Abstract—Multiple channels present IEEE 802.11 MAC protocol designers with a number of options in their attempt to calm the effects of Hidden Terminal Problems (HTPs). The research on multi-channels shows that the effects of HTPs can be reduced and limited to Request To Send/Clear To Send (RTS/CTS) control packets. Unfortunately our analysis shows that data packets can be affected by HTPs. An effective HTP control channel solution may effectively protect data packets in data channels. Our previous work revealed that HTPs can be completely eliminated through the implementation of Long Inter-Frame Space (LIFS) and an intelligent MAC in single channel systems. An intelligent MAC divides terminals into two segments, the Transmitter Carrier Sensing Zone (CSZ) and the Receiver CSZ for the implementation of Extended Inter-Frame Space (EIFS) and LIFS respectively. The extension of our LIFS and CSZ concepts to Multi-channel environments reveals interesting developments that need to be tackled. The HTP may not be completely eliminated as new challenges arise in multi-channel environments. Multiple channels have a delayed effect on HTP manifestation. They do not solve the HTP but they reduce its effects. Our analytical results suggest the existence of a theorem mapping the occurrence of HTPs onto the number of channels implemented.

Index Terms—Control IFS, Hidden Terminal Problem, Missing Receiver Problem, Multi-channel MAC

I. BACKGROUND TO THE STUDY

Multichannel techniques can be regarded as techniques employed to reduce co-channel interference and collisions, at the same time encouraging concurrent transmissions. The implementation of multichannel approach increases network capacity, improves reliability and flexibility of wireless systems. The use, access and coordination of multiple channels in wireless communications is a challenge. Multichannel approach however does not solve HTP and ETP, the single channel systems problems. This is contrary to what other sections of the research community have assumed.

In Multichannel schemes, interference is reduced by assigning different channels to different terminals. However, channel switching leads to missing receiver problem (MRP) and to switching delays.

II. RELATED WORK

In [1] two channels are used to solve the HTP. A common channel is employed as a signaling channel and the other channel is earmarked for data communication. The MAC-P employs a total of five control packets. The first RTS/CTS set establish a session. Thereafter, a probing control packet is sent through the dedicated channel. The last RTS/CTS pair reserves the channel. The scheme uses many packets, resulting in delays and heavy signaling costs. The scheme is not optimized for channel coordination and contention. During the three sets of control packets, another terminal may succeed in reserving the channel ahead of a contending terminal.

The proposed scheme [2] is not optimized for channel switching, coordination and network connectivity for effective communication. For a terminal to communicate with its neighbours, a common channel should exist that links it to its neighbours. The use of switchable and fixed transceivers requires a lot of coordination. The hello messages have a negative effect on the network performance and are prone to collisions. Therefore, the failure of hello messages will have a disastrous effect on this scheme. The implementation of a number of transceivers coupled with lack of coordination, and broadcast hello messages degrades. The approach is complex and too expensive in terms of hardware requirements. Interestingly, the paper did not attempt to solve the Hidden Node problem.

W-CHAMB, a Time Division Multiple Access (TDMA) protocol is proposed [3]. TDMA schemes require global clock synchronization, a challenge for Mobile Ad hoc NETworks (MANET) and Wireless Mesh Networks (WMN). In band, busy-E-signals are employed to inhibit the effects of hidden nodes. It is not clear how these e-signals combat the effects of hidden nodes. However, if energy signals are transmitted at a higher power level, more nodes will be exposed. Broadcasted request packets for TCH
reservation may be harmful to ongoing transmissions. On the other hand, broadcasts degrade network throughput.

In multiple channel systems, collision is assumed to be limited to RTS/CTS packets. However, our analysis shows that collision of data packets is also possible. A collision in the control channel can be detected by the absence of a CTS packet [4]. This suggests that the CTS packet should be closely monitored and be forced to time out to improve the overall system performance.

In dealing with HTP, most schemes rely on the availability of a base station. However, an infrastructure less scheme is sought. The Group Allocation Multi hop Multiple Access (GAMMA) attempts to combat HTP with an infrastructure less scheme [5]. Partial or one hop synchronization creates more problems as the scheme is extended to the entire network. Partial synchronization can not effectively handle communication across the entire network, where different groups are involved. Furthermore a linking node or a group has to be a member of at least two groups to facilitate effective communication across the entire network. These and other issues may lead to implementation challenges of this scheme.

The work in [6] considers a single hop scenario and generalizations were made for multi hop systems. Due to IEEE 802.11 MAC transmit and receive, and broadcast constraints, achievable throughput is very low. Significant improvements may be realized with well designed multi-channel systems. An analysis in [6] shows that the network throughput may double in multi-channels systems. However, authors concluded that network throughput is unlikely to double though it is expected to significantly improve. Where one control channel and two data channels are employed a control channel acts as a bottleneck, as the network load increases. Interestingly, our analysis to the contrary suggests that the bottleneck is in the two data channels.

Work in [6] implements a channel hopping scheme with synchronization to combat the effects of HTPs. The scheme was studied in a single hop environment, hence one hop neighbourhood time synchronization may hold. However, extrapolating the results of this scheme onto a multi hop set up will be a major challenge. Global synchronization is not possible.

Nodes in [6] randomly select home channels to listen to when idle. This approach segments a network and does not facilitate network connectivity for effective communication. Newly registered nodes either passive or active will have a distorted view of the network. They will only hear and be heard by terminals listening in their home channels. Missing Receiver Problem will lead to this distortion and to network segmentation. The scheme can not be extended to multi hop largely due to synchronization challenges, Missing Receiver Problem, and a hazy view of the entire network.

The receiver-based channel selection protocol proposed in [7] wastes a lot of time in sensing available data channels. It senses first the channels listed in the RTS packet. It then selects the best channel among the free channels in the receiver neighbourhood. During this long process, the states of channels may change in the transmitter neighbourhood resulting in more collisions. Interestingly, the CTS in this case reserves the channel and notifies terminals in its neighbourhood. Terminals in the transmitter neighbourhood are not informed. This will result in numerous communication problems.

Slotted Seeded Channel Hopping (SSCH) is a time based protocols and its performance is affected by a need for global time synchronization. The Dynamic Channel Assignment (DCA) concept forms the basis of our approach in channel selection. As stated above, our main interest is in HTP solution as opposed to channel selection. However channel selection is the stepping stone to combating the effects of HTPs.

The receiver directed transmission in [8] suffers from HTP, unfortunately the paper did not identify this as a problem. The quiescent channel of the receiver may be busy when a given sender initiates a communication. Contention is therefore inevitable. Channel coordination is the greatest challenge given the missing receiver problem. Furthermore, the approach is not ideal for ad hoc networks, due to location based channel negotiations.

The second scheme proposed in [8], the Extended Receiver Directed Transmission scheme was designed to combat multichannel HTPs and MRPs. However the use of busy tones is not practical in single transceiver systems. The use of a second transceiver increases costs and add to system complexity. Broadcast messages that notify potential transmitters increase substantially network load. Broadcasts also equally suffer from the MRP, a problem that they are designed to solve. The deaf receiver’s “wake up” call degrades network performance. Furthermore, the Data Transmission Complete (DTC) message transmitter may be hidden to other terminals. Its DTC broadcasts will therefore disrupt on going communication. We contend that there is no need for sending DTC messages before each packet, if subsequent packets will be sent from the previous transmitter.

The scheme proposed in [9] wastes bandwidth, if a polled sender does not have data to send. It is not robust and flexible. Data may be delayed as the sender waits to be polled by a receiver. It is therefore not suitable for time bounded or time sensitive data transmission.

The protocol requires [10] network wide synchronization. It also requires the services of a coordinator, a set up which is not feasible in an infrastructure less system.

In our paper we differentiate HTP from MRP. Our understanding of Multichannel HTP, defer from the one in [11] [12]. What the two papers define as HTP, we understand it as Missing Receiver Problem. We consider hidden terminal issues in both control and data channels. We envisage coming up with a MRP solution in our future work. The use of beacon approach in [12] requires clock synchronization, a wireless communication challenge. Furthermore, the use of Power Saving Mechanism (PSM) packets degrades network performance.
III. THE MODEL

In our model, the Hidden Terminal Problem is treated differently from the Missing Receiver Problem. Unfortunately, the MRP in literature has been referred to as the Multichannel Hidden Terminal Problem. We investigate the presence of HTP in multichannel environment and model a solution to this problem. We will thereafter design a solution to MRP in our future work.

Our work assumed that the effects of HTPs are limited to RTS and CTS durations as suggested by other researchers. However there is a need to closely understand and investigate this claim. We also contend that a channel selection scheme has an effect on the manifestation of HTPs. We therefore proceed to describe our approach under these assumptions.

In our scheme three channels are considered, one dedicated or control channel and two data channels. Signaling will be done in the control channel to reserve one of the two data channels. A transmitter selects a preferred channel in the idle list and this channel has to be accepted by a receiver for data communication to take place.

If the selected channel causes interference in the receiver neighbourhood, the receiver will send a shorter control packet rejecting the sender’s preference. Included in the packet would be the duration of on going transmission in the given channel. The sender may select a different channel if it wins again the right to use the dedicated channel.

The terminals which are in the sender’s neighbourhood will hold off for the summation of CTS and SIFS duration. Nodes in the receiver’s neighbourhood will be expected to contend for channel access immediately after the CTS without having to hold off. This will apply mainly on nodes in the Communication Range (CR) of both transmitter and receiver. The terminals outside this range will not be able to decode the control packets.

However, nodes that receive erroneous packets in the receiver neighbourhood will not disrupt an on going communication. Therefore, there is no need for a special hold off scheme for these nodes. Interestingly, nodes in the sender neighbourhood that are outside the CR of a sender do require a hold off scheme to protect CTS packets. The hold off scheme should be equal to the summation of CTS and one SIFS duration.

IV. ANALYTICAL RESULTS

Our analytical results show that our model assumptions were not conclusive. The effects of HTP are not limited to a control channel. There are Hidden Terminal Problems in both data and control channels. This route was taken given the general view of literature which limits the effects of HTP to a control channel. We have discovered that multichannel systems only separate the effects of HTP to control channel and data channels.

Multichannel systems also have a delayed HTP effect on data channel. HTP can only be loosely detected after every
second cycle of data communication in the data channels. In the first cycles, communication takes place concurrently in two data channels. Thereafter the third transmission can take place after the completion of at least one of the first two transmissions, not before. If it is allowed to go ahead before the two transmissions run to an end, a collision may occur. The details of our model analysis are discussed below.

Figure 1 gives a pictorial view of a system with three channels, one control channel and two data channels. Approximated values are used to easily scale and graph the durations of packets transmissions and channel switching delays. The durations of control packets have been increased while the ones for data packets have been reduced. This means that with actual durations and delays, durations of bottlenecks are anticipated to be longer. Their effects will have a huge and significant impact on the performance of the system.

The first two pairs, AB and CD in figure 1 reserve channel 2 and 3 respectively and are able to complete their transmissions without any interference. However if EF start their handshake soon after CD handshake, there will be a collision in one of the data channels, regardless of which data channel EF chooses.

According to our model, EF has to be starved off for 0.4 milliseconds to protect the ongoing transmission. Given the accurate durations the hold off duration will be much longer. We will consider this fact in the design of these hold off durations in our future work.

It should be noted that, hidden terminals will receive erroneous packets and would not know what to do next. If they are allowed to contend for the medium, they will successfully exchange control packets with their pairs in the control channel. There will be no collisions in the signaling channel. The problem will only be encountered in the data channels. This proves that hidden terminals are not limited to control channels. As can be seen in this example, the effects of HTPs are experienced in the data channels. However this does not mean that there are no Hidden Terminal related problems in the control channel. Our observation challenges the view held in literature and present a HTP as both a control and data channel problem.

A terminal that waits for the stipulated hold off duration should know which channel to select thereafter. For example in figure 1, the second time, A and B are communicating, they select the second data channel instead of the first. This results in a collision.

This piece of information is critical in the design and optimization of multichannel MAC protocols. This approach will reduce “wait on” periods and facilitate the scheduling of more successful transmissions without degrading the performance of the system, when the first channel is selected above.

A terminal that has just finished transmitting in one of the data channels can select the same data channel immediately upon switching back to the control channel. Assuming that there is no other terminal which is in contention, the returning terminal has to select its previous data channel immediately. The terminal should not be starved off since it will not disrupt any on going transmissions.

In the model diagram in figure 1, node E is able to reuse channel 1. EF will select channel 1 to exchange data and ACK packets, a channel that they have just exchanged packets in. They will both switch back to the control channel and E will immediately re-establish a communication link with F. The communication should be initiated immediately by any of the returning terminals with any available terminal.

The returning nodes do not have to hold off according to our model. In the absence of other contending nodes, they will succeed in reserving the recently used channel. We expect some variations though when the accurate figures are used. Nevertheless the model diagram in figure 1 gives us an overview and valuable pieces of information for our future work.

This piece of information is going to be a very useful tool in the design of appropriate Inter Frame Space to force terminals to delay their next transmissions to allow on going transmissions to complete. These IFS will be implemented in the control channel to combat the effects of HTPs in both control and data channels.

Having made the observations enumerated above, we conclude that a Hidden Terminal Problem is an unsolved problem. It should be arrested both in the control and data channels. However care should be exercised in ensuring that as many as possible concurrent transmissions take place without degrading the performance of the system.

There is a need for a similar single channel approach to be implemented in multichannel systems to starve off all potential HTPs in the second cycles. Suitable and appropriate Inter Frame Spaces should be designed and implemented if these second cycle HTPs are to be successfully starved off during a given on going communication. They should be forced to hold off their transmission long enough to allow the on going first cycle transmissions to run into completion before they can contend for the channel.

The length of these IFS should depend on the duration of the first cycle transmissions. Where uniformity in data transmission is assumed, all subsequent transmissions will have to wait for the equal “wait on” duration or hold off to protect ongoing transmissions of the first cycle.

We are currently working on these IFS durations and we call them the Control IFS (CIFS). It is anticipated that the wait on duration, the CIFS will not have a negative effect on network performance. It will significantly reduce the bottlenecks of the two data channels, through the reduction of data packet collisions, retransmissions, exponential back offs, perceived congestions, blocking, false blocking and pseudo congestion states of the IEEE 802.11 CSMA/CA MAC protocols.

The challenges above, account for the major part of
system degradation which affects the scalability of wireless access networks such as MANET, WMN and Wireless Sensor Networks. The solution to these challenges will pave way for the implementation of these access networks and technologies in fourth Generation telecommunications systems (4G). More bandwidth is required for access networks to meet the bandwidth and Quality of Service (QoS) requirements of 4G systems.

V. CONCLUSION
Multi-channel schemes do outperform single channels schemes. However this does not mean they are good. They may be poorly designed and still perform better than single channel schemes. There is need to compare any new multi-channel systems with well established and standardized multiple channel systems. The absence of baseline systems or standards is not helping the situation. A well thought out multi-channel system should be designed to benchmark all future attempts to improve these multi-channel systems. Benchmarking will facilitate the improvement of multi-channel systems and improve fairness in systems comparisons.

The designed CIFS will be simulated in our future work to validate our analytical results and claims in this paper. They will be optimized to trade off HTP effects and wait on durations. Their design will be premised on our earlier similar work in single channel MAC protocols. Multi-channel MAC protocols should consider the effects of channel switching delays. The switching delays are significant and can not be overlooked. They come at the expense of system performance. The implementation of multi-channel systems will improve system performance against channel switching delays. Hence the net effect of switching delays is very minimum, though it is worth any consideration.

The other challenge relates to Head Of Line (HOL) blocking problem. Single or multiple queue management systems should be developed in future. HOL blocking affects relay data in multi hop communication systems and Quality of Service (QoS) issues of MAC protocols.

REFERENCES