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.

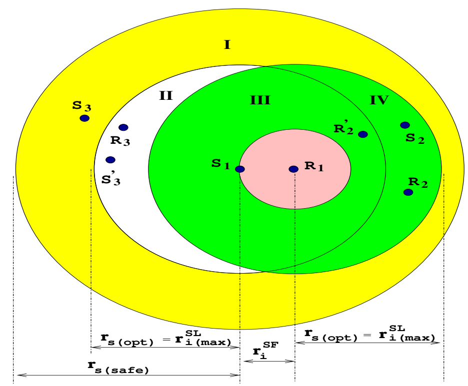

Fig. 1. (S_1,R_1) is a point-to-point communicating pair. Zone-IV has no more hidden terminals for an SF reception at R_1. Zone-I has exposed terminals for $r_{s(safe)}$. Zones II and III may contain exposed terminals despite the use of $r_{s(opt)}$.

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:

$$r_i = (CP_{th})^{\frac{1}{\alpha}} d_s, \tag{1}$$

where d_s is the sender-receiver distance and α 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 **S**ender's **F**irst, or SF case) as compared to the case when the order of arrival is changed (i.e., **S**ender's **L**ast, 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]:

$$r_{s(safe)} = \left(1 + \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}}\right) r_t. \tag{2}$$

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 could be SL case, the optimum required r_s would be:

$$r_{s(opt)} = r_{i(max)}^{(SL)} = \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}} r_t. \tag{3}$$

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

This research was partly supported by the Dept. of Science and Technology (DST) under the grant no. SR/S3/EECE/054/2007 and the Council of Scientific and Industrial Research (CSIR) under the grant no. 22/448/07/EMR-II.

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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 $r_{s(opt)}$, (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 $r_{s(safe)}$ (called conventional carrier sensing with safe r_s, or SCS scheme) and also over the conventional carrier sensing scheme with $r_{s(opt)}$ (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 $d_s > r_t/(CP_{th})^{\frac{1}{\alpha}}$. 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 $r_s \geq 2r_t + r_i$. 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 $r_{s(opt)}$ 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

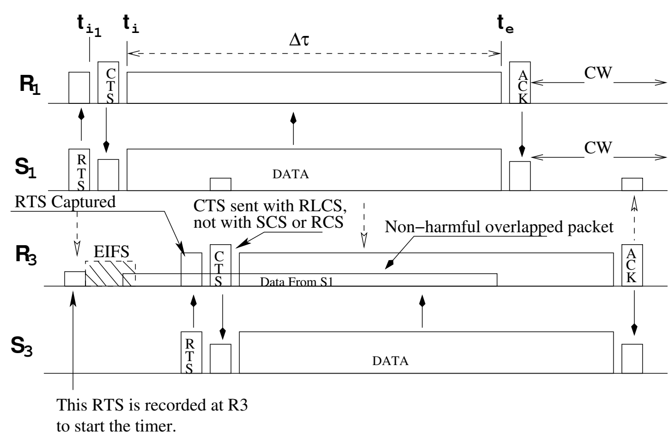

Fig. 2. R_3 is an exposed node in the SCS or RCS scheme and hence it is disallowed from a concurrent reception. But in the RLCS scheme it is allowed to agree on a reception.

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.,

$$d_{R_3S_1} > r_{i_{R_3}}^{(SL)} = \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}} d_{S_3R_3}. \qquad (4)$$

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 ($DATA_{S_1}{}^*$ and ACK_{R_1}) and the

*We use a symbol XYZ_N to denote a frame of type *XYZ* transmitted by node *N* secondary frames (CTS_{R_3}, $DATA_{S_3}$, and 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) 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'_3 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 $DATA_{S_1}$. If permitted, the longer data frame of S'_3 could interfere with (and garble) the 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 $r_i^{(SL)}$ of S_1 too, and hence, the other frames that could interfere with ACK_{R_1} are CTS_{R_3} and ACK_{R_3}. The discussion in Section III-A explains how RLCS always accommodates the CTS_{R_3} within the transmission period of $DATA_{S_1}$, and thus, it never overlaps with ACK_{R_1}. Moreover, as a consequence, it also ensures that the secondary session starts only after the starting of transmission of $DATA_{S_1}$. Hence, an overlap of ACK_{R_1} and 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 ACK.

b) $DATA_{S_1}$ 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_t 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 ACK_{R_1}.

c) $DATA_{S_3}$ at R_3: Successful reception of RTS_{S_3} (i.e., fulfilling the condition (4)) also ensures successful reception of $DATA_{S_3}$ in static networks.

d) 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, ACK_{R_1} and ACK_{R_3} would rarely overlap.

e) CTS_{R_3} at S_3: As discussed in Section III-A, CTS_{R_3} is sent always within the transmission period of $DATA_{S_1}$, and since S_1 is outside r_s of S_3, reception of 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 ($S_2 \rightarrow R'_2$) as well, even though, S_2 is within $r_i^{(SL)}$ of R_1.

A. Accommodating CTS_{R_3} within the $DATA_{S_1}$ period

The proposed RLCS needs to ensure that CTS_{R_3} falls within the $\Delta\tau$ period (between t_i and t_e) 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 $r_t < d \leq r_s$ 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-inferring technique to record this event, and at this instant (i.e., t_{i_1} in Fig. 2), it also starts a timer initialized with a duration required to transmit a frame of length RTSThreshold [10]. In 802.11 based MAC, RTS/CTS are exchanged only for those data packets that are of length at least 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 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 RTS_{S_1} [10]. This EIFS period is more than the difference between t_i and t_{i_1}, which ensures that R_3 will not send CTS before t_i. Moreover, the difference between t_i and t_{i_1} is more than a CTS transmission time. Therefore, the starting instant of the timer being t_{i_1}, ensures its completion at least a CTS transmission time before t_e. Thus, to ensure that 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 $r_{s(safe)}$, we call this basic implementation as SCS, and the implementation with r_s set to $r_{s(opt)}$ is called RCS. After incorporating DCC, we further modified it to incorporate the liberal carrier sensing mechanism. With r_s set to $r_{s(opt)}$ we call this modified scheme as RLCS. The objective is to show the gains of RLCS over RCS as well as over SCS. 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 $r_t = 250$ m, and hence from (2) and (3) $r_{s(safe)} = 695$ m and $r_{s(opt)} = 445$ 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

TABLE I
PARAMETER SETTINGS FOR THE SIMULATIONS

Parameter	Value
ns2	version 2.33
Data rate	1 Mbps
Propagation model	Two ray ground
Transmission range (r_t)	250 meters
Carrier sensing range ($r_{s(safe)}$)	695 meters
Carrier sensing range ($r_{s(opt)}$)	445 meters
SF case capture threshold	0 dB
SL case capture threshold	10 dB
Routing protocol	gpsr
Transport protocol	TCP-Tahoe
TCP packet size	1000 Bytes
RTSThreshold	999 Bytes
Simulation time	120 seconds

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

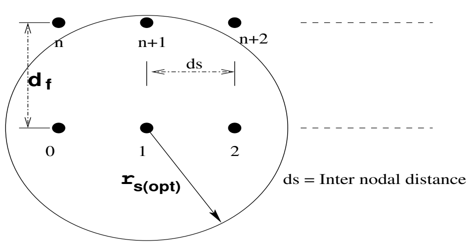

Fig. 3. 2-flow regular parallel chain topology. Two TCP flows are set: $0 \rightarrow n-1$ and $n \rightarrow 2n-1$. d_f is the inter-flow distance.

Fig. 3 shows the first regular topology. Two parallel TCP flows are set: ($0 \rightarrow n-1$) and ($n \rightarrow 2n-1$). 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

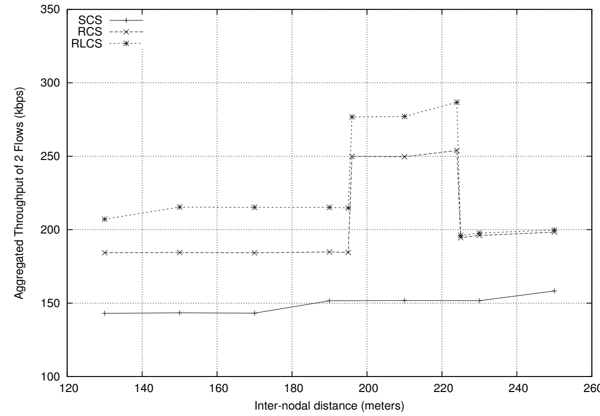

Fig. 4. 2-flow regular parallel chain topology: Aggregate throughput for different inter-nodal distances

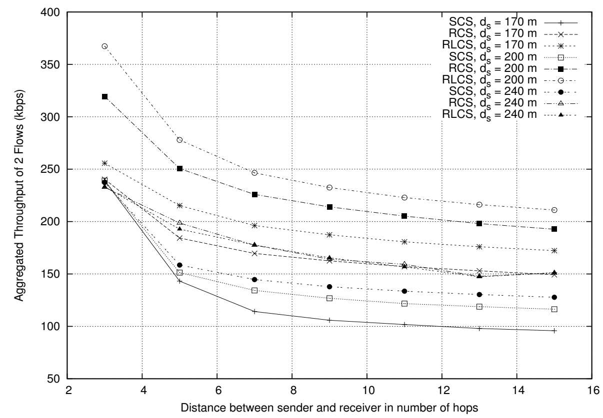

Fig. 5. 2-flow parallel chain topology: Aggregate throughput for different number of hops between end-to-end sender and receiver. $d_s = 200$ m.

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 $ds \geq 225$ 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. 6 shows the square grid topology, where 25 nodes are deployed in a 5 × 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

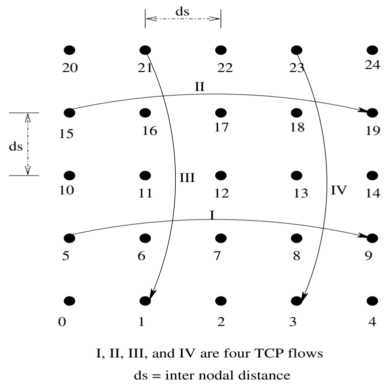

Fig. 6. 5 × 5 Square grid topology.

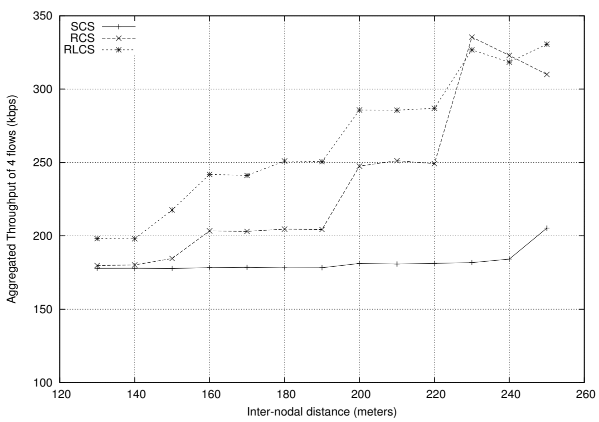

Fig. 7. 5 × 5 Square grid topology: Aggregate throughput for different inter-nodal distances

curve merges with that of RCS at very large values of d_s, because of the reasons explained for Fig. 4.

C. Random topology

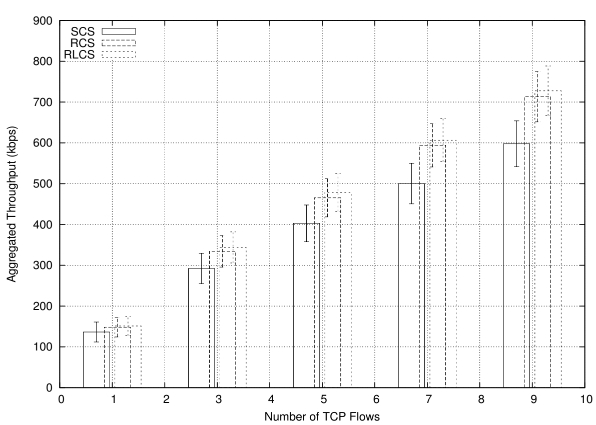

Fig. 8. Random topology: Aggregate throughput for different number of TCP flows. 460 nodes are randomly deployed in 3 km × 3 km area. All the TCP flows are randomly chosen.

460 nodes were deployed randomly in the area of 3 km×3 km and n TCP flows were set with each (end-to-end) communicating pair chosen randomly. This node density corresponds to 10 neighbors on average around any node. Fig. 8 shows the aggregated throughput versus number of flows. Each average reading is also supported with an error-interval with 99% confidence level. While RLCS performs better than the SCS by about 20%, its gain over RCS is only marginal (about 3%). The reason behind this is that, the routing layer protocol (gpsr) acts greedily in exploring the route to the destination, and hence it always attempts to choose the farthest node as the next hop. This leads to a very large average inter-nodal distance in any flow, where RLCS performance tends to merge with that of RCS.

V. Conclusion

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.

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