the existing protocols, this cost is periodic and repetitive. The switching cost and the multi-channel scheduling cost are not evident in the subsequent phases as our cyclic scheduling protocol takes advantage of switching penalty coupled with the inter-cycle duration to schedule concurrent transmissions in a proactive manner. The multi-channel scheduling cost is first identified in [26] and is common with protocols implementing a common control channel.

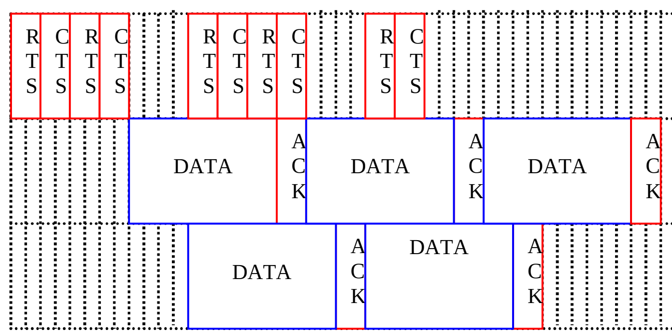

Figure 2. Packet scheduling block diagram.

To calculate the amount of wasted bandwidth caused by the multi-channel scheduling cost in our scheme, the following *for loop* can be implemented:

```
for (i =0; i <= n; i++)
    x += i;
Wasted bandwidth = x * handshake duration;
```

This cost is limited to the first cycle in our scheme and its value depends on the number of data channels *N*. As the number of data channels is increased, the multi-channel scheduling cost will increase as well. In the earlier protocols discussed in the related section, the effect of the multi-channel scheduling cost is repetitive.

To evaluate the proposed scheme an analytical model was designed to model channel occupancy and investigate the capacities of control and data channels. The model examines the saturation of data channels and the capacity of the control channel to schedule successful data transmission onto the available data channels. To test the efficiency and the scalability of the control channel, the number of data channels was increased from two to fourteen.

To investigate the capacity of the channels the following equations based on our proposed idea were employed. The equations capture the essence of our proposed scheme; they emulate the allotment of bandwidth. The variables used in the equations are explained in Table 1. The equations are based on the Institute of Electrical and Electronics Engineers 802.11 Carrier Sensing Multiple Access with Collision Avoidance - IEEE 802.11 CSMA/CA mechanism. They were adjusted to suit and meet the specifications of our protocol.

$$DC = B_{dc} - D_l + 2 * sw * DC_n - msc \quad (1)$$

$$CC = B_{cc} - hd * DC_n - Intcyc \quad (2)$$

$$Intcyc = D_l + 2 * sw - DC_n * hd - sw \quad (3)$$

TABLE I. LIST OF VARIABLE USED IN THE EQUATIONS.

Variable		Variable Meaning
DC		Data Channel
B_{dc}		Data Channel Bandwidth
D_l		Data packet length
Sw		Channel switching delay
DC_n		Number of Data Channels
Msc		Multi-Channel scheduling cost
CC		Control Channel
B_{cc}		Control Channel Bandwidth
Hd		Control Channel handshake duration
Intcyc		Inter-cycle duration

Given the above equations, the capacities of both the control and the data channels were computed, allotment to nodes done and channel saturation investigated. All channels were considered to be having the same bandwidth of 1Mbs. Both data and basic rates were set to 1Mbs. The number of nodes was varied between 30 and 210 depending on the number of data channels. A system with fourteen data channels had the largest topology. In the analysis, however, an average of 30 nodes and two data channels was considered in each case. In some cases the total number of nodes was considered. The data frames were assumed to be 1000 bytes. Other parameters such as the control packet sizes were set to standard lengths specified in the IEEE 802.11 specification.

We now describe the functionality of the network support and its significance in reducing the signalling overhead. We also show how it facilitates communication in a newly deployed network. The network support is also designed to provide joining and returning nodes with information, which allows them to initiate their next transmission immediately instead of deferring them to a later stage. The network support takes advantage of the composition of the WMN and its different nodes, which have different capabilities. Of interest is a hybrid WMN, which has in addition to a backhaul of mesh routers and an Ad hoc network of mesh clients, it has a backbone of fully connected mesh routers within the ad hoc network of mesh clients.

Each node, which is part of the network support, maintains a data structure called a Network Status Table (NST). These nodes are referred to as the NST nodes. The NST nodes will store information about the availability of data channels, list of data channels, which are currently in use and when they will become available. The data channel will be said to be available when the remaining transmission time is equal to the amount of time required for the next pair to reserve it. This remaining time is determined by the inter-cycle duration, which was discussed earlier. The inter-cycle duration is stored in the NST as the duration of the data transmission duration of a given data channel. The network support nodes will also maintain a sequence of data channels to ensure that data transmission is scheduled in a round robin bases. The information maintained in the status tables is made available to any node, which probes the NST node.

When a node wishes to send data and does not have a complete understanding of the network status, it first probes the nearest NST node. Upon receiving this information it will be able to exchange the control packets (RTS/CTS) on the control channel and reserve a data channel, which will be available next. The reservation is done before it becomes idle after the inter-cycle duration.

The network support system is of paramount importance for a network, which has just been deployed. In such a scenario nodes would not have a complete picture of the network status. Instead of waiting indefinitely in attempt to gather information from overheard control packets, nodes will simple probe the nearest NST node. All the nodes current on the control channel and within the coverage of the NST node will receive the probe response. The responses will be used by a number of nodes to update their own local tables. The local tables are expected to be small and limited in size. This will help nodes with limited processing power to store and update their local tables effectively.

The NST information will also be helpful to joining and returning nodes. A node, which has just been registered, is considered to be a joining node. A joining node could be a node, which has moved from one NST node zone into the zone of the next NST node. Nodes can also join a network from other adjacent networks when they have been handed over to the next network. On the other hand, a node is said to be returning if it was busy transmitting or receiving on a data channel. Upon the completion of the transmission, it switches back onto the control channel. This node would have missed the details of data channels, which were reserved during its visit to one of the data channels. When the returning node wants to initiate communication immediate upon its return, they must first send a probe to the nearest NST node otherwise it will not communicate due to lack of sufficient network information. The network support system therefore, prevents the deferment of transmission and reduces bandwidth wastages due to false blocking of nodes with insufficient information.

V. Analytical Results

In this section, the channel saturation problem is investigated analytical. Both control and data channels are investigated. The number of data channels was increased from two to fourteen to investigate how increased capacity and congestion affects the capacity of the control channel. All the channels were assumed to have a bandwidth of 1Mbs. The channels were assumed to be orthogonal for testing purposes. The three equations discussed in the previous section were used in the analysis of the cyclic scheduling algorithm.

It was noted that data channels transmit long packets as compared to the control channel. Data channels are also degraded by channel switching delays. These two observations do affect negatively the capacity of the data channels. On the other hand short packets provide the control channel with more capacity to drive many data channels.

In Figure 3 a system with one control channel and two data channels was considered. The general topology had a total of thirty nodes. It was noted that the capacity of the two data channels caused a bottleneck in the system. Their combined capacity could support up to fourteen nodes. This translates to seven nodes per a data channel. On the other hand the control channel had enough capacity for the thirty nodes.

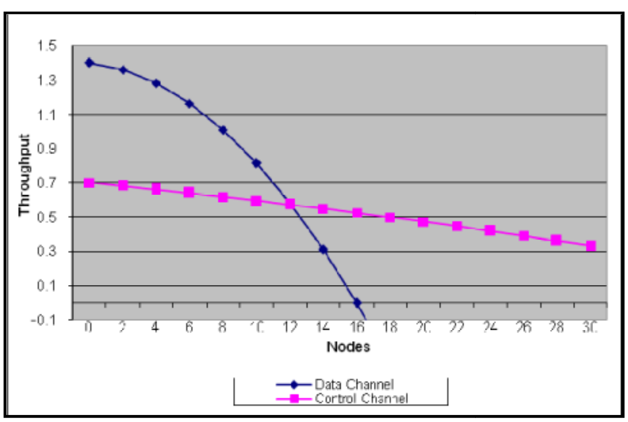

Figure 3. Performance of the control channel when two data channels are considered

The inter-cycle has the longest duration in a two data channels system. Its duration reduces with the every increase in data channels. The inter-cycle duration degrades the capacity of the control channel. Despite this, the capacity of the control channel was still adequate. It can be seen that the control channel was underutilized when there were very few data channels. The number of data channels should be steadily increased to improve the utilization of the control channel.

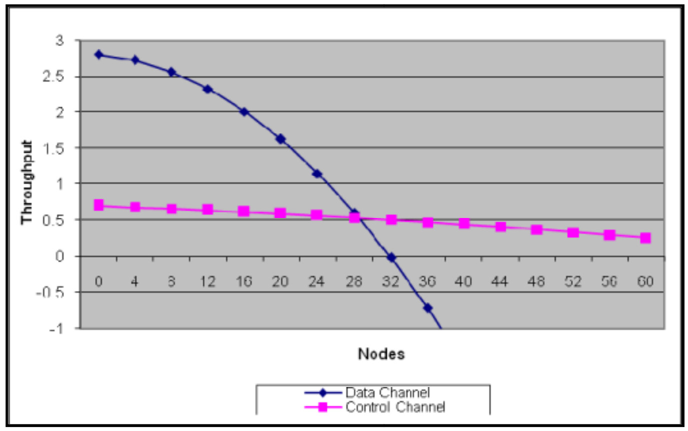

Figure 4. Saturation levels in a system with four data channels.

When the number of data channels was increased to four in Figure4, it was noted that the capacity of the control channel was still underutilized. On the other hand the number of nodes was increased to sixty. The data channels saturated first and their performance was unchanged. However, there was small change in the performance of the control channel. This proves that the number of data channels do affect the performance of the control channel though it this case in is insignificant.

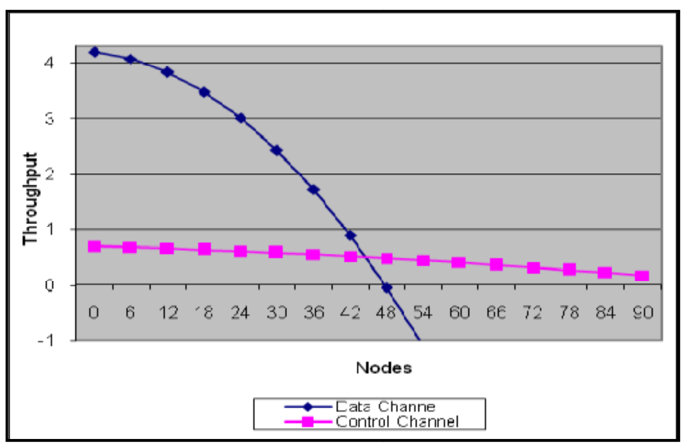

Figure 5. The saturation levels of channels in a network with six data channels.

The number of data channels was further increased to six while the nodes were increased to ninety. The increases were designed to evaluate the effects of the network size and the number of data channels on the performance and capacity of the control channel. As can be seen in Figure5 the capacity of the control channel continues to degrade gracefully, while the performance of the data channels is unchanged. The performance of the data channels does not improve as the number of data channels. It is only affected by the saturation of the control channel is increased. However, it is important to note that the control channel at this stage is still has enough capacity for the six data channels and ninety nodes.

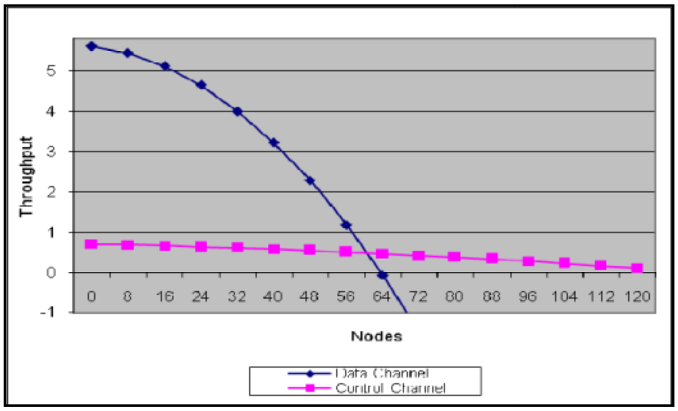

Figure 6. The saturation point of the control channel

In Figure6 the capacity of the control channel continues to degrade, thought it had enough capacity for the 120 nodes, its capacity was now limited. It was fast approaching zero. Figure 6 had eight data channels in total. The control channel still had enough capacity for the eight data channels.

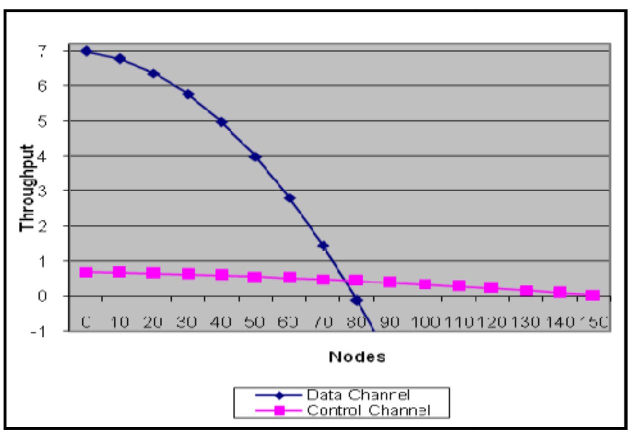

Figure 7. Performance of the control channel when ten data channels are considered.

In Figure 7 the number of data channels was increased steadily to ten. The control channel could drive all the data channels its capacity was not enough for the 150 nodes. The control channel did not have adequate capacity for all the available nodes. Interestingly when the data channels were fewer, the control channel was underutilized. It began degrading as the number of data channels was increased. To optimize the performance of the scheme, the number of the data channels should be increased to a level, which does not underutilize the capacity of the control channel. On the same token, the control channel should run at a level, which does not degrade the performance of the data channels. Although, the control channel began saturating, it did not cause a bottleneck in the system. The bottleneck was caused by the data channels whose capacity was just enough for the first seven nodes in each data channel. There was no degradation on the data channels, which was caused by the saturating control channel.

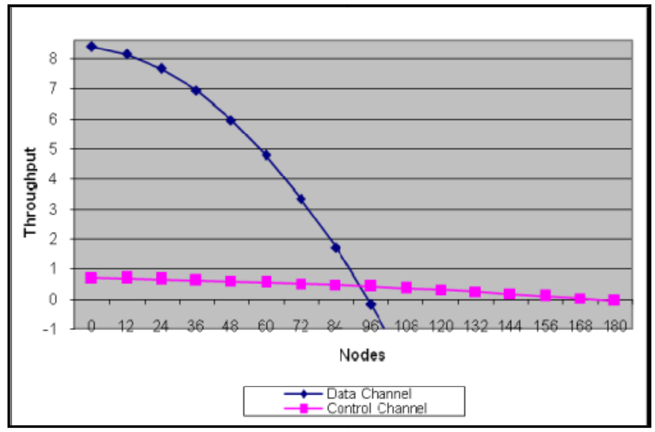

Figure 8. Performance of the control channel when twelve data channels are considered.

The saturation of the control channel becomes more apparent in a system with twelve data channels. In a general topology with 180 nodes, the capacity of the control channel is limited to only 168 nodes in Figure 8. The impact of the saturation of the control channel becomes severe as more data channels are added. The saturation of the control channel at this stage does not degrade the performance the system. The performance of the system would have long been degraded by data channels, which cause a system bottleneck after the 7th node on each data channel. To improve the system performance, higher data rates should be considered for the data channels.

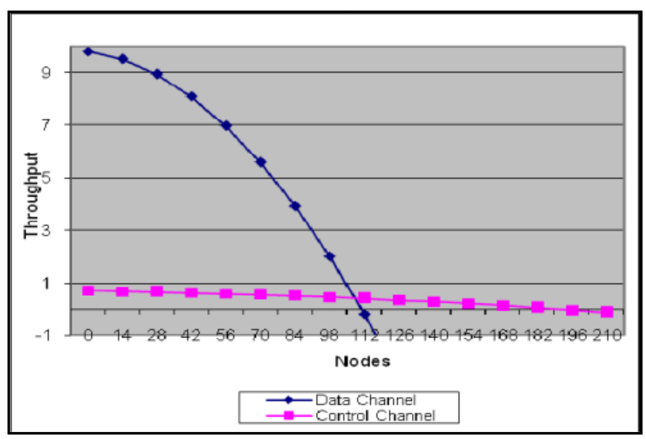

Figure 9. Performance of the control channel when fourteen data channels are considered.

In Figure 9 similar observations were made. In this case a total of fourteen data channels were considered. The general topology had 210 nodes. The combined capacity of data channels was only enough for ninety-eight nodes. The control channel could support 182 nodes instead of 210. The control channel began saturating after the 182nd node mark. This was the largest general topology, which was investigated. The network provided the shortest inter-cycle duration in our experimentation. The inter-cycle reduces with every increase in the data channels as more capacity is required by the control channel to schedule more transmission and drive more data channels. The control channel becomes busier servicing an increasing load of data channels. Furthermore, the multi-channel scheduling cost had its biggest impact on the network with fourteen data channels.

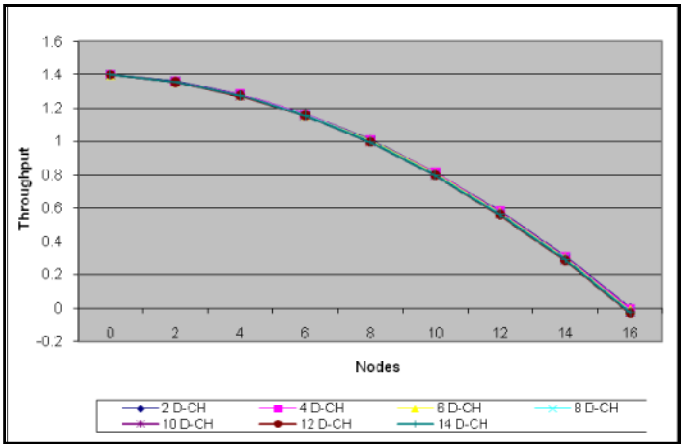

Figure 10. Analysis of the saturation levels of data channels.

A snap shot of the seven different data channels systems ranging from the two data channels to the fourteen data channels system shows a similar pattern in performances of the networks. The performances of these seven networks are depicted in Figure 10. All the data channels in each case saturated after the seventh node. Therefore the average performance of data channels does not increase as the number of the data channels is increased. However the overall increase in capacity can be observed as data channels are increased, though the performance remains the same. It can be concluded that an increase in data rates will also improve system capacity while the performance will remain unchanged. The performance is therefore not expected to improve though network capacity may show an increase in the end to end throughput.

The analysis of the control channel for the seven different cases reveals an interesting development in Figure11. The performance and the capacity of the control channel is affected by the number of data channels. Its performance reduces with each and every increase in data channels. Following this observation, we can conclude that the number of data channels do degrade the performance of a control channel. It should be noted that despite the degradation of the control channel, it still has enough capacity to drive as many as fourteen data channels. This statement is valid given the fact that data channels saturate after every seventh node. However, the fourteen data channels are not orthogonal; they were assumed to be overlapping for experimentation purposes. The idea was to investigate the capacity of the control channel as the network size increases and more data channels are added.

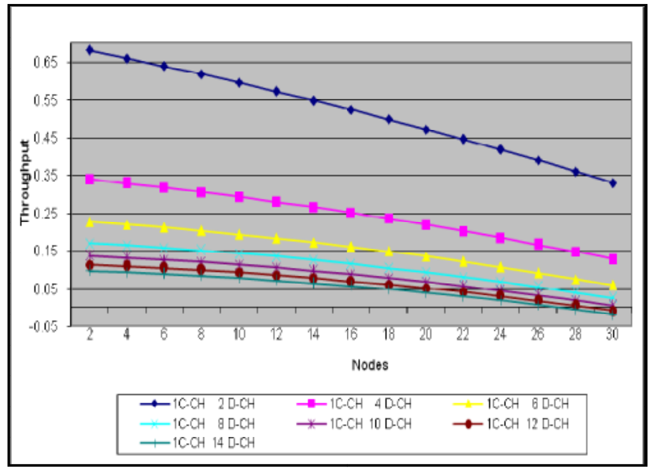

Figure 11. Analysis of the capacity of control channel as data channels are increased from two fourteen.

VI. ANALYZING THE CYCLIC SCHEDULING ALGORITHM

Multichannel MAC protocols implementing a single control channel can be modeled as a queuing network. The network has three distinct service points. The service points are depicted in Figure12. These are the nodes marked Ns1 to Nsn, the control channel identified as Cc1 and then the data channels marked as Dc1 to Dcn. In the queuing model it can be seen that the control channel can slow down the speed of the network as a single service station fed by multiple servers and in turn sending its output to multiple servers. The capacity of the control channel therefore needs to be improved substantially. The control channel server should have reasonable capacity to offer well balanced service so that it can provide an efficient and a very fast link to multiple servers at its input and output ends.

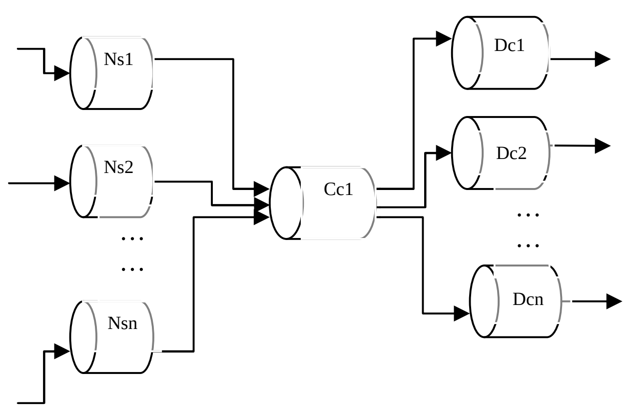

Figure 12. A Multichannel queuing network with a single control channel server

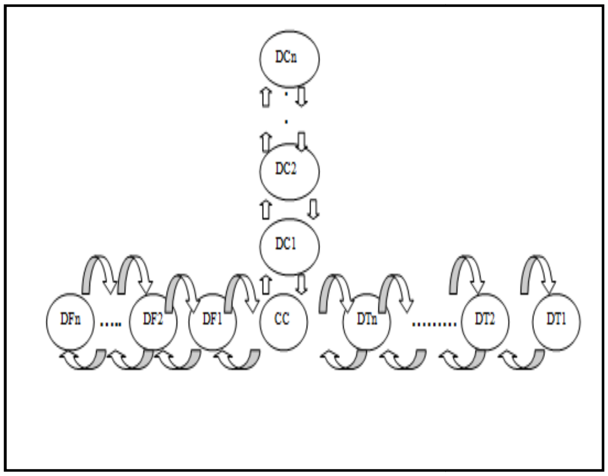

Figure 13. A multiple senerio in multichannel systems with a single signalling channel

Figure 13 shows how the implementation of the common control channel as a single signaling channel results in the formation of multiple queues. Data packets are first queued when the nodes wait for the control channel to be free and contend for it. In our analysis, we consider these packets as data flows queued at the control channel and are denoted as DF1 to DFn. When the data flow is de-queued from the control channel it is then queued in the data channel queue. Thereafter the data flows are served by the data channels. These two models clearly show the significance of the control channel in ensuring better performance of multichannel networks, which implement the notion of a signaling channel.

In the following three figures we evaluate four multichannel MAC protocols, which employ the idea of a control channel as a single signaling channel. We assume a Markovian packet arrival with an exponential inter arrival times. The arrival rate was assumed to vary between 0.1 and 2.9. The control channel service rate is based on the amount of time the control channel will service a pair, which wants to reserve one of the available data channels. The service rates were based on the payload of the control channel of the schemes primarily to show the effects of signaling on the capacity of the control channel. For the AMCP we considered the worst case for control channel utilization where all communicating pairs have to re-initiate data channel reservation after failed first attempts. This is according to the protocol, which allows nodes to attempt to reserve a data channel, which is available at both ends after the first attempt, which was unsuccessful. However, for both waiting and response times we assumed that all the initial attempts would be successful.

The following are of interest in our analysis of the schemes: system utilization, the average time in the queue and system. All the three were limited to the capacity of the control channels of the individual protocol, which were evaluated. The Little's theorem was used in calculating the values of the above parameters. In Figure 14 we evaluate the utilization of the control channel in the four protocols, the MMAC, LCM, AMCP and the CSA. The MMAC had the worst utilization factor followed by the LCM. The AMCP and the CSA offer the best performance. However, the CSA is slightly better. The low utilization factor shows that a given scheme has more capacity to handle increased volumes.

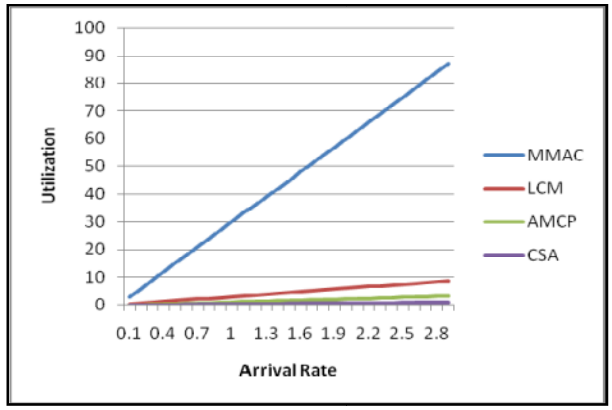

Figure 14. The utilization of the control channel.

The MMAC is not stable for the inter arrival rates that were considered in this analysis in both Figures. 15 and 16 because of its very low service rate. The results of MMAC are therefore not shown in these two figures.

In Figure 15 the CSA offered the best performance. The packets of the CSA were subjected to the smallest amount of delay in the queue. The turnaround of packets in the queue was the fastest as compared to the AMCP and the LCM. The AMCP was the second best. When the protocol offers the least delay in the queue it shows that the service rate of the control channel is good and does not cause significant degradation of the performance of the protocol. The LCM had the largest amount of delay and therefore the control channel is likely to degrade significantly the performance of the protocol. The results for the MMAC are not shown due to its instability within the inter-arrival range considered for this analysis.

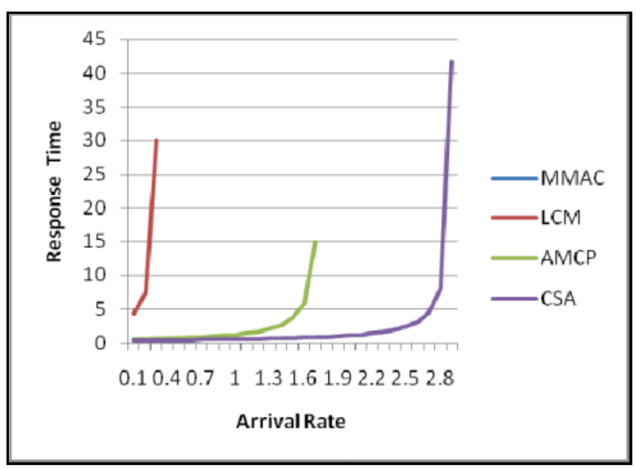

Figure 15. Analysis of the system response time in the queue.

In Figure 16 waiting time was considered. The waiting time is the summation of the response time and the processing time. In this case, it is the amount of delay a packet is likely to be subjected to before it is transmitted on the data channel, where both the queuing and the service times are considered. There was no significant difference between the queue and the system average times results. A similar trend was observed in the two graphs. However the delays were slightly higher in Figure. 16 due to the addition of the service times to the queue delay.

The CSA is therefore effective in reducing the signaling delay of the control channel. The reduction of the signaling delay means that the capacity of the control channel has been improved and its scheduling capacity increased.

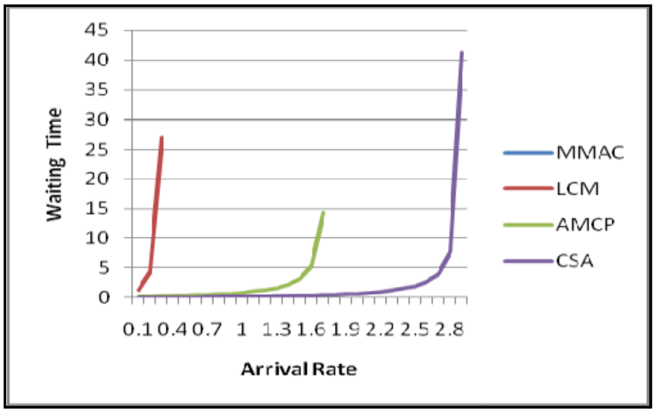

Figure 16. The analysis of the system waiting time in the system

VII. THE SIMULATION MODEL

In this section, we evaluate the performance of our Cyclic Scheduling Algorithm and compare it to the Asynchronous Multi-channel Coordination Protocol (AMCP). The channel switching delay has been included in the AMCP platform for better comparison with our approach. Total throughput achieved was employed as a metric for evaluation purposes. The analysis sought to find out, which of the two schemes achieves better throughput.

The AMCP was evaluated against after multi-channel schemes and was found to be superior in [3]. For this reason, the proposed scheme was only compared with the AMCP.

Default Network Simulator 2 (NS 2) parameters were used. We considered IEEE 802.11 MAC standard in our simulation. The channels were assumed to be orthogonal and of the same bandwidth. The bandwidth of each channel was assumed to be 2Mbs each.

A total of five channels were employed in the simulation with four data channels and one control channel. The number of the channels was fixed throughout of the simulation. However, different network sizes were considered. There were four different network sizes, which were considered. We assumed that all the networks had general topologies.

The switching delay was set to 224µs and two switching delays were considered. The first channel switching delay was incurred when terminals switched from the control channel to the reserved data channel to transmit data frames and ACK packets. The second one is when the nodes switch back onto the control channel after finishing their transmissions on the data channel.

The NO Ad Hoc (NOAH) routing agent was implemented in all the four networks. For each of the four network sizes, at least twenty simulation runs were considered with each simulation run, running for three hundred simulation time. Different network sizes were either expressed in terms of the number of terminals or the number of data flows. The number of terminals was always double the number of data flows. A given data flow links two distinct terminals, a sender and a receiver.

The data packets were assumed to be of type CBR and were all set to 1000 bytes. Both data and control packets were sent between a sender and a receiver. The network was assumed to be single hop network, hence packets were not relayed. The RTS and CTS packets were sent on the control channel, which was set aside as a signaling channel, while the DATA and ACK packets were sent on the data channels. The timers were reconfigured and reset according to the inter-cycle design. The rest of the parameters were unchanged and were set to values specified in the IEEE 802.11 standard.

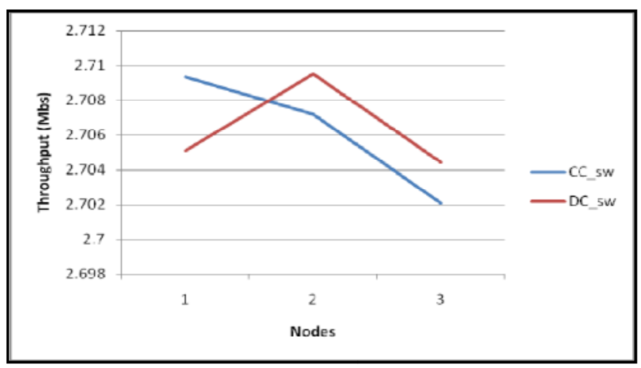

Figure 17. The performance of a network with three data flows subjected under the two channel switching schemes

The smallest network size, which was investigated, had six nodes, three transmitters and three receivers. It can be seen in Figure 17 that the first node in the reference model (AMCP) achieved higher throughput than the CSA. The proposed approach performed better in the second and third nodes. In general, the proposed approach was superior to the reference model.

It should also be noted that in Figure 17, the number of data channels was more than the number of data flows. This resulted in the highest achieved throughput as compared to the subsequent results where data flows were either equal to or more than the number of data channels. Therefore, the highest achieved throughput in Figure 17 was possible due to less interference experienced in a three data flow network.

The network size was changed in Figure.18; the number of nodes was increased to eight with four transmitters and four receivers. The number of data flows was equal to the number of data channels. There was one to one pairing of data channels to data flows.

It can be noted that there was a slight decrease in achieved throughput in the two schemes in Figure 18. The decrease in achieved throughput was caused by the non availability of a free data channel as was the case in the previous figure. The nodes therefore, did not benefit from the extra data channel, which resulted in a decrease in the achieved throughput. The decrease in achieved throughput was caused by the increase in the amount of interference.

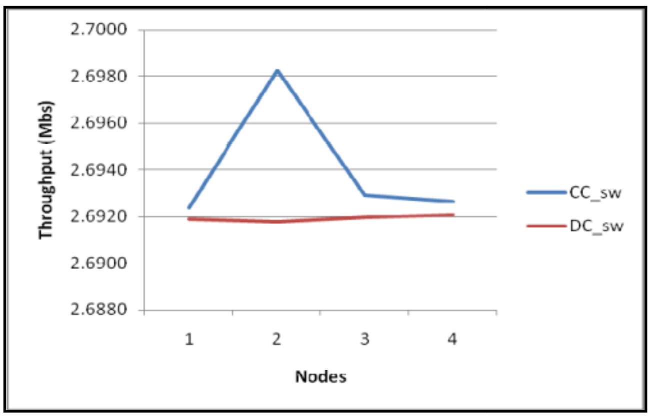

Figure 18. Comparison of two switching approaches with four data flows.

In Figure 18, the reference model was superior to the proposed model in all the data flows. It achieved a higher throughput in all the cases. The reason for the poor performance of the proposed scheme can be attributed to the design of the inter-cycle duration and the observations made on the performance of the inter-cycle duration in the analysis section. It was observed that the inter-cycle duration degrades the performance of the control channel when few data channels are implemented. Its performance improves with the increase of data channels. The duration of the inter-cycle is longer in the smallest possible network and shorter in the largest possible network that can be supported by a single control channel.

The increase in the amount of interference couple with the design aspect of the inter-cycle duration degraded the performance of the proposed protocol in a network with four data flows.

The network size was further increased in Figure.19. The number of nodes was increased to ten with five transmitters and five receivers. The number of data flows was more than the number of data channels. At any given time, there would be one interfering data flow. The interfering data flow caused a severe degradation to the two protocols.

The proposed approach performed better in the last four nodes. It was outperformed in the first node. This shows that the proposed protocol offers better performance as the size of the network is increased. On the other hand, the inter-cycle duration improves the performance of the proposed protocol as more data channels are added. The results in Figure 19 validate this assertion on the performance of the inter-cycle duration.

In Figure 20 the number of nodes was increased to thirty with fifteen data flows. This was the largest network scenario, which was considered in this evaluation. However the achieved throughput was more than the one, which was achieved in Figure. 19. It was almost the same as the throughput, which was achieved in Figure 18. This shows that the proposed scheme is scalable and that the performance of the inter-cycle improves as more data channels are added.

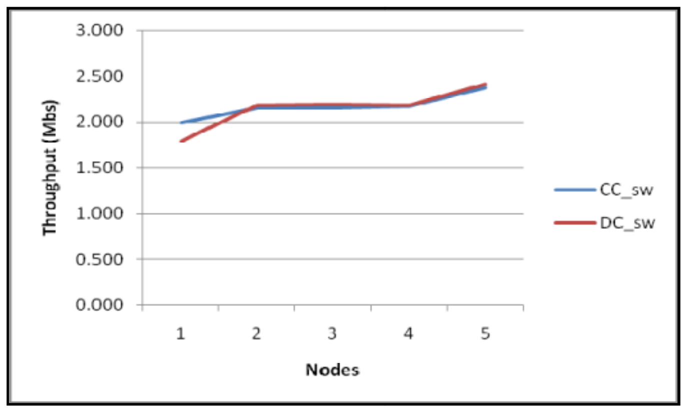

Figure 19. The performance of a system with five data flows implementing both channel switching delay schemes.

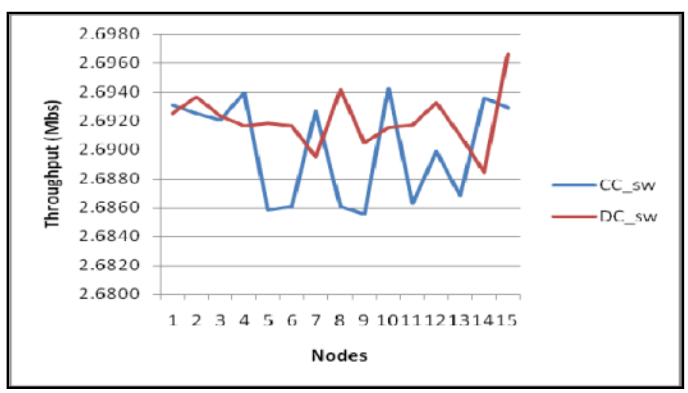

Figure 20. Throughput achieved by the fifteen data flows implementing the two channel switching delay approaches

Figure 20 creates a notion of highly congested and backlogged network. The proposed scheme was evaluated in the largest possible network. As can be seen in the figure, the performance of the proposed scheme was very good. Its performance did improve remarkable in a large network. The performance gains can be attributed to the improved performance of the inter-cycle duration in large networks. Secondly, the achieved throughput remained the same as in Figure. 18 largely due to spatial reuse. These results also show that an interfering data flow causes a significant degradation as compared to the size of the network.

The network in Figure 20 was three times larger than the one in Figure 19. However, its achieved throughput is better despite its size, which would have otherwise degraded its performance. This confirms the argument that the CSA is more scalable and that its performance does improve with network size.

VIII. Conclusion

The paper proposed a cyclic scheduling algorithm, which incorporates channel switching delay in channel scheduling and coordination. The scheme has been analyzed through analytical means and through numerical simulations. The analysis shows that the control channel's capacity does not degrade the system. The data channels on average saturate after the seventh node degrading the performance of the system. To improve the capacity of the data channels higher data rates can be considered. They should not be increased to levels that degrade the performance of the control channel.

The numerical results show that the proposed scheme reduces the signaling delay of the control channel. The capacity of the control channel and its scheduling capacity was show to improve with the addition of more data channel. The implementation of the inter-cycle duration is therefore very effective in large networks. The inter-cycle ensures that a data channel is reserved before the current transmission is completed, and that the multi-channel scheduling cost is not repetitive but limited to the first cycle.

The new multi-channel interference problem referred to as the multi-channel scheduling cost in this project, is associated with multi-channel MAC protocols implementing a single control channel as a signaling channel. The analysis shows that the multi-channel scheduling cost can be limited to the first cycle when the cyclic scheduling algorithm is implemented. In the subsequent cycles it can be eliminated by varying the size of the inter-cycle duration and allowing data channels to be reserved when the ongoing transmissions are about to end.

It is envisaged that this protocol provides a platform through, which interference challenges such as the missing receiver problem; the hidden terminal problem and the exposed terminal problem can be addressed. These interference problems can be reduced and cannot be eliminated.

References

[1] Jungmin So and Nitin vaidya (2004). Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver. MobiHoc 2004, Roppongi, Japan, ACM.

[2] Ritesh Maheshwari, Himanshu Gupta, and Samir R. Das. Multichannel MAC protocols for wireless networks. SECON 2006, Volume 2, Issue , 28-28 Sept. 2006

[3] Jingpu Shi, Theodoros Salonidis, and Edward W. Knightly (2006). Starvation Mitigation Through Multi-Channel Coordination in CSMA Multi-hop Wireless Networks, MobiHoc'06, May 22–25, 2006, Florence, Italy.

[4] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu (2000). A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks, in Int'l Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN), 2000.

[5] A. Tzamaloukas and J.J. Garcia-Luna-Aceves (2001). A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks," in *Proc. of IEEEINFOCOM*, 2001. www.cse.ucsc.edu/ccrg/.../jamal.infocom01.pdf,

[6] Jenhui Chen and Shiann-Tsong Sheu (2004). Distributed multichannel MAC protocol for IEEE 802.11 ad hoc wireless LANs. Computer Communications 28 (2005).

[7] J. Deng and Z. Haas (1998). Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks, in *Proc. of IEEE ICUPC*, Florence, Italy, 1998J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[8] Hoi-Sheung Wilson So and Jean Walrand (2006). Design of a Multi-Channel Medium Access Control Protocol for Ad-Hoc Wireless Networks**.** University of California at Berkeley

[9] Hoi-Sheung Wilson So, Jean Walrand, and Jeonghoon Mo. McMAC: A Parallel Rendezvous Multi-Channel MAC Protocol, www.walrandpc.eecs.berkeley.edu/Papers/**McMAC**.pdf

[10] N. Jain and S. Das (2001). A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks, in *Proc. of the 9th Int.Conf. on Computer Communications and Networks (IC3N), October 2001.*

[11] Jain Nitin, Samir R. Das, and Asis Nasipuri. A multichannel CSMA MAC protocol with Receiver-Based Channel Selection for Multihop Wireless Networks.

[12] Shih-Lin Wu, Yu-Chee Tseng, Chih-Yu Lin, and Jang-Ping Sheu (2002). A multi-channel MAC protocols with power control for multi-hop mobile ad hoc networks. The computer journal, Vol. 45, No. 1, 2002.

[13] Ali Khayatzadeh Mahani, Majid Naderi, Claudio Casetti, and Carla F. Chiasserini (2007). ENHANCING CHANNEL UTILIZATION IN MESH NETWORKS. IEEE MILCOM, Orlando, FL, 2007, 29-31 October 2007. www.ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4454826

[14] A. Nasipuri, J. Zhuang, and S. R. Das (1999). A Multichannel CSMA MAC Protocol for Multihop Wireless Networks, in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, September 1999.

[15] A. Nasipuri and S. R. Das (2000). Multichannel CSMA with Signal Power-based Channel Selection for Multihop Wireless Networks, in *Proc. of IEEE Vehicular Technology Conference (VTC)*, September 2000.

[16] W. Hung, K. Law, and A. Leon-Garcia (2002). A Dynamic Multi-Channel MAC for Ad Hoc LAN," in *Proc. Of 21st Biennial Symposium on Communications*, April 2002.

[17] Arup Acharya, Archan Misra, and Sorav Bansal (2003). MACA-P : A MAC for Concurrent Transmissions in Multi-hop Wireless Networks. Proc. Of PerCom, March 2003

[18] Sudthida Wiwatthanasaranrom and Anan Phonphoem. Multichannel MAC Protocol for Ad-Hoc Wireless Networks. Department of Computer Engineering, Kasetsart University.

[19]] Jeonghoon Mo, Hoi-Sheung Wilson So, and Jean Walrand (2005). Comparison of Multi-Channel MAC Protocols. MSWiM 2005, 10 – 13 October, Montreal, Quebec, Canada.

[20] Pradeep Kyasanur Jungmin So, chandrakanth Chereddi, and Nitin H. Vaidya. Multi-Channel Mesh Networks: Challenge and Protocols. University of Illinois

[21] Myunghwan Seo and Joongsoo Ma (2007). Flexible Multi-channel Coordination MAC for Multi-hop Ad hoc Network. Technical Report, January 2007.

[22] Chandrakanth Chereddi, Pradeep Kyasanur, and Nitin H. Vaidya (2006). Design and Implementation of a Multi-Channel Multi-Interface Network. REALMAN'06, May 26, 2006, Florence, Italy.

[23] EunSun Jung and Nitin H. Vaidya (2002). A Power Control MAC Protocol for Ad Hoc Networks, *MOBICOM'02*, September 23–28, 2002, Atlanta, Georgia, USA.

[24] The editors of IEEE 802.11. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Speci_cation, 1997.

[25] Danilo Valerio, Fabio Ricciato, and Paul Fuxjaeger (2008). On the feasibility of IEEE 802.11 multi-channel multi-hop mesh networks, Computer Communications 31 (2008), www.elsevier.com/locate/comcom

[26] Mthulisi Velempini and Mqhele. E. Dlodlo (2009). A multiple channel selection and coordination MAC Scheme. MESH 2009, June 18 – 23 2009, Glyfada/Anthens, Greece.