Reducing Transmit Power and Extending Network Lifetime via User Cooperation in the Next Generation Wireless Multihop Networks

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Abstract: **In this paper, we introduce a new approach to the minimum energy routing (MER) for next generation (NG) multihop wireless networks. We remove the widely used assumption of deterministic, distance-based channel model is removed, and analyze the potentials of MER within the context of the realistic channel model, accounting for shadowing and fading. Rather than adopting the conventional unrealistic assumption of perfect power control in a distributed multihop environment, we propose to exploit inherent spatial diversity of mobile terminals (MT) in NG multihop networks and to combat fading using transmit diversity. We propose the cooperation among MTs, whereby couples of MTs cooperate with each other in order to transmit the signal using two MTs as two transmit antennas. We provide the analytical framework for the performance analysis of this scheme in terms of the feasibility and achievable transmit power reduction. Our simulation result indicate that significant gains can be achieved in terms of the reduction of total transmit power and extension of network lifetime. These gains are in the range of 20-100% for the total transmit power, and 25-90% for the network lifetime, depending on the desired error probability. We show that our analytical results provide excellent match with our simulation results. The messaging load generated by our scheme is moderate, and can be further optimized. Our approach opens the way to a new family of channel-aware routing schemes for multihop NG wireless networks in fading channels. It is particularly suitable for delivering multicast/geocast services in these networks.**

Index Terms: **Power combining, minimum energy routing, transmit diversity, multihop networks, user cooperation.**

I. INTRODUCTION

Established along the lines of the evolutionary paths within the framework of the existing cellular and local area networks, the third generation (3G) wireless systems continue to partially ignore the essential characteristics of the user environment and services for which they have been designed. These essential characteristics can be represented by the *geography of users, geography of information and geography of signal transmission* [1]. In defining the architectural framework for wireless systems extending beyond 3G boundaries and directly addressing the specifics of the Wireless Internet environment, research community has been exploring the concept of adaptive network architectures [2], based on the concept of peer-to-peer communications. Peer-to-peer communications promote efficient use of electromagnetic resources by all transceivers and offer the flexibility of adaptation to the temporal behavior of traffic, mobility states of users, as well as channel conditions. In an adaptive network of mobile MTs, each mobile device enriches the web of communication by contributing to the MT density, improving the efficiency and resiliency of the network. Solutions that take advantage of the ability of peer-to-peer communications to adapt to the geography of users, information and signal transmission in a locally optimal manner include Infostations, multihop systems, ad hoc networks and hybrid systems.

Wireless channel impairments, such as attenuation, fading and interference, are highly dependent on the location of transmitters and receivers and the locations of the interfering transmitters and receivers. In adaptive networks, there is a potential of taking advantage of the geography of users and geography of signal transmissions so to optimize the transmissions and minimize the channel impairment effects. This mindset immediately points out to user cooperation as a way to promote the advantages of adaptive networks and peer-to-peer communications. In this work, we investigate the potentials of using transmit diversity as a way of implementing user cooperation, aiming at combating fading, reducing the total transmit power and interference in multihop ad hoc wireless networks.

In multihop wireless networks, each MT can serve as a transmitter and/or a receiver and MTs are usually scattered in a uniform fashion over the coverage area. Therefore, multihop networks inherently possess the potential to exploit diversity techniques. Information-theoretical aspects of the cooperative transmission between two MTs in multihop networks have been investigated in [3]. Here, the focus is on the power consumption aspect of the user cooperation. We propose to achieve transmit diversity by transmitting the same signal using two different MTs as two transmit antennas, and we name this type of user cooperation, aiming at minimizing total transmit power, *power combining*. We analyze the transmit power reduction achievable by use of power combining and lay down the theoretical framework for its optimization. Both our analysis and simulation study reveal that significant gains in terms of transmit power reduction are achievable using this approach.

Vast majority of papers treating the problem of energy-efficient multihop wireless networks simply neglect the fact that

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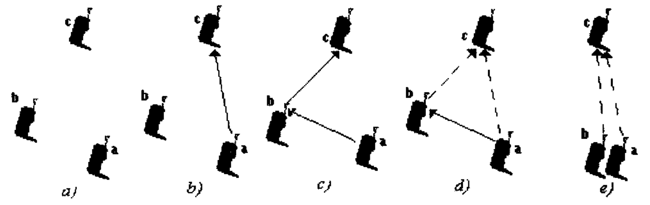


Fig. 1. Power combining triplets.

the wireless channel models are subject to impairments, such as fading and shadowing. They are restricted to the distance-based channel model [4]–[6], thus converting the problem greatly dependent on the nature of the wireless propagation channel into one dependent only on the geometry of the network. This approach is usually justified by the assumption of perfect power control. Two major problems associated with the assumption of power control have been recognized by the research community: the first is the required transmitter dynamic range to overcome fading; the second is the feedback information regarding channel conditions that needs to be made available by the receiver to the transmitter, which results in throughput degradation and considerable added complexity to both transmitter and the receiver. Another problem with the assumption of perfect power control is specific to the NG multihop networks: specifically, the research efforts that have focused on the convergence and the optimality of different power control schemes were restricted to the cellular, centralized, BS-oriented scenario [7], [8]. The stability, convergence and optimality of power control in the context of multihop NG networks, in which MTs are power-controlling each other in a distributed fashion, have not been thoroughly analyzed yet. We therefore remove the assumption of fast-rate power control in combating the fading. In our analysis, we remove the assumption of power control, and propose to combat fading by way of transmit diversity.

Next, we make use of the power combining concept to develop a new minimum energy routing (MER) algorithm in order to minimize the total network interference and extend network lifetime. Our power combining-based routing algorithm takes advantage of the geography of users and geography of signal transmission by creating a transmit diversity mesh along the route from the source to the destination, significantly reducing the total transmit power.

The paper is organized as follows: In Section II, we lay down the theory of power combining by defining performance measures and evaluating them analytically. In Section III, we implement a power combining-based MER algorithm in order to evaluate the benefits of power combining and we present the results. In Section IV, we summarize our contributions and give the conclusion.

II. POWER COMBINING CONCEPT, DEFINITION AND POWER GAIN ANALYSIS

Consider a simple, three-MT network, like the one shown in Fig. 1(a), where MT a, is transmitting a signal to MT c. Depending on the relative location of MT b with respect to MTs a and c, the minimum power route could either be the route $a \rightarrow c$ (Fig. 1(b)) or $a \rightarrow b \rightarrow c$ (Fig. 1(c)). Assume that the mean transmit powers are properly adjusted to overcome the path loss, shadowing and fading and provide equal error probability at all receivers. We investigate the power efficiency of the transmission scenario shown in Fig. 1(d), in which MT a first transmits the signal, destined to c, to b; in the consecutive time slot, both a and b re-transmit the same signal to c, emulating diversity transmission with two transmit antennas. When MTs a and b are very close to each other (Fig. 1(e)), they are equivalent to a single transmitter with two antennas. Based on the well known benefits of the diversity transmission with two transmit antennas with respect to the single transmitter case, this asymptotical case will clearly provide significant gains in terms of the total transmit power. We are interested in this gain for more realistic distances between MTs a and b. In the rest of this section, we will show that substantial gains are achievable for wide range of configurations of MTs a, b, and c.

A. Channel Model

We adopt the channel model accounting for path loss, shadowing and fading. We assume that the fading is frequency nonselective and slow. We assume that the delay spread of the channel is smaller than the inverse of the signal bandwidth. Recent field measurements [10] have shown that the delay spread of the of mobile-to-mobile channel profile ranges between 40 and 110 nanoseconds. Therefore, the chip rates of the standard 2G and 3G CDMA systems are not sufficient to resolve the multipath components of the received signal, which justifies our assumption. At any rate, the extension of our results to the general case of the channel with large delay spread is straightforward, although the benefits of our approach would be reduced. The shadowing is modeled as a lognormal random variable, i.e., its decibel representation has Gaussian distribution with zero mean and standard deviation σ_{sh}. The path loss exponent is denoted as m.

B. Power Combining Triplets (PCT)

Definition 1: The set of MTs $\{a,\ b,\ c\}$, where the packets are transmitted from MT a to MT c using the transmission from MT a to MT c as one diversity branch, and using transmission $a \rightarrow b \rightarrow c$ as the second diversity branch, as shown in Fig. 1(c), is called *power combining triplet*, $PCT_{\{a,b,c\}}$. The transmit diversity in this context is called *power combining*. MTs a, b, and c are denoted as *primary transmitter, secondary transmitter* and *receiver*, respectively.

Definition 2: Let d_{ij} denote the distance between MTs i and j. Vector $\bar{d}_{\{a,b,c\}} = [d_{ab},\ d_{bc},\ d_{ac}]$, is called the *distance vector* of $PCT_{\{a,b\ c\}}$. Note that $\bar{d}_{\{a,b,c\}}$ uniquely defines $PCT_{\{a,b,c\}}$ in terms of mutual positions of MTs.

Definition 3: $\Im(x) = \{\bar{d} : d_{ac} = x\}$ is the subspace spanned by the distance vector $\bar{d}_{\{a,\ b,\ c\}}$ with fixed d_{ac}, i.e., the set of all possible configurations of MTs a, b and c where the distance between the primary transmitter and the receiver, d_{ac}, is fixed.

C. Optimal Transmit Power Configuration and PCT Feasibility Criterion

In this section, we derive the optimal transmit powers on the diversity branches and establish the criteria for PCT initiation. We will start by deriving the total transmit power required to achieve desired error probability at the receiver for scenarios with and without power combining, respectively. As a general rule, the notations with prime denote the case without power combining; the notations with double prime denote the case with power combining.

Let $P_{ij}^{r'}$ denote the mean received power at the receiving MT j required to achieve certain error probability P_e when only one transmitter, MT i, is transmitting. $P_{ij}^{r'}$ is a function of the modulation scheme used, M, and P_e. Since we assume that they are both fixed and identical for all receivers in the system, we can consider $P_{ij}^{r'}$ to be a constant which we denote as α

$$P_{ab}^{r'} = P_{bc}^{r'} = P_{ac}^{r'} = f(M, P_e) = const = \alpha. \tag{1}$$

Since the minimum energy route from MT a to MT c can be either $a \rightarrow c$ or $a \rightarrow b \rightarrow c$, the total consumed power in the case without power combining is

$$\begin{aligned} P'_{tot} &= \min(\alpha 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m + P_{rec}, \alpha 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m \\ &\quad + \alpha 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m + 2P_{rec}), \end{aligned} \tag{2}$$

where γ_{ij} denotes the decibel representation of the lognormal shadowing attenuation between MTs i and j and P_{rec} is the fixed power consumed at each receiver in order to receive the signal.

The total consumed power with power combining is

$$\begin{aligned} P''_{tot} &= \alpha 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m + P_{ac}^{r''} 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m \\ &\quad + P_{bc}^{r''} 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m + 2P_{rec}, \end{aligned} \tag{3}$$

where $P_{ac}^{r''}$ and $P_{bc}^{r''}$ are the received powers on the $a \rightarrow c$ and $b \rightarrow c$ diversity branch, respectively. P_e, $P_{ac}^{r''}$ and $P_{bc}^{r''}$ are interdependent by virtue of the expression for error probability of the two-finger RAKE receiver for a given modulation scheme, M [11]:

$$P_e = f(M,\ P_{ac}^{r''}, P_{bc}^{r''}). \tag{4}$$

We need to find the optimal values for $P_{ac}^{r''}$ and $P_{bc}^{r''}$, denoted as $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$, which minimize P''_{tot}, i.e., we need to solve

$$\frac{\partial(\alpha 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m + P_{ac}^{r''} 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m + P_{bc}^{r''} 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m + 2P_{rec})}{\partial P_{ac}^{r''}} = 0, \tag{5}$$

or the equivalent derivative with respect to $P_{bc}^{r''}$, where the initial condition is given by (4). (5) easily simplifies to

$$\frac{dP_{bc}^{r''}}{dP_{ac}^{r''}} = -\frac{10^{\frac{\gamma_{ac}}{10}} d_{ac}^m}{10^{\frac{\gamma_{bc}}{10}} d_{bc}^m}, \tag{6}$$

which, coupled with (4), gives the system of equations to solve for $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$. The analytical solution is generally not tractable, even using software tools with symbolic mathematics capabilities, such as Matlab or Mathematica. The numerical solution, on the other hand, can be easily computed. Numerical approach is facilitated by the fact that the solution will depend only on the ratio of the composite channel attenuations on the two diversity branches, given on the right-hand side of (6). Therefore, one can numerically compute and tabulate the optimal received powers $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$ for wide range of values of the ratio of the composite channel attenuations and P_e. On the other hand, approximate formulas for (4) for low P_e are available for most modulation schemes. Since the benefit from using transmit diversity is negligible for high P_e, these approximations can be confidently used. For simplicity, we will base our subsequent discussion on BPSK modulation, which nonetheless provides insight into the more general properties of power combining.

The probability of error with power combining for BPSK modulation is the probability of error of a two-leg RAKE receiver with unequal received powers on each branch [11]

$$\begin{aligned} P_e &= \frac{1}{2}\left\{\frac{P_{ac}^{r''}}{P_{ac}^{r''} - P_{bc}^{r''}}\left(1 - \sqrt{\frac{P_{ac}^{r''}}{1 + P_{ac}^{r}}}\right)\right. \\ &\quad \left. + \frac{P_{bc}^{r''}}{P_{bc}^{r''} - P_{ac}^{r''}}\left(1 - \sqrt{\frac{P_{bc}^{r''}}{1 + P_{bc}^{r''}}}\right)\right\}. \end{aligned} \tag{7}$$

As discussed above, analytical solution of (6) given (7) is not feasible. Numerical solutions are given in the appendix. For low P_e, (7) can be approximated by [12]:

$$P_e = \frac{3}{16}\frac{1}{P_{ac}^{r''} P_{bc}^{r''}}, \tag{8}$$

which allows for easy solving for $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$

$$\left(P_{ac}^{r''}\right)_{opt} = \frac{\sqrt{3}}{4\sqrt{P_e}} 10^{\frac{\gamma_{bc}-\gamma_{ac}}{20}} \left(\frac{d_{bc}}{d_{ac}}\right)^m, \tag{9}$$

$$\left(P_{bc}^{r''}\right)_{opt} = \frac{\sqrt{3}}{4\sqrt{P_e}} 10^{\frac{\gamma_{ac}-\gamma_{bc}}{20}} \left(\frac{d_{ac}}{d_{bc}}\right)^m. \tag{10}$$

The transmit powers on the two diversity branches are then

$$\begin{aligned} \left(P_{ac}^{t''}\right)_{opt} &= \left(P_{ac}^{r''}\right)_{opt} 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m \\ &= \frac{\sqrt{3}}{4\sqrt{P_e}} \left(\sqrt{d_{ac} d_{bc}}\right)^m 10^{\frac{\gamma_{ac}}{20}} 10^{\frac{\gamma_{bc}}{20}}, \end{aligned} \tag{11}$$

$$\begin{aligned} \left(P_{bc}^{t''}\right)_{opt} &= \left(P_{bc}^{r''}\right)_{opt} 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m \\ &= \frac{\sqrt{3}}{4\sqrt{P_e}} \left(\sqrt{d_{ac} d_{bc}}\right)^m 10^{\frac{\gamma_{ac}}{20}} 10^{\frac{\gamma_{bc}}{20}} \\ &= \left(P_{ac}^{t''}\right)_{opt}. \end{aligned} \tag{12}$$

It follows from (12) that in the optimal configuration the transmit powers on the diversity branches *are equal.* This property is preserved in the case of the exact formula given in (7) and is valid form any modulation scheme. This reminds of the equal gain combining, only here it is applied to the *transmitted* rather than received powers.

The optimal total consumed power with power combining is

$$(P''_{tot})_{opt} = \alpha\gamma_{ab} d_{ab}^m + (P_{ac}^{t''})_{opt} + (P_{bc}^{t''})_{opt} + 2P_{rec}, \quad (13)$$

which using (12) becomes

$$\begin{aligned}(P''_{tot})_{opt} &= \alpha 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m + \frac{\sqrt{3}}{2P_e}\left(\sqrt{d_{ac}d_{bc}}\right)^m 10^{\frac{\gamma_{ac}}{20}} 10^{\frac{\gamma_{bc}}{20}} \\ &\quad + 2P_{rec}. \quad (14)\end{aligned}$$

Definition 4: Given locations of MTs a and c, we call MT b *feasible for power combining with a for transmission to c* if:

$$(P''_{tot})_{opt} < P'_{tot}. \quad (15)$$

The location of a feasible MT is called a *feasible location.* The power combining triplet $PCT_{\{a,b,c\}}$, where b is feasible for power combining with a for transmission to c, is called *feasible power combining triplet.*

We adopt the feasibility of b as the necessary and sufficient condition for the initiation of power combining between MTs a and b for transmission to MT c.

Definition 5: The region consisting of all feasible locations of MT b for given locations of MTs a and c is called *feasibility region of MT a to MT c,* and denoted as $F(a \to c)$.

Definition 6: Among all MTs feasible for power combining with a for transmission to c, assume that MT b yields the minimum total consumed power, i.e., $PCT_{\{a,b,c\}}$ consumes less power than any other $PCT_{\{a,n,c\}}, n \notin \{a,b,c\}$. MT b is then called *optimal feasible MT for power combining with a for transmission to c. $PCT_{\{a,b,c\}}$* is called *minimal PCT.*

Proposition 1: If there exists $PCT_{\{a,b,c\}}$ then there also exists $PCT_{\{b,a,c\}}$ with the same optimal total consumed power, $(P''_{tot})_{opt}$, and same optimal transmit powers on the power combining branches, $(P_{ac}^{t''})_{opt}$ and $(P_{bc}^{t''})_{opt}$. Consequently, the primary transmitter of $PCT_{\{a,b,c\}}$ is the secondary transmitter of $PCT_{\{b,a,c\}}$, and vice-versa.

Corollary 1: If MT b is the optimal feasible MT for power combining with a for transmission to c, then MT a is also the optimal feasible MT for power combining with b for transmission to c. Equivalently, if $PCT_{\{a,b,c\}}$ is the minimal PCT, then $PCT_{\{b,a,c\}}$ is also the minimal PCT.

D. Power Gain Analysis

In this section, we evaluate the practical benefits of power combining. Our first goal is to evaluate the size and the shape of the feasibility region. This has a twofold rational behind it. First, we would like to determine if the feasibility region $F(a \to c)$ is large enough to insure substantial probability of finding a MT inside it to be used as the second transmitter. Second, the size of the feasibility region may be used to determine the boundary beyond which the search for feasible nodes should stop. Our second goal is to evaluate the average gain in terms of total consumed power achieved by power combining.

Definition 7: Let $\overline{\gamma}_{\{a,b,c\}} = [\gamma_{ab}, \gamma_{bc}, \gamma_{ac}]$. *Relative transmit power gain* of $PCT_{\{a,b,c\}}$ is defined as (16) at the bottom of this page.

We can now give an alternate definition of feasibility.

Definition 8: Given locations of MTs a and c, we call MT b *feasible* for power combining with a for transmission to c if $G(\overline{d}_{\{a,b,c\}}, \overline{\gamma}_{\{a,b,c\}}) > 0$.

Definition 7 assumes the knowledge of the shadowing vector $\overline{\gamma}_{\{a,b,c\}}$. Since $\overline{\gamma}_{\{a,b,c\}}$ is random, we would like to get an estimate of the PCT gain for a given distance vector $\overline{d}_{\{a,b,c\}}$ independent from $\overline{\gamma}_{\{a,b,c\}}$. With that aim, we introduce the following definitions:

Definition 9: The *feasibility probability* of $PCT_{\{a,b,c\}}$ with distance vector $\overline{d}_{\{a,b,c\}}$ is defined as

$$\begin{aligned}&PF(\overline{d}_{\{a,b,c\}} \\ &= \int\limits_{\substack{R^3 \\ G(\overline{d}_{\{a,b,c\}}, \overline{\gamma}_{\{a,b,c\}}) > 0}} f(\overline{\gamma}_{\{a,b,c\}})\, d\overline{\gamma}_{\{a,b,c\}} \\ &= \int\limits_{R^3} u[G(\overline{d}_{\{a,b,c\}}, \overline{\gamma}_{\{a,b,c\}})] f(\overline{\gamma}_{\{a,b,c\}})\, d\overline{\gamma}_{\{a,b,c\}},\end{aligned} \quad (17)$$

where $u[x]$ is the unit step function and pdf. of $\overline{\gamma}_{\{a,b,c\}}$ is Gaussian:

$$f(\overline{\gamma}_{\{a,b,c\}}) = \frac{1}{(2\pi)^{3/2}\sigma_{sh}^3} e^{-\frac{[(\gamma_{ab})^2 + (\gamma_{bc})^2 + (\gamma_{ac})^2]}{2\sigma_{sh}^2}}. \quad (18)$$

Definition 10: *Average transmit power gain* achieved by $PCT_{\{a,b,c\}}$ is defined as (19) at the bottom of next page.

The integrals in (17) and (19) can be computed numerically for a given distance vector $\overline{d}_{\{a,b,c\}}$. In the special case when P_{rec} can be neglected, the following proposition proves useful.

Proposition 2: If $P_{rec} = 0$, then

$$G(\overline{d}_{\{a,b,c\}}, \overline{\gamma}_{\{a,b,c\}}) = \frac{P'_{tot} - (P_{tot})_{opt}}{P'_{tot}} = 1 - \frac{\alpha 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m + (P_{ac}^{r''})_{opt} 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m + (P_{bc}^{r''})_{opt} 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m + 2P_{rec}}{\min(P_{ac}^{r'} 10^{\frac{\gamma_{ac}}{10}} d_{ac}^m + P_{rec}, P_{ab}^{r'} 10^{\frac{\gamma_{ab}}{10}} d_{ab}^m + P_{bc}^{r'} 10^{\frac{\gamma_{bc}}{10}} d_{bc}^m + 2P_{rec})}. \quad (16)$$

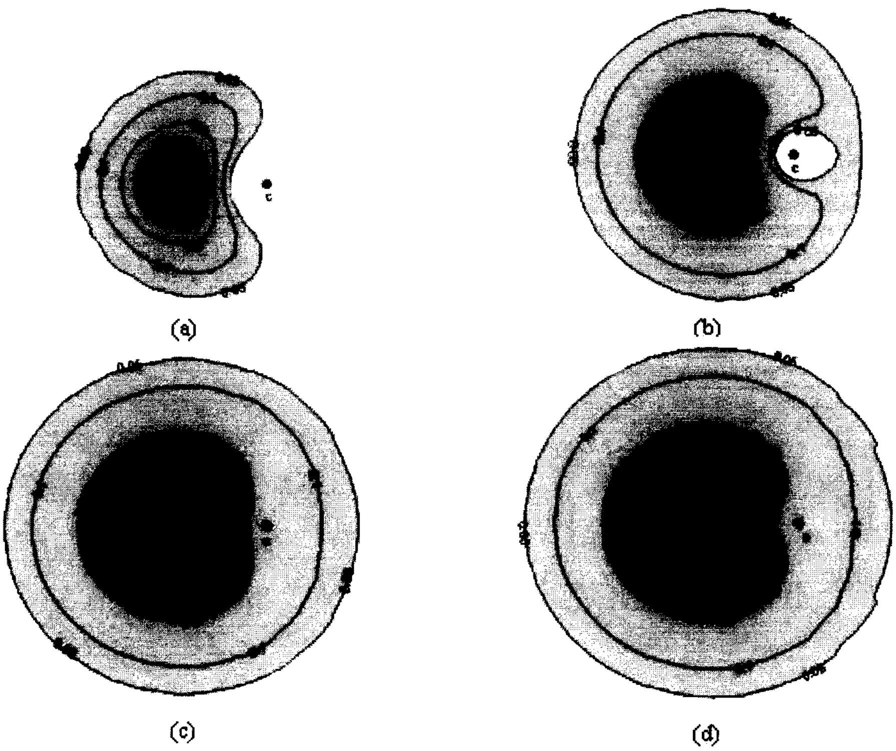


Fig. 2. Feasibility probability regions for $d_{ac} = 1$, $P_{rec} = 0$ and $P_e = 10^{-1}$ (a), $P_e = 10^{-2}$ (b), $P_e = 10^{-3}$ (c), and $P_e = 10^{-4}$ (d).

Table 1. Power combining potential for $P_{rec} = 0$ vs. p_e.

P_e	10_1	10_2	10_3	10_4
PCP_N	0.041	0.295	0.460	0.525

$$\begin{aligned} G(\bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}) &= G(k \cdot \bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}) \\ &= G(\bar{d}^{(N)}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}), \end{aligned} \tag{20}$$

where k is a constant and

$$\bar{d}^{(N)}_{\{a,b,c\}} = \left[\frac{d_{ab}}{d_{ac}}, \frac{d_{bc}}{d_{ac}}, 1\right]. \tag{21}$$

Proof: Follows from (17), putting $P_{rec} = 0$ □

Corollary 2: If $P_{rec} = 0$, then

$$PF(\bar{d}_{\{a,b,c\}}) = PF(\bar{d}^{(N)}_{\{a,b,c\}}). \tag{22}$$

Corollary 3: If $P_{rec} = 0$, then

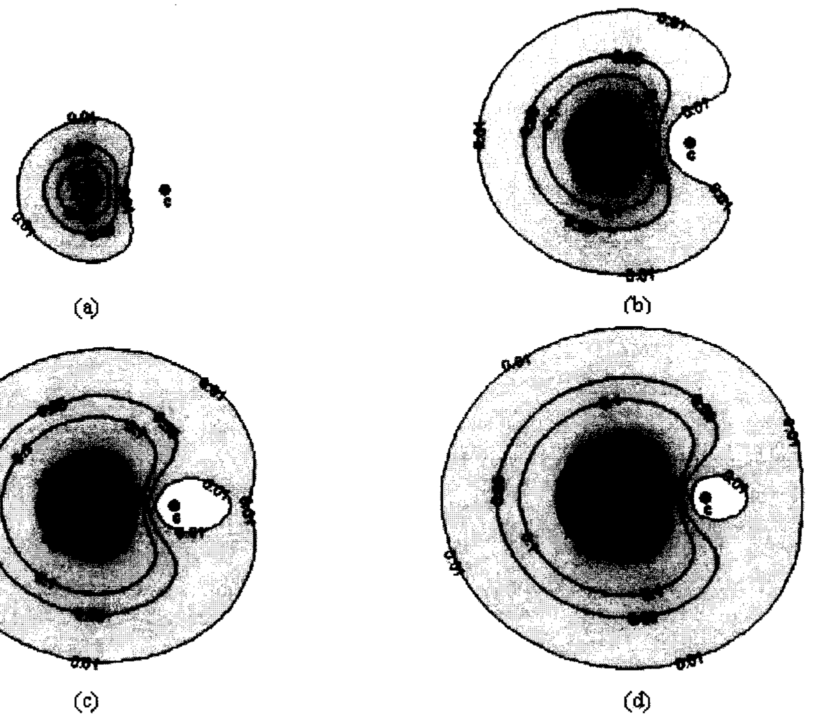
$$G(\bar{d}_{\{a,b,c\}}) = G(\bar{d}^{(N)}_{\{a,b,c\}}). \tag{23}$$

The idea behind the Proposition 2 is that when $P_{rec} = 0$, the triangle $\{a,\ b,\ c\}$ can be scaled by any factor, and its properties defined by Definitions 7 through 10 will not change. This allows tracking of the individual effect of other parameters, such as P_e and σ_{sh}, onto these properties, as well as visualization of the feasibility regions independently from d_{ac}.

Fig. 2(a) through Fig. 2(d) show the feasibility probability for $P_e = 10^{-1}$, $P_e = 10^{-2}$, $P_e = 10^{-3}$ and $P_e = 10^{-4}$, respectively, as a function of the location of MT b, for $P_{rec} = 0$. Black dots denote the locations of MTs a and b. By virtue of Corollary 2.1, the figures are scalable to any value of d_{ac}. Fig. 3(a) through Fig. 3(d) show the average transmit power gain for $P_e = 10^{-1}$, $P_e = 10^{-2}$, $P_e = 10^{-3}$ and $P_e = 10^{-4}$, respectively, as a function of the location of MT b, for $P_{rec} = 0$. By virtue of Corollary 2.2, the figures are scalable to any value of d_{ac}.

Definition 11: *Power combining potential* of MTs a and c at distance d_{ac}, $PCP(d_{ac},\ P_e)$, is

$$\begin{aligned} G(\bar{d}_{\{a,b,c\}}) &= \int\limits_{\substack{R^3 \\ G(\bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}) > 0}} G(\bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}) f(\bar{\gamma}_{\{a,b,c\}})\, d\bar{\gamma}_{\{a,b,c\}} \\ &= \int\limits_{R^3} G(\bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}}) u[G(\bar{d}_{\{a,b,c\}}, \bar{\gamma}_{\{a,b,c\}})] f(\bar{\gamma}_{\{a,b,c\}})\, d\bar{\gamma}_{\{a,b,c\}}. \end{aligned} \tag{19}$$



(a) (b) (c) (d)

Fig. 3. Power combining potential regions for $d_{ac} = 1$, $P_{rec} = 0$ and $P_e = 10^{-1}$ (a), $P_e = 10^{-2}$ (b), $P_e = 10^{-3}$ (c), and $P_e = 10^{-4}$ (d).

$$PCP(d_{ac}) = \frac{\int_{\Im(d_{ac})} G(\bar{d}_{\{a,b,c\}})d(\bar{d}_{\{a,b,c\}})}{\int_{\Im(d_{ac})} FP(\bar{d}_{\{a,b,c\}})d(\bar{d}_{\{a,b,c\}})}. \qquad (24)$$

Note that the denominator represents a normalizing constant. Power combining potential of two MTs is thus the average transmit power gain of any PCT in which one MT serves as the primary transmitter and the other as the receiver, averaged over all feasible locations of the second transmitter.

Proposition 3: If $P_{rec} = 0$, then

$$PCP(d_{ac}) = PCP(k \cdot d_{ac}) = PCP(1) \equiv PCP_N. \qquad (25)$$

Hence, when $P_{rec} = 0$ power combining potential of two MTs is independent from their distance.

Table 1 shows PCP_N as a function of P_e, computed numerically from (24). When $P_{rec} > 0$, the power combining potential will be smaller. The values in Table 1 thus represent an upper bound on the power combining potential. Indeed, it is not reasonable to assume that P_{rec} is zero. Every receiver consumes power for receiving the signal. When P_{rec} is not neglected, it increases the cost of power combining and thus reduces the feasibility region. In this case, G becomes dependent on P_{rec} as well as on d_{ac}. Fig. 4 shows $PCP(d_{ac})$ as a function of d_{ac}, P_{rec} and P_e, computed numerically from (24). The straight horizontal lines represent the values from Table 1 corresponding to the case when P_{rec} is neglected. As can be seen in the Fig. 4, for each pair (P_e, P_{rec}) there exists a value of d_{ac} below which power combining provides no substantial benefit. On the other hand, the distances for which power combining provides benefit are very realistic, especially for low P_e. Also, it can be seen that P_{rec} significantly affects the transmit power gain achievable by power combining.

At this point, we make the following remarks. First, the receivers need not be modified to accommodate diversity reception: from the receiver's perspective the two signals coming from two transmitters are equivalent to a multipath signal coming from one transmitter. Second, the delay between the two transmit signals must be sufficient so that the receiver can resolve them. If the distances between the MTs are not large enough to insure sufficient propagation delay, MT b could easily insert delay to provide resolvable paths at the receiver. Finally, when fading is not present, power combining simplifies to single transmission using the better of the two routes, namely $a \rightarrow c$ or $a \rightarrow b \rightarrow c$.

E. Power Combining Chains (PCC)

In this section, we generalize the concept of PCT and introduce the concept of power combining chains (PCC). Consider the network in Fig. 5(a), in which MT a sends the packets to MT d. Assume that the first hop on the minimum energy route from a to d is MT c, and that $PCT_{\{a,b,c\}}$ is the minimum PCT. In addition, suppose that $PCT_{\{c,b,d\}}$ is also the minimum PCT. Therefore, the transmission mesh of the route from MT a to MT c will be as shown in Fig. 5(b). We can clearly observe that the transmission from MT b to MT c in the second hop is redundant, since MT b has already received the signal from MT a in the first hop in his role as the second transmitter in the $PCT_{\{a,b,c\}}$. As a result, the link $b \rightarrow c$ can be suppressed, and additional energy can be saved (Fig. 5(c)). We call the set of MTs $\{a, b, c, d\}$ that allow the cascading of PCTs and suppression of redundant links *power combining chain* (PCC). As is clear from the above dis-

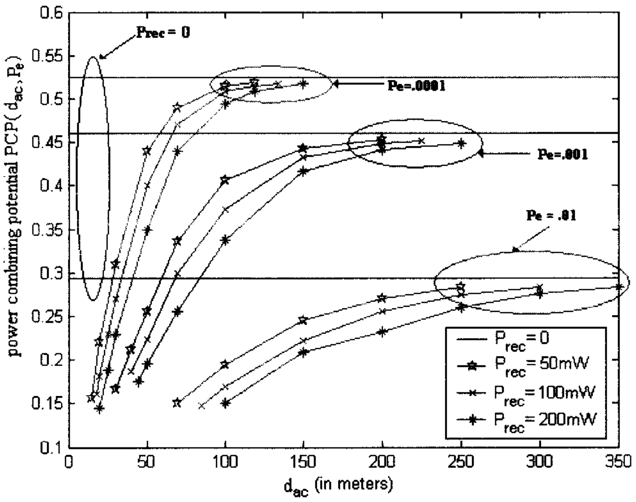


Fig. 4. Power combining potential vs. d_{ac} for different values of P_{rec} and P_e.

cussion, PCC can only occur if a MT, in this case MT b, takes part in both $PCT_{\{a,b,c\}}$ and $PCT_{\{c,b,d\}}$. Furthermore, MT b has to be the second transmitter in both PCTs.

Definition 12: If two PCTs, say $PCT_{\{a,b,c\}}$ and $PCT_{\{c,b,d\}}$, share the same second transmitter, then the set of MTs $\{a,\ b,\ c,\ d\}$ is called *power combining chain*, denoted as $PCC_{\{a,b,c,d\}}$. We say that $PCC_{\{a,b,c,d\}}$ is a *cascade* of $PCT_{\{a,b,c\}}$ and $PCT_{\{c,b,d\}}$.

A PCC can consist of more than two PCTs. Consequently, we need to establish a more general definition of PCC.

Definition 13:

(i) Power combining chain of three MTs, $PCC_{\{n_1,n_2,n_3\}}$ is equivalent to $PCT_{\{n_1,n_2,n_3\}}$.

(ii) Power combining chain of MTs $\{n_1,\ n_2,\ \cdots,\ n_{m-1},\ n_m\}$, denoted as $PCC_{\{n_1,n_2,\ldots,n_{m-1},n_m\}}$, is a cascade of $PCC_{\{n_1,n_2,\ldots,n_{m-2},n_{m-1}\}}$ of length $m-1$ and $PCT_{\{n_{m-1},n_{m-2},n_m\}}$.

Note that Definition 13 defines PCT as a trivial version of a PCC.

It is important to note that the optimal transmit powers on the diversity branches do not change with the pruning of the redundant link. Thus, the optimal powers will be the optimal transmit powers on the diversity branches of the PCT, discussed in Section III-C.2. Along that line of these conclusions, the following proposition is the generalization of Proposition 1.

Proposition 4: If there exists $PCC_{\{n_1,n_2,\ldots,n_{m-1},n_m\}}$ then there also exists $PCC_{\{n_2,n_1,\ldots,n_{m-1},n_m\}}$. Consequently, the primary transmitter of $PCT_{\{a,b,c\}}$ is the first secondary transmitter of $PCT_{\{b,a,c\}}$, and vice-versa. Also, the optimal total consumed power and the optimal transmit powers on the power combining branches of $PCC_{\{n_1,n_2,\ldots,n_{m-1},n_m\}}$ and $PCC_{\{n_2,n_1,\ldots,n_{m-1},n_m\}}$ are the same.

In the sense of feasibility defined by Definition 4, it is clear that if all the PCTs merged into a PCC are feasible, the PCC is also feasible since by pruning the redundant links we are further reducing the total transmit power. The reverse may not be true; that is, the merger of unfeasible PCTs may in fact yield a feasible PCC, because of the pruning of redundant links. In this case, however, the determination of the feasibility of PCCs would be complicated because the feasibility could not be tested until the total cost transmit power of a PCC is determined, by adding the transmit power for all the branches in the PCCs. This could only be performed by the last receiver MT, which would then need to forward the feasibility information to all MTs in the PCC for PCC initiation. This centralized procedure is not suitable for the distributed architecture of ad-hoc networks and would generate too much signaling between MTs.

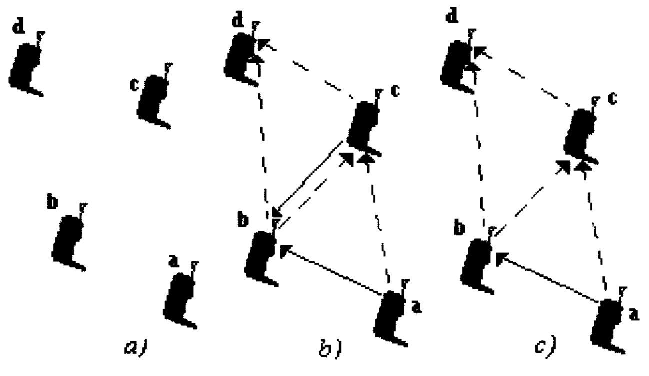


Fig. 5. Power combining chains.

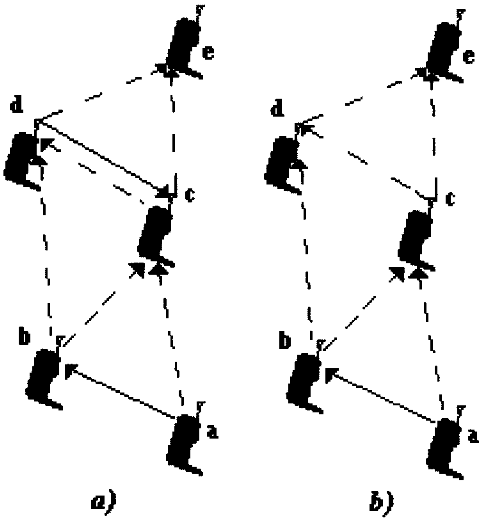


Fig. 6. Cascade of two PCCs.

On the other hand, if the feasibility of all PCTs merged into a PCC is adopted as the feasibility condition, than the feasibility is readily available. Therefore, we adopt the following definition of feasibility of a PCC.

Definition 14:

(i) $PCC_{\{n_1,\ n_2,\ n_3,\ n_4\}}$ is feasible if $PCT_{\{n_1,\ n_2,\ n_3\}}$ and $PCT_{\{n_3,\ n_2,\ n_4\}}$ are both feasible.

(ii) $PCC_{\{n_1,\ n_2,\cdots,n_{m-1},\ n_m\}}$ is feasible if $PCC_{\{n_1,\ n_2,\cdots,\ n_{m-2},\ n_{m-1}\}}$ and $PCT_{\{n_{m-1},\ n_{m-2},\ n_m\}}$ are both feasible.

Based on Definition 12 and Definition 14. (i), it is clear that the condition for the merger of two PCTs is the existence of the common second transmitter, as illustrated in Fig. 5. We now consider the criteria for the merger of a PCT and a PCC. Consider Fig. 6(a). Assume that $PCC_{\{a,b,c,d\}}$ and $PCT_{\{d,c,e\}}$ are feasible. As in the case of cascading two PCTs, the link $d \rightarrow e$ is redundant, since MT c already receives the signal destined to e. In order for this to happen, MT c in $PCC_{\{a,b,c,d\}}$, must at the same time be the secondary transmitter of $PCT_{\{d,c,e\}}$.

It would be interesting to gain insight into the probability of occurrence of PCC. Unfortunately, because of the large number of MTs involved, this analysis is intractable for the general case. For the special case of PCC of length 4, the probability of occurrence amounts to the probability of two PCTs having the same secondary transmitter and can be computed based on the results of Section IV.

Optimal Total Consumed Power

In this section, we derive the optimal consumed power of a PCC and provide the equivalent of Definitions 7 through 10 for the case of PCCs.

Consider again the case shown in Fig. 5. The total consumed power required to send the signal from MT a to MT d without power combining is:

$$\begin{aligned}&(P'_{tot})_{a\rightarrow d}\\&=(P'_{tot})_{a\rightarrow c}+(P'_{tot})_{c\rightarrow d}\\&=\min(\alpha 10^{\frac{\gamma_{ac}}{10}}d_{ac}^{m}+P_{rec},\alpha 10^{\frac{\gamma_{ab}}{10}}d_{ab}^{m}+\alpha 10^{\frac{\gamma_{bc}}{10}}d_{bc}^{m}+2P_{rec})\\&\quad+\min(\alpha 10^{\frac{\gamma_{bc}}{10}}d_{bc}^{m}+P_{rec},\alpha 10^{\frac{\gamma_{bc}}{10}}d_{bc}^{m}+\alpha 10^{\frac{\gamma_{bd}}{10}}d_{bd}^{m}+2P_{rec})\end{aligned} \tag{26}$$

The total consumed power using $PCC_{\{a,b,c,d\}}$ will be:

$$\begin{aligned}(P''_{tot})_{\{a,b,c,d\}} &= (P''_{tot})_{\{a,b,c\}}+(P''_{tot})_{\{c,b,d\}}\\&\quad-\alpha 10^{\frac{\gamma_{bd}}{10}}d_{bc}^{m}-P_{rec}.\end{aligned} \tag{27}$$

The last two terms correspond to the pruned redundant link. Using (14), eq. (27) becomes:

$$\begin{aligned}(P''_{tot})_{\{a,b,c,d\}} &= \alpha 10^{\frac{\gamma_{ab}}{10}}d_{ab}^{m}+(P_{ac}^{t''})_{opt}+(P_{bc}^{t''})_{opt}\\&\quad+(P_{cd}^{t''})_{opt}+(P_{bd}^{t''})_{opt}+3P_{rec}.\end{aligned} \tag{28}$$

Now, we can write the expression for the total consumed power of a PCC of arbitrary length:

$$\begin{aligned}&(P''_{tot})_{\{n_1,n_2,\ldots,n_m\}}\\&=\alpha 10^{\frac{\gamma_{n_1n_2}}{10}}d_{n_1n_2}^{m}+\sum_{i=3}^{m}\left[(P_{n_{i-2}n_i}^{t''})_{opt}+(P_{n_{i-1}n_i}^{t''})_{opt}\right]\\&\quad+(m-1)P_{rec}.\end{aligned} \tag{29}$$

In the case of the approximate BPSK formula (8), eq. (30) becomes:

$$\begin{aligned}&(P''_{tot})_{\{n_1,n_2,\ldots,n_m\}}\\&=\alpha 10^{\frac{\gamma_{n_1n_2}}{10}}d_{n_1n_2}^{m}+\frac{\sqrt{3}}{2\sqrt{P_e}}\sum_{i=3}^{m}\Big[\left(\sqrt{d_{n_{i-2}n_i}d_{n_{i-1}n_i}}\right)^{m}\\&\quad\cdot 10^{\frac{\gamma_{n_{i-2}n_i}}{20}}10^{\frac{\gamma_{n_{i-1}n_i}}{20}}\Big]+(m-1)P_{rec}.\end{aligned} \tag{30}$$

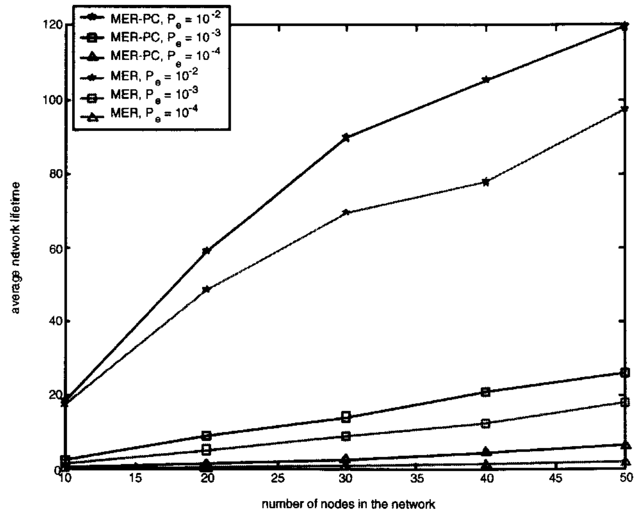


Fig. 7. Network lifetime.

Having defined the total consumed power of PCC with and without power combining, we can define the measures for evaluating the transmit power gain in the same fashion as we did for the case of PCTs in definitions 7 through 10. However, computing their values becomes intractable, as we are dealing with $(m+1)$-tiple integrations for a PCC of length m.

F. Link Costs and Graph Representation

In this section, we discuss the link costs and graphic representation of links employing PCTs and PCCs. In MER, the link cost represents the power consumed to provide successful transmission.

Based on our analysis from the previous section, we know that if $PCT_{\{a,b,c\}}$ was feasible, the total transmit power with respect to the case without PCT would be less, i.e.,:

$$(C_{ac})_{PCT} \leq \min(C_{ac}, C_{ab}+C_{bc}). \tag{31}$$

Therefore, an additional link in the graph is needed to represent the cost of $PCT_{\{a,b,c\}}$. The total consumed power of a PCC is smaller than the total consumed power of PCTs involved in the PCC. This will require establishing direct connection between the end MTs of the PCC in the network graph, reflecting the cost of the PCC. For $PCC_{\{a,b,c,d\}}$ from Fig. 5, we have

$$(C_{ad})_{PCC} < (C_{ac})_{PCT}+(C_{cd})_{PCT}. \tag{32}$$

Therefore, in general we can write

$$(C_{n_1n_m})_{PCC} \leq \sum_{i=1}^{m-2}(C_{n_in_{i+2}})_{PCT}. \tag{33}$$

III. PERFORMANCE ANALYSIS OF MER ALGORITHM FOR RAYLEIGH FADING CHANNELS USING POWER COMBINING

In this section, we present the simulation study of the MER algorithm using power combining (MER-PC) and evaluate the

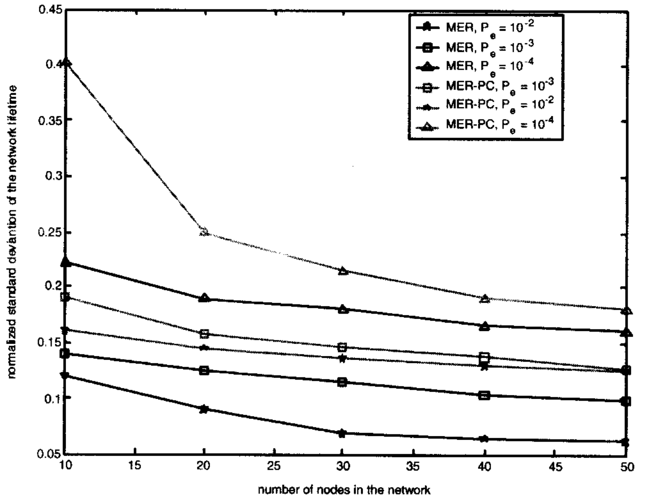


Fig. 8. Standard deviation of network lifetime.

results in terms of their compliance with analytical results deployed in Section II and also in terms of the comparison with the conventional minimum energy routing scheme (MER). Analysis of the messaging load generated by our algorithm is then presented and the tradeoff is discussed.

A. *System Model*

A.1 Network Model

The network area is assumed to be of square shape with 1,000 m on each side. MTs are assumed to be moving uniformly with constant speed, uniformly distributed in the range from 0 to 22 mph. The direction of movement is uniformly distributed from 0 to 360 degrees. When a MT reaches the boundary of the coverage area, it reflects off of it back into the area. Initially, MTs are distributed uniformly within the network area.

A.2 Channel Model

The channel model described in Section II-A is used, accounting for path loss, shadowing and fading. The widely used value for of four is adopted for the path loss exponent m. The shadowing has the standard deviation of $\sigma_{sh} = 8$ dB and correlation of $\rho = 0.5$ at the distance of $d_\rho = 20$ m. In order to accommodate the spatial correlation of shadowing, it is modeled as a first-order auto-regressive (AR) process:

$$\gamma(t) = \xi\gamma(t-1) + \varpi(t), \qquad (34)$$

where ξ is a constant and $\varpi(t)$ is a zero-mean Gaussian noise with standard deviation σ_ϖ.

It can be shown [13] that the above values of σ_{sh} and ρ are achieved with $\xi = 0.84$ and $\sigma_\varpi = 3.26$ dB. Each MT updates its channel attenuations to other MTs at a pre-defined step of 5 meters. Therefore, MTs moving faster will update their channel attenuations more frequently.

A.3 Transceiver Model

Each MT is equipped with a full-duplex transceiver with omni-directional antennas with 0 dB gain. The carrier frequency is assumed to be 1 GHz and the transmission bandwidth is 10 KHz. The receiver has a noise figure of 10 dB, and the background noise has the power level of -160 dBm. For simplicity, the modulation is BPSK. Each receiver is a two-tap RAKE receiver perfectly synchronized with the two multipath components coming from the two transmitters.

Based on these parameters, received power thresholds for successful detection can be computed [3]. In addition, each receiver consumes a constant power of $P_{rec} = 100$ mW for each received signal, which is in the range of values reported in [1] and [3].

A.4 Power Consumption Model

In order to focus on the analysis of the effect of our algorithm onto the network lifetime, MTs do not consume any power when they are not transmitting/receiving. Therefore, MTs consume power only for transmitting/receiving signals to support the incoming connection requests. The connection requests arrive randomly according to the Poisson distribution with the mean of 2 connections per MT per minute. The source MT and the destination MT for each connection are chosen randomly among all MTs. The duration of the connection is set to 10 seconds. Initial battery energy for each MT is set to 50 Whrs, corresponding to the battery capacity of an average laptop computer. MT is considered to have run out of energy when it has not enough energy to support a connection, i.e., to provide reception and/or transmission during the ten-second transmission interval.

B. *Simulation Results*

B.1 Network Lifetime

Fig. 7 shows the network lifetime obtained from the simulation, for MER and MER-PC. As is clearly seen on the graph, power combining significantly increases the network lifetime. The amount of increase depends greatly on the desired signal quality, represented by the received signal error probability P_e. The relative increase is bigger for lower P_e, reflecting the fact that the benefits of transmit diversity increases as P_e decreases. The increase goes from around 30% for $P_e = 10^{-2}$ to more than 100% for $P_e = 10^{-4}$. Fig. 8 shows the standard deviation of network lifetime normalized to the mean. It can be inferred from the graph that power combining helps reduce the standard deviation of the network lifetime by approximately a factor of two. This means that power combining renders the network lifetime more predictable, which is important for some applications.

B.2 Average Power Gain per Route and per MT

Tables 2 and 3 show the average power consumed to route a packet per route in Watts for MER and MER-PC, respectively, as a function of the number of MTs in the network and the error probability P_e. These results were obtained using 10,000 routes randomly selected from the set of all possible routes in the network. The results in the tables indicate that the power gain per routed packet is 1-2% for $P_e = 10^{-1}$, around 20% for $P_e = 10^{-2}$ and goes up to 60% for $P_e = 10^{-4}$. These results are very similar to the average PCT power gains, computed analytically in Section II-D.

Table 2. Average powers per routed packet without power combining.

Number of MTs	10	20	30	40	50
Power per route (in Watts), $P_e = 10^{-}1$	0.77	0.52	0.41	0.36	0.31
Power per route (in Watts), $P_e = 10^{-}1$	6.74	2.92	1.58	1.36	1.18
Power per route (in Watts), $P_e = 10^{-}1$	62.73	21.2	10.3	6.5	4.22

Table 3. Average powers per routed packet with power combining.

Number of MTs	10	20	30	40	50
Power per route (in Watts), $P_e = 10^{-}1$	0.76	0.50	0.39	0.34	0.30
Power per route (in Watts), $P_e = 10^{-}1$	5.81	2.46	1.37	1.18	1.05
Power per route (in Watts), $P_e = 10^{-}1$	38.35	13.13	6.34	4.47	2.93

Table 4. Average powers per routed consumption of a MT without power combining.

Number of MTs	10	20	30	40	50
Power per route (in Watts), $P_e = 10^{-}1$	0.28	0.09	0.06	0.04	0.03
Power per route (in Watts), $P_e = 10^{-}1$	2.78	0.89	0.64	0.51	0.43
Power per route (in Watts), $P_e = 10^{-}1$	25.67	7.65	4.12	2.62	2.01

Table 5. Average power consumption of a MT with power combining.

Number of MTs	10	20	30	40	50
Power per route (in Watts), $P_e = 10^{-}1$	0.27	0.084	0.057	0.038	0.029
Power per route (in Watts), $P_e = 10^{-}1$	2.38	0.81	0.55	0.44	0.37
Power per route (in Watts), $P_e = 10^{-}1$	15.6	4.53	2.55	1.81	1.41

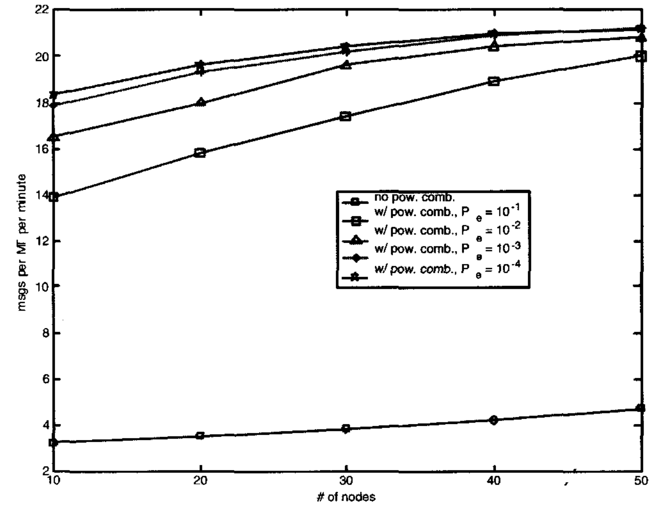


Fig. 9. Messaging load with and without power combining.

Therefore, the simulation results lead to conclusions that go along the lines of the conclusions of Section II-D, i.e., that power combining yields significant gains in terms of transmit power reduction for all but very high error probabilities, i.e., low SNRs.

Tables 4 and 5 show the average power consumption of a MT in Watts for MER and MER-PC, respectively, as a function of the number of MTs in the network and the error probability P_e. The results were computed over the span of the network lifetime and averaged over 20 runs. The same discussion of the results as in the previous section applies here. The consequence of these results is that when power combining is used, MTs consume less power and hence generate less interference. Fig. 10 and Fig. 11 show the examples of the routes for a network with 10 MTs, obtained using MER and MER-PC, respectively, for $P_e = 10^{-3}$. The source MT is denoted as 1 and the destination MT is denoted as 2. The solid lines represent simple links and the dashed lines represent PCT diversity branches.

One can note that gains in terms of network lifetime and average power consumption match good the analytically computed gains achieved by isolated PCTs in Section II-C. This can be explained by the large size of PCT feasibility regions, yielding large probability of the existence of a feasible PCT for any transmitter-receiver pair. Thus, on the average, the transmit power gain per route matches the gain per one hop, which is in fact the gain of one PCT. Hence, our analytical estimates of the transmit power gains for isolated PCTs can be used as a good approximation for actual gains in the network.

C. Messaging Load

The cost of power combining scheme is in the messaging load required to initiate, update and release PCTs in the network. In this section, we compare the messaging load of MER and MER-PC. We will also discuss the methods to optimize this load.

C.1 Messaging Load without Power Combining

Without power combining, the messaging is required to exchange the link (i.e., channel attenuation) information among MTs. We assume that each MT broadcasts a pilot signal whenever it travels a distance of 5 meters. This pilot is picked up by other MTs, which use it to compute channel attenuations between them. Each MT then broadcasts its channel attenuations to all other MTs in a single message.

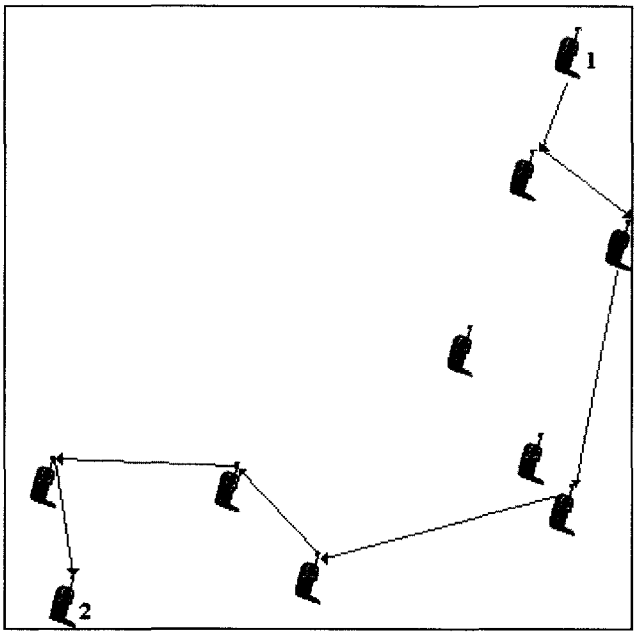


Fig. 10. Minimum power route between MTs 1 and 2 using conventional MER.

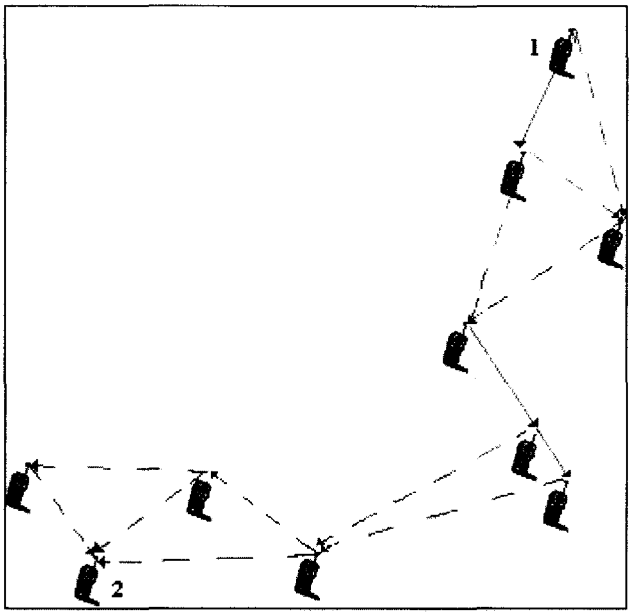


Fig. 11. Minimum power route between MTs 1 and 2 using MER-PC.

C.2 Messaging Load with Power Combining

The two additional sources of messaging with power combining are the initiation and exchange of the PCT and PCC related information among MTs, and the slow-rate power control. We again assume that each MT perform the updates of its links at the steps of 5 meters, at which time it updates its table of minimum PCTs and PCCs. In order to be consistent with the MER case, each MT broadcasts the updates of its table of minimum PCTs and PCCs to all other MTs in a single message. At the same rate, each MT sends slow-rate power control messages to maintain optimal power levels on the diversity branches in its active PCTs and PCCs.

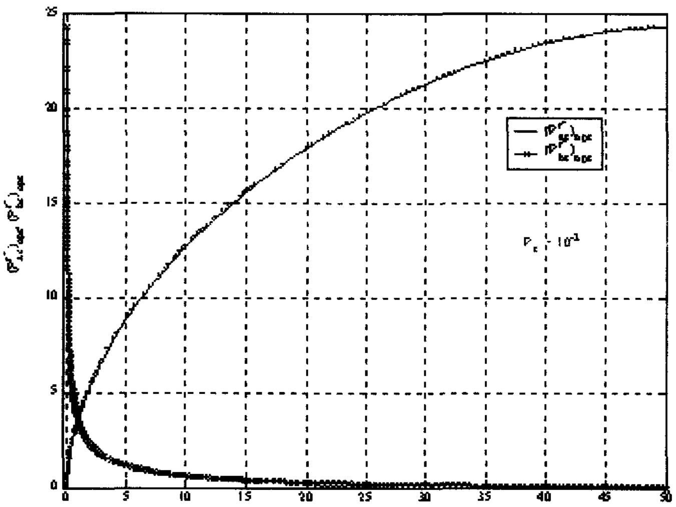


Fig. 12. Optimal received powers on the two diversity branches for a two-leg RAKE receiver for BPSK modulation and $P_e = 10^{-2}$.

Fig. 9 shows the messaging load in terms of number of messages per MT per minute vs. number of MTs in the network. The graphs indicate that power combining generates significant messaging load with respect to the case without power combining. However, this load is only *relatively* large. In the absolute sense, the amount of load ranges from 10 to 15 messages per MT per minute. This is indeed not a large load. On the other hand, based on the idea presented in [3], it is possible for a MT to reduce the number of PCTs it actually initiates or maintains. In such case, the messaging load would also be reduced. Consequently, the graphs in Fig. 11 represent the *upper bound* on the messaging load generated by power combining.

IV. CONCLUSION

In this paper we introduced the use of power combining as a method to reduce total transmit power, combat fading and extend network lifetime of NG multihop wireless networks. The extension of the network lifetime achieved by our scheme ranges from 15% to 90%, depending on the desired error probability, lower error probabilities being more susceptible to benefits from power combining. Therefore, although not originally set out to address the problem of maximizing network lifetime, power combining implicitly extends network lifetime. On the other hand, the average power consumed to route a packet from the source to the destination is reduced by 5% to 95%, again depending on the error probability. This reduction in the average consumed power per routed packet has two implications: one is the extended network lifetime, as discussed above; the other is reduced average total transmit power of the network and hence reduced interference generated to the environment. This is indeed an important achievement, as most of the next generation wireless systems will operate in the unlicensed spectrum, and will therefore be interference sensitive.

The messaging load is relatively much higher than the messaging load without power combining; i.e., related to the exchange of the link information in the network. However, this increase is only relative. We argue that in the absolute sense it is acceptable. In addition to this, the messaging load is subject to further optimization.

Applicability and potential gains of our scheme to the routing problems with multicast nature is a very interesting question. It seems evident that power combining is very suitable for scenarios with multiple destinations.

APPENDIX

In this appendix, the curves of the optimal received powers $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$ for uncoded BPSK modulation, computed numerically as a solution of (6) and (7), are given. As is clear from (6), $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$ depend only on the ratio of channel attenuations, r:

$$r = \frac{d_{bc}^{m}\gamma_{bc}}{d_{ac}^{m}\gamma_{ac}}. \tag{34}$$

Fig. 12 shows $(P_{ac}^{r''})_{opt}$ and $(P_{bc}^{r''})_{opt}$ vs. r for $P_e = 10^{-2}$. The curves for lower P_e are impractical because of the range of both x and y axis, but their trend of increase/decrease is equivalent to the curves shown in the figure.

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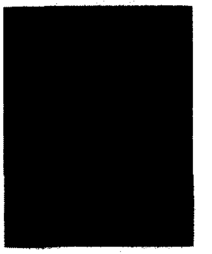

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