

Design and performance analysis of distributed relay selection techniques in wireless networks

Md. Sahabul Alam*, Keyvan Zarifi*[†], Sofiene Affes*, and Ali Ghrayeb[†]

*INRS-EMT, Université du Québec, Montreal, QC, H5A 1K6, Canada, Email: sahabul,zarifi,affes@emt.inrs.ca

[†]Concordia University, Montreal, QC, H3G 1M8, Canada, Email: aghrayeb@ece.concordia.ca

Abstract—We develop and analytically study the performances of three relay selection techniques for a two-hop decode-and-forward (DF) cooperative communication system in a large wireless sensor network with uniformly distributed nodes. It is assumed that there is no central processing unit to optimally select the relay and that the nodes use their locally available knowledge, that is, their distances from the source as well as their backward channel gains, to compete with one another to acquire the relaying status. The relay selection schemes are compared in terms of their fairness and energy efficiency. Taking into account both the fading effect and the nodes' locations distribution, the end-to-end outage probabilities of all relay selection schemes are derived and discussed. In particular, it is proved that when the source transmission power is high enough, the outage performance is independent from the scheme used to select the relay. Moreover, when the node intensity is large enough, the outage probability of the optimal relay selection scheme is almost the same as that of its suboptimal but more energy-efficient counterpart that uses the nearest node to the source as the relay. Computer simulations are used to validate the analytical results.

Index Terms—Wireless sensor network, Cooperative communication, Relay selection, Poisson process, Outage probability.

I. INTRODUCTION

Wireless sensor networks (WSNs) have found applications in various fields such as environmental monitoring, military surveillance, space exploration, and intelligent transportation. WSNs used in these applications are usually comprised of a set of small battery-powered nodes that once exhausted can hardly be replaced or recharged [1]. Therefore, any practical communication protocol used in WSNs should reliably deliver the transmitted message and be energy-efficient at the same time [1], [2].

In this paper, we consider a two-hop decode-and-forward (DF) cooperative communication protocol in the case that the source is located in a large WSN while the destination is in the far field of the WSN. It is assumed that the WSN nodes are uniformly distributed according to a two-dimensional Poisson process. A major factor affecting the received signal quality at the destination is the choice of a relay from the set of available nodes in WSN. Assuming that only the nodes' distances from the source and the nodes backward channel gains are locally available and that there is no information about the nodes' forward channels, three types of distributed competition-based relay selection approaches are developed.

In the first scheme, the node with the highest SNR acts as the relay. This scheme turns out to be energy-inefficient. However, taking into account the obliviousness to the forward

channels, it is optimal in the sense of channel outage performance. It is then shown that the energy efficiency can be significantly improved at the cost of small degradation in the outage performance when selecting the relay as the node with the minimum spatial distance from the source. If WSN has a static topology, the closest node to the source rarely changes. This results in an over-exploitation of the selected relay in the latter scheme. In light of the above fact, we develop a third relay selection technique via which the relay is selected randomly from a neighborhood around the source. While being energy efficient and fair towards all nodes, the latter scheme may show a noticeable outage performance degradation at the destination.

Taking into account that the nodes are distributed according to a two-dimensional Poisson process and that the norms of the channel gains are Rayleigh distributed, we derive the source-destination outage probabilities for all relay selection schemes. Using these analytical results, it is proved that when the source transmission power is high or the node density is large, the outage performance of the optimal relay selection scheme is approximately equal to that of its nearest-neighbor relay selection counterpart. Numerical examples are then used to verify the above results.

The rest of the paper is organized as follows. The system model is introduced in Section II and the relay selection schemes are developed in Section III. Section IV analyzes and discusses the outage performances of the proposed relay selection schemes. Section V demonstrates the simulation results while Section VI includes the concluding remarks.

II. SYSTEM MODEL

We consider a WSN that is comprised of a large number of identical sensor nodes that are uniformly distributed on a planar area. The nodes' distribution can be modeled by a two-dimensional Poisson point process [6], [7] with intensity ρ , that is, the number of nodes in any region with the area Ψ is a Poisson random variable with mean $\rho\Psi$. Using a two-phase DF cooperative communication protocol, the source node S aims to transmit a zero-mean Gaussian signal to the destination node D located in the far field of the WSN. In the first phase, S transmits and other nodes in WSN receive noisy and faded versions of the transmitted signal. In the second phase, the receiving nodes in WSN form a competition (see Section III for more details) and the winner acts as the relay, switches from the listening mode to the transmission mode, decodes

the source message, and then forwards the decoded message to the destination. We assume that all terminals have a single antenna, that the wireless channel between any two nodes in the network is modeled as a frequency flat Rayleigh fading with variance $1/2$ per real dimension, and that noise at all terminals is zero-mean white Gaussian with variance N_0 . All channel links and noises are statistically independent and there is no channel-state information exchange among the WSN nodes and no channel feedback from the destination to the nodes. Each node k knows h_{Sk} , its own backward channel from S , as well as L_{Sk} , its distance from S while being oblivious to h_{kD} , its forward channel to the terminal D . In turn, D knows h_{kD} , $k = 1, 2, \dots$, and its distance L from the network. Note that as D is assumed to be in the far field, its distance from every node in the network can be considered approximately equal to L .

The mutual information between S and k is

$$I_{Sk} = \frac{1}{2} \log_2 \left(1 + \frac{P_S}{N_0} \cdot \frac{|h_{Sk}|^2}{L_{Sk}^\vartheta} \right) \quad (1)$$

where P_S and ϑ are the source transmission power and the path-loss exponent, respectively, and the factor $1/2$ is due to the fact that S transmits only half of the time. From (1) it follows that the Sk channel outage probability is

$$P_{\text{out},Sk} = \Pr \left\{ \frac{P_S}{N_0} \cdot \frac{|h_{Sk}|^2}{L_{Sk}^\vartheta} < 2^{2r} - 1 \right\} = \Pr \{ \gamma_{Sk} < \gamma_{\text{th}} \} \quad (2)$$

where r is the source transmission rate, $\gamma_{Sk} \triangleq \gamma_S |h_{Sk}|^2 / L_{Sk}^\vartheta$ is the SNR at the k -th node with $\gamma_S \triangleq P_S / N_0$, and $\gamma_{\text{th}} \triangleq 2^{2r} - 1$ is the minimum SNR required to decode the source message without any error. Similarly, the mutual information between k and D is

$$I_{kD} = \frac{1}{2} \log_2 \left(1 + \frac{P_R}{N_0} \cdot \frac{|h_{kD}|^2}{L^\vartheta} \right) \quad (3)$$

where P_R is the k -th node transmission power. The kD channel outage probability is then equal to

$$P_{\text{out},kD} = \Pr \left\{ \frac{P_R}{N_0} \cdot \frac{|h_{kD}|^2}{L^\vartheta} < 2^{2r} - 1 \right\} = \Pr \{ \gamma_{kD} < \gamma_{\text{th}} \}, \quad (4)$$

where $\gamma_{kD} \triangleq \gamma_R |h_{kD}|^2 / L^\vartheta$ is the SNR at D with $\gamma_R \triangleq P_R / N_0$. We analyze the transmission performance in terms of the end-to-end channel outage probability. Assume that the node R is selected as the relay. In the DF scheme of our concern, the end-to-end channel outage occurs when at least one of the SR or the RD links is in outage. As h_{SR} and h_{RD} are statistically independent, the mutual information between S and R is independent from that of between R and D . Therefore, the overall outage probability from S to D is given by [3]

$$P_{\text{out},SD} = P_{\text{out},SR} + P_{\text{out},RD} - P_{\text{out},SR} \cdot P_{\text{out},RD}. \quad (5)$$

The choice of relay R can have a significant impact on the overall end-to-end outage probability $P_{\text{out},SD}$. In Section III we discuss some policies for the selection of the node R .

III. RELAY SELECTION RULE

There are two practical constraints when selecting the relay:

- 1) There is no central processing unit to select the optimal node as the relay. Each node has to rely solely on its own local available information when competing with other relays for acquiring the relaying status;
- 2) As discussed in Section II, each node only knows its backward channel and its distance from the source while being unaware of its forward channel to the destination.

Having no knowledge about their forward channels, the nodes have to select the relay based only on their received signal qualities. In such a scenario, the optimal relay is the node with the highest SNR γ_{Sk} . The following competition-based approach can be used to select the optimal relay in a distributed manner (see also [5] for related approaches): First, a clear-to-send (CTS) signal from D triggers each node k to start downcounting its timer from the initial value of

$$T_k^{(o)} = \frac{\lambda^{(o)} L_{Sk}^\vartheta}{|h_{Sk}|^2} \quad (6)$$

where $\lambda^{(o)}$ is a scalar. The first timer that reaches zero belongs to the node with the largest γ_{Sk} . Therefore, as soon as the first timer expires, the corresponding node acts as the relay and all other nodes switch to the sleeping mode to save energy. This continues for a period of $T^{(o)}$ seconds that depends on the prior knowledge about the rate of changes of the channel links h_{Sk} . After $T^{(o)}$ seconds, all the sleeping nodes switch back to the listening mode and set their timers to (6) to participate in a new round of competition. Note that the channel links h_{Sk} , and, therefore, the optimal relay choice may vary frequently. Therefore, in practice, $T^{(o)}$ may have to be selected as small as the time-span of only few transmission cycles. This can be very energy-inefficient as the power consumption of a typical transceiver in the listening/transmission modes is usually three orders of magnitude larger than its power consumption in the sleeping mode [8].

Note that γ_{Sk} is inversely proportional to L_{Sk}^ϑ and the closer nodes to the source tend to receive a higher quality version of the signal. Moreover, L_{Sk} usually changes with a much slower rate than h_{Sk} . In light of the above facts, we may set the initial values of the timers to

$$T_k^{(n)} = \lambda^{(n)} L_{Sk} \quad (7)$$

and follow a similar relay selection procedure as in the optimal relay selection scheme with the only difference that the new sleeping time $T^{(n)}$ can be much larger than $T^{(o)}$. The latter nearest-neighbor relay selection scheme chooses the closest node to S as the relay to facilitate a substantial decrease in the network energy consumption at the expense of a possible increase in the overall outage probability.

Although the above nearest-neighbor relay selection scheme is energy efficient, it may exhaust the nodes around the source if the network topology changes too slowly. For instance, when the network topology is fixed, the closest node to S keeps acting as the relay until its battery is fully depleted. A

technique to avoid this problem is to randomly select the relay from $O(S, \Delta)$, the disc of radius Δ centering at S . To this end, we may have every node on $O(S, \Delta)$ to set its initial timer value to a randomly generated quantity of

$$T_k^{(r)} = \lambda_k^{(r)}. \quad (8)$$

After selecting the relay, all other nodes in $O(S, \Delta)$ are left in the sleeping mode for $T^{(r)}$ seconds. When $T^{(r)}$ seconds is elapsed, all sleeping nodes switch back to the listening mode and initialize their counters with *newly generated* set of $T_k^{(r)}$. As the counters are initialized in each competition round with newly generated set of $T_k^{(r)}$, all nodes in $O(S, \Delta)$ have a similar chance of acting as the relay over a long period of time. It follows from the above discussion that the random relay selection scheme is both energy-efficient and fair towards nodes while it may result in a noticeable performance degradation due to the fact that the relaying nodes are selected randomly from a neighborhood around S . Note that an excessive performance degradation can be avoided if Δ is not very large.

In Section IV, we analyze the outage performances of the above three relay selection schemes.

IV. PERFORMANCE ANALYSIS

Throughout the rest of this manuscript $P_{\text{out,SD}}^{(\bullet)}$, $P_{\text{out,SR}}^{(\bullet)}$, and $P_{\text{out,RD}}^{(\bullet)}$ are used to show the outage probabilities of SD , SR , and RD links, respectively. \bullet can be ‘‘o’’, ‘‘n’’, and ‘‘r’’ to denote the optimal, the nearest-neighbor, and the random relay selection schemes, respectively.

A. Optimal Relaying

Let η^o represent the largest $|h_{S_k}|^2 / L_{S_k}^\vartheta$ among all nodes. It can be shown that the cumulative distribution function (CDF) of η^o is [9]

$$F_{\eta^o}(z) = e^{-u(z)}, \quad (9)$$

where

$$u(z) = \frac{2\rho\pi}{\vartheta} \int_0^\infty y^{2/\vartheta-1} e^{-yz} dy. \quad (10)$$

It directly follows from (2) and (9) that

$$P_{\text{out,SR}}^{(o)} = F_{\gamma_{S_k}^o} \left(\frac{\gamma_{\text{th}}}{\gamma_S} \right). \quad (11)$$

To derive $P_{\text{out,RD}}^{(o)}$, first note that all channel gains are independent realizations of an exponentially distributed random variable with the parameter $\lambda = 1$. Using the latter fact in (4), we have

$$P_{\text{out,RD}}^{(o)} = 1 - e^{-L^\vartheta \gamma_{\text{th}} / \gamma_R}. \quad (12)$$

Using (11) and (12) in (5), we obtain the end-to-end outage probability $P_{\text{out,SD}}^{(o)}$.

B. Nearest-Neighbor Relaying

Without any loss of generality, assume that the first node is the closest node to S . As the nodes are distributed according to a two-dimensional Poisson process with intensity ρ , the probability density function (PDF) of $L_{S_1}^\vartheta$ is [4]

$$f_{L_{S_1}^\vartheta}(y) = \frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}}. \quad (13)$$

From (2) along with the fact that $L_{S_1}^\vartheta$ and $|h_{S_1}|^2$ are independent random variables, we have

$$\begin{aligned} P_{\text{out,SR}}^{(n)} &= \Pr \left\{ \frac{|h_{S_1}|^2}{L_{S_1}^\vartheta} \leq \frac{\gamma_{\text{th}}}{\gamma_S} \right\} \\ &= \int_{y=0}^\infty \int_{x=0}^{y\gamma_{\text{th}}/\gamma_S} \frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}} e^{-x} dx dy \\ &= \int_0^\infty \frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}} \left(1 - e^{-y\gamma_{\text{th}}/\gamma_S} \right) dy. \end{aligned} \quad (14)$$

In general, $P_{\text{out,SR}}^{(n)}$ in (14) may be computed numerically. However, when $\vartheta = 2$ we have

$$P_{\text{out,SR}}^{(n)} = \frac{\gamma_{\text{th}}/\gamma_S}{\rho\pi + (\gamma_{\text{th}}/\gamma_S)}. \quad (15)$$

As all node-destination channels have an identical statistical distribution, it immediately follows that $P_{\text{out,RD}}^{(n)} = P_{\text{out,RD}}^{(o)}$ where $P_{\text{out,RD}}^{(o)}$ is given in (12). Using the latter fact along with (14) in (5), $P_{\text{out,SD}}^{(n)}$ is obtained.

C. Random Relaying

When the relay is randomly selected from $O(S, \Delta)$, we have [5]

$$f_{L_{SR}^\vartheta}(y) = \frac{2y^{2/\vartheta-1}}{\vartheta\Delta^2}. \quad (16)$$

Therefore,

$$\begin{aligned} P_{\text{out,SR}}^{(r)} &= \Pr \left\{ \frac{|h_{SR}|^2}{L_{SR}^\vartheta} < \frac{\gamma_{\text{th}}}{\gamma_S} \right\} \\ &= \int_{y=0}^{\Delta^\vartheta} \int_{x=0}^{y\gamma_{\text{th}}/\gamma_S} \frac{2y^{2/\vartheta-1}}{\vartheta\Delta^2} e^{-x} dx dy \\ &= \int_0^{\Delta^\vartheta} \frac{2y^{2/\vartheta-1}}{\vartheta\Delta^2} \left(1 - e^{-y\gamma_{\text{th}}/\gamma_S} \right) dy. \end{aligned} \quad (17)$$

While $P_{\text{out,SR}}^{(r)}$ in (17) should be numerically computed in general, it can be shown for $\vartheta = 2$ that

$$P_{\text{out,SR}}^{(r)} = 1 - \frac{1}{\Delta^2 \gamma_{\text{th}} / \gamma_S} \cdot \left(1 - e^{-\Delta^2 \gamma_{\text{th}} / \gamma_S} \right). \quad (18)$$

Again, using (17) along with the fact that $P_{\text{out,RD}}^{(r)} = P_{\text{out,RD}}^{(o)}$, $P_{\text{out,SD}}^{(r)}$ can be easily obtained from (5).

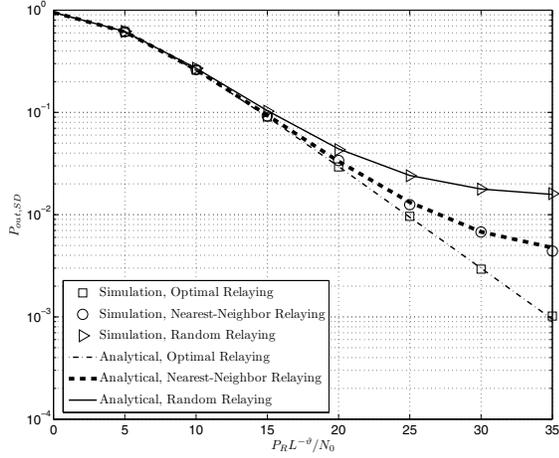


Fig. 1. The $P_{out,SD}$ versus $P_R L^{-\vartheta} / N_0$ with fixed P_S for different relay selection schemes.

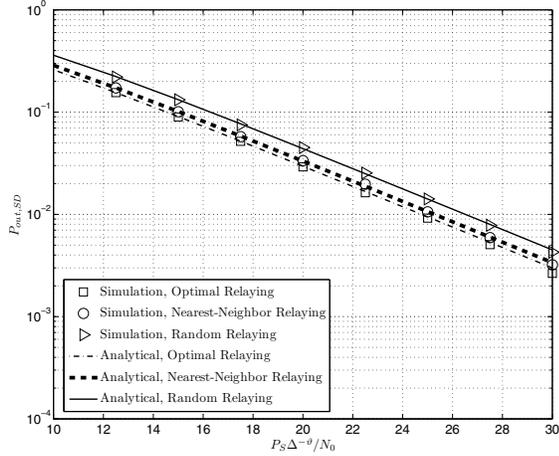


Fig. 2. The $P_{out,SD}$ versus $P_S \Delta^{-\vartheta} / N_0$ with $P_R \triangleq \beta P_S$ with $\beta = 400$ for different relay selection schemes.

D. Equivalence of the Optimal and the Nearest-Neighbor Selection Schemes in the High SNR Regime

It follows from (10) that

$$\begin{aligned} u(\gamma_{th}/\gamma_S) &= \frac{2\rho\pi}{\vartheta} \int_0^\infty y^{2/\vartheta-1} e^{-y\gamma_{th}/\gamma_S} dy \\ &= \frac{2\rho\pi}{\vartheta} \cdot \left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}} \Gamma\left(\frac{2}{\vartheta}\right) = c \cdot \left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}}, \end{aligned} \quad (19)$$

where $\Gamma(t) \triangleq \int_0^\infty x^{t-1} e^{-x} dx$ is the Gamma function and $c \triangleq 2\rho\pi\Gamma\left(\frac{2}{\vartheta}\right)/\vartheta$ is a constant.

Let us assume that $P_R \triangleq \beta P_S$ where β is a constant. Then, for a large P_S we have $\gamma_{th}/\gamma_S \approx 0$, $\gamma_{th}/\gamma_R \triangleq \gamma_{th}/\beta\gamma_S \approx 0$,

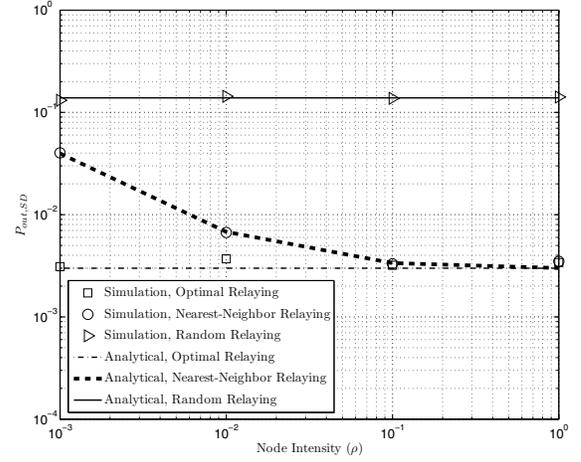


Fig. 3. The $P_{out,SD}$ versus ρ for different relay selection schemes.

and therefore

$$\begin{aligned} \lim_{\gamma_S \rightarrow \infty} \frac{P_{out,SD}^{(n)}}{P_{out,SD}^{(o)}} &= \lim_{\gamma_S \rightarrow \infty} \frac{\int_0^\infty (1 - e^{-y\gamma_{th}/\gamma_S}) \left(\frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}}\right) dy + E}{e^{-c\left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}}} + E} \\ &= \lim_{\gamma_S \rightarrow \infty} \frac{\int_0^\infty (1 - e^{-y\gamma_{th}/\gamma_S}) \left(\frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}}\right) dy + E}{e^{-c\left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}}} + E} \end{aligned} \quad (20)$$

where $E \triangleq 1 - e^{-L^\vartheta \gamma_{th}/\beta\gamma_S}$. Using the Taylor series expansion, the above expression can be further simplified to

$$\lim_{\gamma_S \rightarrow \infty} \frac{P_{out,SD}^{(n)}}{P_{out,SD}^{(o)}} = \lim_{\gamma_S \rightarrow \infty} \frac{\left(\int_0^\infty \frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}} dy\right) + L^\vartheta/\beta}{\frac{\gamma_S}{\gamma_{th}} \cdot e^{-c\left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}}} + L^\vartheta/\beta}. \quad (21)$$

Note that

$$\lim_{\gamma_S \rightarrow \infty} \frac{\gamma_S}{\gamma_{th}} \cdot e^{-c\left(\frac{\gamma_S}{\gamma_{th}}\right)^{\frac{2}{\vartheta}}} = \lim_{n \rightarrow \infty} n^{\vartheta/2} e^{-nc} \approx 0. \quad (22)$$

Substituting (22) into (21) yields

$$\lim_{\gamma_S \rightarrow \infty} \frac{P_{out,SD}^{(n)}}{P_{out,SD}^{(o)}} = 1 + \beta \frac{\left(\int_0^\infty \frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}} dy\right)}{L^\vartheta} \approx 1 \quad (23)$$

where the latter approximation is due to the fact that the destination is in the far field. Note that a similar approach can be used to show that $\lim_{\gamma_S \rightarrow \infty} P_{out,SD}^{(r)}/P_{out,SD}^{(o)} \approx 1$.

E. Higher Node Intensity Approximation

Under higher node intensity approximation, we have

$$\lim_{\rho \rightarrow \infty} \left(\int_0^\infty (1 - e^{-y\gamma_{th}/\gamma_S}) \left(\frac{2}{\vartheta} \rho \pi y^{\frac{2}{\vartheta}-1} e^{-\rho \pi y^{\frac{2}{\vartheta}}}\right) dy\right) \approx 0. \quad (24)$$

Also,

$$\lim_{\rho \rightarrow \infty} \left(e^{-u(\gamma_{th}/\gamma_S)} \right) \approx 0. \quad (25)$$

The above approximation can be used in the expressions of $P_{out,SD}^{(n)}$ and $P_{out,SD}^{(o)}$ to show that

$$\lim_{\rho \rightarrow \infty} \frac{P_{out,SD}^{(n)}}{P_{out,SD}^{(o)}} \approx 1. \quad (26)$$

V. SIMULATIONS

Simulations are used to demonstrate the performance of the proposed relay selection schemes and validate the theoretical results presented in Section IV. In Fig. 1 we use $\rho = 0.001$, $\vartheta = 2$, $r = 1$ (bits/s/Hz), $\Delta = 50$, $L = 1000$, and $P_S \Delta^{-\vartheta}/N_0 = 20$ (dB) and show the analytical and simulated $P_{out,SD}$ versus $P_R L^{-\vartheta}/N_0$ for all proposed relay selection schemes. As can be observed from the figure, the analytical curves closely follow their simulated counterparts. Note from Fig. 1 that even for a ρ as small as 0.001, the performance of the nearest-neighbor relay selection scheme is quite close to that of the optimal relay selection scheme.

Fig. 2 shows $P_{out,SD}$ versus $P_S \Delta^{-\vartheta}/N_0$ in the high SNR regime for different relay selection schemes. It is assumed in Fig. 2 that $P_R = \beta P_S$ with $\beta = (L/\Delta)^\vartheta = 400$. All other parameters remain unchanged from Fig. 1. Both numerical and simulation results illustrate that the outage performances at the destination of all the relay selection schemes are almost the same. This further verifies the analytical results of Subsection IV-D.

Fig. 3 plots the outage probability curves versus ρ . P_S and P_R are selected such that the average SNR at R is $\gamma_1 = P_S \Delta^{-\vartheta}/N_0 = 10$ (dB) while the average SNR at D is $\gamma_2 = P_R L^{-\vartheta}/N_0 = 30$ (dB). All other parameters remain unchanged from Fig. 1. As can be observed from Fig. 3, the nearest relay selection scheme shows optimal performance when the node intensity increases to 0.2.

Fig. 4 shows the same curves as in Fig. 3 for $\gamma_1 = 30$ (dB). All other parameters remain unchanged from Fig. 3. Note that since $\gamma_1 = 30$ (dB) is large, the performance of the random relay selection scheme closely follows that of its optimal counterpart. Corroborating the results of Subsection IV-D, the figure shows that if the average received SNR at the selected relay is high enough, then the outage performance at the destination is independent from the technique used to select the relay.

VI. CONCLUSION

We have considered a two-hop DF cooperative communication scheme for wireless sensor networks wherein only the source-node distance and the source-node channel gain are known at each corresponding node. Using their locally available knowledge, nodes compete with one another to acquire the relaying status. Three different relay selection approaches were studied, namely, the optimal, the nearest-neighbor, and the random relay selection techniques in which a node with the highest SNR, a node with the smallest distance from

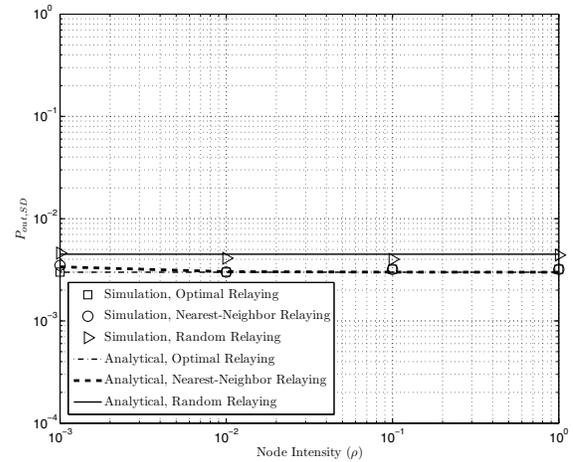


Fig. 4. The $P_{out,SD}$ versus ρ for different relay selection schemes.

the source, and a random node from a neighborhood around the source act as the relay, respectively. The relay selection techniques were compared in terms of energy efficiency and fairness. Taking into account both the small scale and the large scale fading effects, the end-to-end outage probabilities of the three relay selection techniques were derived. Analytical results were used to prove that the optimal and the nearest relay selection schemes have approximately the same outage performances in the high SNR regime and when the node intensity increases.

REFERENCES

- [1] Z. Zhou, S. Zhou, S. Cui, and J. H. Cui, "Energy-efficient cooperative communication in a clustered wireless sensor network", *IEEE Transactions on Vehicular Technology*, vol. 57, pp. 3618-3628, Nov. 2008.
- [2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior", *IEEE Transactions on Information Theory*, vol. 50, pp. 3062-3080, Dec. 2004.
- [3] B. Gui, L. Dai and L. Cimini, "Routing strategies in multihop cooperative networks", *IEEE Transactions on Wireless Communications*, vol. 8, pp. 843-855, Feb. 2009.
- [4] M. Haenggi, "On distances in uniformly random networks", *IEEE Transactions on Information Theory*, vol. 51, pp. 3584-3586, Oct. 2005.
- [5] K. Zarifi, M. Abuthinien, A. Ghrayeb, and S. Affes, "Relay selection schemes for uniformly distributed wireless sensor networks", *IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2009, Budapest, Hungary.
- [6] S. Mukherjee, D. Avidor, and K. Hartman, "Connectivity, power, and energy in a multihop cellular-packet system", *IEEE Transactions on Vehicular Technology*, vol. 56, pp. 818-836, Mar. 2007.
- [7] D. Avidor, S. Mukherjee, and F. Atay Onat, "Transmit power distribution of wireless ad-hoc networks with topology control", *IEEE Transactions on Wireless Communications*, vol. 7, pp. 1111-1116, Apr. 2007.
- [8] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Trans. Networking*, vol. 12, pp. 493-506, June 2004.
- [9] K. Zarifi, M. Abuthinien, A. Ghrayeb, and S. Affes, "Energy-efficient techniques to select multiple relays in wireless sensor networks with uniformly distributed nodes," *IEEE Transactions on Wireless Communications*, to be submitted.