A Liberal Carrier Sensing for Increased Spatial Reuse in Multi-Hop Wireless Ad Hoc Networks

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***Abstract*—Recent experimental results have shown that the minimum signal-to-interference ratio required at a receiver (CP_{th}) depends on the order of arrival of the overlapping frames. For a given sender-receiver distance, this differential capture capability of a receiver leads to two distinct interference ranges (r_i) around the receiver, and its value is much smaller when the sender's frame arrives earlier. This feature also suggests a possibility of increased spatial reuse by allowing the (secondary) nodes outside the primary receiver's r_i to communicate concurrently once the primary receiver starts its DATA reception.**

In this paper, we propose a liberal carrier sensing (LCS) scheme wherein some already available information at an otherwise 'exposed' receiver are exploited to help decide when it is safe to respond to a secondary transmission request. The proposed modification in the carrier sensing approach results in a significantly improved spatial reuse, thereby increasing overall system throughput. Our simulation studies show that, compared to the conventional carrier sensing scheme with differential capture capable receivers, the end-to-end TCP throughput with LCS can be improved by more than 20% in regular topologies and up to about 9% in random topologies.

***Index Terms*—Differential capture capability; exposed terminals; liberal carrier sensing; spatial reuse**

I. Introduction

In wireless networks, the success of a given transmission depends on what happens at the receiver and not what happens at the transmitter or at any other node that overhears the transmission. Hence to minimize the collisions at a receiver, potential simultaneous transmission from another node in the interference range r_i of the receiver has to be minimized. It has been studied in [1], [2] that, despite significant interference from other nodes, as long as the signal-to-interference ratio (SIR) at the receiver is above a minimum acceptable threshold (a.k.a. capture threshold) CP_{th}, it is possible to receive a frame successfully. Considering distance dependent signal power decay, the above condition leads to:

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

where α is the path loss factor and d_{SR} is the distance of the receiver from its sender.

According to recent experimental studies in [2], 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 sender's frame arrives later (the **S**ender's **L**irst, or SL case). From (1), it is clear that, for a given d_{SR}, such differential capture capability (DCC) of the receivers leads to two different r_i's: $r_i^{(SF)}$ and $r_i^{(SL)}$, for SF and SL cases, respectively. Thus, once a receiver starts receiving a frame, all nodes outside its $r_i^{(SF)}$ radius may be allowed to communicate concurrently with its on-going reception. However, in the conventional carrier sensing (CCS) scheme, all nodes that are within the carrier sense range r_s of the current sender are not allowed to initiate any transmission, although some nodes (called the exposed terminals) could be outside r_i of the current receiver. This exposed terminals problem results in suboptimal reuse of the channel bandwidth, leading to a poor network throughput performance.

Prior works aiming to improve spatial reuse either did not consider the DCC of modern radio receivers (e.g., [3], [4], [5]), or it was not fully exploited to reduce the number of exposed terminals [6]. The approach in [6] took DCC into account for effecting concurrent transmissions within the communication range r_t of each other. However, there is quite a large area within the carrier sense range of a trans-receiver pair, and the nodes located in the sense-only region may still be unnecessarily deferred from initiating a communication. Therefore, it is important to investigate if DCC feature can be further beneficial to alleviate the exposed terminals problem.

In this paper we show that, by exploiting the DCC property of receivers it is possible to identify if some of the exposed terminals can be allowed to initiate concurrent transmissions, thus increasing the spatial reuse. We call our proposed scheme as liberal carrier sensing (LCS). The proposed scheme uses some already available local information at a node and requires only a little modification in the existing 802.11 MAC algorithm. Through extensive simulations we show that the proposed scheme performs better in terms of end-to-end throughput compared to the CCS based scheme with DCC. Specifically, the LCS scheme is shown to offer a throughput gain of around 10% in single-flow regular chain topology, about 23% in 2-flow regular chain and square grid topologies, and about 9% in random topology.

The rest of the paper is organized as follows. Section II contains a brief survey of related works. In Section III, the possibility of concurrent transmissions induced due to the DCC feature of radio receivers is demonstrated through illustrations and analytic reasonings. Our proposed LCS scheme is introduced in Section IV. Network simulation environment and performance results are presented in Section V. Finally Section VI concludes the paper.

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II. RELATED WORK

The authors in [3] and [4] identified that the CCS scheme is suboptimal for most scenarios. Ye, et al. [4] assumed a single cell WLAN environment and hence addressed very small values of inter-nodal distances ($d_s \leq 90$ m). In their approach a node is allowed to disregard the reception of RTS (request-to-send) or CTS (clear-to-send) frame if it received only one of them. While this approach works well for small values of d_s, it degrades gradually for moderate to large values of d_s. Xu, et al. [3] analytically showed the ineffectiveness of RTS/CTS and the increased exposed terminals problem with a large r_s. The analysis however did not include the effects of differential capture thresholds for SF and SL cases.

Zhou, et al. [5] studied the various factors involved in the performance issues of MAC layer. They defined a *received-non-responsive-receiver* as a node which does not respond after it has been sent an RTS frame, though it received the frame correctly. They suggested to use a very large r_s such that $r_s \geq 2r_t + r_i$. With this increased r_s a node is permitted to respond with CTS even if it senses the medium busy. Ye, et al. [7] 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.

Santhapuri, et al. [6] observed that, for a small sender-receiver distance, DCC can be exploited to effect spatial reuse even within r_t. They proposed two staggered concurrent transmissions within r_t, where the secondary pair receives decodable RTS/CTS from primary. Their protocol requires a considerable modification in the existing 802.11 MAC.

In contrast to the approaches in [5] and [7], in our work we propose an alternative mechanism to address the *received-non-responsive-receiver* problem in a distributed control wireless ad hoc network. Our method helps tag such a non-responsive receiver to a *received-responsive-receiver* after identifying the possible exposed terminal scenarios. Moreover, we use a nominal value of r_s and hence a node only ignores the reception status and does not disregard the NAV (network allocation vector) while performing the carrier sensing. In contrast to [4] and [6], our proposed approach helps reduce those exposed receivers, which are outside r_t of a communicating pair.

III. CCS WITH DCC-ENABLED RECEIVERS

In this section we look into the DCC feature of radio receivers and its effect on possible concurrent transmissions.

Suppose (S, R) is a point-to-point sender-receiver pair of nodes, in a homogeneous network environment with all nodes having identical transceivers. Considering the power-law decay in signal strength, the condition for successful reception at R in presence of an interfering transmitter I can be stated as:

$$SIR_R = \frac{P_{RS}}{P_{RI}} = \left(\frac{d_{IR}}{d_{SR}}\right)^{\alpha} \geq CP_{th} \tag{2}$$

where P_{RS} is the power received at R due to the transmission from S, located at a distance d_{SR}. The DCC feature of the receivers leads to two r_i's for any node as given below:

$$r_i^{(SF)} = \left(CP_{th}^{(SF)}\right)^{\frac{1}{\alpha}} d_{SR}, \text{ for SF case, and} \tag{3a}$$

$$r_i^{(SL)} = \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}} d_{SR}, \text{ for SL case.} \tag{3b}$$

As observed in [2], $CP_{th}^{(SF)}$ could be quite low for lower data rate operations (e.g., $CP_{th}^{(SF)} = 0$ dB for ≤ 6 Mbps). From (3a), the corresponding maximum value of $r_i^{(SF)}$ is: $r_{i_{\max}}^{(SF)} \approx r_t$, when $d_{SR} = r_t$. Thus, with $CP_{th}^{(SF)} = 0$ dB, no node outside the r_t of a receiver can interfere with its data reception.

Suppose the pair of nodes (S_1, R_1) and (S_2, R_2) are located as shown in Fig. 1, and the first (primary) pair starts the communication session earlier than the second (secondary) one. Fig. 2 shows a usual sequence of transmissions in such scenario. S_2, being outside r_s of S_1, is unaware of the on-going transmission from S_1. Hence, this hidden node may send an RTS to R_2 to initiate a transmission process during the period $\Delta\tau$, as shown in Fig. 2. This RTS will be successfully received at R_2 if (from (2) and (3b))

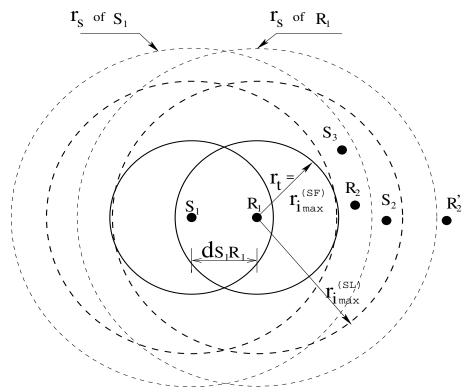

Fig. 1. (S_1, R_1) and (S_2, R_2) are two point-to-point communicating pairs, in which one starts earlier than the other.

$$d_{S_1R_2} > r_{i(R_2)}^{(SL)} = \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}} d_{S_2R_2}. \tag{4}$$

However, in the CCS scheme, R_2 does not respond with a CTS to S_2, as the physical carrier sensing at R_2 identifies the medium to be busy. Clearly, R_2 is an exposed receiver. From Fig. 2 it is also clear that, a long DATA frame from S_1 to R_1 will result in R_2 not being able to respond to multiple RTSs from S_2. The problem may worsen if S_1 wins subsequent contention(s). In an extreme scenario S_2 may reach the short retry limit of RTS (which is 7 by default), resulting in a route recovery procedure at the network layer. If the above problem is not addressed at the MAC layer, it would impact severely at the transport layer.

Although through the above example the weakness of CCS is highlighted, DCC-enabled receivers offer improved performance with respect to the system of nodes with a fixed CP_{th}, which can be justified as follows. If the hidden node S_2 in the above example initiates a communication to another node R_2' (Fig. 1) which is outside the r_s of R_1, both S_1-R_1 and S_2-R_2' communications could be successful by virtue of DCC. Since

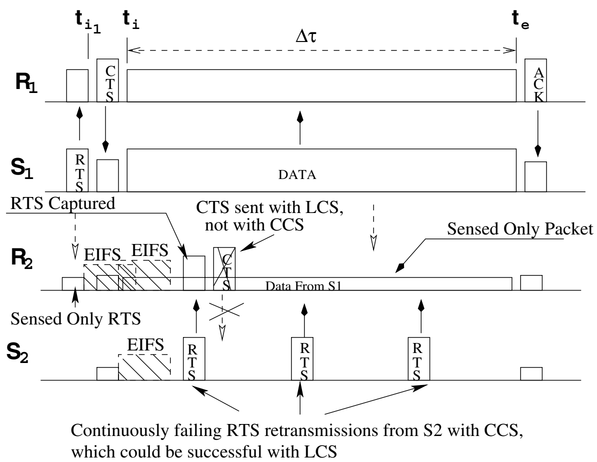

Fig. 2. With DCC feature R_2 is an exposed node in the CCS scheme, and hence it is disallowed from a concurrent reception. But in the LCS scheme R_2 is allowed to initiate a reception.

the DCC itself results in an improved system performance, in our discussion henceforth, we will consider the network with DCC enabled receivers only. We will show that our proposed LCS scheme improves the performance further.

IV. Proposed Liberal Carrier Sensing Scheme

Referring to Figs. 1 and 2, when R_2 is outside $r_t = r_i^{(SF)}$ of R_1, it can be safely allowed to send its CTS to S_2 during $\Delta\tau$ period. In this section we discuss our proposed LCS scheme which exploits DCC feature to identify the *exposure* of receivers like R_2. LCS allows such a receiver to respond with CTS ignoring the physical carrier sensing to effect a concurrent secondary reception. Note that, LCS does not disregard the virtual carrier sensing. We will show that if allowed by LCS, both primary and secondary sessions would be successful.

The successful reception of RTS of S_2 at R_2 ensures successful reception of data from S_2 as well. Moreover, reception of RTS from S_2 at R_2 during $\Delta\tau$ period also indicates that S_2 is outside r_s of S_1 and (at least) outside $r_t = r_i^{(SF)}$ of R_1. Thus, all primary frames are safe from transmissions at S_2. The ACK of R_2 will never overlap with the ACK of R_1 under equal-sized data packets assumption, and would happen rarely for variable-sized data packets. However, as R_2 could be located within $r_i^{(SL)}$ of S_1, its CTS transmission must be accommodated within $\Delta\tau$ period so as to ensure successful reception of ACK at S_1. Let us define 'liberty period' as the time duration when R_2 is free for its own CTS transmission ignoring the physical carrier status. In the following, we explain how this 'liberty period' is accommodated within the $\Delta\tau$ period.

Conventionally, the transmission from a node at a distance d can only be detected but not decoded if $r_t < d \leq r_s$. Though such 'sensed only' frame cannot be decoded, its length can be inferred accurately from its transmission time [8]. In IEEE 802.11 MAC, out of the three control frames (RTS, CTS, and ACK), the size of RTS frame is unique and hence it can be easily identified. Note that, this length inferring technique for a 'sensed only' frame works only for the ones that are received in isolation, i.e., devoid of an overlap with any other frames.

Thus, referring to Fig. 2, when S_1 sends an RTS to R_1, the aforementioned length inferring technique is used at R_2 to record this event. Because it is a 'sensed only' frame, it ensures that R_2 is outside r_t (and hence $r_i^{(SF)}$) but within r_s of the S_1. Moreover, because it is an RTS, it indicates the beginning of a primary session. In the standard MAC protocol, after receiving an erroneous (or a 'sensed only') frame, a node waits for an extended-inter-frame-space (EIFS) period [9], which is larger than the difference $|t_i - t_{i_1}|$ by 2 slot times. Thus, it ensures that the 'liberty period' will not start before t_i. Note that, for the case illustrated in Fig. 1 and 2 where R_2 is also within r_s of R_1, the 'liberty period' will further be postponed until another EIFS period after R_2 receives the 'sensed-only' CTS from R_1.

To mark the end of 'liberty period', R_2 starts a timer Tm at t_{i_1}, initialized with a period it takes to transmit a DATA frame of length RTS-Threshold [9]. According to the standard 802.11 MAC protocol, a node uses RTS/CTS only for the data packets that are larger than RTS-Threshold. This ensures that the timer Tm, and hence, the 'liberty period' will expire before t_e. The difference $|t_i - t_{i_1}|$ also ensures that, it expires at least one CTS_{time} before t_e, which further guarantees that R_2 will not start sending a CTS if there is no sufficient time left for completing it before t_e. Algorithm 1 shows in procedural notations the modification required in the carrier sensing procedure that is exercised before every transmission attempt except MAC ACK.

Algorithm 1 procedure: $CarrierSense()$ returns status of the channel in chStat

// Called before making a transmission attempt
Require: pktTx = next frame to be transmitted
chStat = idle
if not(pktTx is CTS **and** Tm is active) **then**
chStat = PhysicalCS() // idle or busy
end if
chStat = VirtualCS() // idle or busy
return chStat;

The triggering event for Tm and the chosen initial value of Tm also emphasize that LCS does not allow a secondary session to start when the primary session did not use RTS/CTS. Thus, all broadcast messages and other smaller than RTS-Threshold data packets' transmissions all go without LCS. Here we assume that all nodes' RTS-Threshold is set with the same value. Moreover, this value should be sufficiently high to give nodes (like R_2 in this example) a sufficient room to exploit LCS.

It should be noted that LCS allows only exposed receivers (like R_2) and not exposed senders (like S_3, located within $r_i^{(SL)}$ of S_1) to initiate a secondary session. This restriction is required to ensure successful reception of the subsequent ACK at S_1, which could be otherwise overlapped with a longer DATA frame of S_3. The exposed senders' restriction could be relaxed (thereby further increasing spatial reuse) in case of data transmissions without link layer ACK, however at the cost of reduced guarantee of end-to-end data delivery.

V. Simulations and Results

We chose ns2 (ver. 2.33) and modified its source code to incorporate the differential capture capability in SF and SL cases with capture thresholds 0 dB and 10 dB, respectively, as suggested in [2]. We call this implementation as the CCS scheme. Beyond incorporating DCC, we modified the source code further to model our proposed LCS scheme. Our evaluation focused on end-to-end system throughput measured at the transport layer. We considered two regular topologies: chain and square grid, carrying multi-hop TCP flows. In the chain topology, a single multi-hop flow performance as well as two parallel (and anti-parallel) flow performance were studied. Besides, the network performance in a random topology with multiple number of TCP sessions were also studied.

All simulations were run at 1 Mbps homogeneous data rate. Two-ray-ground propagation model was used. RTS-Threshold was set to 999 Bytes in accordance with the fixed TCP packet size of 1000 Bytes. Note that, though our simulations assume a homogeneous channel rate of 1 Mbps, from the CP_{th} values observed in [2], the performance gain results are equally valid at higher data rates, up to 12 Mbps. All nodes are assumed equipped with a single radio with the *message-in-message* (MIM) [2] switch enabled to activate DCC in them. r_t and r_s were taken 250 m and 550 m, respectively. GPSR (greedy perimeter stateless routing) was taken as the underlying routing protocol.

In all experiments, the errors were assumed to be caused by MAC collisions only. The simulation time for each experiment was 120 seconds. The experiments of regular topologies were repeated 30 times, each with a different seed for the MAC layer random back-off, while the random topology results were based on 200 runs, each with a different seed for the random topology generator. Performance estimates in random topology scenario were reliable within 99% confidence interval.

A. Regular topologies

1) Chain topology with only one flow: Fig. 3(a) shows a single-flow regular chain topology that we used for the simulation. When $d_s \leq \frac{r_t}{2}$, the routing protocol (GPSR) does

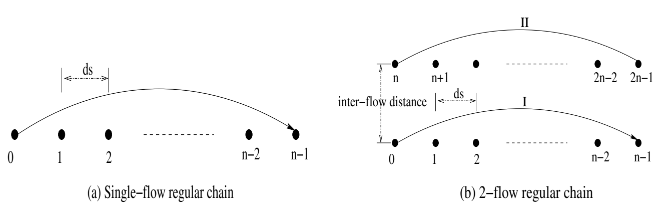

Fig. 3. 125 m $< d_s \leq$ 250 m. TCP flows were set as shown by arrowed lines, except for the direction of flow II in 2-flow case, which is from node n to $2n-1$ for parallel topology and from $2n-1$ to n for anti-parallel topology.

not choose the immediate neighbor as its next hop. For this reason, we considered only the cases with $d_s > \frac{r_t}{2}$. A single TCP flow is set between the two extreme nodes in the chain. The plots in Fig. 4 show the throughput at different inter-nodal distances. It shows four sets of curves, with 3, 4, 5, and 10 hops. LCS does not come into play in the 3-hop case, because any two communicating pairs lie always within r_t of each other. The improvement starts in 4-hop communication,

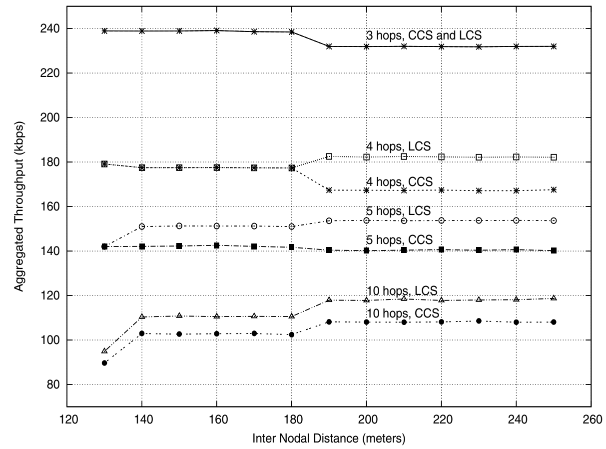

Fig. 4. Network performance in a single flow regular chain topology.

when an LCS induced concurrency is exploited by the two end-pairs. This concurrency happens when $d_s > \frac{r_s}{3}$, i.e., for $d_s > 183.33m$. Chain topologies with more than 5 hops start showing improvements even at a shorter inter-nodal distance, obviously because one or more number of pairs can exploit LCS in these cases. Here, LCS performance is found about 10% better over CCS.

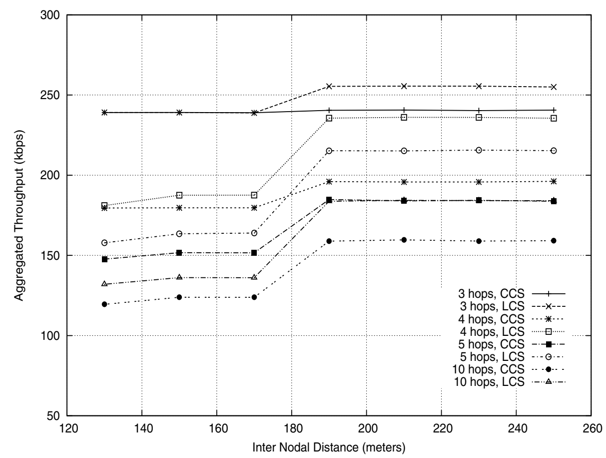

Fig. 5. Network performance in chain topology with 2 parallel flows.

2) Chain topology with two flows: To see the additional effect of LCS on inter-flow nodes, we tested two 2-flow chain topologies: parallel and anti-parallel, as shown in Fig. 3(b). The results shown here are for inter-flow distance of 400 m, which belongs to the range $[r_{i(max)}^{(SL)}, r_s]$, giving a better opportunity for LCS exploitation. However, we have verified that LCS performance is better than CCS for any other inter-flow distances. As shown in Fig. 5 the LCS starts showing improvement from 3-hops itself. As the number of LCS exploiting nodes are more with (both, parallel and anti-parallel) 2-flow cases, as compared to single-flow case, the LCS performance relative to CCS is clearly better in the 2-flow case. Specifically, LCS offers performance gains of 20% over the CCS scheme. The performance gain with anti-parallel topology has been observed to be similar (about 23%). The figure is omitted due to space limitation.

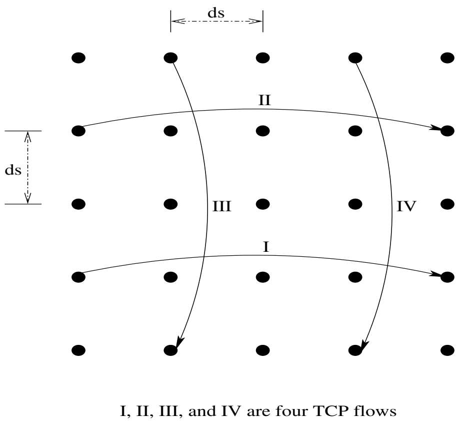

Fig. 6. Square grid topology with 125 m $< d_s \leq$ 250 m.

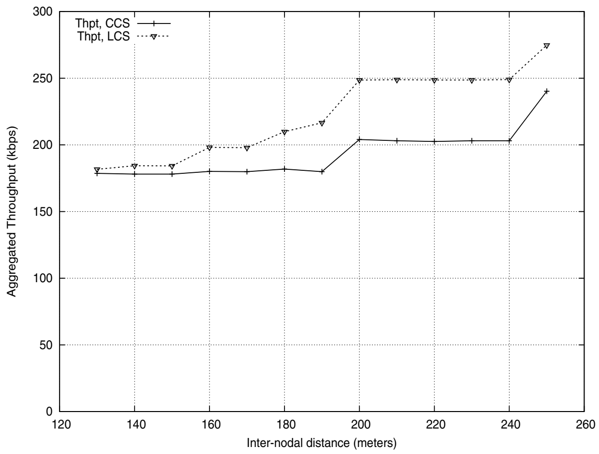

Fig. 7. Network performance in a square grid topology.

3) Grid Topology: In our considered square grid topology (Fig. 6), it has equally spaced 4 flows in the grid of 25 nodes arranged in a 5×5 square. Fig. 7 shows the aggregate end-to-end throughput for different inter-nodal distances. The LCS performance gain becomes substantial when the distance between the two parallel flows becomes large enough that allows LCS to be effective. In this case, the performance gain in LCS with respect to CCS is 23%.

B. Random Topology

The topographical area chosen for random topology was 5000m$\times$5000m and total 1020 nodes were randomly deployed, which corresponds to an average number of neighbors around any node to be 8. Since LCS is mainly designed for multi-hop scenarios, the choice of such a large area is justified so as to get an appropriately large average inter-nodal distance. However, the chosen random topology is unbiased enough to cover all possible inter-nodal distances, and thus it shows the average performance of LCS based scheme. As observed in Fig. 8, LCS performs consistently better than the CCS by about 9%. A TCP sender has a major role in deciding the agent level throughput, as compared to the transport layer ACK sender. The more the number of such TCP-senders exploiting the LCS, the higher the throughput gain.

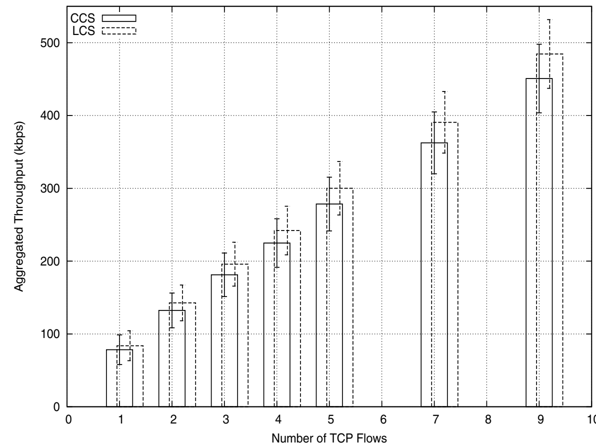

Fig. 8. Network performance in a random topology.

VI. Conclusion

The minimum SIR required for successful reception of a signal is much less when the sender's frame arrives earlier than that of an interferer. This differentiating capture behavior offers an attractive opportunity of concurrent transmissions in the region between the communication range and the carrier sensing range. Using some already available local information, our proposed LCS technique exploits above opportunity at a prospective receiver to identify its *exposure* and then possibly allow it to respond with CTS to its RTS sender. Our network simulation studies have shown that the LCS scheme achieves a throughput enhancement with respect to the conventional carrier sensing mechanism by up to 23% in regular topologies and about 9% in the random topologies.

Our current work considered link-layer ACK, thereby aiming at reducing exposed receivers problem. The exposed senders problem will be addressed in our future work.

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