Mitigation of Exposed Terminals Problem with Differential Capture Capable Receivers

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Abstract—Recent experimental studies on physical layer capture in 802.11 based networks have demonstrated that the minimum signal-to-interference ratio required for successful reception of a frame depends upon the order of arrivals of the sender’s frame and the interference, and it is much less when the sender’s frame arrives earlier. This differential capture capability (DCC) leads to a very small interference range around the receiver once it starts receiving a frame, and hence it allows considerable reduction in the required carrier sensing range. While the DCC feature of receivers helps alleviate some hidden and exposed terminal problems, there still remains many exposed nodes.

In this paper, we further exploit the DCC feature to mitigate the problem of these exposed terminals that remain even after optimum reduction in carrier sensing range. We propose a liberal carrier sensing scheme that helps identify some of the exposed prospective receivers by using some already available local information and allow them to initiate secondary sessions. Through extensive simulations we demonstrate that the proposed scheme offers significant throughput gain over the conventional carrier sensing scheme that ignores the DCC feature.

I. INTRODUCTION

In wireless networks, two frames overlapping in time need not result in the loss of both the frames. The term ‘capture effect’ refers to the phenomenon by which a receiver is able to recover one of such overlapping frames successfully, as long as the signal-to-interference ratio is above a minimum acceptable threshold (a.k.a. capture threshold) $CP_{th}$. This ‘capture effect’ along with the distance dependent signal power decay gives a variable interference range around any receiver as:

$$r_i = (CP_{th})^{\frac{\alpha}{d_s}} d_s,$$  

(1)

where $d_s$ is the sender-receiver distance and $\alpha$ is the path loss factor. Applicability of ‘capture effect’ in IEEE 802.11 based wireless networks has also been experimentally studied [1], [2] and it is found that the capture behavior is differential based on the order of arrival of the frame of interest. The value of $CP_{th}$ is much lesser when the sender’s frame arrives earlier than that of an interferer (the Sender’s First, or SF case) as compared to the case when the order of arrival is changed (i.e., Sender’s Last, or SL case).

For a successful reception, it is essential to prevent all the nodes in the interference range of the receiver from transmission. Referring to Fig. 1, without differential capture capability (DCC) enabled receivers, $S_2$ and $R_2$, being within $r_i$ of $R_1$, are potential hidden terminals despite the use of RTS/CTS [3]. To prevent all such nodes of zone-IV in Fig. 1 from transmission while $R_1$ is receiving the data frame from $S_1$, the physical carrier sensing range $r_s$ of $S_1$ should cover the interference range of $R_1$ too. Catering for the worst case (i.e., when $d_s = r_t$, the communication range), the safest value of $r_s$ should be [3]:

$$r_{s(safe)} = \left(1 + (CP^{(SL)}_{th})^{\frac{1}{\alpha}}\right)r_t.$$  

(2)

However, from (1) it is clear that, two different values of $CP_{th}$ for a DCC enabled receiver imply there are two different values of $r_i$’s for a given $d_s$, namely, $r_{i(SF)}$ for SF case, and $r_{i(SL)}$ for SL case. As observed in [2], at lower data rate operations $CP_{th}^{(SF)}$ could be much lower. In particular, at $\leq 6$ Mbps, $CP_{th}^{(SF)} = 0$ dB, ensuring $r_{i(max)}^{(SF)} = r_t$. Thus, once a receiver starts receiving a data frame, no node outside its communication range can interfere with it. Thus, in Fig. 1 $S_2$ and $R_2$ are no more hidden terminals when $R_1$ has DCC feature. Accounting for the requirement of successful reception of subsequent ACK at $S_1$, which is SL case, the optimum required $r_s$ would be:

$$r_{s(opt)} = r_{i(max)}^{(SL)} = \left(1 + (CP^{(SL)}_{th})^{\frac{1}{\alpha}}\right)r_t.$$  

With this reduced $r_s$ to $r_{s(opt)}$, all the terminals in the zone-I in Fig. 1 are no more exposed now. However, this reduced value of $r_s$ does not eliminate all the exposed terminals. As shown in Fig. 1, zone-II contains the exposed terminals even with the $r_{s(opt)}$ setting at the nodes. Additionally, by exploiting...
the order of arrival of a desired frame, (i.e., due to a smaller interference range of $R_1$), all nodes in zone-III also are marked as exposed terminals.

In this paper we investigate how some of the exposed terminals (as identified above) can be enabled to communicate without harming the existing communications. We propose a liberal carrier sensing scheme that further exploits the DCC feature and helps identify some of the prospective exposed receivers by using some already available local information and then allows them to initiate secondary sessions. The proposed scheme is backward compatible, as it requires only a little software modification in the existing 802.11 MAC algorithm without needing any change in the hardware.

Through extensive simulations we show that the proposed scheme with $r_s(\text{opt})$, (called liberal carrier sensing with reduced $r_s$, or RLCS scheme) performs better in terms of end-to-end throughput over the conventional carrier sensing scheme with $r_s(\text{safe})$ (called conventional carrier sensing with safe $r_s$, or SCS scheme) and also over the conventional carrier sensing scheme with $r_s(\text{opt})$ (called conventional carrier sensing with reduced $r_s$, or RCS scheme). Specifically, the RLCS performance is shown to offer a throughput gain of as high as 80% in regular topologies and about 20% in random topology over the SCS scheme, and these respective gains are 20% and 3% in regular and random topologies over those in a RCS scheme.

The remaining paper is organized as follows: The related work is surveyed in Section II. In Section III, we present our RLCS scheme. Section IV shows the simulation results, and finally Section V concludes the paper.

II. RELATED WORK

Xu, et al. [3] showed analytically that RTS/CTS exchange is ineffective, particularly when $d_s > r_i/(CP_{th})^\frac{1}{2}$. In their analysis they did not consider DCC feature and hence, assumed only one value of $CP_{th}$ irrespective of the order of arrival of the overlapping frames.

Ye, et al. [4] also identified that RTS/CTS exchange is ineffective because of the dependence of $r_i$ on $d_s$. In their approach of improving spatial reuse, a node is allowed to disregard the reception of RTS or CTS frame if only one of them is received. They assumed a single cell WLAN environment and hence addressed relatively only small values of inter-nodal distances ($d_s < 90$ m). This approach also do not consider DCC feature of modern receivers.

Showing that the origins of unfairness of TCP connections is at the MAC layer, Zhou, et al. [5] have studied the received-non-responsive-receiver problem where a node does not respond with CTS even though it has received an RTS frame correctly. They suggested to use a very large $r_s$ such that $r_s \geq 2r_i + r_t$. A node is then permitted to respond with CTS even if the medium is reported ‘busy’. Ye, et al. [6] have also addressed the received-non-responsive-receiver problem (naming it the problem of unattended RTS). Not considering a possible exposure of the non-responding node, their scheme adaptively controls the MAC level transmission rate at the sender.

From (1), it is easy to notice that for very small inter-nodal distances, the $r_i^{(SF)} \ll r_t$ and the DCC feature can be exploited to effect concurrent transmissions even within a communication range. Using this fact, Santhapuri, et al. [7] proposed to allow two staggered transmissions, where both the communicating pairs are completely within each other’s communicating range. This approach requires considerable modification in the existing 802.11 MAC and it does not address the exposed terminals that are out of the communication range of the sender and receiver.

Like in [7], our proposed scheme in this paper also exploits the DCC feature to improve spatial reuse. But, unlike [4] and [7] our approach focuses on those exposed terminals that are outside the communication range of the primary communicating pair. By allowing some exposed terminals to respond with CTS, our scheme mitigates the received-non-responsive-receiver problem addressed in [5] and [6].

III. MITIGATION OF EXPOSED TERMINALS PROBLEM WITH DCC

Despite the reduction of $r_s$ to $r_s(\text{opt})$ as given in (3), there are exposed terminals, the remaining and the newly identified ones in the union of zones II and III of Fig. 1. In this section, we propose the RLCS scheme that mitigates the problem of such remaining exposed terminals.

Referring to Fig. 1, we consider the possibility of a secondary session $S_3 \rightarrow R_3$, to be run concurrently with the primary session $S_1 \rightarrow R_1$. Fig. 2 shows a usual sequence of transmissions. $S_3$, being outside the $r_s$ of $S_1$, is unaware of the transmissions from $S_1$, and hence could initiate a secondary session with $R_3$ by sending an RTS. $R_3$ is a prospective exposed receiver only if it is able to capture this RTS. This requires $S_1$ to be located outside $r_i^{(SL)}$ of $R_3$, i.e.,

$$d_{R_3S_1} > r_i^{(SL)} = \left(\frac{CP_{th}^{(SL)}}{\Delta \tau}\right)^\frac{1}{2} d_{S_3R_3}. \tag{4}$$

The RLCS allows $R_3$ to respond with CTS only if it could ensure that, both the sessions would end successfully. That is, the primary frames ($DATAS_1^*$ and ACK$R_1^*$) and the

*We use a symbol $XYZN$ to denote a frame of type $XYZ$ transmitted by node $N$
secondary frames \((\text{CTS}_{R_3}, \text{DATA}_{S_3}, \text{ACK}_{R_3})\) should each be successfully received at their designated destinations. To this end, RLCS uses some information already available locally at \(R_3\), as described below:

a) \(\text{ACK}_{R_1}\) at \(S_1\): In RLCS, liberty of ignoring ‘busy-medium’ could be enjoyed only for responding with a CTS and not for initiating a new session with an RTS. i.e., RLCS limits the solution to the problem of prospective exposed receivers (like \(R_3\) in Fig. 1) only, but not the exposed senders (like \(S_1\) in Fig. 1). This is necessary because the ‘exposure’ of some of the nodes in zones II and III could be ‘ad hoc’ and valid only during the period of \(\text{DATA}_{S_1}\). If permitted, the longer data frame of \(S_1\) could interfere with (and garble the) \(\text{ACK}_{R_1}\). Thus, a sender of the secondary session induced by RLCS is always outside the \(r_s\) of \(S_1\).

However, \(R_3\), being within the \(r_s\) of \(S_1\), could also be within \(r_i^{(\text{SL})}\) of \(S_1\) too, and hence, the other frames that could interfere with \(\text{ACK}_{R_3}\) are \(\text{CTS}_{R_3}\) and \(\text{ACK}_{R_3}\). The discussion in Section III-A explains how RLCS always accommodates the \(\text{CTS}_{S_1}\) within the transmission period of \(\text{DATA}_{S_1}\), and thus, it never overlaps with \(\text{ACK}_{R_1}\). Moreover, as a consequence, it also ensures that the secondary session starts only after the starting of transmission of \(\text{DATA}_{S_1}\). Hence, an overlap of \(\text{ACK}_{R_1}\) and \(\text{ACK}_{R_3}\) is impossible if the data packets are equal-sized, and it would also be very rare if the data packets are of different size, due to the small size of \(\text{ACK}\).

b) \(\text{DATA}_{S_1}\) at \(R_1\): As elaborated in Section III-A, \(R_3\) ensures that data reception at \(R_1\) is always an SF case. Hence, it only remains necessary to see that \(S_3\) and \(R_3\) are out of the communication range from \(S_1\). RLCS facilitates this by respecting the virtual carrier sensing mechanism of the basic 802.11 MAC. That is, had \(R_3\) (or \(S_3\)) been inside the \(r_i\) of either \(S_1\) or \(R_1\) (or both), it would have received the RTS or CTS (or both) and would have deferred its transmission at least until the completion of \(\text{ACK}_{R_1}\).

c) \(\text{DATA}_{S_3}\) at \(R_3\): Successful reception of \(\text{RTS}_{S_3}\) (i.e., fulfilling the condition (4)) also ensures successful reception of \(\text{DATA}_{S_3}\) in static networks.

d) \(\text{ACK}_{R_3}\) at \(S_3\): No frame from \(S_1\) could interfere any reception at \(S_3\), because \(S_3\) is always located out of \(r_s\) of \(S_1\). However, \(R_3\) could be a potential interferer for \(S_1\), but as discussed above, \(\text{ACK}_{R_1}\) and \(\text{ACK}_{R_3}\) would rarely overlap.

e) \(\text{CTS}_{R_3}\) at \(S_3\): As discussed in Section III-A, \(\text{CTS}_{R_3}\) is sent always within the transmission period of \(\text{DATA}_{S_3}\), and since \(S_1\) is outside \(r_s\) of \(S_3\), reception of \(\text{CTS}_{R_3}\) is always successful.

Note that, though we have illustrated with \((S_3 \rightarrow R_3)\) as the possible secondary session, RLCS equally facilitates a concurrent secondary session \((S_2 \rightarrow R_2^{(\text{SL})})\) as well, even though, \(S_2\) is within \(r_i^{(\text{SL})}\) of \(R_1\).

A. Accommodating \(\text{CTS}_{R_3}\) within the \(\text{DATA}_{S_1}\) period

The proposed RLCS needs to ensure that \(\text{CTS}_{R_3}\) falls within the \(\Delta \tau\) period (between \(t_i\) and \(t_c\)) shown in Fig. 2. To achieve this, we propose that every node records an ‘RTS-sending’ event even if the RTS sender is outside its communication range. Though, an RTS frame transmitted from a distance \(r_t < d \leq r_e\) is not decodable, its length can be accurately inferred from its transmission period \([8],[9]\), because, in 802.11 out of the three control frames, RTS, CTS, and ACK, the length of RTS is unique. Thus, when \(S_1\) sends RTS to \(R_1\), \(R_3\) uses this length-inferencing technique to record this event, and at this instant (i.e., \(t_i\) in Fig. 2), it also starts a timer initialized with a duration required to transmit a frame of length \(\text{RTSThreshold}\) \([10]\). In 802.11 based MAC, RTS/CTS are exchanged only for those data packets that are of length at least \(\text{RTSThreshold}\). Thus, it ensures that the timer will expire before the end of \(\Delta \tau\) period. Here, RLCS makes a liberal assumption that all the participating nodes in the network has the same value of \(\text{RTSThreshold}\) and it is sufficient to give some room for node like \(R_3\) to grab the opportunity of concurrency.

According to the basic 802.11 MAC algorithm, \(R_3\) is prevented from transmission for Extended Inter Frame Space (EIFS) period after it receives the undecodable \(\text{RTS}_{S_1}\) \([10]\). This EIFS period is more than the difference between \(t_i\) and \(t_c\), which ensures that \(R_3\) will not send CTS before \(t_c\). Moreover, the difference between \(t_i\) and \(t_c\) is more than a CTS transmission time. Therefore, the starting instant of the timer being \(t_i\) ensures its completion at least a CTS transmission time before \(t_c\). Thus, to ensure that \(\text{CTS}_{R_3}\) falls within the \(\Delta \tau\) period, it is only necessary for \(R_3\) to start CTS only if this timer is active.

IV. SIMULATIONS AND RESULTS

For verification of the gain of the proposed scheme, we performed extensive simulations on ns2 [11] network simulator. We modified its source code to incorporate DCC feature. With \(r_s\) set to \(r_s(\text{opt})\), we call this basic implementation as RCS, and the implementation with \(r_s\) set to \(r_s(\text{opt})\) is called RCS. After incorporating DCC, we further modified it to incorporate the liberal carrier sensing mechanism. With \(r_s\) set to \(r_s(\text{opt})\) we call this modified scheme as RLCS. The objective is to show the gains of RLCS over RCS as well as over RCS. Our simulation studies considered two regular topologies, namely, a 2-flow parallel chain and a square grid, and a random topology with different number of TCP flows.

Table I lists the common parameter settings used in our simulations. For multi-hop ad hoc networks, Two-Ray-Ground channel propagation model is well suited [12] and hence we used it. All nodes are assumed equipped with a single radio transceiver with the message-in-message (MIM) [2] switch ON, to enable them with DCC. Physical layer wireless channel errors are neglected and all the errors are assumed to be caused by collisions only. The simulation time for each experiment is 120 seconds. For regular topology plots, each point is an average of 30 simulation runs, each with a different seed for the MAC layer random back-off, while for the random topology, the number of runs are 200, each with a different seed for the random topology generator. We chose \(r_1 = 250\) m, and hence from (2) and (3) \(r_s(\text{opt}) = 695\) m and \(r_s(\text{opt}) = 445\) m. The values of \(CP_{th}^{(SF)}\) and \(CP_{th}^{(SL)}\) were set to 0 dB and 10 dB respectively, as suggested in [2] for operations at \(\leq 6\) Mbps.
data rates. Thus, though, our simulation results are for 1 Mbps data rate, the RLCS performance gains shown here are valid up to 6 Mbps. Moreover, even for 12 Mbps data rate, the values of $CP_{th}^{SF}$ and $CP_{th}^{SL}$ are 3 dB and 10 dB respectively, and hence, from (1) it can be easily inferred that RLCS will perform equally better for inter-nodal distances $d_s \leq 210$ m even at 12 Mbps data rate.

### A. 2-flow regular parallel chain topology

![Fig. 3. 2-flow regular parallel chain topology. Two TCP flows are set: 0 → n − 1 and n → 2n − 1. $d_f$ is the inter-flow distance.](image)

Fig. 3 shows the first regular topology. Two parallel TCP flows are set: (0 → n − 1) and (n → 2n − 1). Hence, n − 1 is the number of hops between the end-to-end sender-receiver pair. Fig. 4 shows the aggregated throughput of two flows for different inter-nodal distances for $n = 6$ (i.e., 5 hops). Though the results shown are for the inter-flow distance $d_f = 400$ m, we have verified that RLCS performance is better than SCS and RCS over all the other values of $d_f$ too. As compared to SCS, RLCS performs better by about 85% in the range $195$ m $\leq d_s \leq 224$ m and by about 50% for other $d_s$ values. When compared to RCS, the RLCS performance is better by 10 to 17% except for the range $d_s \geq 225$ m where both the schemes performs equally good. The reason behind the higher gain over SCS in the range $195$ m $\leq d_s \leq 224$ m can be understood as follows: As shown in Fig. 3, when $d_s \geq \sqrt{r_{s(opt)}^2 - d_f^2}$, only one node (the nearest one) of the other flow is in its $r_s$ range. For example, for node 1, only $n + 1$ of the other flow is in its $r_{s(opt)}$ range. As a consequence many concurrent communications are made possible in RCS and RLCS both, which are not possible with the large $r_s$ in SCS. In the range $d_S \geq 225$ m, $r_{i(SL)} \geq 400$ m = $d_f$, and hence, for any node, the nearest node of the other flow comes within its $r_{i(SL)}$. Consequently, it is not able to exploit RLCS any more, and the gain here is mainly due to the number of concurrently communicating pairs induced due to the reduction of $r_s$ only.

To see the effect of number of hops specifically, in Fig. 5 same data were used to plot system throughput versus number of hops between the (end to end) sender and the receiver for three different values of $d_s$: 170 m, 200 m, and 240 m. RLCS performs significantly better than SCS for all the values of $d_s$ and for any number of hops. While, in comparison to RCS, its performance is better for $d_s = 170$ m and $200$ m, and is almost at par for $d_s = 240$ m as this inter-nodal distance is $> 225$ m.

### B. Square grid topology

![Fig. 4. 2-flow regular parallel chain topology: Aggregate throughput for different inter-nodal distances](image)

![Fig. 5. 2-flow parallel chain topology: Aggregate throughput for different number of hops between end-to-end sender and receiver. $d_s = 200$ m.](image)

Fig. 6 shows the square grid topology, where 25 nodes are deployed in a $5 \times 5$ square pattern with four TCP flows. The aggregated throughput for different inter-nodal distances is as shown in Fig. 7. RLCS performs as high as 80% and 22% better over SCS and RCS, respectively. Here also RLCS performance

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At lower data rates, the arrival order dependent capture behavior of modern receivers helps improve spatial reuse by allowing a safe reduction in the carrier sensing range. However, even with an optimally reduced carrier sensing range there still remain many exposed terminals. In this paper, we proposed a liberal carrier sensing scheme that further exploits the differential capture behavior to help identify the potential receivers among the exposed terminals. With existing virtual carrier sensing mechanism, the proposed scheme allows some of the exposed receivers to initiate a communication process without harming the concurrent neighboring transmissions. The benefit of enhanced spatial reuse has been demonstrated in terms of increased system throughput via extensive network simulations.

**V. Conclusion**

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**REFERENCES**


