Reconsideration of carrier sensing range for 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 arrivals of overlapping frames, and it is much less when the sender's frame arrives earlier. With such differentiating capture capable receivers, in this paper we reconsider the optimal choice for carrier sense range r_s of wireless nodes. Through simple analysis and simulations we show that r_s need not be more than $(CP_{th})^{\frac{1}{\alpha}}\, r_t$, where α is the wireless path loss factor and r_t is the nodal communication range.**

I. INTRODUCTION

In wireless networks, to minimize the collision at a receiver, potential simultaneous transmission from another node in the interference range of a receiver has to be minimized. Referring to Fig. 1, a reception overlapped with another unwanted signal could be avoided if the carrier sense (CS) zone of radius r_s of the sender S_1 covers the interference zone of radius r_i around the receiver R_1 [1]. The r_s required would be maximum when $d_{S_1R_1}$ = communication range r_t, which suggests that the safest value of r_s (denoted as $r_{s(safe)}$) should be:

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

where CP_{th} (called capture threshold) is the minimum signal-to-interference ratio (SIR) required for successful reception at the receiver and α is the path loss factor. However, a large r_s implies more exposed terminals which has the effect of reduced network throughput (bits per second).

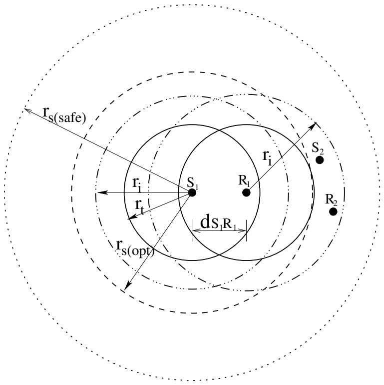

Fig. 1. (S_1, R_1) and (S_2, R_2) are two point-to-point communicating pairs, in which one starts earlier than the other.

The interference consideration used to decide the r_s has an hypothesis that every overlapping signal at a receiver results in a collision, which is not necessarily valid with the modern receivers. It is known that one frame can be received despite the interference from other nodes if the SIR is more than a threshold. Also, a recent experimental finding [2] shows that the value of CP_{th} depends on the order of the frames' arrival at the receiver, and it 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 other arrival order (the **S**ender's **L**ast, or SL case).

In this paper, in context of differentiating capture capability of the receivers we revisit the optimal choice of r_s. Through simple analysis and simulations we demonstrate that, with differentiating capture capable receivers and the virtual-carrier-sense (VCS) mechanism at MAC layer, the optimum r_s is: $r_{s(opt)} = (CP_{th})^{\frac{1}{\alpha}}\, r_t$. We show that, $r_{s(opt)}$ increases the spatial reuse significantly, while inviting only a negligible additional data packet collisions even in the worst case scenarios.

II. RECONSIDERATION OF CS RANGE

Suppose (S, R) is a point-to-point sender-receiver pair, in a homogeneous network environment with all nodes having identical transceivers. The condition for successful reception in presence of 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} indicates the power received at a receiver R due to the transmission from a node S, located at a distance d_{SR}. The differentiating capture capability 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 noted in [2], $CP_{th}^{(SF)}$ could be quite low for lower data rate operations. For example, at ≤ 6 Mbps, $CP_{th}^{(SF)} = 0$ dB. From (3a), the corresponding maximum value of $r_i^{(SF)}$ is r_t, when $d_{SR} = r_t$. Thus, in the SF case, any node outside the r_t range from a receiver can not interfere with a data reception. Referring to Fig. 1, once R_1 starts receiving a data packet from S_1, no node outside the $r_i^{(SF)}$ of R_1 can harmfully interfere with it. Hence it is safe to reduce r_s of S_1 even if it does not cover S_2 or R_2. However, for successful reception of the subsequent ACK at S_1, it is required that S_2 and R_2 must be outside $r_i^{(SL)}$ of S_1. Thus, r_s of S_1 should not be less than its

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own $r_i^{(SL)}$. Considering the worst case $r_i^{(SL)}$ (when, $d_{SR} = r_t$) in (3b), this leads to the choice of an optimal r_s:

$$r_{s(opt)} = r_{i(max)}^{(SL)} = \left(CP_{th}^{(SL)}\right)^{\frac{1}{\alpha}} r_t. \quad (4)$$

Obviously, with $r_{s(opt)}$, for a successful concurrent transmission, S_2 or R_2 must start the transmission process only after R_1 has started receiving the data packet from S_1. We now show that the transmissions are well facilitated by the existing VCS mechanism of 802.11 MAC. We consider only those topologies in which an uncovered area (i.e., the zone of radius r_i of R_1 not covered by the zone of radius r_s of S_1) contains either a source (S_2) or a destination (R_2) or both within it [1]. Based on the locations of S_2 and R_2 three different cases need to be considered:

Case I: S_2 and R_2 both are uncovered terminals, such that,

$$r_t < d_{S_2R_1} \leq r_s^{(opt)} \text{ and } r_t < d_{R_1R_2} \leq r_s^{(opt)}. \quad (5)$$

Case II: S_2 is uncovered terminal, while R_2 is not, i.e.,

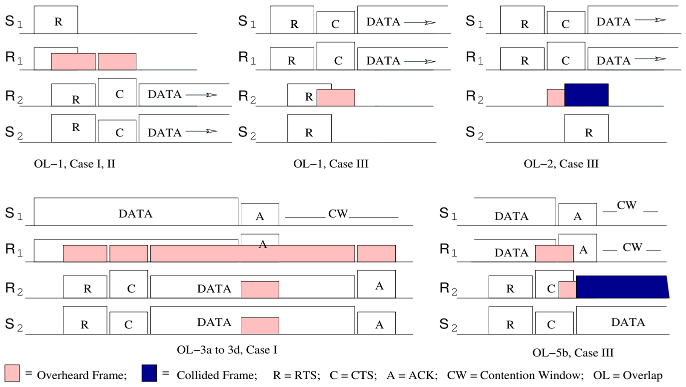
$$r_t < d_{S_2R_1} \leq r_s^{(opt)} \text{ and } d_{R_1R_2} > r_s^{(opt)}. \quad (6)$$

Case III: R_2 is uncovered terminal while S_2 is not, i.e.,

$$r_t < d_{R_1R_2} \leq r_s^{(opt)} \text{ and } d_{S_2R_1} > r_s^{(opt)}. \quad (7)$$

Table I describes the major overlaps possible in all the three cases, along with the capture or collision possibilities at the concerned receivers in each. To aid brevity of presentation, only some selected overlaps are shown diagrammatically in Fig. 2.

Note that, both the sessions (S_1,R_1) and (S_2,R_2) can run concurrently in many overlaps, e.g., in overlap number 3. Though there is an increased number of control packet (RTS/CTS) losses, the probability of data packet collisions is negligible (which occurs only in overlap number 5b). Moreover, the (control and data) collisions at S_2 or R_2 would occur only at very large values of $d_{S_2R_2}$, when the location of R_1 would be covered by either of their respective $r_i^{(SL)}$'s (by (3b)).


OL–1, Case I, II

OL–1, Case III

OL–2, Case III

OL–3a to 3d, Case I

OL–5b, Case III

Fig. 2. Some representative overlaps. Overlap numbers refer to those in Table I. Other cases can be drawn similarly. SF capture is assumed to be always successful. 'No overlap' occurs at a node when it is at least r_s distance far from the transmitter of the other pair.

III. Network Performance Results

To confirm our analytical observations on the effect of reduced r_s, we have performed simulations using ns2 (ver. 2.33) after modifying its code to incorporate the differentiating capture capability at the physical layer. We have chosen a simple 4 node topology as shown in Fig. 3. The distance between X and Y is used as the running variable, and hence, depending on the role of X and Y (i.e., X is S_2 and Y is R_2, or vice versa) and the value of $d_{S_2R_2}$, it represents one of the cases (I, II, or III) as discussed in Section II. Table II lists the simulation parameters. The values of $CP_{th}^{(SF)}$ and $CP_{th}^{(SL)}$ are based on the results in [2] for $\leq$ 6 Mbps operations. Based on the parameters listed, $r_{s(safe)} = 695$ m and $r_{s(opt)} = 445$ m. We have taken the starting time of S_1 earlier by 5 ms. However, in the subsequent contention windows, due to the inherent random nature of 802.11 MAC, S_1 or S_2 may be the first sender.

TABLE II
PARAMETER SETTINGS FOR THE SIMULATIONS

Parameter	Value
MAC protocol	IEEE 802.11b
Routing protocol	gpsr
Transport protocol	UDP
Application traffic	Two CBR flows, 500 kbps each, with 1000 Bytes packets
Data rate	1 Mbps
Propagation model	Two ray ground (which gives $\alpha = 4$)
Transmission range (r_t)	250 meters
$CP_{th}^{(SF)}$	0 dB
$CP_{th}^{(SL)}$	10 dB
Simulation time	120 seconds

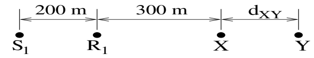


Fig. 3. A simple 4 node topology used for evaluating Case I, II and III. X and Y could be $S_2(R_2)$ or $R_2(S_2)$. For $d_{S_2R_2} \leq 145m$, S_2 and R_2 both are within r_s of R_1, representing Case I and beyond this distance, it is Case II(III) when X = $S_2(R_2)$ and Y=$R_2(S_2)$.

We used two metrics for comparison, data packet corruption ratio (PCR) and aggregated throughput (kbps), where PCR is defined as the fraction of data packets lost due to MAC layer collision. Performance of $r_{s(opt)}$ with $CP_{th}^{(SF)} = 0$ dB, (called $r_{s(opt)-0}$) was compared with $r_{s(safe)}$. It may be noted that $r_{s(safe)}$ performance does not change with the value of $CP_{th}^{(SF)}$ in this scenario, as a larger r_s never allows any two nodes to transmit concurrently. Results for $r_{s(opt)}$ with $CP_{th}^{(SF)} = 10$ dB (called $r_{s(opt)-10}$) are also plotted to visualize the impact of the difference made due to the differentiating capture behavior. Fig. 4 and 5 show the results. The transition from Case I to Case II (respectively, III) occurs at $d_{S_2R_2} = 145$ m in Fig. 4 (respectively, 5). Note that, the high PCR (31% to 89%) and the correspondingly affected aggregated throughput (550 kbps to 160 kbps) with $r_{s(opt)-10}$ shows that a large r_s is definitely required if the differentiating capture capability is

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[1] Here we do not consider the other possible cases where S_2 and/or R_2 are within r_t of R_1, as they are well handled by the VCS mechanism of 802.11.

TABLE I
POSSIBLE CASES OF SUCCESS AND COLLISION. SSF: SUCCESS IN SF CASE. SNO: SUCCESS DUE TO NO OVERLAP. COLL: COLLISION

OL No.	Overlap (Fr_1, Fr_2)	Possible cases	At Receiver 1	At Receiver 2	Consequences
1	(RTS_{S_1}, RTS_{S_2})	I, II, III	R_1:SSF(I,II) /SNO(III)	R_2:SNO	Either (S_2,R_2) or (S_1,R_1) starts the session successfully. No response from $R_1(R_2)$ with CTS to $S_1(S_2)$ because of busy medium. No collision.
2	(CTS_{R_1}, RTS_{S_2})	III	S_1: SNO	R_2:COLL	(S_1,R_1) starts successfully. RTS_{S_2} lost in collision.
3a	$(DATA_{S_1},RTS_{S_2})$	I, II, III	R_1:SSF(I,II) /SNO(III)	R_2:SNO	(S_1,R_1) and (S_2,R_2) both successful.
3b	$(DATA_{S_1},CTS_{R_2})$	—do—	—do—	S_2:SNO	—do—
3c	$(DATA_{S_1},DATA_{S_2})$	—do—	—do—	R_2:SNO	—do—
3d	$(DATA_{S_2},ACK_{R_1})$	—do—	R_2:SSF(I,III) /SNO(II)	S_1:SNO	—do—
4a	(RTS_{S_2}, ACK_{R_1})	I, III	R_2:SSF	S_1:SNO	(S_1,R_1) ends successfully. No response from R_2 with CTS due to busy medium. No collision.
4b	(RTS_{S_2}, ACK_{R_1})	II	R_2:SNO	S_1:SNO	(S_1,R_1) ends successfully. COLL(CTS_{R_2}, ACK_{R_1}) at S_2; CTS_{R_2} lost.
4c	(ACK_{R_1}, RTS_{S_2})	III	R_2:COLL	S_1:SNO	(S_1,R_1) ends successfully. RTS_{S_2} lost in collision.
5a	(CTS_{R_2}, ACK_{R_1})	I, II	S_2:SSF	S_1:SNO	(S_1,R_1) ends successfully. No data sent to R_2 due to busy medium. No collision.
5b	(CTS_{R_2}, ACK_{R_1})	III	S_2:SNO	S_1:SNO	(S_1,R_1) ends successfully. COLL$(ACK_{R_1}, DATA_{S_2})$ at R_2; $DATA_{S_2}$ lost.

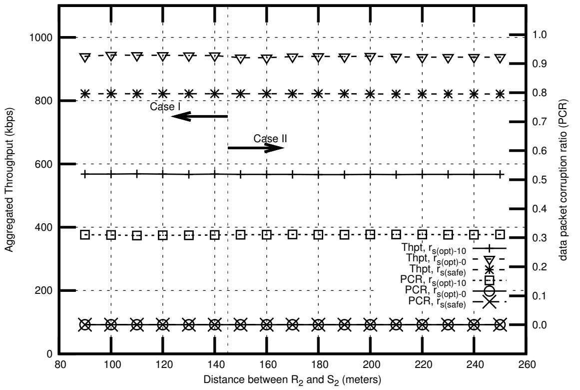

Fig. 4. Comparison of $r_{s(opt)-10}$, $r_{s(safe)}$, and $r_{s(opt)-0}$ in Case I and II. $d_{S_1R_1} = 200$ m. $d_{R_1S_2} = 300$ m.

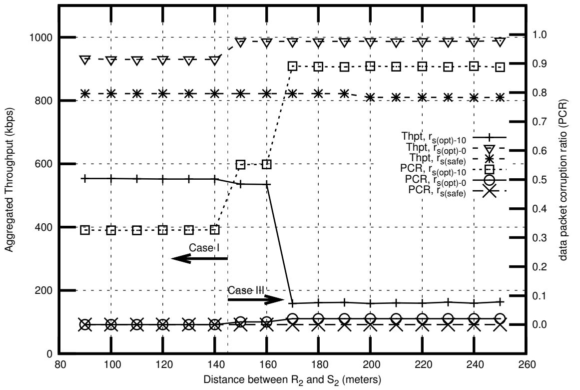

Fig. 5. Comparison of $r_{s(opt)-10}$, $r_{s(safe)}$, and $r_{s(opt)-0}$ in Case I and III. $d_{S_1R_1} = 200$ m. $d_{R_1R_2} = 300$ m.

not considered. In Case III, while R_2 is always within $r_i^{(SL)}$ of R_1, when $d_{S_2R_2} > 168.54$ m, according to (3b), R_1 also falls within $r_i^{(SL)}$ of R_2, causing the aggregated throughput of $r_{s(opt)-10}$ to drop drastically to 160 kbps. As S_2 and R_2 never go out of the sensing range of R_1 with $r_{s(safe)}$, it has always zero PCR. As compared to this, $r_{s(opt)-0}$ also has zero PCR except for very large value of $d_{R_2S_2}$ in the Case III (Fig. 5) where it is up to 2.1%. This non-zero PCR corresponds to the rare data packet collisions as pointed out in the overlap number 5b in Table I. However, note from Fig. 4 and 5 that, in spite of this little increased PCR, aggregated throughput performance of $r_{s(opt)-0}$ is 13 to 22% higher than that with $r_{s(safe)}$. This is due to the many successful concurrent transmissions with $r_{s(opt)-0}$, as shown in overlap number 3a to 3d in Table I.

Due to space limit spatial reuse improvement results are omitted. However, the results shown for the specific topologies are indicative of the spatial reuse gain.

IV. CONCLUSION

In this paper, we have shown that the differentiating capture capability of modern radio receivers combined with the standard virtual carrier sensing mechanism at the MAC layer can be used effectively to reduce the carrier sense range significantly to aid the spatial reuse and hence overall network throughput. As a comprehensive study, we will evaluate the network performance in a random network setting with multiple concurrent communication activities.

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