Understanding Channel Saturation in Multi-channel MAC Systems

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Abstract—Multi-channel MAC systems offer high capacity, a prerequisite for the next generation networks. High capacity will ensure that the requirements of delay sensitive and time bounded flows are met. For high capacity to be a reality, a good channel selection, coordination scheme and network connectivity is required. A common control channel approach addresses the connectivity challenge. However, it is perceived to be a bottleneck as it saturates degrading data channels. The saturation problem is not widely studied. This paper investigates saturation levels of both control and data channels. The length and channel occupancy of control and data channels are explored. The analytical results show that data channels saturates ahead of the control channel. The model is premised on short control packets requiring shorter transmission durations; meaning that a control channel is not capacity constrained as compared to data channels.

Index Terms—Bottleneck, Channel Saturation, Control Channel, Data Channels

I. INTRODUCTION

MULTI-CHANNEL MAC protocols offering high capacity are set to improve the quality of service provisioning of wireless access networks. However, network connectivity in a multi-channel environment is a challenge. An ideal multi-channel scheme should facilitate network connectivity. The scheme should also implement good channel selection and coordination techniques which improve network connectivity. Multi-radio and multi-channel systems were proposed to solve the connectivity problem and other multi-channel challenges. One of the proposed approaches is the implementation of a common dedicated control channel to ensure total network connectivity. Unfortunately this approach is perceived as causing a system bottleneck. The related work discusses some of the views that have been brought forward on this issue.

The control channel approach facilitates network connectivity and provides a common platform upon which nodes can listen on when idle. Terminals can also contend for the data channels through the control channel. Other terminals within range can overhear packets of nodes contending for data channels. It also simplifies channel coordination and it reduces a number of wireless interference challenges. Unfortunately, the perceived system bottleneck caused by the control channel has made this approach less attractive. The approach has been considered unfavourable. However, optimization techniques trading off the saturation challenge with connectivity may be the best approaches that can solve the multi-channel coordination challenges. There is a need to study the saturation challenge extensively. The saturation problem is caused by the capacity of either the control or of the data channels which fast approaches zero while the other channel (data or control) has enough capacity to service the next terminal.

In this paper we assume a system with one control and at least two data channels. The number of data channels was increased steadily from two to ten during the analysis. The main objective of varying the number of data channels was to analyze the saturation rates of channels and the impact of saturation on network performance. The size of packets was considered in the study and their transmission durations.

We explain the channel saturation problem in terms of channel utilization. The channel occupancy of both the control and the data packets shows that the data channels saturates ahead of the control channel. The control channel saturated ahead of the data channels when the number of data channels was increased to ten or more.

The study provides insight into the multi-channel system bottlenecks. It also positions the implementation of a single control channel approach as a technique of choice in the design of multi-channel MAC protocols that facilitate network connectivity. Network connectivity through a common control channel provides a common reference point for all the terminals. Unfortunately, the implementation of a common control channel causes a bottleneck in large networks. The onset of the saturation of channels should be delayed to improve the scalability of multi-channel networks.

The following section justifies the need for a single control channel. Related work is discussed in section III. The system model is presented in section IV. Section V presents the analytical results. Future work is summarized in section VI and section VII concludes the paper.

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II. MOTIVATION

A scheme which employs a common control channel equipped with a single transceiver is cost effective. It also facilitates network connectivity. The scheme is compatible with the IEEE MAC 802.11 standard and does not utilize expensive hardware systems such as multi-radio equipments. The scheme is less complex and easy to implement. It does not suffer from signal linkages, a root problem of multi-radio systems. The approach also reduces the terminal deafness problem. Channel selection and scheduling can therefore be implemented in a more transparent manner equipping nodes within transmission zones of transmitters with enough information on the status of the network. Terminals can also synchronize quickly on the control channel.

The saturation challenge has been viewed largely as a control channel problem. It has not been recognized as a data channel problem. In this paper we consider the data channels as the main cause of system bottleneck. The channel utilization and the transmission durations of both control and data packets have not been considered in the analysis of the saturation problem. The channel saturation challenge is explained through channel occupancy and utilization.

III. RELATED WORK

A single control channel causes system bottleneck in [1]. As the number of data channels is increased the control channel acts as a bottleneck. A point at which it saturates should be ascertained to facilitate the design of optimization techniques. The control channel saturation is also related to a number of data channels in [2]. As the number of data channels increase, the control channel is degraded, while channel utilization becomes low as the number of channels is reduced in [3] and [4].

In [5] the saturation problem is related to the bandwidth of the control channel. However, an optimal number of data channels that can be supported by a single control channel should be established. The paper in [6] established that a control channel constitute 33% of network capacity in a network with three channels. The number of data channels has the same effect as described in [3].

In [7] control channel bottleneck is presented as a function of the network load. Several short packets are transmitted which overload the network. The short packets are transmitted on the control channel and the long packets on the data channels. Work in [8] discusses a similar viewpoint. This argument needs to be evaluated.

In [9] a similar analysis to our approach was done however, the paper did not consider overhead costs and channel switching delays. Channel switching delay degrades the performance of the network as noted in [10]. In our approach we also assume that flows can be scheduled concurrently and we explore the channel saturation challenge under these assumptions. According to work done in [11], there are only three orthogonal channels. However in this analysis we assume that all the channels are orthogonal.

IV. THE MODEL

The use of a dedicated control channel has not attracted considerable research. The approach has been regarded as not feasible owing to the saturation of the control channel. Unfortunately, alternative approaches have their own demerits, for example lack of network connectivity, hardware costs and system complexity. There is therefore a need for control channel saturation analysis and optimization.

A network with at least three channels is assumed. All the channels are assumed to have equal bandwidth of 1Mbs. One dedicated control channel and at least two data channels are implemented. The control packets are sent on the control channel to reserve one of the available data channels. Terminals then switch on to the reserved data channel to exchange data and acknowledgement (ACK) packets. Terminals are subjected to a switching penalty of 224μs when they switch first to the data channel from the control channel. They also incur a second switching penalty of the same value when they switch back to the control channel from the data channels. The Short Inter-Frame Space (SIFS) and Distributed Coordination Function (DCF) IFS (DIFS) durations are included in the analysis.

The analysis evaluates the utilization of the control and of the data channels and tries to establish their saturation rates. A network with two data channels and a single control channel is first evaluated before the number of data channels is increased steadily from two to ten. The analysis attempts to find out which channel saturate first. Secondly, it attempts to find out the optimal number of data channels that can be supported by a single dedicated control channel before it reaches its saturation point.

The transmission duration of a single transmission on the control channel, denoted by *C* is a summation of *DIFS*, Request-To-Send (*RTS)*, *SIFS*, and a Clear-To-Send (*CTS)* durations. While the transmission time on the data channel, *D*, is the summation of two switching delays (*sw*), one *DATA* transmission, one *SIFS* and an ACK duration. Propagation delay (*pd*) is considered for both the control and the data channels. The propagation of the control channel is set to 2μs, while the data channel propagation is set to 4μs. The *C* and *D* above can be represented with the following formulas:

$$C = DIFS + RTS + SIFS + CTS + pd + Slot\text{-}Time + SIFS \quad (1)$$

$$D = sw + DATA + SIFS + ACK + sw + pd \quad (2)$$

Assuming that bandwidth will be depleted at a rate of *r* multiplied by the transmission time *t*, channel saturation can be predicted. The *r* variable denotes the *nth* terminal. Given that the bandwidth available to the next terminal *a* is *b*, then the bandwidth of *n+1* terminal can be generalized as follows:

$$a = b - rt. \quad (3)$$

We then proceed to calculate the transmission times, *t* of both control and data channels using (1) and (2) respectively. When channel utilization is uniform, channel saturation can be easily predicted. The data and the basic rates are assumed to be the same and are set to 1Mbs. Table I shows all the parameters used in the analysis and their respective values. The transmission duration is expressed as achievable throughput and represented graphically for terminals 1 to *r* in a general topology. The control channel is assumed to be subjected to significant amount of interference and overhead costs. We therefore assume that *x* bandwidth is lost at every node, and *x* is assumed to be 30% as shown in (4).

Given that bandwidth is *b*, the n^{th} terminal *r*, channel occupancy *t*, bandwidth loss due to interference and overhead *x*, and (4), the analytical results in the next section were generated. Channel occupancy of the control and the data channels were derived using (1) and (2) respectively.

$$a = bx - rt \qquad (4)$$

TABLE I. LIST OF PARAMETERS USED IN THE ANALYSIS

	Octets	Bytes	Bits	Duration
DIFS				50µs
SIFS				10µs
RTS	20	20	160	160µs
CTS	14	14	112	112µs
ACK	14	14	112	112µs
DATA	2342	2342	18736	18736µs
SW				224µs
Control pd				2µs
Data pd				4µs
Slot-time				20µs
PLCP Preamble	18	18	144	144
PLCP Header	6	6	48	48

V. ANALYTICAL RESULTS

We show analytically that data channels saturate ahead of the control channel and cause a bottleneck, when they are few. However when they are ten or more, a single control channel causes a system bottleneck.

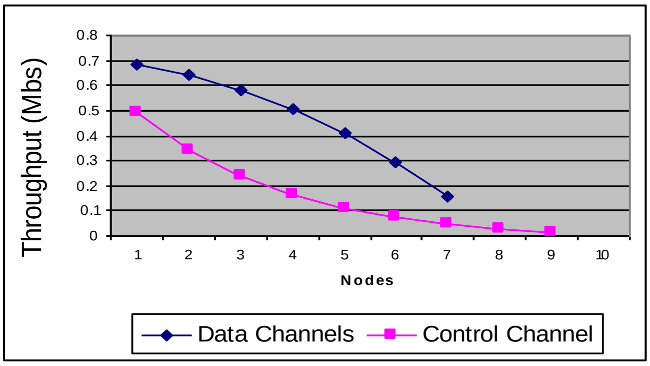

Fig. 1. Performance of a single control channel with two data channels.

Equation (4) was employed in generating the results in this paper for 1 to *r* nodes. A total of ten nodes were considered in each case. Fig 1 depicts the performance of a single control channel with two data channels. In this case two data channels saturate after the 7th node while a single control channel has capacity for the first ten nodes. It can be seen that the capacity of the data channels caused a system bottleneck and affected the performance of the control channel.

As the number of data channels was increased, a single control channel began to degrade. The increase in data channels degrades the performance of the control channel. However, the control channel saturated after the data channels, hence its degradation had no impact on the performance of the data channels. The number of data channels was increased from two to ten while a single control channel was fixed. The results which explain this analysis are discussed in the sequel.

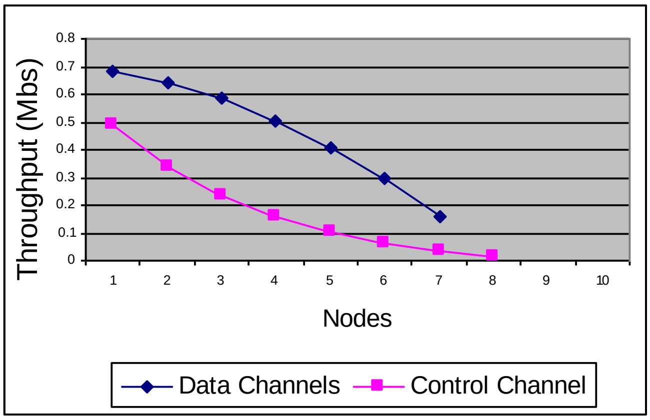

Fig. 2. Performance of a single control channel with four data channels.

In Fig 2, four data channels were considered. All the data channels saturated after the seventh terminal. On the other hand the control channel began saturating, though it had enough capacity for the first eight terminals. However, its saturation did not affect the performance of the data channels. It should be noted that the performance of the data channels did not change from the previous results. The data channels were still saturating ahead of the control channel thereby affecting its performance.

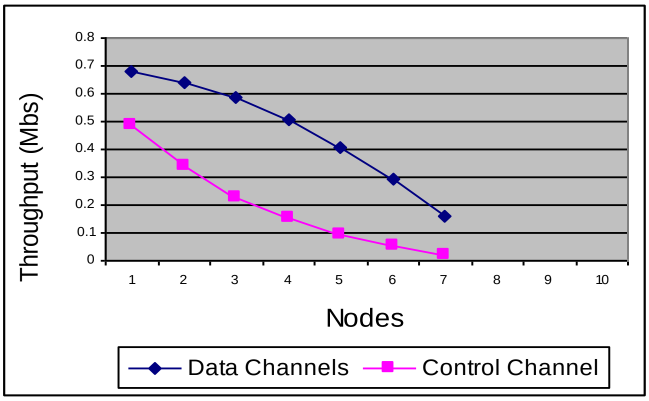

Fig. 3. Performance of a single control channel with six data channels.

Fig 3 shows a further degradation to both the control and the data channels. A total of six data channels were considered. A single control channel was maintained in all the experiments. The control channel could only support up to a maximum of seven terminals, while the performance of data channels did not change much. The effects of the number of data channels on the control channel can be seen in Fig 3. However, up to this point the degradation of the control channel has not affected the performance of the data channels. Both channels saturated after the seventh node.

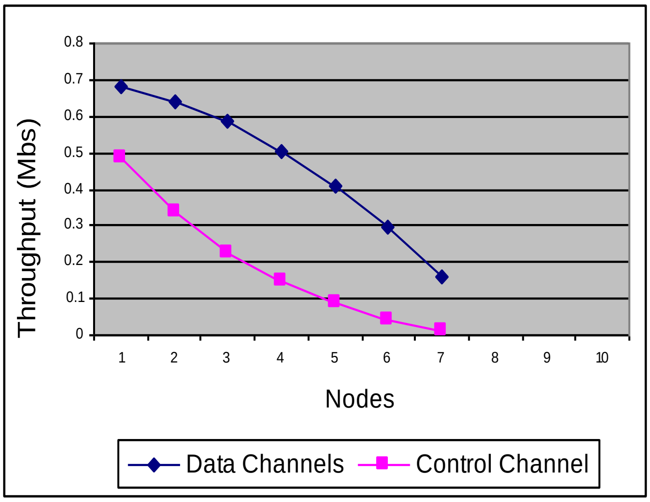

Fig. 4. Performance of a single control channel with eight data channels.

The channel which saturates first causes a bottleneck in the system. We investigated channel saturation levels to inform our future design of multi-channel MAC protocols. We also investigated the possible drawbacks of implementing a dedicated common control channel.

In Fig 4 we increased the number of data channels to eight. The obtained results did not differ significantly from the previous results in Fig 3. The saturation levels of both control and data channels were the same. Both channels saturated after the seventh node. However, the achieved throughput in Fig 4 was slightly less that the one achieved in Fig 3. The saturation of the control channel can not be recognized as causing the systems bottleneck at this stage.

The implementation of a single dedicated common control channel has not resulted in a bottleneck and has not affected the performance of the data channels.

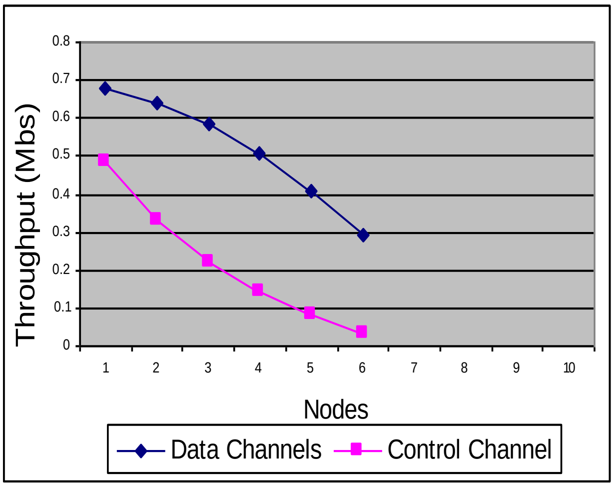

Fig. 5. Performance of a single control channel with ten data channels.

In Fig 5 the data channels were increased to ten. It was noted that a single control channel saturated after the 6th node and could support the first six terminals in each of the ten data channels. The data channels had enough capacity for the first seven nodes. As a result the implementation of the control channel resulted in a bottleneck in this case.

The control channel degraded very fast as more data channels were added. As more data channels were added, the degradation of the control channel affected the performance of the data channels and caused a bottleneck. These results suggest that the performance of the control channel will remain favourable until a certain threshold of the number of data channels is reached. Thereafter, it will cause a bottleneck in the system.

As observed above, when a few data channels were considered, data channels were the first to saturate, while every increase in data channels degraded the performance of the control channel. We therefore need to ascertain the optimal number of data channels that can be supported by a single control channel before it degrades the performance of the system. These performance graphs give us an idea as to how the control channel behaves with every increase in the number of data channels. The optimum number of data channels according to this analysis is eight data channels.

Fig 6 presents the various performance graphs of a control channel for the network systems with two to ten data channels. There are five different networks of multiples of two from two to ten data channels. The results show how the control channel performed as the number of data channels was increased. They also show the saturation levels of the control channel in each case.

The control channel performed better than the data channels when the number of data channels was less than ten. It then performed poorly when the number of data channels was increased to at least ten. To improve the performance of the control channel beyond this threshold, higher data rates may be considered. On the other hand, optimization techniques may be considered. In overall, the upper bound of the control channel will help the MAC protocol designers in mapping the maximum number of channels to transceivers in an efficient manner. This is a necessity for the multi-radio and the multi-channel systems.

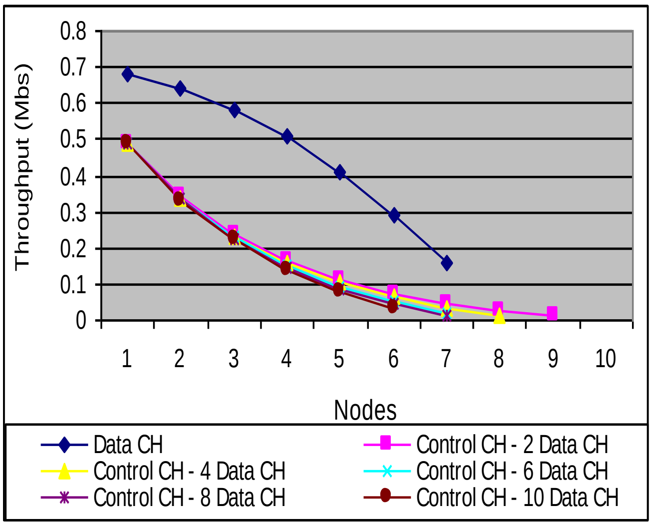

Fig. 6. Performance of a single control channel for two to ten data channels systems.

The performance of a single control channel was degraded by data channels when the number of data channels was less than ten. Both the control and the data channels saturated after the seventh node when the number of data channels was increased to six and eight. The control channel had more capacity in the two cases. The maximum number of data channels that can be supported by a single control channel is therefore eight.

We conclude that a single control channel can support up to eight data channels before it degrades the data channels and cause a bottleneck. These results show the maximum number of channels that can be supported by a single transceiver. It should also be noted that in this study all the available channels were assumed to be orthogonal. According to [11] there are only three non overlapping channels. The goal of this paper was to establish whether there is any performance benefit of adding more channels while maintaining a single transceiver. Network connectivity was regarded as a critical aspect of multi-channel schemes. Lastly, we considered the cost of hardware in relation to the implementation of multi-radios and the signal linkage problem caused by two radios transmitting close to each other.

VI. FUTURE WORK

The observation of this paper will lead to the design of multi channel MAC protocols which map a single control channel onto a number of data channels. The maximum number of data channels that can be supported by a single control channel was determined by the saturation levels of the control channel. In our future work, a single and dedicated control channel approach will be explored as it facilitates network connectivity. Optimization techniques will be employed to increase the capacity of the wireless networks and to increase the scalability of the multi-channel networks

The performance of data channels as they were increased from one to *n* was not closely analyzed. We only analyzed the impact and performance of the control channel in this context. We will evaluate the impact of increasing data channels and their performance in our future work. This analysis will help in the design of the multi-channel MAC protocols.

VII. CONCLUSION

We presented a modest model for a channel saturation state. We noted that the number of data channels caused a bottleneck when they were less than ten. The fast degradation of the control channel was also noted as the number of data channels was increased. The control channel did not cause any bottleneck until the number of data channels was increased to ten.

This paper provides some insights into the performance of the multi-channel systems which implement a single dedicated control channel. It shows the possible upper bounds of both the control and the data channels. Furthermore, a single transceiver was mapped onto a maximum of nine channels. The channel to transceiver mapping is a necessity for the implementation of multi-radio systems designed to use radio resources and multiple channels in an efficient manner.

Optimization techniques may be considered in an attempt to improve the performance of the control channel. The benefits of the improved performance of the control channel will translate to overall improved system performance. We present the single control channel as the key parameter for improving the performance of the network.

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