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Abstract

We address issues with the performance of IEEE 802.11, when used in the adhoc mode, in the presence of hidden terminals. We present results illustrating the strong dependence of channel capture behavior on the SNR observed on contending hidden connections. Experimental work has illustrated that in a hidden terminal scenario, the connection having the strongest SNR is able to capture the channel, despite the use of the RTS-CTS-DATA-ACK 4-way handshake designed to alleviate this problem. Our results indicate that the near-far SNR problem may have a significant effect on the performance of an adhoc 802.11 network.

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Unfairness and Capture Behaviour in 802.11 Adhoc Networks

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Abstract—**In this paper we address issues with the performance of IEEE 802.11, when used in the adhoc mode, in the presence of hidden terminals. We present results illustrating the strong dependence of channel capture behavior on the SNR observed on contending hidden connections. Experimental work has illustrated that in a hidden terminal scenario, the connection having the strongest SNR is able to capture the channel, despite the use of the RTS-CTS-DATA-ACK 4-way handshake designed to alleviate this problem. Our results indicate that the near–far SNR problem may have a significant effect on the performance of an adhoc 802.11 network.**

I. Introduction

An Adhoc network is a wireless network in which hosts are free to form dynamic connections with other hosts in radio range. The resulting multihop topologies present many challenges for Media Access Control (MAC) and reliable transport protocol designers, with the potential for dynamically changing routes to a destination, and continuously varying radio characteristics between prospective hosts. This challenge is amplified when considering multihop adhoc networks where data transport is not constrained to a single wireless network link.

A significant problem for all adhoc wireless networks is the poor performance displayed by the transport protocol over a number of different MAC protocols [1], [2]. Critical to the transport protocol is the performance of the MAC protocol in terms of fairness and delay. For wireless, and other shared media, one characteristic of poor MAC performance is 'channel capture'. A capture state arises when a given host is able to monopolise the channel resource at the expense of contending connections. With adhoc networks, channel capture has also been identified as a significant problem, particularly in the presence of hidden terminals [3].

This paper presents results which show contending hidden terminals are placed at a disadvantage due to channel capture conditions in IEEE 802.11 [4] networks. The results published here are obtained from a number of experiments examining data transfer using TCP Reno over an IEEE 802.11 network in both adhoc and non-adhoc modes. It is found that an IEEE 802.11 network exhibits channel capture in the presence of hidden terminals when the signal to noise ratio (SNR) of contending connections differ. The connection with the stronger SNR always captures the channel. Importantly, the SNR does not have to differ by very much. It is found that channel capture reliably occurs despite contending connections having an SNR difference of only 5dB. This is despite specific enhancements to IEEE 802.11 MAC protocol designed to avoid this problem. Simulation studies show that with these enhancements, channel capture should not be a problem [5], [6], [7]. The work presented here addresses the lack of experimental results in this area.

This result has implication for the design of both single and multihop adhoc networks where we expect hidden terminals to be common and equal SNR for contending connections to be rare. It also indicates that the large amount of simulation and analytical work presented in recent contributions [6], [5], [1], [2], [8], [9] on single and multihop adhoc networks may be optimistic in the estimates of the expected performance of such networks.

The remainder of this paper is organised as follows, Section II provides background in the area of reliable wireless data transport, highlighting the relevance of this investigation. Section III describes the experiments performed using TCP Reno over an IEEE 802.11 wireless network. Section IV presents our results, Section V discusses issues arising from the results, and Section VI concludes the paper.

II. Background

The two major interactions of interest concerning reliable data transport protocols in wireless networks are between the MAC and the transport protocols, and between the routing and transport protocols. Investigations into both areas form the basis of much of the published work in the area of data transport over wireless networks [1], [2], [5], [8], [9].

MAC protocols are required to overcome two of the most fundamental problems for wireless multi-access networks. The first is the so-called 'hidden terminal' scenario, in which two mutually out of range hosts are competing over a common host resulting in undetectable receiver side collisions. Secondly, the MAC protocol is charged with providing fairness of access across contending connections, without adversely affecting transport (or other higher layer) protocol behaviour.

Several different MAC protocols [3], [10], [11], [12], [13], [14], [15] have been proposed for use in common channel wireless networks, both single and multi-hop, which make an attempt to alleviate the hidden terminal problem. The main approach has been to extend the basic Carrier Sense Multiple Access (CSMA) technique [11] to include a Request-To-Send / Clear-To-Send (RTS/CTS) exchange. The IEEE 802.11 MAC [4] protocol uses this exchange in a 4 way handshake (RTS-CTS-DATA-ACK).

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Gerla et.al. [1], [9] have performed a simulation study of TCP performance over various multihop wireless network architectures, focusing on interactions with the MAC layer. This work also includes an experimental component in which non-802.11 wireless LAN equipment is used to test the channel capture problem for hidden senders. Three different MAC protocols are investigated, CSMA/CA, Multiple Access Collision Avoidance for Wireless (MACAW) [10], and Floor Acquisition Multiple Access (FAMA) [12]. Their results indicate that, in many circumstances, TCP requires a window size of 1 packet (effectively becoming a stop and wait protocol) in order to achieve any throughput across a multiple number of hops. Further experimental investigation has illustrated that TCP does not alleviate, and may even complicate, channel capture when the hidden terminal problem arises while using a non reservation based MAC protocol.

FAMA bears significant resemblance to IEEE 802.11, employing both local carrier sense, as well as the RTS/CTS collision avoidance exchange for data transmission. The variant of FAMA closest to IEEE 802.11 makes use of both RTS and CTS packets having a duration at least as long as the maximum propagation time, yet small compared to data packets to ensure minimal overhead [12]. An extension to FAMA has also been proposed [6] in which the duration of the CTS message is increased to be one RTS packet plus the maximum round trip time. This is designed to give the CTS message dominance and prevent a new RTS or data frame from 'breaking' the handshake currently underway. This ensures better throughput for the channel, but has been shown to exhibit capture under heavy load conditions [1].

It is also known that the timer back-off mechanisms within TCP adversely affect the fairness between competing hidden connections with a non reservation based MAC protocol [1], [9]. IEEE 802.11 uses a physical and virtual carrier sense mechanism in order to prevent receiver side collision [4]. The physical mechanism is a straight forward physical layer non-persistent carrier sense, and will not detect potential receiver collisions with an out of range host. The virtual carrier sense mechanism relies on the reception of CTS messages, indicating the period over which the medium will be occupied by a hidden host. The CTS is used to update a Network Allocation Vector (NAV), used by the MAC to defer transmission upon virtual carrier sense. This mechanism is governed by the *aRTSThreshold* parameter, which indicates the number of bytes a frame must contain prior to the exchange of RTS/CTS messages.

Tang [5] presents simulation results illustrating that the IEEE 802.11 MAC protocol provides fair channel access in the hidden terminal scenario. The simulation environment used in [1], [9], [5] is based on an ideal channel, in which each host receives all intended packets without error. Unfortunately this approach seems to be unable to investigate the impact varying radio conditions can have on the performance of the protocols. Our study, based on experiments with an IEEE 802.11 adhoc network, includes actual radio conditions in examining the performance of TCP over the IEEE 802.11 MAC protocol.

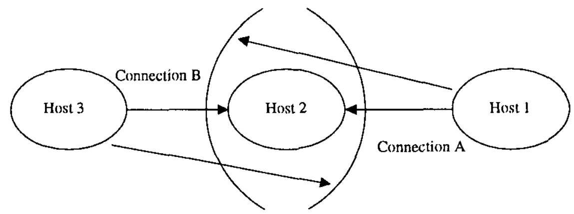

Fig. 1. Experimental Topology

TABLE I
EXPERIMENTAL TRIALS

Trial No	RTS/CTS (bytes)	SNR Scenario
1	none	25dB equi-distant hidden sender
2	500	25dB equi-distant hidden sender
3	500	near(25dB) / far(20dB) hidden sender
4	500	controlled

III. IEEE 802.11 MAC Channel Capture Experiment

A number of experiments were devised to investigate the performance of TCP over wireless links implementing the IEEE 802.11 [4] MAC protocol. The primary scenario under investigation is one involving multiple hidden terminals with a range of SNR conditions. The topology involves three hosts in a linear arrangement, two hidden terminals communicating with a common host. Previous work, [1], [9], [5] based on simulation, has illustrated how the RTS/CTS handshake can alleviate the hidden terminal collision scenario in terms of reduced receiver side collision, but on the other hand may remain prone to channel capture. This experiment tests both the performance of TCP under these conditions, and the ability of the MAC protocol to avoid channel capture under heavy load conditions.

The experimental topology, illustrated in Figure 1, has hosts 1 and 3 mutually out of range, attempting to communicate with host 2. Each experiment consists of a simultaneous 500 kbyte file transfer from hosts 1 and 3 into host 2. The network 'snooping' program, *tcpdump* [16], is used at host 2 to trace the progress of each file transfer. Each host has an 802.11 wireless network interface, used in the adhoc mode and employs a collision avoidance RTS/CTS handshake governed by the *aRTSThreshold* parameter. The hidden terminal topology described above will be common in a true multihop adhoc network. It is also unlikely that the channel conditions will be equal on each of the contending connections. To address this, we have investigated the impact near-far SNR conditions have on the performance of the RTS/CTS mechanism. We are particularly interested in the ability to overcome capture and prevent TCP timers from excessive backoff. Several parameter combinations are investigated, as listed in table I.

Following previously published simulation results, it was anticipated that the reservation mechanism should enable reasonable sharing of the radio resource. It was also anticipated that the TCP connections should suffer no serious ill effects (in terms of excessive retransmission or timeouts), given that each connection is only a single hop, and that the MAC protocol employs positive acknowledgment with retransmission. The experiments were performed using three Pentium PCs. Each PC was equipped with Lucent WaveLAN-II IEEE 802.11 network interface cards, and the experiments were perfomed using both Linux (2.2.6 kernel) and Windows 98 operating systems.

As outlined earlier, the authors of [1] have used non-802.11 equipment in their experimental investigation, relying instead on simulation of similar MAC protocols, MACAW [10], and FAMA [12], [6] for their reservation based investigation. The interaction between a non-reservation based MAC protocol and TCP was shown to result in a capture state for one of the contending hidden terminals, with the most '802.11 like' MAC, FAMA, being most prone to this state. If TCP is adversely affected by the presence of a hidden terminal, even with a reservation scheme, then further research will be necessary to overcome this common scenario.

IV. Results

A. Trial 1

The initial trial investigates the performance without the RTS/CTS handshake and an equal SNR on each connection. The results, illustrated in Figure 2, show that even though connections A and B have an equal SNR as measured at host 2, Connection A is able to capture the channel for the duration of the transfer. The results in this simple case, illustrate the impact timing mechanisms can have on contending connection. Connection B has begun transferring data when Connection A commences. This leads to a period of receiver side collisions, won by Connection A, which eventually manages to capture the channel. Host 3 (Connection B) now invokes TCP congestion control measures, and undergoes periods of exponential backoff. During this period, host 3 is unable to receive an acknoledgment for any data frame it has attempted to transmit as host 1 has monopolised the channel. These results are as expected, having been previously illustrated through simulation [9].

B. Trial 2

The next trial is a simple case where the SNR of each connection is again equal and the *aRTSThreshold* is set to 500 bytes. An example of the resulting file transfer is shown in Figure 3. We found that even though TCP connection setup (SYN) messages of 40 bytes are exchanged without an RTS/CTS handshake, the channel is effectively shared. We suspect that the small packets were able to contend and be re-transmitted during a period of low channel utilisation. This experiment was run multiple times with a range of *aRTSThreshold* parameter values from 0 bytes to the maximum TCP segment size of 512 bytes, with little impact on the relative fairness provided by the MAC. Despite the delayed start of the Connection A data transfer in the example shown in Figure 3, it can be seen that the use

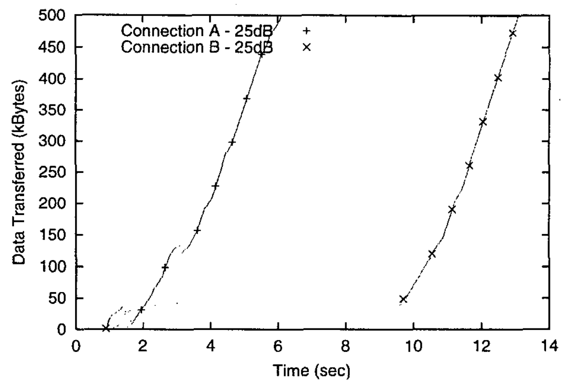

Fig. 2. Trial 1: Equal SNR 25dB, No RTS/CTS

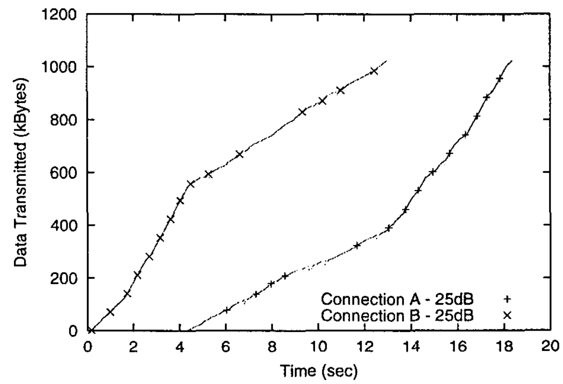

Fig. 3. Trial 2: Equal SNR 25dB, *aRTSThreshold* 500 bytes

of RTS/CTS has an impact on the fairness of the throughput achieved by each connection. Each host maintains a roughly equal share of the channel capacity throughout the contending transfer. The most interesting result is the sensitivity of the capture behaviour. A very subtle change in physical orientation of a terminal was able to sufficiently alter the SNR, preventing fair access for both connections to the channel. Even though both data transfers were initiated simultaneously the Connection B transfer appears to capture the channel through the first four seconds. This varied randomly from experiment to experiment. In the previous trial, where no RTS/CTS is employed, this sensitivity was observed in the randomness in which connection was able to capture the channel.

C. Trial 3

The third experiment, in which Connection A has a SNR 5dB higher than Connection B, again uses an *aRTSThreshold* of 500 bytes. The scenario is designed to investigate the performance under a 'near-far' hidden terminal scenario. The trial results in behaviour illustrated in the example shown in Figure 4 where Connection A is able to dominate, capturing the

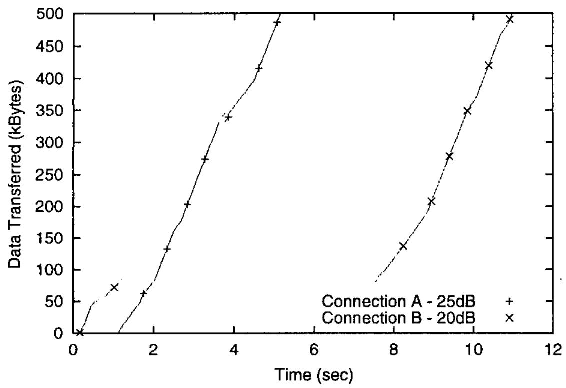

Fig. 4. Trial 3:Unequal SNR 20dB and 25dB, *aRTSThreshold* 500 bytes

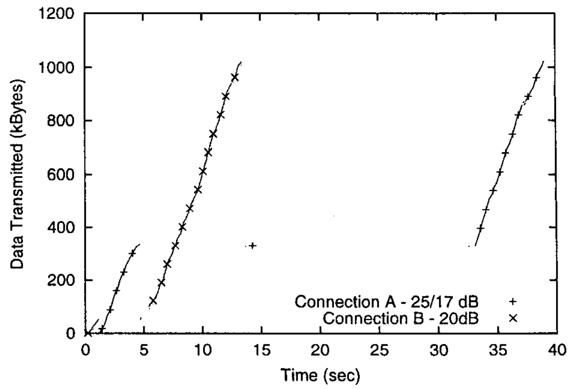

Fig. 6. Trial 4:Controlled SNR, *aRTSThreshold* 500 bytes

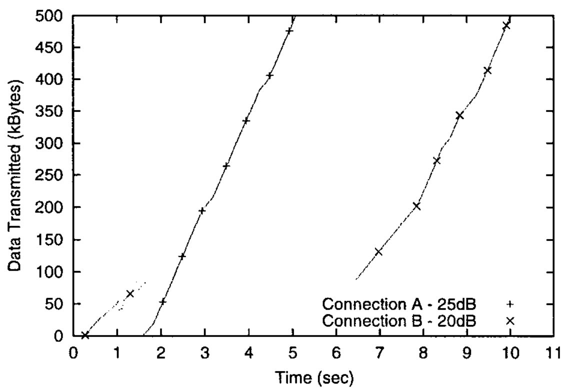

Fig. 5. Trial 3:Unequal SNR 20dB and 25dB, *aRTSThreshold* 0 bytes

channel. Here, Connection A starts marginally after Connection B, yet manages to dominate the contending host. None of the randomness of the previous two experiments was evident. Over multiple trials the connection associated with the higher SNR always captured the channel. Again, the sensitivity to the *aRTSThreshold* parameter was examined. Figure 5 illustrates a trial during which the SNR is unequal, and the *aRTSThreshold* reduced to 0 bytes. An *aRTSThreshold* of 0 bytes implies an RTS/CTS handshake for *every* packet, including signaling (SYN/FIN) packets. A lack of sensitivity to the *aRTSThreshold* parameter was again evident.

A 5dB difference between connections is quite minor and in practice can be simply due to subtle variations in multipath propagation as the surrounding environment changes. We expect the scenario presented in the first experiment (equal SNR) will rarely arise with a hidden terminal topology in a multi-hop wireless network, particularly given the number of factors affecting the SNR observed on each connection. This result demonstrates that the use of the RTS/CTS mechanism within 802.11 is very sensitive to the SNR seen on competing hidden connections.

D. Trial 4

The final experiment involved reducing the SNR on the stronger connection, Connection A, below the weaker Connection B midway through the file transfer. It is anticipated that Connection B should be able to capture the channel at the expense of Connection A. This experiment provided a concrete test of the SNR dependence observed in previous trials. Connections A and B commence the test with a SNR of 25dB and 20dB respectively. Five seconds into the trial the SNR of Connection A was reduced to approximately 17dB through to the end of the experiment. An example of the resulting transfer is shown in Figure 6. The sensitivity to SNR is clearly illustrated. The new stronger host, Connection B, manages to 're-capture' the channel once the SNR of Connection A is sufficiently reduced. Once Connection B has finished Connection A is able to regain access to the channel.

These results highlight a significant problem for data transport. The IEEE 802.11 MAC protocol is unable to provide fairness of access among contending hidden terminals. In each case, the connection which manages to capture the channel suffers relatively few TCP timeouts, and transmission errors are simply handled by the MAC and TCP retransmission mechanisms. Conversely, the contending connection undergoes continual timeout and exponential backoff at both the MAC and TCP levels. This results in significant unfairness in heavy load conditions, such as those investigated here.

V. Discussion

The initial experiments were performed using the Linux (2.2.6 Kernel) drivers for the WaveLAN IEEE 802.11 PC cards, with each host in the adhoc network mode. To check for operating system dependent faults the tests were repeated using Windows 98. The behaviour was identical to that observed with Linux. The experiments were also repeated with the host 2 accessed via a Lucent WavePoint basestation using the standard access point operating mode. Again the behaviour was identical.

The experiments have been performed in an indoor office environment subject to multipath and other signal degrading effects. The propagation delay over the links employed in the experiment is 50 nsec, significantly less than the Short Inter-Frame Space (SIFS) of 10 μsec, and the Distributed Interframe Space (DIFS) of 50 μsec, defined in the IEEE 802.11 Direct Sequence Spread Spectrum physical layer standard [4]. Multipath reflections were thought to have been a possible explination for this effect, though subsequent experiments in a controlled multipath environment have illustrated identical behaviour. Other possible explanations for the behaviour we have observed include:

- Timing problems within the DIFS period. This period is used for the transmission of ACK and CTS frames, and timing problems may be responsible for the behaviour we have observed. A backoff period that is too short will adversely affect the fairness achieved by the protocol. We are presently investigating methods of tuning the SIFS and DIFS parameters within the current implementation. Interestingly, Tang [5] found that adjustment of the DIFS period was necessary when a ring topology was employed.
- Aggressive radio modem capture may also be a significant factor. If a stronger packet is being received and a weaker RTS arrives at the receiver, the modem will be unable to receive the RTS, and may even lose the current data packet if interference levels become too high. The sender of the RTS will retransmit the RTS until a CTS is successfully received or a retransmission limit is reached. It is known that modem capture can improve system throughput [17], [18], though our experimental results indicate this may be at the expense of fair access for all hosts. How modem capture decisions are made may have a significant impact on the channel capture behaviour we have observed.

VI. Conclusion

The experiments discussed in this paper, employing a hidden terminal topology, have illustrated the strong SNR dependence of channel capture behaviour with the IEEE 802.11 MAC protocol. The various scenarios investigated have illustrated that the collision avoidance RTS/CTS handshake, employed within the IEEE 802.11 MAC protocol, is unable to prevent unfair behaviour in the form of channel capture. A SNR differential as small as 5dB was shown to result in capture for the stronger connection.

Under all but the most ideal of conditions, channel capture is evident during periods of higher load. While the capture phenomenon is not new to MAC protocols, the sensitivity to SNR for wireless links uncovered here poses a significant problem for both the operation of higher layer protocols and the design of multihop wireless networks. The possible impact modem capture behaviour is having on the fairness provided by an adhoc network illsutrates the potential tradeoff that exists between the higher system throughput modem capture provides, and the reduced fairness the network is able to provide as a result. In this case, the host with the best SNR conditions was able to capture the channel excluding all other hosts. While this results in higher network throughput, it is obviously an unfair scenario for other hosts wishing to share the same medium. Further work will investigate this apparent tradeoff.

Our results indicate that interactions between MAC protocol behaviour and TCP in adhoc wireless networks will continue to be the subject of much research in the future.

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