Interference Aware Power Controlled Forwarding for Lifetime Maximization of Wireless Ad Hoc Networks

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Abstract

In a distributed control multi-hop wireless ad hoc network, multi-user interference plays a significant role in determining the network performance. Although the effects of hidden/exposed terminals on the system throughput in wireless ad hoc networks have been extensively studied, the multi-user interference power computation without as well as with distributed power control and their effects on the network level performance have not been analyzed in the literature. In this paper, via probabilistic analysis we capture the total interference power that a receiver node experiences for fixed power transmissions as well as variable power transmissions. In fixed as well as variable power scenarios, we demonstrate the impact of interference on the effective communication range of the nodes. Subsequently, we study the joint impact of interference, power control, and different forwarding strategies on the network lifetime. We propose two variants of forwarding protocols, power controlled nearest forward (PCN) and network lifetime extending PCN (E-PCN), which are interference aware and offer network lifetime maximization in power controlled transmission scenarios. The numerical results on random static network performance are verified by MATLAB as well as NS-2 based network simulations. Unlike the other existing protocols, our proposed protocols consider a close-to-real interference model. The results show that the proposed protocols outperform the existing ones in terms of network lifetime.

Index Terms

One-to-one communication, distributed control, transmit power control, hidden/exposed terminals, multi-user interference, multi-hop forwarding, network lifetime

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 between two hosts may involve

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intermediate nodes. Generally one-to-one and sporadic communication activity between any two nodes makes random multi-access a suitable candidate for sharing the common channel resource.

Carrier sense multiple access (CSMA), which has the 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 transmission of longer data packets.

In PCS, carrier sensing (CS) range of the transmitter determines the number of exposed terminals, whereas the receiver's interference range is determined by its signal detection sensitivity*. Hidden terminals are the nodes that are located outside the CS sense range of the transmitter but inside the interference range of the corresponding active receiver. The problem due to hidden terminals is that, these nodes can cause interference to an ongoing reception should they choose to initiate transmission during the receiver's activity. It has been already shown in several prior works (e.g., [1], [2]) that, due to distributed communication control, even with VCS hidden/exposed terminals problem cannot be completely eliminated. This hidden/exposed terminals problem exists in a scenario with homogeneous communication range of the nodes, which is further aggravated with decentralized power control.

Although the interference problem in CSMA-based access systems has been identified and several alternative proposals have been presented in recent research literature [3]–[8], most of the prior works are protocol level studies. To our knowledge, an analytic view of interference power without or with power control, and its impact on successful communication has not got sufficient attention.

In the context of energy saving, there have been several studies reported in recent years (e.g., [9], [10]). These protocols may not necessarily offer maximization of network lifetime. Recently, some protocols have been proposed aiming at increased network lifetime [11], [12]. While the protocols demonstrate increasingly improved network lifetime, they all consider fixed nodal coverage range and homogeneous network. Moreover, multi-user interference has not been accounted in these studies.

In this paper, we consider a wireless ad hoc network with static or semi-static node deployment, where the interference dynamics is slow compared to the user data packet transmission duration. We develop probabilistic models of interference power at a receiver for the scenarios without as well as with transmit power control. In fixed power transmissions, we demonstrate that, for a given acceptable bit error rate (BER) the effective communication range is distinctly reduced when the interference is accounted. With distributed power control, the performance largely depends on the chosen forwarding protocol, and we show that, the nearest forward progress approach (called Power Controlled Nearest forward, or PCN protocol) offers a higher energy efficiency. We further propose a network lifetime extending PCN (E-PCN), that offers a significantly higher performance. For example, our NS-2 based

*In general carrier sense range of a node could be different from its interference range.

simulation studies indicate that, with nodal communication range of 20 m and average node density of 0.016, E-PCN offers 2.8 times increased network lifetime compared to PCN, whereas the gain with respect to the lifetime aware forwarding without power control [12] is 2.4 times.

The related works are surveyed in Section II. The analysis of interference without as well as with transmit power control is presented in Section III. In Section IV, the proposed network lifetime aware forwarding is presented and the energy consumption performance is characterized. Section V contains numerical and simulation based performance results. The paper is concluded in Section VI.

II. Related Works

The issue of interference was studied by Hou and Li [13] to capture the effects of 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). Based on normalized progress and success rate in one hop, it was concluded that NFP is a better alternative. NFP was used by Mathar and Mattfeldt [14] to achieve road traffic forwarding throughput gain. While the work in [13] gave for the first time a very important basis of capturing the effect of interference, it did not distinguish between communication range and interference range. In fact, interference range was taken the same as nodal full communication range irrespective of power control. Besides, the energy efficiency, which does not necessarily follow the trend of normalized progress and packet success rate, was not addressed. The difference in communication range and CS range in wireless nodes was experimentally demonstrated later by Kamerman and Monteban [15].

Several recent works have investigated the hidden/exposed terminals issues. In a network with a *regular topology* (two dimensional grid), optimal CS threshold was studied by Zhu et al. [4] to maximize the spatial reuse while maintaining a minimum required signal-to-interference-and-noise ratio (SINR) at the receiver, where the interference was assumed arising from only a *single interferer*. Later, Zhai and Fang [6] studied the optimum carrier sensing range assuming that the worst case interference occurs when the *six* nodes at the boundary of CS range of the receiver transmit simultaneously. By considering traditional CSMA/CA (CSMA with collision avoidance) mechanism, Yang et al. [8] analyzed the throughput of individual nodes, where the sum interference was assumed to arrive all the nodes in the receiver's interference zone. The exclusivity of potential interferers' transmission activity within the CS zone of an active transmitter was not accounted in the analysis.

Another set of studies (e.g., [2], [5], [16]–[19]) on 802.11 ad hoc networks aimed at reduced exposed and hidden nodes by exploiting the differential capture capability of modern transceivers. However these solutions work well only at lower data rates. Also, they did not address the issues of interference associated with power control. In [17], Zhu and Zheng showed that the performance of collaborative relays in large wireless networks degrades significantly due to interference. Sollacher and Greiner in

[18] analyzed the effect of interference on the outage probability of a link and connectivity of large networks. Gummadi et al. [19] reported significant performance degradation with a shorter ISM band transmission range due to high interference. They predicted that the channel hopping technique is a best solution to counter the effects of interference. However, for low power ad hoc networks, such as in sensor networks, this may not be a feasible approach.

A key aspect of energy consumption has to do with the chosen forwarding protocol. Pure location aware greedy forwarding without power control is called least remaining distance (LRD) forwarding [20], [21]. In order to minimize the number of hops to the destination, in each hop LRD tries to select a forwarding neighbor that would minimize the remaining distance to the destination. This results in a high average inter-nodal distance and consequently a more vulnerable link quality, which may lead to an increased energy consumption per successful delivery. In geographic energy-aware routing (GEAR), proposed by Yu et al. [22], geographically informed neighbor selection heuristics is used to route a packet towards the target region. The probabilistic energy-aware routing (PEAR) by Shah and Rabaey [9] defines a probabilistic cost function in choosing a forwarding node, which considers the energy consumption of the transmitter-receiver pair and the remaining energy of the receiver. To improve on network lifetime, a deterministic forwarding scheme, called maximum remaining energy - directed diffusion (MRE-DD), was proposed by Hwang et al. [10], where a transmitter selects a set of nodes with highest remaining energy, and among them it chooses the minimum energy consuming node.

Zurita et al. [23] proposed dynamic power control strategies by exploiting the dependency between received signal strength and SINR. Panichpapiboon et al. [24] derived an expression for the minimum necessary transmit power for all nodes to ensure network connectivity. The impact of variable transmit power on network capacity was studied by Gomez and Campbell [25]. Cooperative [26] and non-cooperative [27], [28] game theoretic techniques have also been applied on distributed power control. These approaches of power control, however, did not aim at maximization of network lifetime.

Aiming at network lifetime maximization, Panigrahi et al. [11], [12] have proposed two variants of forwarding protocols, where it was shown that a combination of greedy minimum energy forwarding (called GMFP) and nodal remaining energy awareness (called LM-GMFP) helps maximize the network lifetime. These protocols operate without transmit power control, but the same forwarding principle may not work optimally when distributed transmit power control is applied.

In the current work, we combine distributed power control and interference aware forwarding mechanisms, and look to maximize the network lifetime without as well as with power control.

III. Multi-User Interference Analysis

A. Assumptions and definitions

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

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

Thus, the average number of neighbors of a node in its communication range R is $N = \rho \pi R^2$. The deployed nodes are assumed static or semi-static, so the dynamics of interference is slow compared to the user data packet transmission duration.

2) *Channel access:* The entire channel bandwidth is available to all users. Communication is any-to-any, and traffic is uniform across all nodes. The access protocol is slotted CSMA/CA without RTS/CTS (request-to-send/clear-to-send) hand shake†. Note that, transmission without RTS/CTS would be suitable for short data frames. For example, IEEE 802.11 standard [29] specified RTS threshold is 1000 Bytes.

3) *Equal CS range and interference range:* Although precisely the interference range R_i of a node can be different from (larger or smaller than) the CS range R_c [30], [31], as a simplifying assumption for our analysis we consider they are equal, i.e., $R_i = R_c$.

4) *Uncorrelated neighboring nodes' channels:* In forwarding node selection, the channel state of a node pair X-Y does not reveal any information about the channel state of the pair X-Y$'$.

5) *Memoryless channel errors:* A current error does not have any bearing on the future errors. Thus, beyond MAC contention and Gaussian noise, fading dependent errors are not accounted.

B. Interference at a receiver without transmit power control

Referring to Fig. 1, a successful transmission from X to Y occurs if Y does not transmit and the sum of channel noise and interference power from the neighbors of Y is acceptably low for a successful signal reception. The typical value of R_i is taken as $R_i \approx 2R$ [15], [32]. The area of the interference zone of Y (the total shaded area in Fig. 1) 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 at Y increases with d. Thus, to calculate the interference power at the receiver Y, the total area $A(d)$ should be scanned for potential interferers to obtain the cumulative power at Y from the interfering transmitters. An example case of four simultaneous interferers is shown in Fig. 1, where $A(d) = A_1 \cup A_2 \cup A_3 \cup A_4$.

†The current work aims at the energy efficiency performance comparison among the various forwarding approaches, with the assumption of data frame transmission without RTS/CTS handshake (i.e, with basic CSMA/CA only).

We first compute the maximum number of simultaneous interferers that an active receiver can encounter. Then the interference power from individual interferers and the resultant effect on the signal quality is obtained. Henceforth, for notational convenience, $A(d)$ is simply represented as A.

Upper bound on the number of simultaneous interferers: In Fig. 1, Y can be located anywhere in the circle of radius R around X, excluding the reference distance r_0, i.e., $r_0 < d < R$. During the transmission from X, by CSMA principle, the nodes in its CS zone of radius R_i are kept from transmitting. The number of nodes in the area A is a function of 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. By inspection, for a given d this number is maximum when the transmitting nodes in the shaded zone are on its outer rim. Hence, the maximum number of simultaneously transmitting interferer nodes n_i around Y can be found as:

$$n_i = \left\lfloor \frac{2\left(\pi - \arccos\frac{d}{2R_i}\right)}{\pi/3} \right\rfloor + 1. \tag{2}$$

It can be easily verified that the maximum value of n_i is always 4; its probability being the highest when $d = R \approx \frac{R_i}{2}$. By inspection, this number has a weak dependence on the ratio of R and R_i.

Receiver-interference model without transmit power control: We have the polynomial decay of RF (radio frequency) signal power with distance d expressed as:

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

where $P_r(d)$ is the average signal power at a distance d from the transmitter, P_t is the transmitted signal power, $\overline{\kappa}$ is a constant of proportionality – a function of antenna gains, signal carrier frequency, and the receiver antenna diameter [33], and γ is the path loss exponent (generally, $2 \leq \gamma \leq 4$).

For computing the interference power at the receiver Y, we divide the area A into a number of micro-strips. Let us consider a micro-strip of area $da = r \cdot dr \cdot d\theta$ (see Fig. 1) at a distance r from Y at an angle θ with respect to the line joining X and Y. With $r_0 \leq d \leq R$, r varies as: $R_i - d \leq r \leq R_i$. Correspondingly, the angle θ varies as $-\Theta(r) \leq \theta \leq \Theta(r)$, where $\Theta(r)$ is given by:

$$\Theta(r) = \cos^{-1}\left(\frac{R_i^2 - d^2 - r^2}{2rd}\right). \tag{4}$$

The micro-strip of area da is infinitesimally small such that, $\Pr[\underline{n} \geq 2] \approx 0$ (see (1)). The probability that there exists a node in the area da is defined as:

$$P(da, 1) \triangleq p_e. \tag{5}$$

Each micro-strip can be distinguished by the following five factors: (i) *position probability*, defined by the distance r from the receiver and angle θ of the micro-strip; (ii) *selection probability*, defined by the possibility that a particular micro-strip is selected among all micro-strips within the area A; (iii) *node existence probability*, defined in (5); (iv) *transmission probability* p_t that a node transmits from a given micro-strip (considered fixed for all nodes in A), provided that there exists a node in that micro-strip; (v) *interference power* $P_i(r)$, from a micro-strip at a distance r from the receiver, obtained by (3). Some of the above factors can vary with respect to the sub-zone of area A_k, $k = 1, 2, 3, 4$, to which it belongs. Accounting all micro-strips in A, the expected total interference power is obtained.

To find the total expected interference power from the area A, we define two functions $F(A)$ and $F^C(A)$. $F(A)$ is the probability that one transmitting node is chosen from all nodes in A, given by:

$$F(A) = \sum_{J=1}^{\infty} P(A, J) p_t \sum_{j=1}^{J} \frac{1}{j} \binom{J-1}{j-1} p_t^{j-1} (1 - p_t)^{J-j}, \tag{6}$$

where J is the total number of nodes in the area A.

$F^C(A)$ is the probability that none out of J nodes in the area A is transmitting, and is given by:

$$F^C(A) = \sum_{J=0}^{\infty} P(A, J)(1 - p_t)^J. \tag{7}$$

Using (6) and (7), we find the average interference due to a transmitting node, if it exists in a chosen micro-strip, and due to the other possible transmitting nodes with respect to the first node. By observation on the maximum number of interferers in Section III-B (see (2)), there can be 1, 2, 3, or 4 nodes interfering at Y. The interference associated with these cases is formulated as follows.

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

$A_1 =$ the effective interference zone covered by the first interferer;

$A_1^C = A - A_1$, the remaining interference zone of Y, beyond the first interferer;

$A_2 =$ the effective interference zone covered by the second interferer;

$A_{12}^C = A - (A_1 + A_2)$, the remaining interference zone of Y, beyond the first two interferers;

$A_3 =$ the effective interference zone covered by the third interferer;

$A_{123}^C = A - (A_1 + A_2 + A_3) = A_4$, the remaining interference zone of Y, for the fourth interferer.

Clearly, the areas A_1, A_2, A_3, A_4 are mutually exclusive, the sum of which is A. The average interference power due to only one interfering transmitter can be expressed as:

$$I_1(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) P_i(r) F^C(A_1^C). \tag{8}$$

The average interference due to two interferers is obtained by additionally capturing the interference from the area A_1^C, where the second micro-strip is considered about a reference point (r_2, θ_2). Accordingly, the expression for $I_2(d)$ is obtained as:

$$I_2(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \big[P_i(r_1) + P_i(r_2)\big] F^C(A_{12}^C). \tag{9}$$

Similarly, the average interference due to three and four interferers are respectively obtained as:

$$I_3(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \sum_{(r_3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \cdot \big[P_i(r_1) + P_i(r_2) + P_i(r_3)\big] F^C(A_{123}^C), \tag{10}$$

and

$$I_4(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \cdot \sum_{(r3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \sum_{(r_4,\theta_4)} \sum_{\in A_{123}^C} p_e F(A_{123}^C) \cdot \big[P_i(r_1) + P_i(r_2) + P_i(r_3) + P_i(r_4)\big]. \tag{11}$$

In obtaining the expression (10), the area A_1^C is scanned with reference (r_2, θ_2) and the remaining area A_{12}^C is scanned with reference (r_3, θ_3). Likewise, for $I_4(d)$ in (11), additionally the reference (r_4, θ_4) is used for scanning the remaining area A_{123}^C.

The total interference power at Y is obtained from the average interference powers in (8)-(11) as:

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

SINR at the receiver: The total interference power $I(d)$ can be approximated as Gaussian, albeit with some error in this case of limited number of interferers [34]. With this approximation, denoting the variance of Gaussian channel noise as $\mathcal{N}$, the SINR at the receiver can be approximated as:

$$SINR(d) = \frac{P_r(d)}{I(d) + \mathcal{N}}. \tag{12}$$

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

C. Interference at a receiver with distributed transmit power control

In a network with distributed power control, every transmitter tries to control its transmit power independently, so that it can at most reach up to its intended next hop receiver with a desired threshold SINR_{th}. Note that, the potential receiver interference zone in case of fixed transmissions solely depends on the transmitter-receiver distance. However, determining receiver interference zone in a distributed power controlled network is more complex and no longer dependent on the distance of the intended transmitter-receiver pair only. Fig. 2 depicts the receiver's interference zone in power control scenario. In variable power transmission, the exposed terminals zone around the transmitter X is approximated as a circular region of radius R_i^x, which is a function of the X-Y distance d, whereas the circular interference zone of the receiver Y is of radius R_i^y. Because of the distributed control, the transmitters may choose different transmit power, and as a result, the intersection of their interference zones with the intended receiver's interference zone becomes unpredictable. We propose an iterative approach to compute the average interference power in distributed power controlled transmission scenario.

Iterative approach to interference aware power controlled transmissions: In the first iteration, X does not have the knowledge of interference $I(d)$ at Y. So, for a given SINR_{th}, P_t is initially a function of X-Y distance d only. Thus, using (3), the initial profile of controlled transmit power is:

$$SINR_{th} = \frac{P_r(d)}{\mathcal{N}} = \frac{\overline{\kappa} P_t(d)}{d^\gamma \cdot \mathcal{N}}, \text{ or, } P_t(d) = \frac{\mathcal{N} \cdot d^\gamma \cdot SINR_{th}}{\overline{\kappa}}.$$

But, due to the interference power $I(d)$ from the neighboring transmissions, P_t needs to be increased from $P_t(d)$ in order to maintain the SINR at a level of the desired SINR_{th} irrespective of d. Thus, once the exact interference power profile $I(d)$ is known $P_t(d)$ can be increased to a new value as:

$$P_t(d) = \frac{(\mathcal{N} + I(d)) \cdot d^\gamma \cdot SINR_{th}}{\overline{\kappa}}.$$

In the subsequent iterations, by re-arranging the respective transmit powers, the nodes again try to maintain the SINR_{th}. As the transmit power of a node X is increased, its CS range also increases. As a result, the other currently active neighboring transmitters also try to increase their respective transmit power in order to mitigate the effect of increased interference, which further increases the interference at an intended receiver Y. On the other hand, to maintain a desirable SINR_{th} at the receiver, as the transmit power is increased, more nodes in the vicinity of the transmitter are exposed to (aware of) the transmission process, which results in keeping the surrounding less active. Hence, the average interference power at a receiver tends to reduce, which has an effect of pulling down the transmit power for maintaining a target SINR_{th}. These two opposing causes on power control eventually stabilize the transmit power of a node at a saturation value.

We observe that, a stabilized controlled transmit power to an intended receiver $P_t(d)$ is strongly dependent on the chosen forwarding protocol. Below, we consider the two cases: PCN (Power Controlled Nearest forward) and Power Controlled Greedy forwarding (PCG).

Power controlled forwarding protocols: The two contrasting protocol variants of power controlled forwarding are PCN and PCG. In PCN, at any stage of multi-hop data forwarding to the destination, a transmitter selects the next forwarding node that is its nearest forward-direction neighbor. As highlighted in Section II, unlike in [13], our approach to interference computation in PCN distinguishes between communication and interference ranges, and also accounts for a variable interference zone associated with dynamic transmit power control. On the other hand, if the forwarding protocol follows the LRD criteria with power control in selecting a receiver, we call it PCG approach. The interference power at a receiver in PCG is expected to be different from the case when the protocol is PCN. Therefore, to obtain $P_t(d)$, along with the SINR_{th} information the knowledge of X-Y distance distribution is also necessary, which is a function of the chosen forwarding protocol.

Considering the reference distance r_0 (within which range a forwarding node should not be located to avoid near field effect), the modified approximate probability density function (pdf) expressions of the Euclidean distance progress $\underline{\text{d}}$ in PCN and PCG protocols with $r_0 \leq \underline{\text{d}} \leq R$ can be obtained respectively from [13] and [21]. For PCN, the pdf is:

$$f_{\underline{\text{d}}}(d|\text{PCN}) = \frac{\rho\pi d \; e^{-\rho\pi d^2/2}}{1 - e^{-\rho\pi(R^2 - r_0^2)/2}}, \tag{13}$$

and for PCG the expression is:

$$f_{\underline{\text{d}}}(d|\text{PCG}) = \frac{2\rho\sqrt{R^2 - r_0^2 - d^2}}{1 - e^{-\rho\pi(R^2 - r_0^2)/2}} \; e^{-\rho Q(d)}, \tag{14}$$

where $Q(d) = R^2 \left[cos^{-1}\left(\frac{d}{(R-r_0)}\right) - \frac{d}{(R-r_0)}\sqrt{1-(d/R)^2}\right]$.

Average interference in power controlled transmission scenario: We consider the transmitter-receiver pair X-Y in Fig. 2. To obtain the transmit power distribution of X we need to find the interference power distribution at Y. Interference at Y due to the nodes in its interfering zone (the shaded region in Fig. 2) depends on the transmit power distribution of its potential interferers. The average interference range at Y is obtained using the pdf of $\underline{\text{d}}$, $f_{\underline{\text{d}}}(.)$ as:

$$R_i^y = \int_{r_0}^{R} R_i^y(s) f_{\underline{\text{d}}}(s) ds,$$

where the expression for $f_{\underline{\text{d}}}(.)$ is given by (13) for PCN and (14) for PCG, respectively.

With the knowledge of average interference range, the process of obtaining the approximate interference power I in power controlled transmission is similar to that in fixed power transmissions. The X-Y distance d can vary between r_0 and R, whereas the distance of an interfering node r varies between $R_i^x - d$ and R_i^y. Correspondingly, the value of θ varies between $-\Theta(r)$ and $\Theta(r)$, where $\Theta(r)$ is given by (4). In order to obtain the total expected interference power due to all micro-strips (see Fig. 2), we use the two functions $F(A)$ and $F^C(A)$, given in (6) and (7). It can be noted that, unlike in the case of fixed power transmissions, the maximum number of simultaneous interferers k at Y can be more than 4, i.e, $1 \leq k \leq \infty$. Recollecting that the interference zones A_1, A_2, $\cdots$, A_k are mutually exclusive such that $A_1 \cup A_2 \cup \cdots \cup A_k = A(d)$, we can write,

$$I_k(d) = \sum_{r=R_i^x(d)-d}^{R_i^y} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \cdot \sum_{(r3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \cdots \tag{15}$$
$$\cdots \sum_{(r_k,\theta_k)} \sum_{\in A_{12\cdots(k-1)}^C} p_e F(A_{12\cdots(k-1)}^C) \cdots \left[P_i(r_1) + P_i(r_2) + \cdots + P_i(r_k)\right] F^C(A_{12\cdots k}^C),$$

where $P_i(r_k)$ is the interference power at Y from the k-th interferer located at a distance r_k from Y, and is given by:

$$\overline{P_i}(r_k) = \frac{\overline{\kappa}}{r_k^\gamma} \int_{r_0}^{R} P_t(x) f_{\underline{\text{d}}}(x) dx.$$

Hence, the total interference power at Y in controlled power transmissions is

$$I(d) = \sum_{k=1}^{\infty} I_k(d), \tag{16}$$

using which the SINR(d) in (12) in distributed power controlled transmissions is obtained.

IV. Network lifetime aware forwarding protocols

Network lifetime enhancing PCN (E-PCN) protocol: Along the line of lifetime enhancing greedy forwarding protocols in [11], [12] without power control, respectively called GMFP and lifetime maximizing GMFP (LM-GMFP), we propose a lifetime enhancing PCN, called E-PCN. While selecting a forwarding node, among the set of minimum energy consuming nodes based on PCN protocol criteria, the E-PCN choses a node that additionally has the highest remaining energy. The interference computation in E-PCN is similar to that in PCN; the difference comes only in forwarding node selection phase. To evaluate and contrast the performances of the forwarding protocols, we define two performance criteria, namely, *normalized energy consumption* and *network lifetime*.

Definition 1: Normalized energy consumption is defined as the energy consumed per successful forwarding of a packet per unit Euclidean distance progress.

Note that, since the success rate and the Euclidean distance progress would vary in different forwarding protocols, normalized energy consumption is a function of the chosen forwarding protocol.

In a multi-hop environment, the network is said be dead when a node is unable to forward a packet because none of its forwarding neighbors have sufficient energy to help forward the packet.

Definition 2: Network lifetime is defined as the number of packets successfully delivered to the destination nodes before the network is declared to be dead.

Normalized energy consumption and nodal remaining energy are computed as follows:

Packet error rate (PER) $p_p(d)$ depends on BER $p_b(d)$, which in turn is a function of SINR(d), where d is the transmitter-receiver distance. We consider, a packet of length L bits can be decoded successfully as long as the number of bits in error is limited to l bits $(l \ll L)$. Thus we have,

$$p_p(d) = 1 - \sum_{i=0}^{l} \binom{L}{i} \Big(p_b(d)\Big)^i \Big(1 - p_b(d)\Big)^{L-i},$$

where, for BPSK signal $p_b(d) = \frac{1}{2}\text{erfc}\Big(\sqrt{\text{SINR}(d)}\Big)$, and SINR$(d)$ in (12) is obtained differently for fixed power transmissions and power controlled transmissions, as analyzed in Sections III-B and III-C. Note that, in the original GMFP and LM-GMFP approaches [11], [12] the multi-user interference was not accounted, and hence $p_b(d)$ was considered only as a function of SNR. In our relative performance studies in this paper, we have accounted for the multi-user interference as well in these protocols.

Assuming infinite retries possible, the expected number of attempts per successful delivery is: $N_a(d) = \frac{1}{1-p_p(d)}$. The energy consumption per successful packet forwarding $E_s(d)$ is given by,

$E_s(d) = (e_t + e_r) \cdot N_a(d)$, where e_t and e_r are the energy required at the transmitter and receiver, respectively, per attempt. Hence, the normalized energy consumption, $E_c(d)$ is obtained as:

$$E_c(d) = \frac{E_s(d)}{d_p},$$

where d_p is the distance progress offered by the forwarding node from the current transmitter toward the destination. If the forwarding node is at d distance apart from the transmitter and ψ is the angle between the lines connecting the forwarding node to the transmitter and the transmitter to the destination, then $d_p = d \cos \psi$. In the network lifetime aware forwarding (LM-GMFP and E-PCN), the ratio of $E_c(d)$ of the candidate forwarding nodes and their respective remaining battery energies $E^{(r)}$ are computed and the candidate with the minimum ratio is chosen as the forwarding node.

V. Results and Discussion

Basic numerical and simulation based results were obtained using MATLAB. The network lifetime enhancing protocol studies were carried out via NS (ver. 2.31) based simulations.

For simulations, the nodes were uniformly randomly placed in a 700×700 square meter area. Unless otherwise specified, the spatial node density was kept at $\rho = 0.016$, which corresponds to the average number of neighbors $N = 20$ when the communication range is $R = 20$ m. For fixed power transmission, the output power was taken -11 dBm, and channel noise power was taken -80 dBm. BPSK modulation with NRZ signal was considered. For different transmitter-receiver distance, the individual components of interference power $I_k,\ k = 1, 2, 3, 4,$ were numerically computed using (8)–(11) for fixed power transmissions and (15) for variable power transmissions. For simulation based verification of numerical results, sufficient runs were conducted with varying seed values to have confidence level of 95% within the range of $\pm 2\%$ of the average results. For network lifetime studies, the number of nodes were varied to achieve different network density.

A. Network performance with fixed power transmissions

Fig. 3 shows the probabilities of interference from k nodes, where $k = 1, 2, 3, 4$. The plots show that the probability of having two active interferers is generally higher than in any other cases. At very short values d, the receiver's interference area is small and hence the chance of having more than one interferer is also small. As the distance d increases, the likelihood of having more than one interferer increases. But, beyond two active interferers, the remaining area in the interference zone being small, the probability of having more than two active interferer is small. Also, though theoretically there can be a fourth interferer, the probability is negligible, as the remaining exclusion region for the fourth interferer is very small. Additionally, it can be verified from the sum of probabilities for any given value of d that the probability of having no interferer around a receiver is negligibly small. The analytical plots match fairly well with the simulation results. The little mismatches can be attributed to the analytical approximation of uncorrelated channels in the interference computation.

Fig. 4 shows the analytic and simulation results on the average interference power at a receiver at different values of d. The simulation results match quite well with the analytic plot, validating the analysis. The effect of increased interference area is visible as the distance d increases, although the variation becomes increasingly smaller for a higher value of d.

In Fig. 5, the average SINR at the receiver is shown, with $\text{SINR}_{\text{th}} = 6$ dB. It can be observed that, without accounting the interference, $\text{SINR}_{\text{th}} = 6$ dB was achieved at $d \approx 20$ m. However, the effect of added interference shows that, about 6 dB threshold level is achieved only at about $d = 14$ m distance. Thus, in presence of multi-user interference, if a forwarding technique tends to choose a one-hop receiver at a distance more than 14 m, the reception quality could be unacceptably bad. So, the effect of interference creates limitation to some greedy forwarding strategies, like LRD.

Below we present the effect of dynamic transmit power control on signal reception quality.

B. Network performance with transmit power control

From (15) and (16), the SINR at the receiver is used to obtain the saturated transmit power distribution. Fig. 6 shows the SINR values of the two forwarding approaches after the first iteration in a network with distributed transmit power control. The increasing trend of SINR with transmitter-receiver (X-Y) distance d for both PCG and PCN is intuitive, as for a given d the SINR is dominated by the interferer's radiated power. At a very low value of d, the SINR is significantly low because of the dominating effect of the interference power with respect to the d-dependent controlled transmit power from X. But, it may be observed that, with PCG and PCN protocols the SINR values at different node densities show the opposite trends. At a higher node density, PCG has a poorer SINR, whereas PCN offers a higher SINR value. The reverse is true at a lower density. This is because, at a higher node density the probability of choosing a farthest away forwarding node increases in PCG, which is true for an interfering transmitter as well, thereby increasing the interference power at an active receiver. In contrast, in PCN, the interference power level is small due to the tendency of choosing a forwarding node nearby a transmitter, which is aided at a higher node density.

In order to maintain a desired SINR_{th} at the receiver, in the second iteration $P_t(d)$ is increased. After a finite number of iterations, steady state transmit power profile is obtained. We have observed that, PCN attains the saturation state after an average of 4 iterations, whereas PCG attains it after an average of 2 iterations. PCN takes a higher number of iterations because of its wider range of possible transmit power variation starting with a low value. In PCG, on the other hand, by the greedy principle it starts with a closer to the maximum transmit power, and the room for further incremental adjustment is much smaller. A lower node density in PCG necessitates a higher power transmission to combat the multi-user interference, while the reverse is the case in PCN. Overall, the saturated transmit power in PCN is also significantly smaller than that in PCG.

From Fig. 6 we anticipate to have opposing trends of the two protocols in terms of normalized energy consumption per successful packet transfer. Fig. 7 shows that the average normalized energy consumption E_c in PCN and PCG at various node densities. The trends clearly demonstrate that, with distributed power control enabled transmitters, E_c associated with PCN is significantly less than that with PCG. The decrease in energy consumption in PCN also supports the finding in Fig. 6.

C. Network lifetime aware forwarding protocol

We evaluated the network lifetime in a multi-hop network with fixed power transmissions as well as with distributed transmit power control using NS-2. Fig. 8 shows the lifetime, in terms of number of successful end-to-end packet delivery before the network dies. It is observed that, E-PCN offers 2.8 times increased lifetime with respect to the PCN. This observation demonstrates the importance of awareness of energy consumption and remaining energy in extending the network lifetime. The gain with respect to the lifetime aware protocols with fixed power transmissions, GMFP and LM-GMFP, are respectively 7.25 and 2.4 times. The significant gain with respect to PCG is also visible.

The lifetime of E-PCN at different network densities is depicted in Fig. 9, where it is apparent that the network lifetime increases with node density. This observation corroborates the trends in Fig. 7.

VI. CONCLUSION

In this work we have analytically evaluated the total interference power at a receiver with the nodes having different transmission range and interference range. In a homogeneous network scenario with fixed power transmissions, 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. The interference power in a network with distributed transmit power control has been quantified. While network density has a detrimental effect on network lifetime without distributed power control, a reverse effect has been observed with power control. We have demonstrated that, the optimum forwarding strategy in a power controlled scenario is different from that without power control. To this end, we have also proposed two variants of network lifetime enhancing forwarding strategy with power control. The numerical performance studies have been verified by MATLAB as well as NS-2 based network simulations. The results confirm that the proposed interference aware power controlled forwarding policies increase the network lifetime significantly as compared to other forwarding protocols without or with transmit power control.

REFERENCES

[1] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks," in *Proc. IEEE GLOBECOM*, Taipei, Taiwan, Nov. 2002.

[2] F. Ye, H. Yang, H. Yang, and B. Sikdar, "A distributed coordination scheme to improve the performance of IEEE 802.11 in multi-hop networks," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 2903–2908, Oct. 2009.

[3] J. Deng, B. Liang, and P. Varshney, "Tuning the carrier sensing range of IEEE 802.11 MAC," in *Proc. IEEE GLOBECOM*, Dallas, TX, USA, Dec. 2004.

[4] J. Zhu, X. Guo, L. L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proc. IEEE Intl. Conf. Commun. (ICC)*, Paris, France, June 2004.

[5] Z. Li, S. Nandi, and A. K. Gupta, "ECS: An enhanced carrier sensing mechanism for wireless ad hoc networks," *Elsevier Computer Commun.*, vol. 28, no. 17, pp. 1970–1984, 2005.

[6] H. Q. Zhai and Y. G. Fang, "Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks," in *Proc. IEEE INFOCOM*, Barcelona, Spain, Apr. 2006.

[7] S. De, K. Egoh, and G. Dosi, "A receiver initiated power control multi-access protocol in wireless ad hoc networks," in *Proc. IEEE Sarnoff Symp.*, Princeton, NJ, USA, May 2007.

[8] Y. Yang, J. C. Hou, and L.-C. Kung, "Modeling the effect of transmit power and physical carrier sense in multi-hop wireless networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, USA, May 2007.

[9] R. C. Shah and J. M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Proc. IEEE WCNC*, FL, USA, Mar. 2002.

[10] A. Hwang, J. Lee, and B. Kim, "Design of maximum remaining energy constrained directed diffusion routing for wireless sensor networks," in *Proc. Intl. Conf. Computational Science and Its Applications, (ICCSA)*, Glasgow, UK, May 2006.

[11] B. Panigrahi, S. De, and J.-D. Lan Sun Luk, "A greedy minimum energy consumption forwarding protocol for wireless sensor networks," in *Proc. IAMCOM wksp. (co-located with COMSNETS)*, Bangalore, India, Jan. 2009.

[12] B. Panigrahi, S. De, B. S. Panda, and J.-D. Lan Sun Luk, "Energy-efficient greedy forwarding protocol for wireless sensor networks," in *Proc. IEEE Vehicular Tech. Conf. (VTC-Spring).*, Taipei, Taiwan, May 2010.

[13] T.-C. Hou and V. O. K. Li, "Transmission range control in multihop packet radio networks," *IEEE Trans. Commun.*, vol. 34, no. 1, pp. 38–44, Jan. 1986.

[14] R.Mathar and J.Mattfeldt, "Analyzing routing strategy NFP in multihop packet radio network on a line,," *IEEE Trans. Communications*, vol. 43, no. 2-4, pp. 977–988, Mar. 1995.

[15] A. Kamerman and L. Monteban, "WaveLAN-II: A high-performance wireless LAN for the unlicensed band," *Bell Labs Tech. Journal*, vol. 2, pp. 118–133, Summer 1997.

[16] M. M. Vegad, S. De, and B. Lall, "A liberal carrier sensing for increased spatial reuse in multi-hop wireless ad hoc networks," in *Proc. IEEE Intl. Conf. Commun. (ICC)*, Cape Town, South Africa, May 2010.

[17] Y. Zhu and H. Zheng, "Understanding the impact of interference on collaborative relay," *IEEE Trans. Mobile Computing*, vol. 7, no. 6, pp. 724–736, June 2008.

[18] R. Sollacher, M. Greiner, and I. Glauche, "Impact of interference on the wireless ad-hoc networks capacity and topology," *Springer Wireless Networks*, vol. 12, no. 1, pp. 53–61, Feb. 2006.

[19] R. Gummadi, D. Wetherall, B. Greenstein, and S. Seshan, "Understanding and mitigating the impact of rf interference on 802.11 networks," in *Proc. ACM SIGCOMM*, Kyoto, Japan, Aug. 2007.

[20] B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless rounting for wireless networks," in *Proc. ACM MobiCom*, Boston, MA, USA, Aug. 2000.

[21] S. De, "On hop count and Euclidean distance in greedy forwarding in wireless ad hoc networks," *IEEE Commun. Letters*, vol. 9, no. 11, pp. 1000–1002, Nov. 2005.

[22] Y. Yu, D. Estrin, and R. Govindan, "Geographical and energyaware routing: a recursive data dissemination protocol for wireless sensor networks," *UCLA Computer Science Dept. Tech. Rep., UCLA-CSD TR-01-0023*, May 2001.

[23] B. Z. Ares, P. Park, C. Fischione, A. Speranzon, and K. H. Johansson, "On power control for wireless sensor networks: System model, middleware component and experimental evaluation," in *Proc. European Control Conference (ECC)*, Kos, Greece, July 2007.

[24] S. Panichpapiboon, G. Ferrari, and O. K. Tonguz, "Optimal transmit power in wireless sensor networks," *IEEE Trans. Mobile computing.*, vol. 5, pp. 1432–1447, Oct 2006.

[25] J. Gomez and A. T. Campbell, "Variable-range transmission power control in wireless ad hoc networks," *IEEE Trans. Mobile computing.*, vol. 6, no. 1, pp. 87–99, Jan 2007.

[26] W. Wang, M. Chatterjee, and K. Kwiat, "Enforcing cooperation in ad hoc networks with unreliable channel," in *Proc. IEEE Intl. Conf. Mobile Ad Hoc and Sensor Systems (MASS)*, Atlanta, GA, USA, Oct. 2008.

[27] V. Srinivasan, P. Nuggehalli, C. Chiasserini, and R. Rao, "Cooperation in wireless ad hoc networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, Apr 2003.

[28] S. Sengupta, M. Chatterjee, and K. A. Kwiat, "A game theoretic framework for power control in wireless sensor networks," *IEEE Trans. Computers*, vol. 59, no. 2, pp. 231–242, Feb. 2010.

[29] "Wireless LAN medium access control and physical layer specifications, IEEE Std. 802.11," 1999 Ed. (R2003).

[30] J. Lee, W. Kim, S. Lee, D. Jo, J. Ryu, T. Kwon, and Y. Choi, "An experimental study on the capture effect in 802.11a networks," in *Proc. ACM Intl. wksp. Wireless Network Testbeds, Experimental Evaluation and Characterization*, Montreal, Quebec, Canada, Sept. 2007.

[31] N. Santhapuri, S. Nelakuditi, and R. Choudhury, "On spatial reuse and capture in ad hoc networks," in *Proc. IEEE WCNC*, Las Vegas, NV, USA, Mar.-Apr. 2008.

[32] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," in *Proc. ACM MobiCom*, Atlanta, GA, USA, Sept. 2002.

[33] T. Rappaport, *Wireless Communications: Principles and Practice*. Prentice Hall, Upper Saddle River, NJ, 2nd ed., 2002.

[34] S. Verdu, *Multiuser Detection*. Cambridge University Press, Cambridge, UK, 1998.

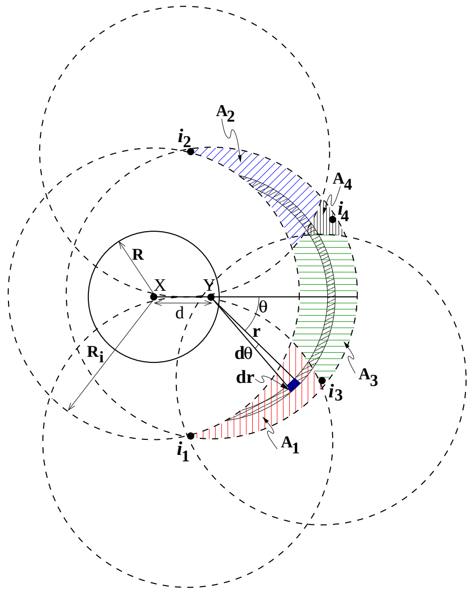

Fig. 1. Receiver's interference zone without transmit power control.

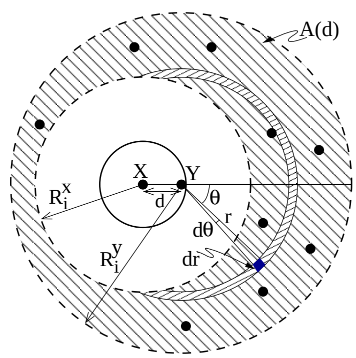

Fig. 2. Receiver's interference zone in power control case.

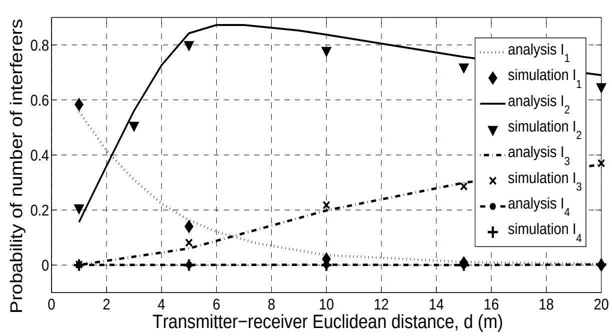

Fig. 3. Probability of having k interfering nodes at various transmitter-receiver distances d. $k = 1, 2, 3, 4$.

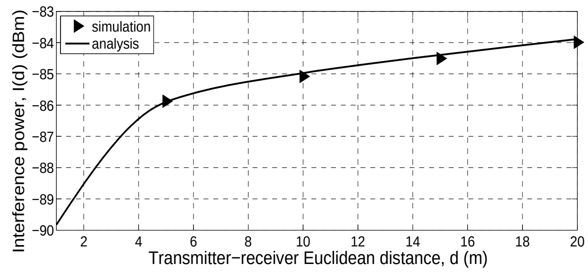

Fig. 4. Interference power at a receiver for various transmitter-receiver distances.

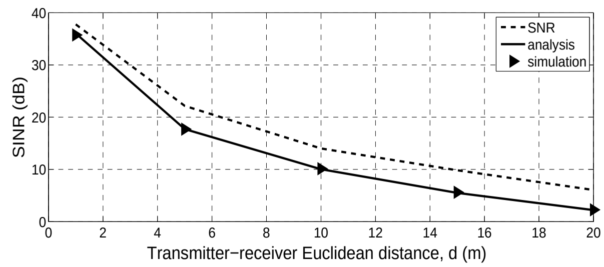

Fig. 5. SINR at various receiver distance d. Tolerable SNR at $R = 20$ m was set at 6 dB.

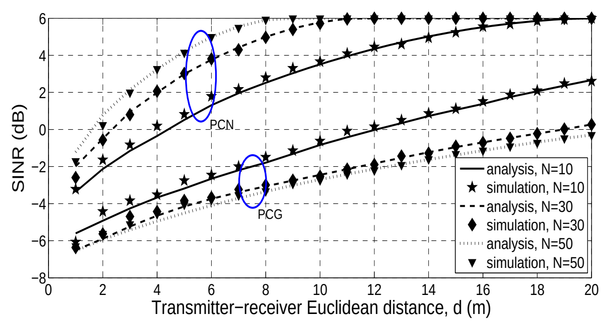

Fig. 6. SINR at a receiver in a network with distributed transmit power control.

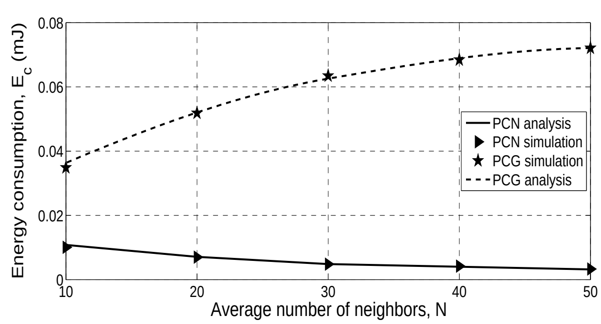

Fig. 7. Normalized energy consumption with distributed power control.

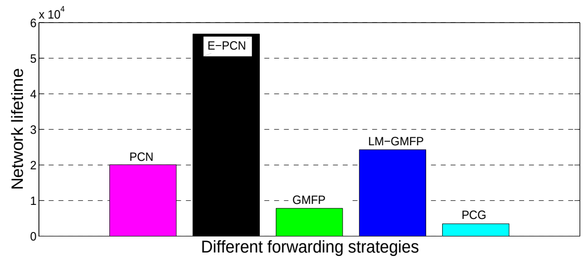

Fig. 8. Network lifetime (number of packets delivered to the destinations before the network dies). $N = 50$.

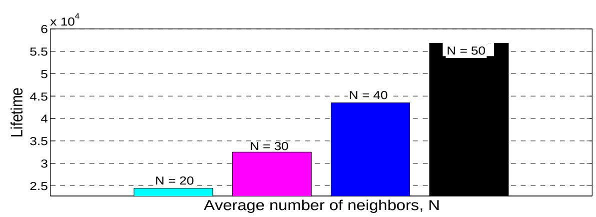

Fig. 9. Network lifetime in E-PCN versus node density.