Distance-Based Node Activation for Geographic Transmissions in Fading Channels

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Abstract

In wireless multi-hop packet radio networks (MPRNs) that employ geographic transmissions, sleep schedules or node activation techniques may be used to power off some nodes to conserve energy. We consider the problem of selecting which nodes should power on to listen to a scheduled transmission when the channel suffers from random fading. We consider the problem of maximizing the expected value of the single-hop transmission distance between a transmitter and the farthest receiver that successfully receives the packet, under a constraint on the expected number of receivers that turn on. Since there is a tradeoff between the distance of a node from the transmitter and the probability that the node receives the message correctly, we propose to use node-activation based on link-distance (NA-BOLD). We investigate optimal and sub-optimal NA-BOLD schemes and compare their performance with that of schemes that use a constant sleep schedule for every node within some radius of the transmitter. Our results show that the proposed NA-BOLD schemes achieve significantly larger transmission distances than conventional schemes.

Keywords: geographic transmission, sleep schedules, node activation, maximizing transmission distance, energy constraints

I. Introduction

In multi-terminal packet radio networks, the channels vary randomly because of small-scale fading or shadowing (large-scale fading). *Opportunistic* transmission schemes take advantage of these variations by transmitting to a node that has a good channel gain [1], [2], thus achieving multiuser diversity. Centralized control in cellular networks makes it relatively easy to achieve

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multiuser diversity, and such schemes have been implemented in the 3G cellular standards. However, achieving multiuser diversity in wireless multi-hop packet radio networks (MPRNs) is more challenging, primarily because medium access control is usually a fully distributed process. However, at any instant of time in a MPRN, there may be several potential routes might exist between a transmitter (source) and a destination, thus allowing more options for multiuser diversity transmissions if these potential routes can be properly exploited.

Previous work on achieving multiuser diversity in MPRNs may be classified as using either *opportunistic transmission (OpTx)* or *opportunistic reception (OpRx)*. OpTx schemes, such as those proposed in [3], [4], are based on the approach in [1]. Another type of OpTx is proposed in [5], in which mobility is used to move packets closer to their destinations. OpRx schemes are described in [6]–[11]. These schemes generalize routing by allowing any of a group of receivers to act as the next-hop forwarding agent for a packet. OpTx schemes are dependent on having packets available for many next-hop radios and on having packets that can tolerate additional latency. Many types of traffic cannot tolerate such delays and hence OpRx schemes are favored in such situations. We consider such a situation in this paper.

One of the first OpRx schemes described in the literature is the alternate routing scheme described in [12, Section IV.D], in which a packet may be forwarded by a node other than that selected by the routing table after a certain number of transmission failures occurs. More recently, Larsson described a similar scheme, called selection diversity forwarding (SDF) [6], [13], in which acceptable an list of forwarding agents is pre-determined using channel state information fed back from neighboring nodes. In [14], the authors consider maximizing information efficiency (the product of expected progress and spectral efficiency) and design routing schemes that take advantage of multiuser diversity. In [9], [10], a MAC protocol that is similar to alternate routing was investigated for communication over fading channels.

Geographic routing approaches [15]–[17] eliminates the need for table-based routing and can provide multiuser diversity against channel fading. Energy efficiency is often important in the design of communication protocols for MPRNs, which motivates sleep scheduling of nodes (cf. [18]). In [7], [19], Geographic Random Forwarding (GeRaF) is proposed to overcome random sleep schedules. GeRaF is applied to fading channels in [20]. In these works, nodes are assumed to follow a random sleeping pattern. In [21], the authors integrate hybrid-ARQ techniques into GeRaF and design the HARBINGER protocol that provides a better energy-latency tradeoff. In these previous works, the sleeping pattern is assumed to be random. In [22], [23], Deng *et al.* propose sleeping schemes in which the probability that a node sleeps is a linear function of its distance from a cluster head. The linear function is not shown to be optimal and is designed to compensate for additional transmit power needed by the nodes to communicate with the cluster head. Only exponential path loss is considered.

Under fading channels, the probability that a node can receive a message is a decreasing function of the distance of that node from the transmitter. Thus, from the viewpoint of a single transmitter, there is an inherent tradeoff in selecting which of its neighbors should activate (i.e., not sleep): If nodes close to the transmitter activate, there is a higher probability that the message is successfully received, but the message does not make much progress toward the destination. If nodes far from the transmitter activate, the message goes farther if it is successfully received, but the probability of the message being successfully received is low. In this paper, we consider the design of schemes to determine whether a node should activate to receive a transmission under an energy constraint on the expected number of nodes that activate. We call this approach node activation based on link distance (NA-BOLD), and design and evaluate the performance of optimal (but computationally intensive) and suboptimal NA-BOLD schemes.

II. System Model

We consider a single hop transmission of a wireless communication system that uses geographic routing. We assume that the destination node is far from the transmitter, so that it is sufficient for the transmitter to send the message in the direction of the destination, without needing to consider minimizing the residual distance (cf. [7], [19], [20]). Thus, we assume that the transmitter broadcasts the message to receivers located within some sector of angle θ centered on the line to the destination. If θ is small, then the common goal of maximizing the expected progress [24], [25] is closely approximated by maximizing the transmission distance.

We consider fixed-rate transmission, so maximizing the expected transmission distance is also equivalent to maximizing the transport capacity[1]. Thus, we wish to maximize the transmission distance from the source under a constraint on the expected number of receivers in the sector that activate to receive a broadcast from the transmitter. We assume that the transmission distance achieved is equal to the distance to the most distant active receiver that successfully recovers the message. Our objective is the design of the node activation function, not the MAC protocol to select the best node, which has already been considered in [7], [19].

We assume that the nodes are distributed according to a homogeneous, isotropic Poisson point process in $\mathbb{R}^2$ with intensity λ nodes per unit sector. If we consider the nodes within some annular sector of inner and outer radii R_1 and R_2, respectively, then the distance X_i to the ith node in the annular sector has density $f_{X_i}(x) = 2x/(R_2^2 - R_1^2)[\mathrm{u}(x - R_1) - \mathrm{u}(x - R_2)]$, where $u(x)$ is the unit step function. We assume that nodes are aware of their own location and the location of the transmitter. This situation can arise in framed transmission when the network reservations occur during a contention access period (CAP) and the transmissions occur during a contention free period (CFP), as in the IEEE 802.15.4 standard [27]. Another scenario that can result in knowledge of the transmitter location but not the channel state is when the RTS/CTS messages are carried over a separate low-rate paging channel [28].

We consider a block fading channel in which the fading gain at every node remains constant over each packet, and these gains are independent among nodes. We assume that the fading gains are not known before the data transmission begins, and thus nodes cannot use this information in deciding whether to sleep. We assume a wireless network that has a low-traffic load, so that we can ignore the impact of interference on the received signal. Thus, the signal power at receiver

[1]We consider the more general transport capacity problem in [26].

i depends on X_i and the squared channel fading gain, H_i, during the transmission. Without loss of generality, we normalize all distances so that the transmission distance in the AWGN channel is one. Thus, under the assumption of unity transmit power, the signal power at receiver i can be modeled as $\gamma_i = H_i X_i^{-n}$, where n denotes the path-loss exponent.

III. NA-BOLD : Node Activation Based on Link Distance

A. *Optimum NA-BOLD strategy : (NA-BOLD(O))*

We consider the design of NA-BOLD schemes that maximize the expected value of the transmission distance to the farthest successful receiver under a constraint on the expected number of nodes that activate to receive a transmission. Let $\psi(x)$ be the conditional probability that a node activates given that it is at at distance x from the transmitter. We call $\psi(x)$ the *node activation function*. We use a protocol model to determine if a message is received successfully. Let ρ be the SNR threshold for successful reception. Then if γ_i is the SNR at receiver i then the message is successfully received at node i if $\gamma_i > \rho$. Let U_i be a uniform random variable on $[0, 1]$. Then we define

$$V_i = \begin{cases} X_i, & \gamma_i > \rho \quad \cap \quad U_i < \psi(X_i) \\ 0, & \text{otherwise;} \end{cases} \tag{1}$$

i.e., V_i is the transmission distance if the message is received correctly and zero otherwise.

Consider first transmission into a region of finite area A, which contains $\aleph$ nodes (awake and asleep). Then the distance to the farthest successful receiver is

$$V_{max} = \begin{cases} \max\Big\{V_1, V_2 \ldots V_\aleph\Big\}, & \aleph = 1, 2 \ldots \\ 0, & \aleph = 0. \end{cases} \tag{2}$$

Denote the distribution of the i.i.d. random variables $\{V_i\}$ as $F_V(t)$. Then, conditioned on $\aleph$, $F_{V_{max}}(t|\aleph)$ can be expressed as $F_{V_{max}}(t|\aleph) = [F_V(t)]^\aleph$. Since $\aleph$ is a Poisson random variable with mean λA, the distribution of V_{max},

$$F_{V_{max}}(t) = \exp\Big(\lambda A\left(F_V\left(t\right) - 1\right)\Big) \tag{3}$$

Note that V_{max} may be zero if there are no receivers inside the region, no receivers activate, or none of the receivers that activate have a sufficiently high received SNR.

Let K denote the number of nodes that activate. We wish to find the optimum $\psi(x)$ such that $\mathbb{E}\left[V_{max}\right]$ is maximized, subject to a constraint on the expected value of K. Hence, we can express our optimization problem as

$$\hat{\psi}(X_i) = \arg\max_{\psi(X_i)} \ \mathbb{E}\left[V_{max}\right] \tag{4}$$
$$\text{subject to: } \ \mathbb{E}\left[K\right] = \mu_0 \text{ and } 0 \leq \psi(X_i) \leq 1.$$

Since V_{max} is non-negative, we can express $\mathbb{E}\left[V_{max}\right]$ as

$$\mathbb{E}\left[V_{max}\right] \ = \ \int_0^\infty 1 - \exp\left(\lambda A \left(F_V\left(t\right) - 1\right)\right) \, dt. \tag{5}$$

Let us denote $Y_i = \sqrt[n]{(H_i \rho^{-1})}$. Denote the distribution and the complementary distribution function of Y by $G(y)$ and $\widetilde{G}(y)$ respectively, where $\widetilde{G}(y) = 1 - G(y)$. Using (1),

$$\begin{aligned} F_V(t) = 1 - P(V_i > v) \ &= \ 1 - P(X_i > v, \ X_i < Y_i, \ U_i < \psi(X_i)) \\ &= \ 1 - \int_v^\infty \psi(x)\tilde{G}(x) f_X(x) dx \end{aligned} \tag{6}$$

Substituting (5) in (4), and using (6), we can express our optimization problem as

$$\hat{\psi}(X) = \arg\max_{\psi(X)} \left[\int_0^\infty 1 - \exp\left(-\lambda A \int_t^\infty \psi(x)\tilde{G}(x) f_X(x) dx\right) dt\right] \tag{7}$$
$$\text{subject to: } \ \lambda A \int_0^\infty \psi(x) f_X(x) \ dx = \mu_0 \text{ and } 0 \leq \psi(x) \leq 1.$$

A closed-form solution to this problem is difficult to obtain. Hence we obtain the optimum node activation function numerically. Towards that end, we introduce the following theorem.

Theorem 1. *If we denote the set* $\mathbf{\Psi}$ *as*

$$\mathbf{\Psi} = \{\psi : 0 \leq \psi \leq 1, \ \int \psi \ d\mu = c\},$$

where c *is a fixed positive value and* ψ *is a measurable function on the finite measure space* $(\Omega, \mathcal{F}, \mu)$, *then the extreme points of the convex set* $\mathbf{\Psi}$ *are indicator functions.*

Proof: Let $0 < t < 1$ and $0 < \nu < 1$. Define

$$\psi_1 = \begin{cases} t^{-1}\psi, & 0 < \psi \le t, \\ \nu, & t < \psi \le 1 + t\nu - t, \\ \psi, & 1 + t\nu - t < \psi \le 1 \end{cases}$$

and $\psi_2 = (\psi - t\psi_1)/(1-t)$. Then, $0 \le \psi_1,\ \psi_2 \le 1$ and $t\psi_1 + (1-t)\psi_2 = \psi$. Now we have,

$$\int (\psi_1 - \psi)\ d\mu = \frac{1-t}{t} \int_{0<\psi\le t} \psi\ d\mu + \int_{t<\psi\le 1+\nu t - t} (\nu - \psi)\ d\mu. \tag{8}$$

Suppose for some $0 < t < 1$,

$$\int_{0<\psi\le t} \psi\ d\mu > 0. \tag{9}$$

We show that as a function of (ν, t), (8) assumes both positive and negative values in $(0,1) \times (0,1)$. Hence it must vanish somewhere. We discuss below separately the cases when (8) assumes negative and positive values, respectively.

Negative values of (8): Consider some t for which (9) is true. Then,

$$\frac{1-t}{t} \int_{0<\psi\le t} \psi\ d\mu \le (1-t)\ \mu\{0 \le \psi \le t\} \quad \to \ 0 \ \text{ as } \ t \to 0.$$

Furthermore, we have,

$$\lim_{\nu\to 0,\ t\to 0} \ \int_{t<\psi<1+\nu t - t} (\nu - \psi)\ d\mu \ = \ \int_{0<\psi<1} -\psi\ d\mu < 0 \ \text{ using (9).}$$

Hence, it follows that (8) attains negative values.

Positive values of (8): Notice that

$$\lim_{t\to 1} \ \int_{0<\psi\le t} \frac{1}{t}\psi\ d\mu = \int_{0<\psi\le 1} \psi\ d\mu > 0 \ \text{ using (9).} \tag{10}$$

Also,

$$\frac{1}{1-t} \int_{t<\psi\le 1+\nu t - t} |\nu - \psi|\ d\mu \le \int d\mu \ \to \ 0 \ \text{ as } \ t \to 1, \tag{11}$$

because on the set $t < \psi \le 1 + \nu t - t$, $|\nu - \psi| \le 1 - t$. Hence (10) and (11) imply that (8) attains positive values. Thus, if ψ is an extreme point of the convex set $\boldsymbol{\Psi}$, then (9) must be false, i.e. $\displaystyle\int_{0<\psi\le t} \psi\ d\mu = 0$ for every $0 < t < 1$, i.e., μ a.e. $\psi = 0$ or 1. ■

Theorem 1 establishes that the optimum node activation function can be represented as

$$\hat{\psi}(x) = \int \mathbf{1}_{\mathcal{A}} \ \chi(d\mathcal{A})(x) \tag{12}$$

for some probability measure χ where $\mu(\mathcal{A}) = c \ \forall \mathcal{A}$. In general, the measure χ can be concentrated on any set $\mathcal{A}$ with $\mu(\mathcal{A}) = c \ \forall \ \mathcal{A}$. However, we have found the following heuristic useful for computational purposes; we consider the set $\mathcal{A}$ to be intervals of the form, $\mathcal{A} = [a, b)$. Further we approximate χ as, $\chi = \sum_j \alpha_j \delta_{\mathcal{A}_j}$ where δ is the Dirac measure and $\mathcal{A}_j = [a_j, b_j)$. Thus, we can rewrite (7) as the following convex optimization problem,

$$\hat{\psi}(X) = \arg\max_{\{\alpha_j\}} \left[\int_0^\infty 1 - \exp\left(-\lambda A \int_t^\infty \sum_j \alpha_j \mathbf{1}_{\mathcal{A}_j} \left(1 - \tilde{G}(x)\right) f_X(x) dx \right) dt \right] \tag{13}$$

$$\text{subject to: } \begin{cases} \lambda\pi(R_2^2 - R_1^2) \int_0^\infty \sum_j \alpha_j \mathbf{1}_{\mathcal{A}_j} f_X(x) \ dx = \mu_0 \\ \displaystyle\sum_j \alpha_j = 1, \ 0 < \alpha_j \leq 1 \quad \forall j. \end{cases}$$

This allows us to express the optimum node activation function as

$$\hat{\psi}(x) \ = \ \sum_j \alpha_j \mathbf{1}_{\mathcal{A}_j}(x), \tag{14}$$

where $\mathcal{A}_j = [a_j, b_j)$ and the α_j's can be obtained by solving (13) numerically.

B. Sub-optimum NA-BOLD Strategy : (NA-BOLD(S))

We consider the transformation of the probabilistic problem (7) into an analytical problem, the solution of which is a sub-optimum solution to (7). Instead of a random number of nodes activating, suppose that a fixed number of nodes, N, activate to listen to a transmission. We derive the optimum density of link distances for N active nodes and then obtain a node activation probability $\psi(x)$ that achieves this density and for which $\mathbb{E}[K] = \mu_0$ holds. One nice feature of this approach is that the difficult work of finding the optimum density of link distance for N active nodes can be found offline, and the activation function that achieves this distance can be easily computed on-line based on estimates of the actual distribution of nodes.

Since we assume that a fixed number of nodes are turned on, we can redefine V_i from (1) as,

$$V_i = \begin{cases} X_i, & X_i < Y_i \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

The $\{V_i\}$ are assumed to be i.i.d. with distribution function

$$F_V(t) \;=\; P(V_i \leq t,\ X_i < Y_i) + P(V_i \leq t,\ X_i \geq Y_i)$$

After some simplifications, $F_V(t)$ may be obtained as

$$F_V(t) \;=\; 1 - \int_t^\infty \widetilde{G}(u) dF(u), \tag{16}$$

where F is the distribution function of the link distance X_i. Then,

$$\mathbb{E}\left[V_{max}\right] \;=\; \int_0^\infty 1 - \left[1 - \int_t^\infty \widetilde{G}(u) dF(u)\right]^N dt \tag{17}$$

Then we wish to find the F that maximizes (17).

Proposition 1. *A maximizing distribution, $\hat{F}$ exists and is unique in the set of all distribution functions F.*

Proof: The convex set of probability measures on $[0, \infty]$ is compact in the topology of weak convergence. (Note that ∞ is included). From (17), we see that the map, $dF \mapsto \mathbb{E}\left[V_{max}\right]$ is strictly concave if $N > 1$. It is not difficult to show that it is continuous in the weak topology. Therefore, there is a unique distribution F for which $\mathbb{E}\left[V_{max}\right]$ is maximized. ■

To find an expression for F, we need to investigate some of its properties. Let F_1 be another distribution function that maximizes (17). Then, for each $\nu,$ with $0 < \nu < 1$, we have,

$$\int_0^\infty 1 - \left[1 - \int_t^\infty \widetilde{G}(u)\Big(\nu dF_1(u) + (1-\nu)\, dF(u)\Big)\right]^N dt \leq \int_0^\infty 1 - \left[1 - \int_t^\infty \widetilde{G}(u) dF(u)\right]^N dt. \tag{18}$$

I.e., the function of ν on the LHS of (18) is maximized when $\nu = 0$. Consequently, its derivative at $\nu = 0$ is less than or equal to zero. In other words,

$$N \int_0^\infty \left\{ \left[1 - \int_t^\infty \widetilde{G}(u) dF(u)\right]^{N-1} \int_t^\infty \widetilde{G}(u) \Big(dF_1\left(u\right) - dF\left(u\right)\Big) \right\} dt \leq 0.$$

So for all distributions F_1,

$$\int_0^\infty \left[\left[1-\int_t^\infty \widetilde{G}(u)dF(u)\right]^{N-1}\int_t^\infty \widetilde{G}(u)dF_1(u)\right]dt$$
$$\leq \int_0^\infty \left[\left[1-\int_t^\infty \widetilde{G}(u)dF(u)\right]^{N-1}\int_t^\infty \widetilde{G}(u)dF(u)\right]dt. \quad (19)$$

If $F_1(u) = \mathbf{1}_{[s,\infty]}(u)$ is the distribution function of a point mass at s, then (19) implies,

$$\int_0^s \left[1-\int_t^\infty \widetilde{G}(u)dF(u)\right]^{N-1}\widetilde{G}(s)dt \leq \int_0^\infty \left[\left[1-\int_t^\infty \widetilde{G}(u)dF(u)\right]^{N-1}\int_t^\infty \widetilde{G}(u)dF(u)\right]dt. \quad (20)$$

We can rewrite the RHS of (20) as

$$\begin{aligned}
&\int_0^\infty \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1}\left[\int_0^\infty \mathbf{1}_{[t,\infty]}(u)\,\widetilde{G}(u)dF(u)\right]dt \\
=\ &\int_0^\infty \widetilde{G}(u)dF(u)\int_0^\infty \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1}\mathbf{1}_{[t,\infty]}(u)dt \\
=\ &\int_0^\infty \widetilde{G}(u)\int_0^u \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1} dt\ dF(u). \quad (21)
\end{aligned}$$

Let us define the set $\mathcal{A}$ as,

$$\mathcal{A} = \left\{s : \widetilde{G}(s)\int_0^s \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1} dt = \max_u \left\{\widetilde{G}(u)\int_0^u \left[1-\int_t^\infty \widetilde{G}(z)\,dF(z)\right]^{N-1} dt\right\}\right\}.$$

Then from (20) and (21), dF is concentrated on $\mathcal{A}$. Let us define the function $\sigma(s)$ as,

$$\sigma(s) \;=\; \widetilde{G}(s)\int_0^s \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1} dt. \quad (22)$$

Clearly, $\sigma(s) \leq s\widetilde{G}(s)$, so $\lim_{s\to 0}\sigma(s) = 0$. Also, $s\widetilde{G}(s) \leq \mathbb{E}[Y : Y > s]$, which tends to zero as $s \to \infty$ because $\mathbb{E}[Y] < \infty$. Hence, we have

$$\lim_{s\to\infty}\sigma(s) = 0 \text{ and } \lim_{s\to 0}\sigma(s) = 0.$$

Thus, there is a finite interval $[\alpha, \beta]$ with $\alpha \neq 0$ such that $\mathcal{A} \in [\alpha, \beta]$. Let $C^{N-1} = \max_s\ \sigma(s)$. Then clearly, $\mathcal{A} = \left\{s : \sigma(s) = C^{N-1}\right\}$. So for each $s \in \mathcal{A}$,

$$\int_0^s \left[1-\int_t^\infty \widetilde{G}(u)\,dF(u)\right]^{N-1} dt = \frac{C^{N-1}}{\widetilde{G}(s)} \quad (23)$$

Note that in (23), both F and C are unknown. Let us assume for the moment that $\mathcal{A}$ is an interval $[\alpha, \beta]$. Differentiating (23) leads to

$$1 - \int_s^\beta \widetilde{G}(u) dF(u) = C \left[-\widetilde{G}'(s) \Big(\widetilde{G}(s) \Big)^{-2} \right]^{\frac{1}{N-1}} \tag{24}$$

for every $\alpha \leq s \leq \beta$. Let us now define

$$\mathcal{K}(s) = \left\{ -\widetilde{G}'(s) / \left[\widetilde{G}(s) \right]^2 \right\}^{\frac{1}{N-1}}. \tag{25}$$

Using integration by parts, we can rewrite (24) as

$$1 + \int_s^\infty g'(u) F(u) du + F(s) \widetilde{G}(s) = C \mathcal{K}(s) \tag{26}$$

To formalize our approach further, we impose the following (mild) conditions on $\widetilde{G}$.

Hypothesis 1. *$\widetilde{G}$ is twice continually differentiable and bounded away from zero on compact sets.*

Applying this hypothesis, (26) shows that F is differentiable, so that $dF(u) = f(u)du$. Using this in (24) and differentiating,

$$f(s) \;=\; C \frac{\mathcal{K}'(s)}{\widetilde{G}(s)}, \quad \alpha \leq s \leq \beta \tag{27}$$

Note that we have still not identified C, α and β in (27). Substituting (27) into (24),

$$1 - C \int_s^\beta \mathcal{K}'(u) du = C \mathcal{K}(s) \quad \Rightarrow C \mathcal{K}(\beta) = 1. \tag{28}$$

We also have $\int_\alpha^\beta dF(u) = 1$, which implies that

$$C \int_\alpha^\beta \frac{\mathcal{K}'(s)}{\widetilde{G}(s)} ds = 1. \tag{29}$$

Recall that we have assumed $\mathcal{A} = [\alpha, \beta]$ before. Thus, for $\alpha \leq s \leq \beta$, we can rewrite (23) as,

$$\int_0^s \left[1 - \int_{t \vee \alpha}^\beta \widetilde{G}(u) f(u) du \right]^{N-1} dt \;=\; \frac{C^{N-1}}{\widetilde{G}(s)}. \tag{30}$$

Using the definition of $\mathcal{K}(s)$ in (30) and then applying (28), we have for $\alpha \leq s \leq \beta$,

$$\alpha \left[1 - C\mathcal{K}(\beta) + C\mathcal{K}(\alpha) \right]^{N-1} + \int_\alpha^s \left[1 - C\mathcal{K}(\beta) + C\mathcal{K}(t) \right]^{N-1} dt \;=\; \frac{C^{N-1}}{\widetilde{G}(s)}. \tag{31}$$

Applying (28) to (31), we obtain,

$$\alpha\left[C\mathcal{K}(\alpha)\right]^{N-1}+\int_{\alpha}^{s}C^{N-1}\mathcal{K}(t)^{N-1}dt=\frac{C^{N-1}}{\widetilde{G}(s)}. \tag{32}$$

Using the definition of $\mathcal{K}(s)$ in (32) and simplifying, we have for $\alpha \leq s \leq \beta$,

$$\alpha\left[C\mathcal{K}(\alpha)\right]^{N-1}+C^{N-1}\int_{\alpha}^{s}\frac{d}{du}\left(\frac{1}{\widetilde{G}(u)}\right)du=\frac{C^{N-1}}{\widetilde{G}(s)}.$$

Some algebra yields $\alpha\left[\mathcal{K}(\alpha)\right]=\widetilde{G}^{-1}(\alpha)$, which implies

$$\left(-\widetilde{G}'(\alpha)\right)=\widetilde{G}\left(\alpha\right) \tag{33}$$

The following lemma provides sufficient conditions on $\widetilde{G}$ for α,β and C, to be unique.

Lemma 1. *Suppose* $\widetilde{G}(s)=\exp\left(-\varphi(s)\right)$, *where* $\varphi(0)=0,\ \varphi>0,\ \varphi'$ *is strictly increasing, continuous and* $\varphi'(\infty)>0$. *Then* (28), (29) *and* (33) *determine* α,β,C *uniquely.*

See Appendix for the proof. It remains to prove that α,β,C and f (given by (27)) is indeed the solution to our problem. For that purpose, it is sufficient to prove the following theorem.

Theorem 2. *Let* α,β,C *and* f *be defined as above. Then* (23) *holds and* $\sigma(s)\leq C^{N-1}$, *where* $\sigma(s)$ *has been defined in* (22).

See Appendix for the proof.

The optimum density for a fixed number of nodes turning on can be used to find a suboptimal node activation function $\psi(x)$ for the probabilistic node activation problem (7). $\psi(x)$ is chosen so that the conditional distribution of the link distance to receiver i, given that receiver i is active, achieves the desired distribution of node distances and the constraint on the expected number of nodes that activates is met with equality. Thus, $F_{X_i}(x|\ \zeta_i=1)=\hat{F}(x)$,

$$\begin{aligned}\frac{P\left(X_i\leq x\cap\ \zeta_i=1\right)}{P\left(\zeta_i=1\right)} &= \hat{F}(x)\\ \frac{\int_0^x\psi(u)f_{X_i}\left(u\right)du}{\int_0^\infty\psi(u)f_{X_i}\left(u\right)du} &= \int_0^x\hat{f}(t)dt.\end{aligned}$$

Thus,

$$\psi(x)=\frac{\hat{f}_{X_i}(x)}{f_{X_i}(x)}\int_0^\infty\psi(u)f_{X_i}\left(u\right)du. \tag{34}$$

is the unique solution (except on a set of measure zero, and up to a scaling factor). Let $\psi(x) = M^{-1}\hat{f}(x)/f_{X_i}(x)$, where

$$M = \lambda\pi\left(R_2^2 - R_1^2\right)/\mu_0, \text{ and } M \geq 1 \tag{35}$$

to satisfy the constraints in (7). Since $\psi(x)$ is a conditional probability $\psi(x) \leq 1$ imposes a lower bound on λ. If we denote $\widetilde{\lambda}$ as the minimum density of nodes needed to be deployed for which the expected number of nodes that turn on is μ_0, then

$$\widetilde{\lambda} = \frac{\mu_0}{\pi\left(R_2^2 - R_1^2\right)} \max_{R_1 < x \leq R_2} \left\{\hat{f}(x)(f_{X_i}(x))^{-1}\right\} \tag{36}$$

IV. Outage Probability for geographic transmission schemes

Outage occurs if no active receiver recovers the message, i.e., $V_{max} = 0$. The conditions that can lead to outage are 1) no nodes are available in the network to receive the transmission ($\aleph = 0$), 2) nodes are present physically but every node is powered off, or 3) the received SNR falls below the threshold at every active node, ($\gamma_i < \rho \ \forall i$). Using (3), the outage probability p_{out} is $p_{out} = P(V_{max} \equiv 0) = \exp\left\{\lambda A\left[F_{V_i}(0) - 1\right]\right\}$.

V. Rayleigh channel model

For Rayleigh fading $\{H_i\}$ are i.i.d. exponential random variables with mean 1. Thus $\tilde{G}(y) = \exp\left(-\rho y^n\right)\mathbf{1}_{[y>0]}(y)$, which satisfies the conditions of Lemma 1. Using(28), (29), and (33), the optimum density of link distances, $\hat{f}(x)$ on $R_1 < x \leq R_2$ is

$$\begin{aligned} \hat{f}(x) &= \frac{1}{(N-1)R_2^{\frac{n-1}{N-1}}\exp\left(\rho\frac{R_2^n}{N-1}\right)} x^{\frac{n-1}{N-1}}\exp\left(\rho\frac{N}{N-1}x^n\right)\left[\frac{n-1}{x} + n\rho x^{n-1}\right], \text{ and} \\ \psi(x) &= \frac{1}{M}\frac{(R_2^2 - R_1^2)}{2(N-1)R_2^{\frac{n-1}{N-1}}\exp\left(\rho\frac{R_2^n}{N-1}\right)} x^{\frac{n-N}{N-1}}\exp\left(\rho\frac{N}{N-1}x^n\right)\left[\frac{n-1}{x} + n\rho x^{n-1}\right]. \end{aligned} \tag{37}$$

Here, $R_1 \equiv \alpha = \sqrt[n]{(n\rho)^{-1}}$, $R_2 \equiv \beta$ is found numerically by solving the integral equation

$$\int_{R_1}^{R_2} \hat{f}(x)dx = 1,$$

and M is given by (35).

The distribution function $\hat{F}(x)$ for the NA-BOLD(S) scheme is necessary to evaluate the outage probability analytically and is given by

$$\hat{F}(x) = c_1 \frac{n-1}{n} g\left(x;\omega;\frac{n-1}{n(N-1)};\frac{Nn-1}{n(N-1)}\right) + \rho c_1 g\left(x;\omega;\frac{Nn-1}{n(N-1)};\frac{2Nn-n-1}{n(N-1)}\right),$$

where

$$\begin{aligned} g(x;\omega;a,b) &= B(1,a)\ x^a\ {}_1F_1(a,b,\omega x^n) - B(1,b)\ R_1^a\ {}_1F_1(a,b,\omega R_1^n) \\ c_1 &= \left((N-1) R_2^{\frac{n-1}{N-1}} \exp\left(\rho \frac{R_2^n}{N-1}\right)\right), \text{ and} \\ \omega &= \rho N (N-1)^{-1}. \end{aligned}$$

Here, $B(x,y)$ is the beta function, defined as,

$$B(x,y) = \int_0^1 u^{x-1}(1-u)^{y-1} du$$

and ${}_1F_1(a;b;z)$ is the confluent hypergeometric function of the first kind, defined as,

$${}_1F_1(a;b;z) = \frac{\Gamma(b)}{\Gamma(b-a)\Gamma(a)} \int_0^1 \exp(zt)\ t^{a-1}(1-t)^{b-a-1} \quad dt$$

The outage probability is then

$$p_{out} = \exp\left(-\mu_0\left(\frac{n-1}{n} c_1 g\left(x;\frac{\omega}{N};\frac{Nn-1}{n(N-1)}\right) + \rho c_1 g\left(x;\frac{\omega}{N};\frac{Nn-1}{n(N-1)};\frac{2Nn-n-1}{n(N-1)}\right)\right)\right).$$

VI. Geographic Transmission with Constant Node Activation Probabilities

For the purpose of comparing our NA-BOLD approach with conventional schemes that employ fixed node activation techniques, we consider the following strategies. These schemes have the same objective and constraints as NA-BOLD schemes, but have an activation function that is constant out to a fixed radius from the transmitter (and zero beyond that), as shown in Fig.3. Consider first a simple strategy in which *all* nodes inside a sector around the transmitter up to a fixed distance are awake to receive the transmission; i.e. $P(\zeta_i = 1) = p \equiv 1\ \forall i$ as shown in Fig.2. We refer to this strategy as the DISC strategy.

A more sophisticated strategy is to turn on nodes with a fixed probability p out to a larger radius than the DISC scheme, where this radius is obtained to satisfy the constraint that the expected number of nodes that activate is μ_0. Letting $\psi(x) = p, 0 < x \leq R_d$, with $R_1 = 0, R_2 = R_d$ in (7), we obtain,

$$\hat{p} = \arg\max_p \left[\int_0^\infty 1 - \exp\left(-\lambda A p \int_t^\infty \left(1 - \tilde{G}(x)\right) f_X(x) dx \right) dt \right] \tag{38}$$

$$\text{subject to: } \begin{cases} \lambda \pi R_d^2 p = \mu_0 \\ 0 \leq p \leq 1. \end{cases}$$

We refer to this scheme as the Optimized-DISC strategy (DISCO). For the Rayleigh fading channel, the objective function is

$$\hat{p} = \arg\max_p \left[\int_0^{R_d} 1 - \exp\left(\frac{-2\pi\lambda}{n \sqrt[n]{\rho}} p \left(\gamma\left(\frac{2}{n}, \rho R_d^n\right) - \gamma\left(\frac{2}{n}, \rho t^n\right) \right) \right) dt \right].$$

The outage probability for this scheme is

$$p_{out} = \exp\left(-\lambda \pi R_d^2 \frac{p}{R_d^2} \left(\frac{1}{\rho}\right)^{\frac{2}{n}} \frac{2}{n} \gamma\left(\frac{2}{n}, \rho R_2^n\right) \right).$$

VII. Results

In this section, we present the performance of the DISC, DISC-O, and NA-BOLD schemes. All results presented are for a Rayleigh fading channel with path-loss exponent $n = 4$. The receive SNR threshold is $\rho = 1$, and the node density is $\lambda = 10$ nodes per unit sector. The NA-BOLD approach turns on nodes located inside a sector annulus, as shown in Fig. 1. The expected number of nodes that turn on is μ_0. The NA-BOLD(S) scheme is based on $N = \lceil \mu_0 \rceil$, which is found to offer good performance ($N = \lceil \mu_0 - 1 \rceil$, which maximizes the Poisson pmf offers nearly the same performance [29]). For the NA-BOLD(O) scheme, we obtained the optimum node activation function using a piece-wise linear approximation with the help of the α_j's numerically obtained by solving (13). The node activation probability for the sub-optimum NA-BOLD(S) scheme is given in (37).

The node activation functions for the various schemes are shown as a function of distance from the transmitter in Fig. 4 for $\mu_0 = 3$. For the NA-BOLD(S) scheme, $R_1 = 0.7071$ for any μ_0, and we numerically found $R_2 = 0.8825$ for $\mu_0 = 3$. The corresponding values for the optimum scheme, NA-BOLD(O) are 0.63 and 0.84 respectively.

The expected values of the maximum transmission distance to the farthest receiver that successfully received the transmission are shown in Fig. 5. The sub-optimum NA-BOLD(S) scheme show almost identical performance to the optimal NA-BOLD(O) scheme. We provide Table IX in order to evaluate how close this performance is, relative to the optimal scheme. We find that the sub-optimal scheme performs within 1% of the optimal scheme for $2 \leq \mu_0 \leq 10$. For this range of μ_0, the NA-BOLD schemes significantly outperform the conventional schemes that employ fixed node activation. In particular, the NA-BOLD approach is better than the DISC scheme by more than 100%. The DISCO scheme is within 9.5% to 5.5% of NA-BOLD for $\mu_0 = 3$ to 10. In a practical MPRN, the number of nodes that turn on in is typically less than 6.0 [24] and hence NA-BOLD schemes might be better suited for such scenarios.

The outage probabilities are plotted in Fig. 6. Since outage is less likely to occur when more nodes are present, the curves are decreasing functions of μ_0. The DISC schemes have relatively lower outage probabilities as they turn on more nodes that are located closer to the transmitter. The NA-BOLD(S) shows a slight degradation in outage performance with respect to NA-BOLD(O). However, this degradation is nominal – when the number of active nodes is as high as 10, the outage probabilities are 4.5% and 3.6%, for the NA-BOLD(O) and the NA-BOLD(S) schemes respectively.

VIII. Conclusions

In this paper, we propose node activation schemes that use distance to increase the expected transmission distance for geographic transmissions over fading channels. Optimal and suboptimal node activation schemes are developed and compared. Node activation based on link-distance offers significant performance schemes over conventional approaches that activate nodes with equal probabilities. The suboptimal scheme that gives a node-activation function in closed form, yields performance close to the optimal scheme.

IX. APPENDIX

Proof of Lemma 1: The uniqueness of α and C are trivial if there is a unique β. From (28) and (29),

$$\int_{\alpha}^{\beta} \frac{\mathcal{K}'(s)}{\widetilde{G}(s)} ds = \mathcal{K}(\beta). \tag{39}$$

For a given α, (39) has a unique solution. From (25),

$$\begin{aligned} \mathcal{K}(s) &= \left[\frac{d}{ds}\left(\frac{1}{\widetilde{G}(s)}\right)\right]^{\frac{1}{N-1}} \\ &= \left[\varphi'\left(s\right)\exp\left(\varphi\left(s\right)\right)\right]^{\frac{1}{N-1}} \end{aligned}$$

Since φ' and φ are increasing, $\mathcal{K}$ is strictly increasing, so $\mathcal{K}' > 0$. Since $\varphi'(\infty) > 0, \varphi(\infty) = \infty$, and $\mathcal{K}(\infty) = \infty$. By assumption, $\dfrac{1}{\widetilde{G}(s)}$ is increasing and tends to infinity. Consider the funcion,

$$\tau(s) = \frac{1}{\mathcal{K}(s)} \int_{\alpha}^{s} \frac{\mathcal{K}'(u)}{\widetilde{G}(u)} du, \quad s \geq \alpha.$$

Then, $\tau(\alpha) = 0$ and for any s and $t,\ s > t$, we have,

$$\begin{aligned} \tau(s) &= \frac{1}{\mathcal{K}(s)} \int_{\alpha}^{t} \frac{\mathcal{K}'(u)}{\widetilde{G}(u)} du + \frac{1}{\mathcal{K}(s)} \int_{t}^{s} \frac{\mathcal{K}'(u)}{\widetilde{G}(u)} du \\ &> \frac{1}{\mathcal{K}(s)} \int_{\alpha}^{t} \frac{\mathcal{K}'(u)}{\widetilde{G}(u)} du + \frac{1}{\widetilde{G}(t)\mathcal{K}(s)} \int_{t}^{s} \mathcal{K}'(u) du \\ &= \frac{1}{\mathcal{K}(s)} \int_{\alpha}^{t} \frac{\mathcal{K}'(u)}{\widetilde{G}(u)} du + \frac{1}{\widetilde{G}(t)\mathcal{K}(s)} \left[\mathcal{K}(s) - \mathcal{K}(t)\right]. \end{aligned} \tag{40}$$

Since $\mathcal{K}(\infty) = \infty$, letting $s \to \infty$ in (39) we see $\tau(\infty) > \dfrac{1}{\widetilde{G}(t)}$ for any t, i.e. $\tau(\infty) = \infty$ and $\tau(s)$ is strictly increasing in s. Since $\tau(\alpha) = 0$, there is a unique β such that $\tau(\beta) = 1$. This proves that a unique β satisfies (29). ∎

Proof of Theorem 2: Using (27) and (28) we find,

$$\int_0^s \left(1-\int_{t\vee\alpha}^{\beta} \widetilde{G}(u)f(u)du\right)^{N-1} dt = \begin{cases} C^{N-1}s\left(-\widetilde{G}'(\alpha)\Big(\widetilde{G}(\alpha)\Big)^{-2}\right), & 0 \le s \le \alpha \\ C^{N-1}\alpha\left(-\widetilde{G}'(\alpha)\Big(\widetilde{G}(\alpha)\Big)^{-2}\right) & \\ +C^{N-1}\left(\Big[\widetilde{G}(s)\Big]^{-1}-\Big[\widetilde{G}(\alpha)\Big]^{-1}\right), & \alpha \le s \le \beta \\ C^{N-1}\Big[\widetilde{G}(\beta)\Big]^{-1}+s-\beta, & s > \beta. \end{cases} \tag{41}$$

Applying (23) to (41), note that this is equivalent to proving

$$\frac{1}{\widetilde{G}(s)} \ge \begin{cases} s\left(-\widetilde{G}'(\alpha)\Big(\widetilde{G}(\alpha)\Big)^{-2}\right), & 0 \le s \le \alpha \\ \alpha\left(-\widetilde{G}'(\alpha)\Big(\widetilde{G}(\alpha)\Big)^{-2}\right)+\left(\Big[\widetilde{G}(s)\Big]^{-1}-\Big[\widetilde{G}(\alpha)\Big]^{-1}\right), & \alpha \le s \le \beta \\ \Big[\widetilde{G}(\beta)\Big]^{-1}+s-\beta, & s > \beta. \end{cases} \tag{42}$$

We consider the three cases separately as follows.

<u>Case 1, $0 \le s \le \alpha$:</u> We need to prove that $s - \widetilde{G}'(\alpha)\left(\widetilde{G}(\alpha)\right)^{-2} \le \left(\widetilde{G}(s)\right)^{-1}$ Using (33), it follows that we need to show,

$$\frac{sg(s)}{\alpha\widetilde{G}(\alpha)} \le 1. \tag{43}$$

$$\text{Notice that } \frac{d}{ds}\Big[s\widetilde{G}(s)\Big] = \widetilde{G}(s)+s\widetilde{G}'(s) = \widetilde{G}(s)s\left[\frac{1}{s}+\frac{\widetilde{G}'(s)}{\widetilde{G}(s)}\right] > 0, \quad 0 \le s \le \alpha$$

We know from (33) that α^{-1} is a unique solution of $\alpha^{-1}+\widetilde{G}'(\alpha)/\widetilde{G}(\alpha) = 0$. Since $s^{-1} + \widetilde{G}'(s)/\widetilde{G}(s) \to \infty$ as $s \to 0$, it follows that, $s^{-1}+\widetilde{G}'(s)/\widetilde{G}(s)$ is greater than or equal to zero if $0 \le s \le \alpha$ and less than 0 if $s > \alpha$. Thus, $s\widetilde{G}(s)$ is increasing in $0 \le s \le \alpha$, implying (43). Hence, the case $0 \le s \le \alpha$ is proved.

<u>Case 2, $\alpha < s \le \beta$:</u> Using (33) we see that the RHS of (42) in this case reduces to $C^{N-1}/\widetilde{G}(s)$, as required.

<u>Case 3, $s > \beta$:</u> We need to prove that $C^{N-1}/\widetilde{G}(\beta)+s-\beta \le C^{N-1}/\widetilde{G}(s)$ or

$$C^{N-1}\left[\frac{1}{\widetilde{G}(\beta)}-\frac{1}{\widetilde{G}(s)}\right]+s-\beta \le 0. \tag{44}$$

Differentiating the LHS of (44) w.r.t. s, we have, $C^{N-1}\widetilde{G}'(s)\left[\widetilde{G}(s)\right]^{-2}+1$, which we can rewrite as $1-C^{N-1}\left(-\widetilde{G}'(s)\right)\left[\widetilde{G}(s)\right]^{-2}$. Substituting the value of $\mathcal{K}(s)$ from (25) into this expression, we obtain, $1-\left[C\mathcal{K}(s)\right]^{N-1}$. Since $\mathcal{K}'(s)>0,\ \mathcal{K}(s)$ is strictly increasing and using (28), we have, $1-\left[C\mathcal{K}(s)\right]^{N-1}\leq 0, \quad$ for $s\geq\beta$. Thus the derivative of the function in the LHS of (44) is ≤ 0, i.e. this function is decreasing and it vanishes at $s=\beta$. Hence the case $s>\beta$ is proved.

■

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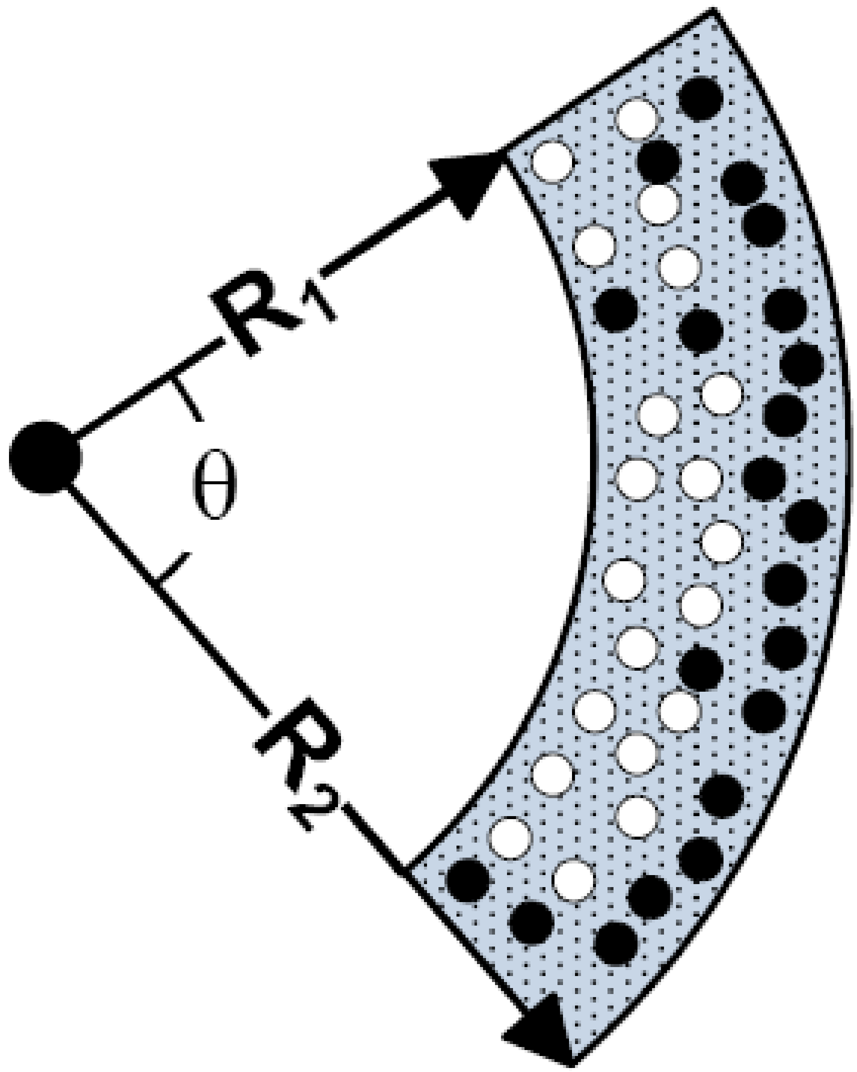

Fig. 1. Geographic Transmission region : annulus of a sector with inner radius R_1, outer radius R_2 with transmitter at center.

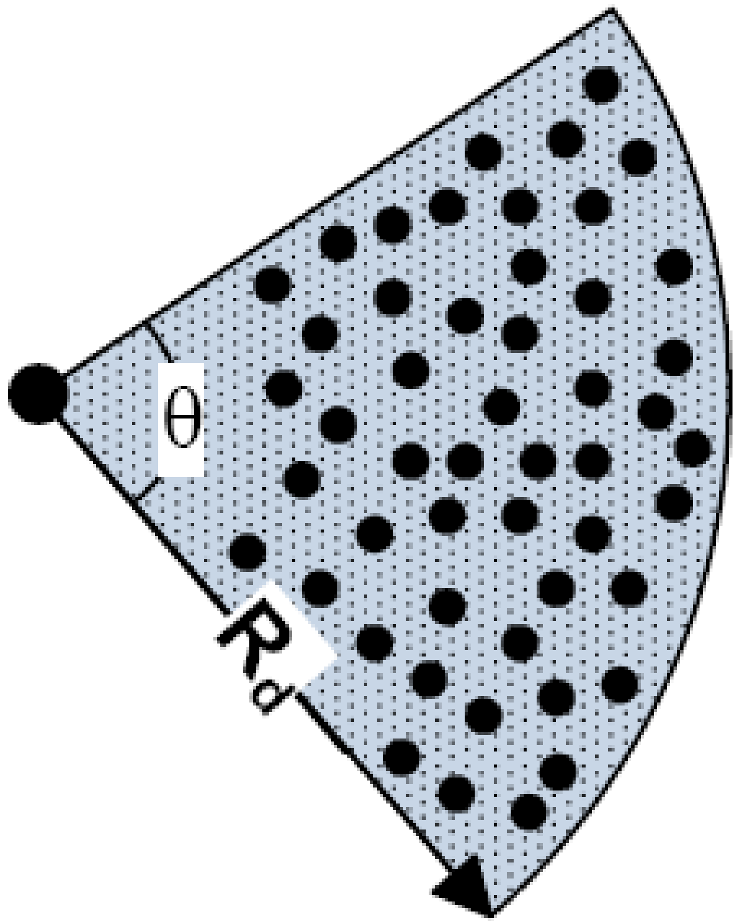

Fig. 2. DISC strategy : all nodes are activated inside a sector with radius radius R_d.

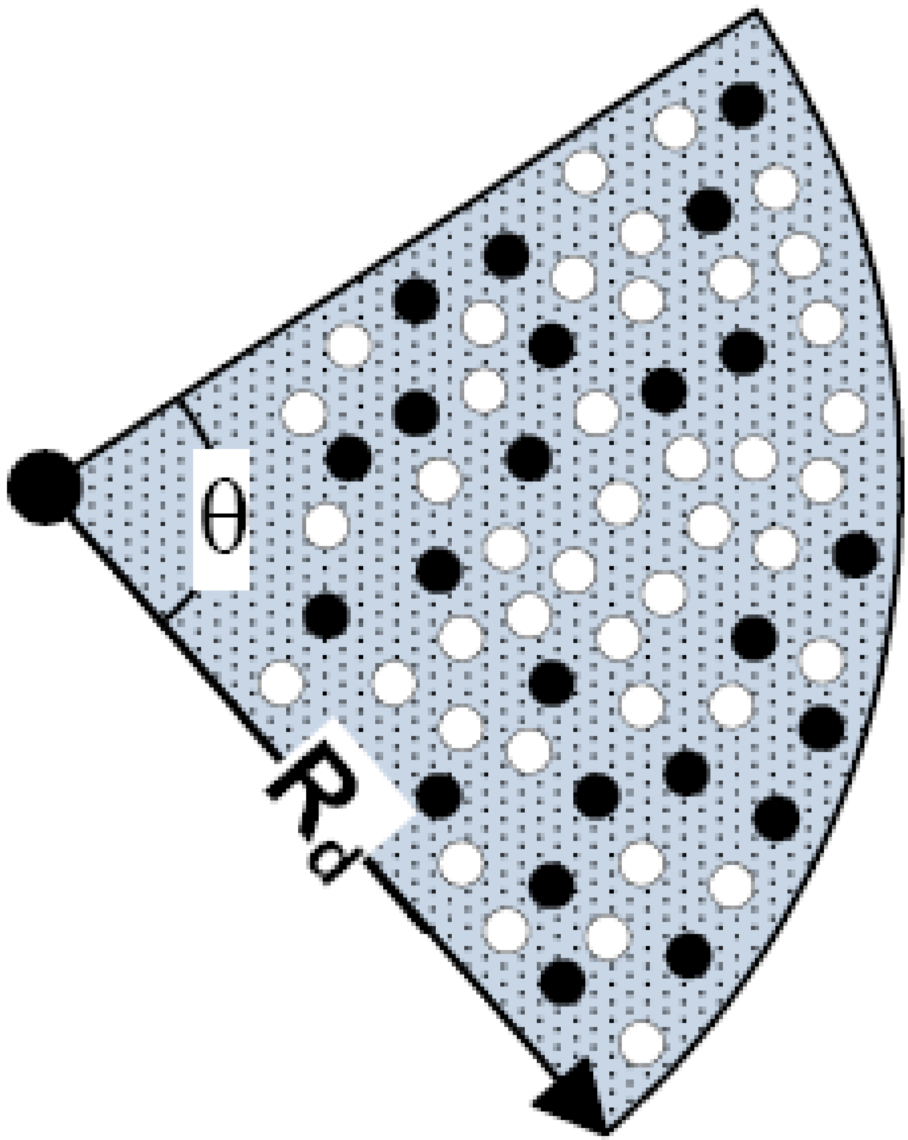

Fig. 3. DISCO strategy : nodes are activated with fixed probability p inside a sector with radius R_d.

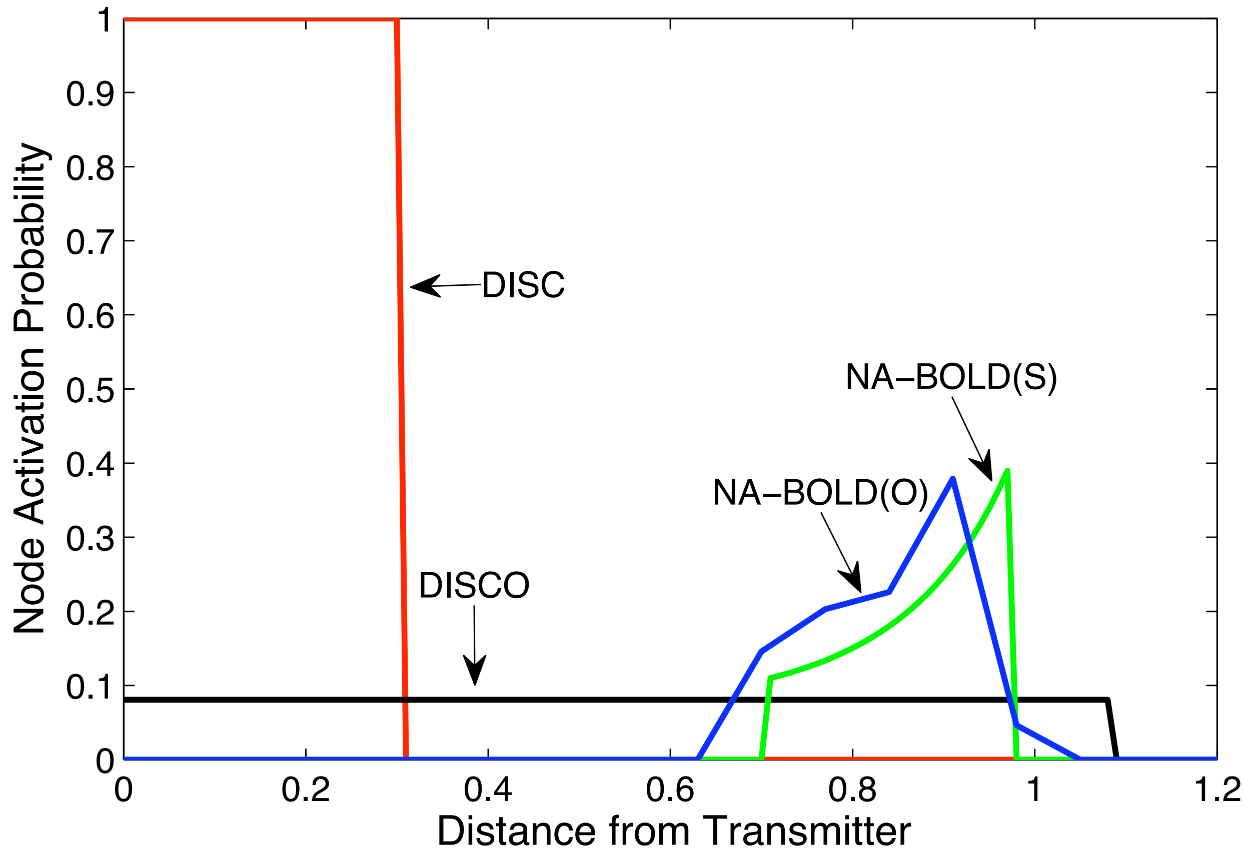

Fig. 4. Node activation probability for $\lambda = 10$ nodes per unit sector, with expected number of active nodes $\mu_0 = 3$.

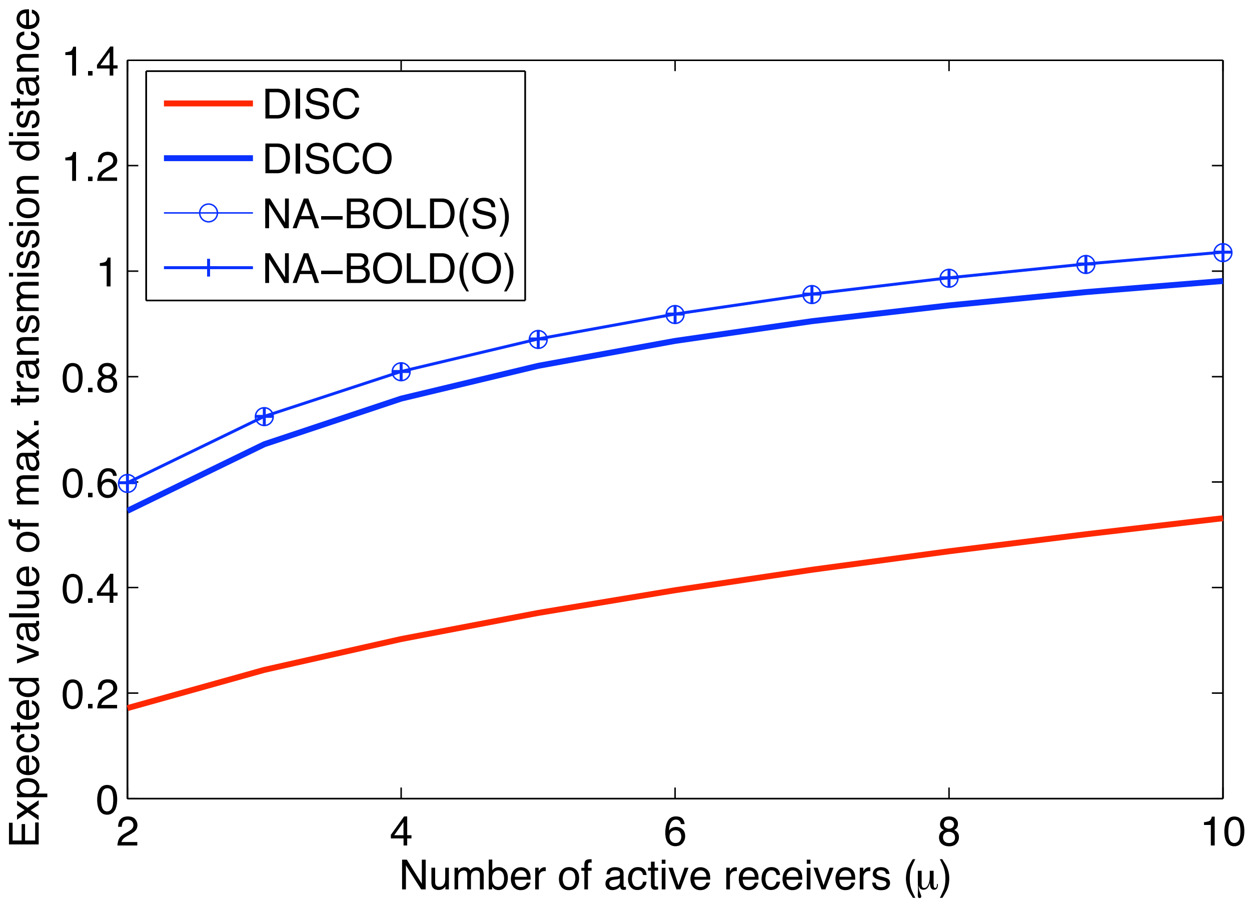

Fig. 5. Expected value of the maximum transmission distance $\mathbb{E}[V_{max}]$ vs. the expected number of active nodes μ_0.

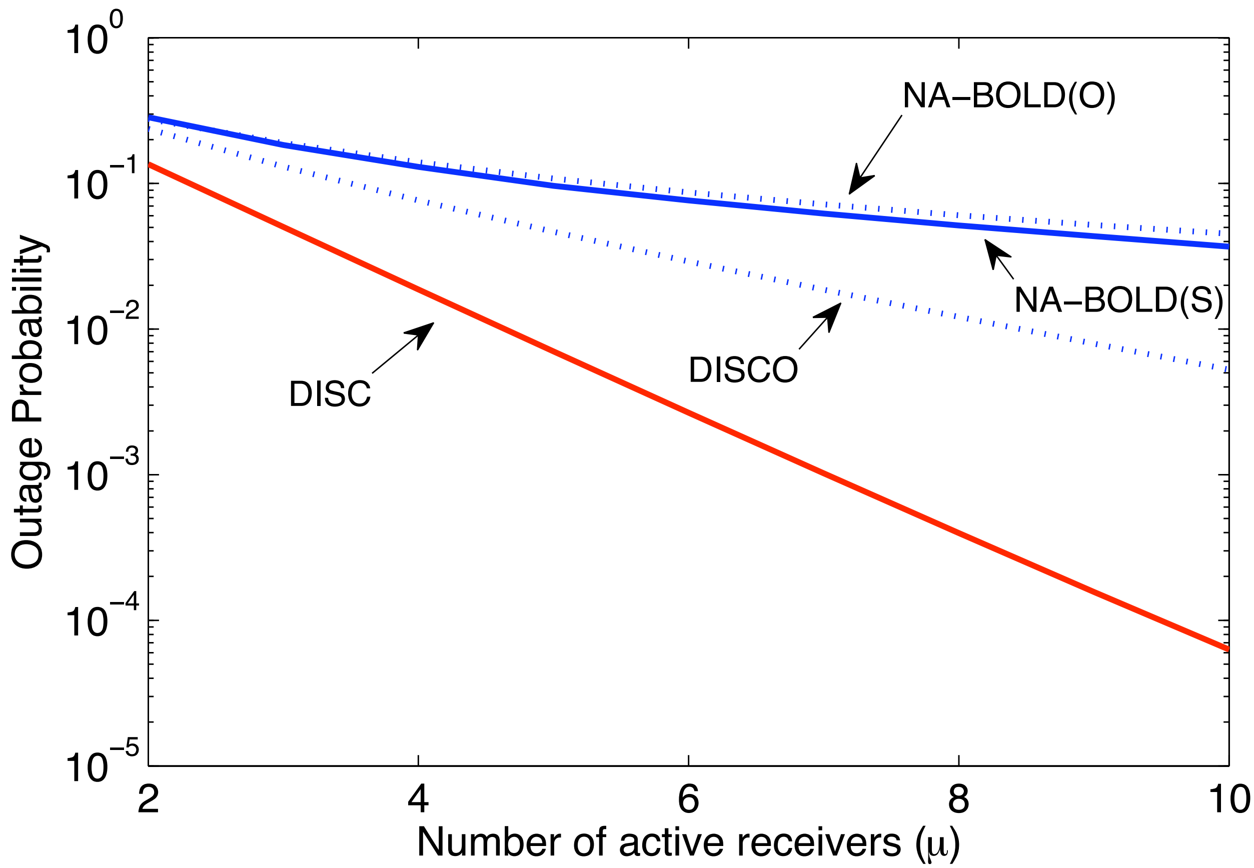

Fig. 6. Outage probabilities for the NA-BOLD and conventional schemes versus the expected number of active nodes μ_0.

TABLE I

EXPECTED VALUE OF MAXIMUM TRANSMISSION DISTANCE FOR VARIOUS NODE ACTIVATION SCHEMES

	Constant node activation approach		NA-BOLD Approach	
μ	DISC	DISCO	NA-BOLD(S)	NA-BOLD(O)
2	0.1714	0.5455	0.5976	0.5989
3	0.2437	0.6718	0.7243	0.7247
4	0.3025	0.7580	0.8091	0.8097
5	0.3519	0.8201	0.8707	0.8713
6	0.3950	0.8677	0.9179	0.9186
7	0.4335	0.9049	0.9556	0.9565
8	0.4686	0.9351	0.9866	0.9875
9	0.5012	0.9602	1.0127	1.0135
10	0.5316	0.9814	1.0350	1.0356