

Impact of Interference on Nodal Communication Range in Wireless Ad Hoc Networks

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Abstract—In a distributed control wireless ad hoc network, multi-user interference plays a significant role in determining one-to-one communication throughput performance of the network. Although the effects of exposed/hidden terminals on the network throughput in a single-channel wireless ad hoc network have been extensively studied, the interference power computation at the receiver and its effect on the acceptable communication range has not been analyzed in the literature. In this paper, via probabilistic analysis we capture the total interference power that a receiver node experiences. We then demonstrate the impact of interference power on the effective communication range of the nodes. Our analytic results are validated by C-based network simulation. The observations in this paper can be used in deciding interference-aware multi-hop forwarding strategies in wireless ad hoc networks.

Index Terms—Any-to-any communication, distributed control ad hoc networks, multiuser interference, hidden/exposed terminals

I. INTRODUCTION

A wireless ad hoc network is typically characterized by distributed control, i.e., any node can set up a communication session with another node without needing any central coordination. Limited communication range of each node implies that a communication session between two nodes may involve intermediate nodes. Communication sessions are generally one-to-one, and sporadic communication activity between two nodes makes random multi-access a suitable candidate for sharing the common channel resource.

Carrier sense multiple access (CSMA), which has in-built physical carrier sensing (PCS) procedure at the transmitter before the actual communication, is popularly used for setting up a communication link between two ad hoc wireless nodes. A two-way handshake (also called virtual carrier sensing – VCS) is also commonly used along with PCS for longer data packet transmission. It has been already shown in several prior works that (see, e.g., [1], [2]), due to distributed communication control, exposed/hidden terminals problem still remains in VCS based transmissions. This problem exists even in a scenario with homogeneous communication range of the nodes, and it is more aggravated due to a larger interference range compared to the communication range, which is typically the case in wireless ad hoc networks.

Hidden terminals are the nodes that are located outside the carrier sense range of the transmitter but inside the interference range of the corresponding active receiver. The problem due to hidden terminals is that, these hidden nodes can cause interference to an ongoing reception should they choose to initiate transmission during the receiver's activity.

Although the multi-user interference problem in CSMA-based wireless access systems have been identified and several alternative proposals have been proposed in recent past

[3]–[8], most of the prior works are protocol level studies. To our knowledge, an analytic view of interference power quantification and its impact on successful communication has not got sufficient attention. A relevant analytic study on interference was presented in [9], where the focus was to compare the performance of different forwarding strategies with power control. The analysis however did not account for hidden terminals in the receiver's interference zone.

In this paper, we take a relook at the interference analysis accounting for the interference range of the receivers beyond the communication range. We first give a geometrical proof that, the maximum number of interferers around an active receiver is limited to 4. Next we capture the total interference power at a receiver node as a function of the active transmitter-receiver distance. We demonstrate that, for a given acceptable bit error rate (BER), the communication range is distinctly shrunk when the interference power at the receiver is accounted. Specifically, with our preset acceptable BER threshold 10^{-3} , a given signal transmit power and a receiver sensitivity, the acceptable communication range of a receiver is shrunk from 25 m (when only signal-to-noise ratio (SNR) is accounted) to about 15 m (when signal-to-interference-and-noise ratio (SINR) is accounted).

The rest of the paper is presented as follows. The related works pertinent to our proposed protocol are briefly surveyed in Section II. The proposed interference model and its analysis is presented in Section III. Section IV contains analysis as well as simulation based performance results and discussions. The paper is concluded in Section V.

II. RELATED WORKS

Several authors over the years have looked into multi-user interference and related protocol issues in random access networks. Below, we survey the ones that are pertinent to the context of our current study.

The issue of interference was studied in [9] to capture the effects of transmission power control on different forwarding strategies, such as maximum forward progress with fixed radius (MFR), maximum forward progress with variable radius (MVR), and nearest forward progress with variable radius (NFP), and based on normalized progress and packet success performance in one hop it was concluded that, NFP is a better energy saving alternative. Later on, NFP strategy was further studied in [10] in context of multi-hop road traffic forwarding to achieve a higher network throughput. While the work in [9] gave for the first time a very important basis on capturing performance of a network with heterogeneous coverage range, it did not distinguish between communication range and interference range exclusively. This different communication

range, carrier sense range, and interference range in wireless nodes experimentally captured later in [11].

Recently, several works have also identified the issues related to hidden/exposed terminals and the optimum carrier sensing range. The impact of physical carrier sensing range on the aggregated network throughput of one-hop flows was studied in [3], where the authors proposed to have a tunable carrier sensing range and showed the trade-off between spatial reuse and packet collisions. In an ad hoc network with a *regular topology*, optimal carrier sense threshold was studied in [4] to maximize spatial reuse while maintaining a minimum required SINR at the receiver. The study was also based upon the assumption of interference from only a *single interferer*. Optimum carrier sensing range was also studied in [6], where the worst case interference was considered, and it was assumed that the maximum interference level is achieved when the *six* closest nodes are transmitting simultaneously at the boundary of carrier sense range of the receiver. By considering traditional back off embedded CSMA/CA (CSMA with collision avoidance) mechanism, [8] characterized channel activities governed by IEEE 802.11 DCF (distributed coordination function) in multi-hop wireless networks and derived analytic expressions for the throughput of individual sender nodes. They represented the set of nodes in the receiver's interference zone and obtained the sum of interference power from all these nodes. The exclusivity of potential interferers' transmission activity within the carrier sense zone of an active interferer was not accounted here.

Another set of recent work with single channel transceivers aim at exploiting the differential capture capability of receivers [12] to increase the spatial reuse and also reduce the hidden terminals (see, e.g., [2], [5]).

We note that, while the issues of interference is well-known, the analytic quantification of exact interference power with the knowledge of wireless nodes' coverage range properties and the effect of interference on effective communication range is still missing. Our current work is aimed at filling this gap, which can be taken further to compute the forwarding performance with power control.

III. MULTI-USER INTERFERENCE ANALYSIS

A. Assumptions and definitions

First, we outline the system model and associated assumptions, and present the definitions.

Although precisely interference range of a node can be different from (greater or smaller than) the carrier sense range [12], [13], as a simplifying assumption for our analysis we consider they are equal. We term the zone where the receiver's potential interferers are located as receiver's interference zone.

- 1) *Nodal distribution*: The nodes are distributed uniformly randomly in a two-dimensional location space, which is approximated as a two-dimensional spatial Poisson point process with density ρ . That is, the probability of n nodes in a area A , $P(A, n)$ is given by:

$$\Pr[\mathbf{n} = n] \triangleq P(A, n) = \frac{(\rho A)^n}{n!} e^{-\rho A}. \quad (1)$$

- 2) *Channel access*: The channel access protocol is slotted CSMA/CA based. The traffic is uniform across all nodes,

i.e., every node transmits to every other node with equal probability, and all nodes have an equal traffic load.

- 3) *Equal carrier sense range and interference range*: Although precisely interference range R_i of a node can be different from (greater or smaller than) the carrier sense range R_c [12], [13], as a simplifying assumption for our analysis we consider they are equal, i.e., $R_i = R_c$. We term the zone where the receiver's potential interferers are located as receiver's interference zone.
- 4) *Average neighbors*: All nodes have equal and circular coverage (i.e., the network is homogeneous) with each having communication range R and interference range (also the carrier sense range) R_i . Thus, the average number of neighbors within the communication range of a node is $N = \rho\pi R^2$.
- 5) *Uncorrelated neighboring nodes' channels*: The channel state of a node pair X-Y does not reveal any information about the channel state of the pair X-Y'.
- 6) *Memoryless channel errors*: An error in the current instant does not have any bearing on the future errors.

With the above considerations about the nodal coverage and interference ranges, a receiver's interference range is depicted by the shaded regions in Fig. 1. In this figure, X-

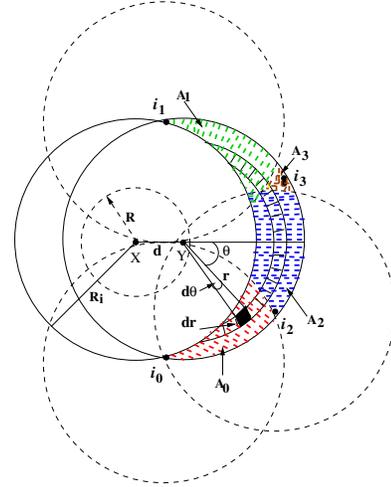


Fig. 1. Receiver's interference zone.

Y is a transmitter-receiver pair at a distance d . A successful transmission occurs from X to Y if Y does not transmit and the neighbors of Y do not interfere with Y, i.e., they do not transmit in the same slot. As a typical value, R_i is taken almost twice that of R . The total area of the interference zone of Y is denoted as $A(d)$, which is a function of X-Y distance d . The area $A(d)$ and hence the total interference power P_i increases with increase in d . An example case of number of simultaneous interferers are shown in the figure, where i_k , $k = 0, 1, 2, 3$, are the position of the interferers and the total interference area $A = A_0 \cup A_1 \cup A_2 \cup A_3$.

In the following, we first compute the maximum number of simultaneous interferers that an active receiver can have. Then we will compute the individual interference power and their resultant effect on the receiver's interference zone.

B. Upper bound on the number of simultaneous interferers

In Fig. 1, the receiver Y can be located anywhere in the circle of radius R around X, i.e., $0 < d < R$. During the transmission from X, by CSMA principle the nodes in its carrier sense zone of radius R_i are kept from transmitting. The interference zone of Y, i.e., the shaded area in Fig. 1, is the area of the circle of radius R_i around Y that does not overlap with the circular zone of radius R_i around X.

The number of nodes in the shaded zone is a function of X-Y distance d . Due to CSMA, out of these nodes the ones that are away from each other by at least a distance R_i are allowed to simultaneously transmit. Also, by inspection, for a given d this number can be maximum when the transmitting nodes in the shaded zone are on its outer rim. Hence, the maximum total number of simultaneously transmitting interferer nodes n_i around Y can be found as:

$$n_i = \left\lceil \frac{2 \left(\pi - \arccos \frac{d}{2R_i} \right)}{\pi/3} \right\rceil + 1. \quad (2)$$

From (2), n_i is maximum when $d = R \approx \frac{R_i}{2}$, and the maximum value is 4. Thus, *In a network with homogeneous communication coverage and CSMA/CA based channel access, the maximum number of interferer nodes around a receiver that can simultaneously transmit is limited to 4.* By inspection it can be noted that, this number has a weak dependence on the ratio of R and R_i . Thus, even though in general it is possible that $R_c \neq R_i$, the above result will hold.

C. Probabilistic receiver-interference model

We have the polynomial decay of RF (radio frequency) signal power with distance d expressed as:

$$P_r(d) = \frac{\bar{\kappa} P_t}{d^\gamma}, \quad (3)$$

where $P_r(d)$ is the average signal power at a distance d from the transmitter, P_t is the output signal power at the transmitter (assumed constant for all transmitters), $\bar{\kappa}$ is a constant of proportionality (normally $\bar{\kappa} < 1$) – a function of antenna gains, signal carrier frequency, and the receiver antenna diameter, and γ is the path loss exponent (generally, $2 \leq \gamma \leq 4$). The constant $\bar{\kappa}$ can be expressed as $\bar{\kappa} = \frac{d_0^\gamma}{\text{PL}[d_0]}$, where d_0 is the reference distance, and $\text{PL}[d_0]$ is the fixed loss up to d_0 . $\text{PL}[d_0]$ is given by, $\text{PL}[d_0] = \frac{16\pi^2 d_0^2 L}{G_r G_t \lambda^2}$, where G_r and G_t are the gains of the receiving and transmitting antennas respectively, λ is the RF signal carrier wavelength, and L is the system loss factor.

For computing the interference power and hence SINR at the receiver, we divide the whole *receiver-interference-zone* $A(d)$ into a number of small microstrips of area $da = r \times dr \times d\theta$ (see fig. 1). Consider such a microstrip at a distance r from the receiver Y at an angle θ with respect to the line joining X and Y. As the X-Y distance, d can vary between 0 and R , the distance of any interfering node r would vary between $R_i - d$ and R_i . Correspondingly, the value of θ varies between $-\Theta(r)$ to $\Theta(r)$ where $\Theta(r)$ is given by:

$$\Theta(r) = \cos^{-1} \left(\frac{R_i^2 - d^2 - r^2}{2rd} \right)$$

We have $P(A, n)$ in (1) as the probability that there exist n nodes in area A . Our considered microstrip of area da is infinitesimally small such that it can accommodate at most one node, i.e., $\Pr[n \geq 2] \approx 0$. The probability that there exists a node in the area da is given as:

$$P(da, 1) \triangleq p_e. \quad (4)$$

Each microstrip can be distinguished by the following five factors:

- *Position probability*: It is defined by the distance r from the receiver and angle θ of the microstrip.
- *Selection probability*: This defines the probability that a particular microstrip is selected among all the microstrips available within the area A .
- *Node existence probability*: It accounts for whether there is a node present or not in a given microstrip, given by (4).
- *Transmission probability* p_t : This is the probability that a node transmits from a given microstrip, provided that there exists a node in that microstrip. This probability is considered fixed for all nodes in A .
- *Interference power* $P_i(r)$: It is the amount of interference contributed from a microstrip at a distance r from the receiver. This can be obtained from (3).

Some of the above factors of a microstrip can vary with respect to the sub-zone of area A_k , $k = 0, 1, 2, 3$, to which it belongs. Accounting all microstrips in A , the expected total interference power is obtained.

In order to obtain the expression for the total expected interference power due to all the microstrips, we define two functions $F(A)$ and $F^C(A)$. $F(A)$ is the probability that a particular transmitting node is chosen from all nodes in the Area A , and is given by:

$$F(A) = \sum_{J=1}^{\infty} P(A, J) p_t \sum_{j=1}^J \frac{1}{j} \binom{J-1}{j-1} p_t^{j-1} (1-p_t)^{J-j},$$

where J is the number of total nodes in area A and j is the number of potential interferers among them.

The function $F^C(A)$ is the probability that no node out of total J nodes in the area A is transmitting, and is given by:

$$F^C(A) = \sum_{J=0}^{\infty} P(A, J) (1-p_t)^J$$

We find the probabilistic interference due to the transmitting node, if it exists at a chosen microstrip, and due to the other possible transmitting nodes with respect to this first node. By the observation in III-B, there exists a possibility of 1, 2, 3, or 4 nodes interfering at Y. The interference associated with these cases can now be formulated as follows.

The total interference power, if only k nodes are interfering from the whole area A , is denoted as $I_k(d)$, where $0 \leq k \leq 4$. Referring to Fig. 1, we denote:

A_0 = the effective interference zone covered by the first interferer;

$A_0^C = A - A_0$ is the area complementary to A_0 in A , which is the potential interferer zone for the other possible interferers;

A_1 = the effective interference zone covered by the second interferer;

$A_{01}^C = A - (A_0 + A_1)$ is the possible area of the interference zone for finding the third and fourth interferers;

A_2 = the effective interference zone covered by the third interferer;

$A_{012}^C = A - (A_0 + A_1 + A_2) = A_3$ is the possible interference zone for the fourth node.

Clearly, the areas A_0, A_1, A_2, A_3 are mutually exclusive interference zones, the sum of which is A .

The probabilistic interference power due to only one interfering transmitter can be expressed as:

$$I_1(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) P_i(r) F^C(A_0^C). \quad (5)$$

The probabilistic interference due to two interferers is obtained by additionally capturing the interference from the area A_0^C , where the second microstrip is considered about a point (r_1, θ_1) . Accordingly, the expression for I_2 is obtained as:

$$I_2(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_1, \theta_1) \in A_0^C} p_e F(A_0^C) [P_i(r) + P_i(r_1)] F^C(A_{01}^C). \quad (6)$$

Similarly, the probabilistic interference due to three and four interfering transmitters are respectively obtained as:

$$I_3(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_1, \theta_1) \in A_0^C} p_e F(A_0^C) \sum_{(r_2, \theta_2) \in A_{01}^C} p_e F(A_{01}^C) \cdot [P_i(r) + P_i(r_1) + P_i(r_2)] F^C(A_{012}^C), \quad (7)$$

and

$$I_4(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_1, \theta_1) \in A_0^C} p_e F(A_0^C) \cdot \sum_{(r_2, \theta_2) \in A_{01}^C} p_e F(A_{01}^C) \sum_{(r_3, \theta_3) \in A_{012}^C} p_e F(A_{012}^C) \cdot [P_i(r) + P_i(r_1) + P_i(r_2) + P_i(r_3)]. \quad (8)$$

In obtaining the expression (7), the area A_0^C is scanned by using the reference (r_1, θ_1) and the remaining area A_{01}^C is scanned by using (r_2, θ_2) . Likewise, for $I_4(d)$ in (8), additionally the reference (r_3, θ_3) is used for scanning the remaining area A_{012}^C .

The total interference power at Y is obtained by summing up the probabilistic interference powers in (5) to (8) as:

$$I(d) = \sum_{k=1}^4 I_k.$$

D. SINR at the receiver node

The total interference power $I(d)$ can be approximated as Gaussian, albeit with some error in this case of limited number of interferers [14]. With this approximation, and denoting the variance of Gaussian noise of the channel as \mathcal{N} , the SINR at the receiver node can be approximately expressed as: $\text{SINR}(d) = \frac{P_r(d)}{I(d) + \mathcal{N}}$.

In Section IV, we will compare the deterioration of signal quality in presence of multi-user interference versus that without interference.

IV. RESULTS AND DISCUSSION

For the numerical results as well as simulations we have used MATLAB. In a two-dimensional area of 500×500 square meters we placed nodes according to Poisson distribution with node density $\rho = .02$. For a communication range of 25 m with constant transmit power level at -11 dBm, and the long-term average noise power was chosen -80 dB. BPSK modulation with NRZ signal was considered. A random node is selected and the interference power at all its forwarding neighbors are calculated. For different distance of the one-hop receiver from the transmitter, the area of the receiver's interference zone varies. In each case, the total interference power was calculated using the developed equations (5)-(8). Probability (which is zero) for the case of no interference, i.e., I_0 , was also calculated for comparison of its impact with respect to I_k , $k = 1, 2, 3, 4$. For analytic results, we have divided the whole interference zone of area A into number of small microstrips of area $da = r \times dr \times d\theta$. The value of d was varied from $0.1R_i$ to $0.45R_i$ because we have the constraint $d \leq R$ and $R = 0.5 \times R_i$. We scan through all the microstrips in that area and determine the estimated interference at each. Sufficient simulation runs were conducted with varying seed values to have reasonably high confidence on the results. And the analysis results are mostly matching with the simulation ones.

Fig. 2 shows the analytic and simulation results on the expected interference power at the receiver node with different transmitter-receiver distance d . The simulation results match quite well with the analytic plot, validating the analysis. The effect of increased interference area is visible, as the total interference power increases, however small the variation may be.

Figure 3 shows the probabilities of interference from k nodes, where $k = 0, 1, 2, 3, 4$. The plots show that the probability of having two interferers is more than the other cases. The probability of having no interferer ($k = 0$) as well as the highest number of interferers ($k = 4$) are negligible for any value of d . The analytic plots also match well with the simulation results.

In Fig. 4, the average SINR at the receiver is shown. We have taken the threshold BER as 10^{-3} . As it can be observed from the above figure that without taking the interference into

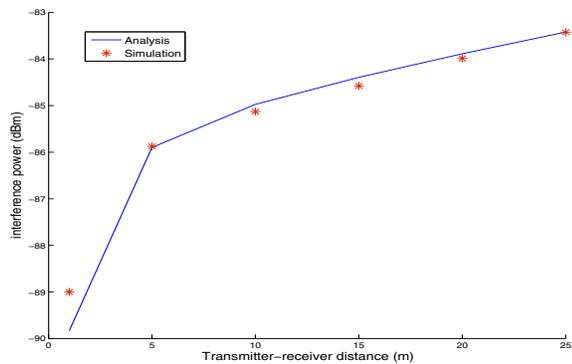


Fig. 2. Interference power at the receiver node for various transmitter-receiver distances. $\rho = 0.02$

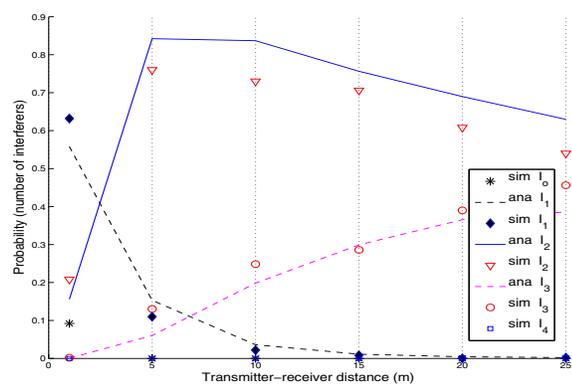


Fig. 3. Probability of having k interfering nodes at various transmitter-receiver distances. $k = 0, 1, 2, 3, 4$

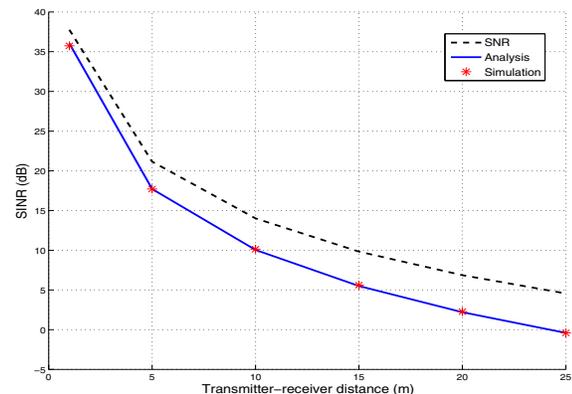


Fig. 4. SINR at various receiver distance d . Communication radius was set at $R = 25$ m with a tolerable SNR = 5 dB.

account the threshold SNR about 5 dB (correspondingly, 10^{-3} BER) was achieved at the X-Y distance R . However, the effect of added interference shows that, about 5 dB threshold level is achieved only at about 15 m distance from the transmitter. Thus, in presence of multiuser interference, if any forwarding technique tends to choose a one-hop receiver at a distance more than 15 m, the reception quality could be unacceptably

bad. It creates limitations to some greedy forwarding strategies like MFR which tries to choose the next forwarding node at a maximum forward distance away towards the destination.

V. CONCLUSION

In summary, in this work we have analytically quantified the total interference power at a receiver. We have shown that the total number of simultaneous interferers is upper-bounded to a small value. We have further shown that, in presence of interference, the effective nodal communication range is significantly reduced. Our analytic observations have also been verified by network simulations.

As a future work we plan to investigate the receiver's interference with power control. We will also conduct further analytic studies to quantify the network performance gain with a reduced effective communication range.

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