Energy Aware Power Allocation strategies for Multihop-Cooperative transmission schemes

Stefano Savazzi, *Student Member, IEEE,* and Umberto Spagnolini, *Senior Member, IEEE*

***Abstract*— This paper is focused on the optimization of transmitted power in a cooperative decoded relaying scheme for nodes belonging to the single primary route towards a destination. The proposed transmission protocol, referred to as Multihop Cooperative Transmission Chain (MCTC), is based on the linear combination of copies of the same message by multiple previous terminals along the route in order to maximize the *multihop diversity*. Power allocations among transmitting nodes in the route can be obtained according to the average (not instantaneous) node-to-node path attenuation using a recursive power assignement. The latter can be employed locally on each node with limited signalling exchange (for fixed or nomadic terminals) among nodes. In this paper the power assignments for the MCTC strategy employing conventional linear combining schemes at receivers (i.e., selection combining, maximal ratio combining and equal gain combining) have been derived analytically when the power optimization is constrained to guarantee the end-to-end outage probability. In particular, we show that the power assignment that minimize the maximum spread of received power (min-max strategy) can efficiently exploit the multihop diversity. In addition, for ad hoc networks where the energy of each node is an issue, the MCTC protocol with the min-max power assignment increases considerably the network lifetime when compared to non-cooperative multihop schemes.**

***Index Terms*— Multihop diversity, cooperative diversity, power allocation, energy efficient transmission techniques, ad-hoc and sensors networks, wireless networks.**

I. Introduction

An ad hoc wireless network consists of mobile terminals (or nodes) that may form a temporary network without the aid of any established infrastructure. If any two nodes are outside their transmission ranges, they could communicate only if other nodes are able to relay their packets. Designing a multihop routing and a resource allocation strategy together with energy preserving transmission techniques is a fundamental issue that synergically involves all layers of the communication system, from the transmission level up to the applications [1]-[3] .

In wireless networks channel fading is one of the main source of impairment that could be mitigated through the use of appropriate spatial redundancy also known as diversity. Since the use of nodes equipped with multiple antennas is not a viable solution, space diversity can be exploited by using distributed antennas belonging to different nodes of the route so as to have a *virtual array* from node cooperation. Through antenna sharing and distributed transmission this cooperative diversity yields to meaningful energy savings and throughput enhancement [4]-[5].

In this paper we investigate the problem of allocating the transmission power among cooperative relaying nodes when the route has been optimized separately (e.g., by any energy aware routing algorithm [6]) and the network design is based on the outage probability. A conventional (non-cooperative) multihop (MH) transmission scheme consists of relaying information on several hops to reduce the need of large power levels at the transmitters and thus prolong node battery lifetime. Transmit power can be assigned on each independent hop according to the constraints on the outage probability [3] or by maximizing end-to-end reliability subject to a power budget [7]. A further reduction of energy consumption follows from the MH transmission scheme that takes advantage of cooperative diversity. This is obtained when multiple previous nodes along the route cooperate to relay the same message to the receiving nodes thus exploiting the benefits of the *multihop diversity* [8].

Energy savings potentialities of multihop diversity mechanisms have been recently investigated in [9] when a selection combining scheme is adopted at the receivers. Starting from these benefits, in this paper we introduce a transmission protocol referred to as Multihop Cooperative Transmission Chain (MCTC) where some nodes along the route cooperate to relay the same message over independent fading channels and the receiving node linearly combines all these contributions. The power assignment of the MCTC is optimized in order to maximize network lifetime by constraining the end-to-end outage probability. More specifically, it is proposed an incremental power assignment algorithm that adds on each hop the minimum power necessary to guarantee end-to-end link quality requirements. The proposed recursive power allocation is based on the knowledge of the average (not instantaneous) channel power attenuation (i.e., path loss and shadowing) and on the combining scheme at each receiving node.

The paper is organized as follows. After a description of the system model (Sect.II), in Sect.III it is reviewed the MH transmission scheme while the MCTC protocol is analyzed in Sect.IV. Two recursive power allocation techniques for the MCTC scheme are optimized (Sect.V) for conventional combining techniques: Maximal Ratio Combining (MRC), coherent Equal Gain Combining (EGC) and Selection Combining (SC). Since the neighboring nodes of the route have to be aware of the average channel state to optimize the power

Manuscript received February 1, 2006; revised June 2, 2006. This work was partially developed within the IST-FP6 Network of Excellence in Wireless Communications (NEWCOM). The authors are with the Dipartimento di Elettronica e Informazione, Politecnico di Milano, I-20133 Milano, Italy (e-mail: savazzi@elet.polimi.it; spagnoli@elet.polimi.it). The material in this paper was presented in part at the IEEE Conference on Information Sciences and Systems, Princeton University, March 2006 and at the 6th Scandinavian Workshop on Wireless Ad-hoc Networks, Stockholm, May 2006.

assignment, in Sect.VI it is proposed a specific signalling protocol that conveys the required estimates at the cooperating nodes. Numerical analysis (Sect.VII) compares the network lifetime of the MCTC with selection combining (SC-MCTC) or maximal ratio combining (MRC-MCTC) with respect to MH for settings with randomly placed nodes having a limited battery energy supply (routing is not dealt with here and it is optimized according to [6]). Furthermore, lifetime benefits from an MCTC protocol are shown for an increasing number of cooperating nodes and sensors deployed.

II. Network and Link model

Let a wireless ad hoc network be represented by a set $\mathcal{G}$ of randomly distributed nodes within a specific area, each node is characterized by a single omnidirectional antenna transceiver and a limited battery energy supply mainly used for the transmission and reception of data. Therefore, careful energy management systems have to be developed in order to cope with network lifetime maximization.

A sequence of messages is continuously transmitted by a *source* node S to a *destination* node D over an optimal "connection oriented" unicast route path $\mathcal{R} \subset \mathcal{G}$. The optimal path towards the destination is established from the network layer and it is composed by a set $\mathcal{R}$ of $|\mathcal{R}| = M$ nodes ordered according to some optimum criterion to relay the data stream to node D. This ordering is labelled as $\mathcal{R} = \{S, 1, 2, ..., M-2, D\}$. Nodes $\mathcal{G} \setminus \mathcal{R}$ that do not belong to the route are kept into a sleep mode by the power management system. The route is assumed to have no interference from other routes and from other nodes by employing a transmission strategy based on time division.

Let the relay processing be characterized by the decode and forward (DF) strategy: when active, the kth node with relaying capabilities is subject to the half duplex constraint and thus it first decodes and then it transmits to the mth node with a power P_k. Propagation between node k and m (with $m, k \in \mathcal{R}$) is characterized by the *link-state* $A_{k,m}$ that accounts for path loss and shadowing. Therefore, the signal received by node m with node k relaying the source message x_S during the time slot t is

$$y_{k\to m}(t) = \sqrt{P_k A_{k,m}} h_{k,m} x_S + n_m(t) \tag{1}$$

where the instantaneous received power $\gamma_{k\to m} = P_k A_{k,m} |h_{k,m}|^2$ has been decoupled into an exponentially distributed fluctuating term $|h_{k,m}|^2 \sim \chi_2^2$ (as $h_{k,m} \sim \mathcal{CN}(0,1)$) that accounts for Rayleigh fading and the average power

$$\bar{\gamma}_{k\to m} = E[\gamma_{k\to m}] = P_k A_{k,m}. \tag{2}$$

The message x_S is one (or a sequence of) complex data symbol(s) drawn from a unit energy constellation and AWGN $n_m(t) \sim \mathcal{CN}(0,1)$ has unit power. According to the normalization of the AWGN, terms $\gamma_{k\to m}$ and $\bar{\gamma}_{k\to m}$ can also be stated as instantaneous and average signal to noise ratio (SNR) at node m, respectively.

In the following we consider a *threshold link model* [10] where the successful reception for the link $k \to m$ is guaranteed as long as $\gamma_{k\to m} \geq \beta$. The outage probability is $\mathcal{P}_{out} = \Pr(\gamma_{k\to m} < \beta)$ while the probability of successful reception is thus $1 - \mathcal{P}_{out}$. To simplify, we assume that each hop of the primary route has the same outage probability $\mathcal{P}_{out} = 1 - (1 - \mathcal{P}_{EE})^{\frac{1}{M-1}}$, to ensure the end-to-end outage reliability $\mathcal{P}_{EE}$. In addition, the transmitting power is also constrained to the maximum power $P_{\max}$ as $P_k \leq P_{\max}$ for every node k.

III. Multihop (MH) transmission

Multihop relaying when the link-layer level cannot support node cooperation is based on the design of the transmission power level P_k^{MH} at node k for the link $k \to k+1$ to account for the fade margin in order to cope with the Rayleigh fading. In order to review the basics of MH transmission (see e.g., [1], [3]), let us refer to the channel model introduced in the previous Sect.II. The cumulative density function (CDF) of the exponentially distributed SNR $\gamma_{k\to k+1}$ is $F_{k\to k+1}(\gamma) = \Pr(\gamma_{k\to k+1} \leq \gamma)$, by introducing a link quality requirement in terms of the pair $(\beta, \mathcal{P}_{out})$ the power P_k^{MH} follows from the constraint

$$F_{k\to k+1}(\beta) = \Gamma\left(\frac{\beta}{A_{k,k+1} P_k^{MH}}\right) = \mathcal{P}_{out} \tag{3}$$

where $\Gamma(\alpha) = 1 - \exp(-\alpha)$. The solution

$$P_k^{MH} = \frac{\beta}{A_{k,k+1} \ln(1 - \mathcal{P}_{out})^{-1}} \tag{4}$$

shows that in MH transmission a fade margin of $1/\ln(1 - \mathcal{P}_{out})^{-1}$ is added to the minimal required transmitting power $\beta/A_{k,k+1}$ in order to cope with channel impairments. The total power consumption of the M nodes along the route $\mathcal{R}$ is

$$P_{(\mathcal{R})}^{MH} = \sum_{k\in\mathcal{R}\setminus\{D\}} P_k^{MH} + (M-1) P_{RX} \tag{5}$$

where P_{RX} is the power consumption of each node during the receiving phase of each message. In the following all the power assignments will be scaled with respect to the MH assignment (4) used as a reference.

IV. Multihop Cooperative Transmission Chain (MCTC) Protocol

Enabling cooperation among transmitting nodes guarantees to efficiently exploit the available node energy. The basic idea is that the required transmitting power P_k from node k towards the next node $k+1$ in the route can be considerably reduced with respect to the MH case if node $k+1$ has the capability of receiving and combining up to c copies of the same message from the previous nodes $\{k-c, ..., k-1\} \in \mathcal{R}$ in addition to the copy from kth node. Let the link quality requirements be given by the pair (β, $\mathcal{P}_{out}$) as for MH (Sect. III); here we adopt the simple repetition based cooperative scheme where $c+1$ copies of each message to be delivered to terminal $k+1$ are transmitted over $c+1$ orthogonal (i.e., non-interfering) subchannels characterized by statistically independent fading to yield a multihop diversity up to degree $c+1$. To take advantage of the diversity from

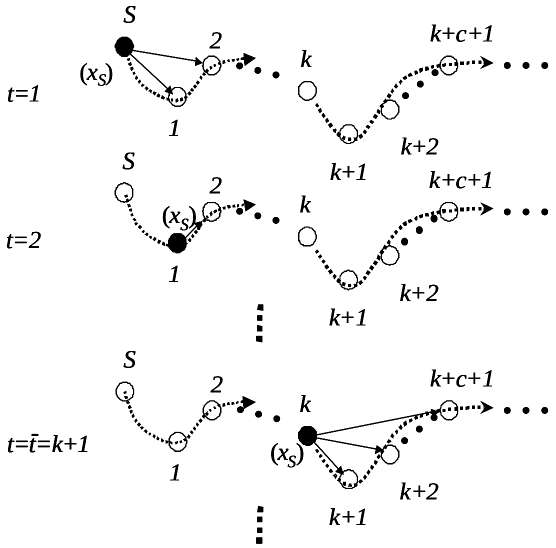


Fig. 1. MCTC timing and propagation of the transmitted message x_S (filled marker).

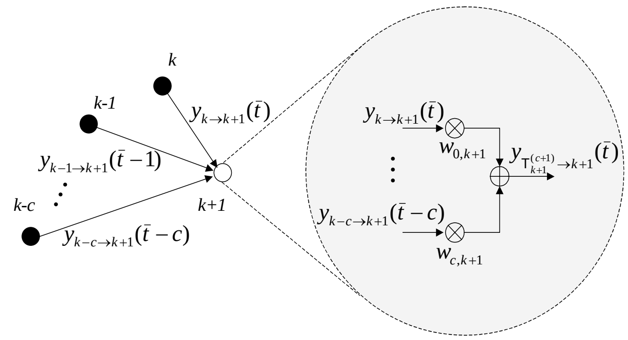


Fig. 2. Cooperating set of nodes relaying copies of the message x_S and the linear combining at the $(k+1)$th node (shaded area).

orthogonal transmissions, in this paper we consider a time division based scheme, the extension to frequency division sub-channelling is straightforward.

The propagation of the message as well as the MCTC scheme is illustrated in figure 1. At time slot $t = 1$ (for convenience the time slots are numbered as for the nodes) the message x_S is transmitted from S and relayed at time $t = 2$ from node 2 and so on. In general, for each transmitting node $k \in \mathcal{R}\diagdown D$ there are $c+1$ subsequent nodes $k+1, ..., k+c+1$ in the route that are receiving. From receiving link (see figure 2), the $(k+1)$th receiver has $c+1$ copies of the same message during $c+1$ subsequent time slots from $\bar{t}-c$ to $\bar{t}$ that can be combined to exploit the multihop diversity order of $c+1$. The cooperative set of nodes that are transmitting towards terminal $k+1$ can be thus defined as:

$$\mathcal{T}_{k+1}^{(c+1)} = \{k-c, ..., k\} \subset \mathcal{R} \tag{6}$$

From figure 2, let the received signals that contain the $c+1$ copies of the same message be collected into the $(c+1) \times 1$ vector $\mathbf{y}_{k+1} = [y_{k\to k+1}(\bar{t}), ..., y_{k-c\to k+1}(\bar{t}-c)]^T$, the model (1) reduces to

$$\mathbf{y}_{k+1} = \mathbf{h}_{k+1} x_S + \mathbf{n}_{k+1} \tag{7}$$

where $\mathbf{n}_{k+1} = [n_{k+1}(\bar{t}), ..., n_{k+1}(\bar{t}-c)]^T$ and $\mathbf{h}_{k+1} = [\sqrt{P_k A_{k,k+1}} h_{k,k+1}, ..., \sqrt{P_{k-c} A_{k-c,k+1}} h_{k-c,k+1}]^T$ accounts for the instantaneous path-gain. According to the assumptions above (i.e., $\mathbf{n}_{k+1} \sim \mathcal{CN}(0, \mathbf{I})$), the $(c+1)$ links can be characterized by the set of average SNRs $\bar{\gamma}_{k+1} = [\bar{\gamma}_{k\to k+1}, ..., \bar{\gamma}_{k-c\to k+1}]^T$. At time slot $\bar{t}$ the only power allocation that needs to be assigned is the one of kth node P_k, this needs to be constrained so that the instantaneous SNR at node $k+1$ *after* the combination of the received copies of the message $\mathbf{y}_{k+1}$ is larger than the threshold β with probability at least $1 - \mathcal{P}_{out}$. As shown in figure 2, each cooperative set may be viewed as composed by one virtual source (node k) and c relays (nodes $k-1, ..., k-c$) cooperating with the source. Moreover, at the same time, data forwarding is carried out through multihop transmission so that an hybrid cooperative and multihop strategy is accomplished. Here we consider a linear combining technique from the cooperative transmitting set $\mathcal{T}_{k+1}^{(c+1)}$ as (see the detailed view in the shaded area of figure 2)

$$y_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(\bar{t}) = \sum_{i=0}^{c} w_{i,k+1}^{*} y_{k-i\to k+1}(\bar{t}-i) = \mathbf{w}_{k+1}^{H} \mathbf{y}_{k+1} \tag{8}$$

where $\mathbf{w}_{k+1} = [w_{0,k+1}, ..., w_{c,k+1}]^T$ is the unit-norm ($\mathbf{w}_{k+1}^{H}\mathbf{w}_{k+1} = 1$) combining vector evaluated from any combining scheme. The instantaneous SNR for the cooperative relays evaluated after the combiner

$$\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} = \mathbf{w}_{k+1}^{H} \left[\mathbf{h}_{k+1}\mathbf{h}_{k+1}^{H}\right] \mathbf{w}_{k+1} \tag{9}$$

has to be optimized to guarantee the outage $\mathcal{P}_{out}$ (see Sect. V).

The total power consumption of the M nodes along the route $\mathcal{R}$ reads:

$$P_{(\mathcal{R})}^{MCTC} = \sum_{k\in\mathcal{R}\diagdown\{D\}} P_k^{MCTC} + G_{RX}(c)(M-1)P_{RX}, \tag{10}$$

where

$$G_{RX}(c) = \frac{(M-1-\frac{c}{2})(c+1)}{M-1} \tag{11}$$

accounts for the power consumption increase during the receiving phase when compared to MH.

V. Power allocation for MCTC

MCTC protocol is intrinsically recursive in the way multihop diversity is employed. Recursive structure maps into the power allocation as we can decide the power assignment for one hop based only on the power values for the previous c hops to guarantee the hop-by-hop outage constraint $\mathcal{P}_{out}$. In this section we propose two energy efficient power allocation strategies tailored for MCTC scheme. Since the performances in terms of outage depend on the choice of the linear combining (8), here we consider the following schemes: Maximal Ratio Combining (MRC), coherent Equal Gain Combining (EGC), and Selection Combining (SC). Notice that, although

MRC and EGC can achieve an higher diversity gain with respect to SC, they both require *instantaneous* channel state information (CSI) for all the cooperating nodes.

A. Recursive Power Allocation (RPA)

Regardless of the linear combining technique adopted, the analytical derivation of the CDF $F_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(\gamma) = \Pr(\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} \leq \gamma)$ for the instantaneous SNR $\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}$ at node $k+1$ is intractable. However, the CDF follows from the Moment Generating Function and it can be stated as (Appendix A)

$$F_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(\gamma) = \psi\left(\gamma; P_k, \mathbf{P}_{(c)}, \mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)},k+1}\right). \quad (12)$$

It depends on the (known) power assignments of the c previous nodes collected into the $c \times 1$ vector $\mathbf{P}_{(c)} = [P_{k-c}, ..., P_{k-1}]^T$, the (unknown) power allocation (P_k) of node k and the (known) link states $\mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)},k+1} = [A_{k-c,k+1}, ..., A_{k,k+1}]^T$ between each node belonging to the cooperative set $\mathcal{T}_{k+1}^{(c+1)}$ and the $(k+1)$th node. The Recursive Power Allocation (RPA) scheme proposed here can be obtained by assigning to each node the minimum power level P_k^{RPA} in order to achieve the link quality requirement $\mathcal{P}_{out}$. Differently from (3), the power allocation P_k^{RPA} can be simplified by taking advantage of (known) power assignments for previous nodes $\mathbf{P}_{(c)}^{RPA} = [P_{k-c}^{RPA}, ..., P_{k-1}^{RPA}]^T$. Power P_k^{RPA} on the last cooperating hop is thus obtained by solving with respect to P_k

$$\psi\left(\beta; P_k, \mathbf{P}_{(c)}^{RPA}, \mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)},k+1}\right) = \mathcal{P}_{out} \quad (13)$$

for each $k \in \mathcal{R} \diagdown \{S, D\}$. The solution of (13) can be found only if $\mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)},k+1}$ is assumed to be known by the kth node. For any pair (β, $\mathcal{P}_{out}$), the resulting power level P_k^{RPA} depends on the power assignment for the previous nodes in the route and on the specific combining scheme (see subsections below) according to the function $\Lambda_{\mathbf{w}}(\cdot)$:

$$P_k^{RPA} = \Lambda_{\mathbf{w}}\left(\mathbf{P}_{(c)}^{RPA}, \mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)},k+1}\right), \quad (14)$$

where subscript $\mathbf{w}$ is used so as to clarify the dependence of the required power levels on the selected combining scheme. Recursive structure has now been made explicit. Of course, for the source $k = S$ there is no cooperation to be exploited and $P_S^{RPA} = P_S^{MH}$. Notice that powers $\mathbf{P}_{(c)}^{RPA}$ are necessary for the computation at node k, estimates of the SNRs $[\bar{\gamma}_{k-c\to k}, ..., \bar{\gamma}_{k-1\to k}]$ and of the link states $\mathbf{A}_{\mathcal{T}_k^{(c)},k} = [A_{k-c,k}, ..., A_{k-1,k}]^T$ are needed too. We refer to Section VI for a discussion on a specific signalling scheme that conveys the estimates of the required link states.

Power assignments with different combining schemes

In this section the power assignments along the route path are derived for $c = 1$ with MRC (Maximal Ratio Combining) and SC (Selection Combining) schemes. Since with EGC (Equal Gain Combining) exact outage probability evaluation can be obtained only through numerical techniques (similarly as in ref. [11]), power values for EGC have been dealt with under the simplifying large fade margin assumption:

$$\bar{\gamma}_{\ell\to k+1} = A_{\ell,k+1} P_\ell^{RPA} \gg \beta \quad (15)$$

for $\ell = k-c, ..., k$. Extension to the case $c > 1$ have been considered separately for all the three combining techniques. Notice that the total power consumption of the route with MCTC protocol follows by substituting the resulting power allocations into (10).

a) Power assignments for the case $c = 1$:

- Power assignments for MRC, $P_k^{RPA}(MRC)$: MRC is known as the optimum combining scheme in AWGN that requires a full CSI at the receiver [11]. The received copies of the signal vector $\mathbf{y}_{k+1}$ at node $k+1$ during the $c+1$ time slots can be coherently combined as

$$w_{i,k+1} = \sqrt{\frac{P_{k-i} A_{k-i,k+1}}{\sum_{i=0}^{c} \gamma_{k-i\to k+1}}} \cdot h_{k-i,k+1}, \quad (16)$$

for $i = 0, 1, ..., c$. The total SNR at the decision variable (9) is:

$$\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} = \sum_{\ell=k-c}^{k} \gamma_{\ell\to k+1}. \quad (17)$$

A closed form solution for the CDF (12) of $\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}$ can be found when $c = 1$ as it reduces to [12]:

$$F_{\mathcal{T}_{k+1}^{(2)}\to k+1}(\gamma) = = \frac{\bar{\gamma}_{k-1\to k+1}\Gamma\left(\frac{\gamma}{\bar{\gamma}_{k-1\to k+1}}\right) - \bar{\gamma}_{k\to k+1}\Gamma\left(\frac{\gamma}{\bar{\gamma}_{k\to k+1}}\right)}{\bar{\gamma}_{k-1\to k+1} - \bar{\gamma}_{k\to k+1}}. \quad (18)$$

By assuming $\mathcal{P}_{out} \ll 1$ and $\Gamma\left(\frac{\gamma}{\bar{\gamma}_{k\to k+1}}\right) \simeq \frac{\gamma}{\bar{\gamma}_{k\to k+1}}$ it is straightforward to prove that the power assignment (14) is:

$$P_k^{RPA}(MRC) \simeq \simeq P_k^{MH}\left(1 - \frac{A_{k-1,k+1}P_{k-1}^{RPA} \cdot \Gamma\left(\frac{\beta}{A_{k-1,k+1}P_{k-1}^{RPA}}\right)}{\beta}\right), \quad (19)$$

for $k \in \mathcal{R} \diagdown \{S, D\}$.

- Power assignments for EGC, $P_k^{RPA}(EGC)$: Although suboptimal, the coherent Equal Gain Combining (EGC) with coherent detection is an attractive solution since it does not require estimation of the fading amplitudes and it results in a reduced complexity receiver when compared to the MRC scheme. In this case the received signals are co-phased before summation. EGC has been proved to be useful in practice for coherent modulation techniques having constant envelope (and constant energy), e.g., M–ary PSK, and OQPSK [13]. If the $k+1$ receiver can exploit $c+1$ copies of the signal, the entries of the vector $\mathbf{w}_{k+1}$ are

$$w_{i,k+1} = \frac{1}{\sqrt{c+1}} \cdot \frac{h_{k-i,k+1}}{|h_{k-i,k+1}|} \quad (20)$$

for $i = 0, 1, ..., c$. The total average SNR at the decision variable (9) is

$$E\left[\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}\right] = \frac{1}{c+1}\left(\sum_{\ell=k-c}^{k}\sqrt{\bar{\gamma}_{\ell\to k+1}}\right)^2 \quad (21)$$

Exact expression for the CDF can be derived by numerical techniques as shown in [11]. However, by adopting the large fade margin assumption (15): $\bar{\gamma}_{\ell\to k+1} = A_{\ell,k+1}P_{\ell}^{RPA} \gg \beta$, the CDF (12), for the case $c = 1$, reduces to

$$F_{\mathcal{T}_{k+1}^{(2)}\to k+1}(\gamma) \simeq \frac{2\gamma^2}{3\prod_{\ell=k-1}^{k}\bar{\gamma}_{\ell\to k+1}} \quad (22)$$

and the power level (14) can be derived in closed form as

$$P_k^{RPA}(EGC) \simeq P_k^{MH}\frac{2\beta}{3A_{k-1,k+1}P_{k-1}^{RPA}}. \quad (23)$$

- Power assignments for SC, $P_k^{RPA}(SC)$: MRC (or EGC) requires full (or partial) CSI at the receiver. On the contrary, in Selection Combining (SC) scheme, the receiver decodes only the received signal in $\mathbf{y}_{k+1}$ with the best SNR. The total SNR at node $k+1$ after selection is

$$\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} = \max\left\{\gamma_{k-c\to k+1}, ..., \gamma_{k\to k+1}\right\}, \quad (24)$$

and the CDF (12) for $c = 1$ is

$$F_{\mathcal{T}_{k+1}^{(2)}\to k+1}(\gamma) = \Gamma\left(\frac{\gamma}{\bar{\gamma}_{k-1\to k+1}}\right)\cdot\Gamma\left(\frac{\gamma}{\bar{\gamma}_{k\to k+1}}\right). \quad (25)$$

The power allocation among nodes in the route (14) can be easily found:

$$P_k^{RPA}(SC) = P_k^{MH}\cdot\Gamma\left(\frac{\beta}{A_{k-1,k+1}P_{k-1}^{RPA}}\right). \quad (26)$$

b) Power assignments for the case $c > 1$: In principle, the extension to $c > 1$ for all the combining schemes needs to follow the same steps above. Exact power assignment can be easily dealt with for the SC case (see Table I). Moreover, by introducing the large fade margin assumption (15), the approximate CDF (12) and power levels (14) can be derived in closed form for MRC and EGC. Both CDF and power assignments are summarized in Table I.

The energy consumption gain of MCTC with recursive power allocation is trivial once proved the inequality

$$P_k^{RPA}(MRC) < P_k^{RPA}(EGC) < P_k^{RPA}(SC) < P_k^{MH}, \quad (27)$$

see Appendix IX-B for detailed proof.

B. Min-Max Power Allocation (MMPA)

Although multihop diversity yields to substantial energy savings with respect to MH, the recursive scheme RPA can be considered as sub-optimal since the power allocation for a kth node relies on power assignment for the previous $c+1$ nodes and it coincides with the minimum power level in order to meet the link quality requirements for the hop $k \to k+1$. Restricting our analysis to $c = 1$, solutions (19), (23) and (26) show that power assignment P_k^{RPA} is minimized when previous assignment P_{k-1}^{RPA} is maximized. Therefore, by choosing the minimum power value on each hop, the RPA strategy does not exploit the full cooperative diversity degree offered by the MCTC scheme as the received powers from the cooperating nodes are unbalanced.

SC
$F_{T_{k+1}^{(c+1)}\to k+1}(\gamma) = \prod_{\ell=k-c}^{k}\Gamma\left(\frac{\gamma}{\bar{\gamma}_{\ell\to k+1}}\right)$
$P_k^{RPA}(SC) = P_k^{MH}\cdot\prod_{\ell=k-c}^{k-1}\Gamma\left(\frac{\beta}{A_{\ell,k+1}P_{\ell}^{RPA}}\right)$
MRC (for $A_{\ell,k+1}P_{\ell}^{RPA} \gg \beta$)
$F_{T_{k+1}^{(c+1)}\to k+1}(\gamma) \simeq \frac{\gamma^{c+1}}{(c+1)!\prod_{\ell=k-c}^{k}\bar{\gamma}_{\ell\to k+1}}$
$P_k^{RPA}(MRC) \simeq \frac{P_k^{MH}\beta^c}{(c+1)!\prod_{\ell=k-c}^{k-1}\bar{\gamma}_{\ell\to k+1}}$
EGC (for $A_{\ell,k+1}P_{\ell}^{RPA} \gg \beta$)
$F_{T_{k+1}^{(c+1)}\to k+1}(\gamma) \simeq \frac{[2(c+1)\gamma]^{c+1}}{[2(c+1)]!\prod_{\ell=k-c}^{k}\bar{\gamma}_{\ell\to k+1}}$
$P_k^{RPA}(EGC) \simeq \frac{[2(c+1)\beta]^c P_k^{MH}}{(2c+1)!\prod_{\ell=k-c}^{k-1}\bar{\gamma}_{\ell\to k+1}}$

TABLE I

CDFs AND RPA BASED POWER ASSIGNMENTS FOR $c \geq 1$.

Optimal power allocation for kth node P_k is a trade off between the minimum power level P_k^{RPA} required according to the RPA strategy and the maximum available power $P_{\max}$ that minimizes the minimum required power level for the next node $k+1$ in the route $P_{k+1}^{RPA} = \Lambda_{\mathbf{w}}\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right)$. By allowing the kth node to be aware of the link states $\mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2} = [A_{k,k+2},\ A_{k+1,k+2}]$ necessary to compute the minimum power level P_{k+1}^{RPA} required by the *next* node in the route, the power assignment at the kth node, herein referred to P_k^{MMPA}, can be stated as the solution to the following min-max optimization problem

$$P_k^{MMPA} = \arg\min_{P_k\in\mathcal{I}_k}\left[\max\left\{\Lambda_{\mathbf{w}}\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right), P_k\right\}\right] \quad (28)$$

where the power is constrained to be within the support: $\mathcal{I}_k = [P_k^{RPA}, P_{\max}]$ and $P_k^{RPA} = \Lambda_{\mathbf{w}}\left(P_{k-1}^{MMPA}, \mathbf{A}_{\mathcal{T}_{k+1}^{(2)},k+1}\right)$. Solution for problem (28) can be reduced as (Appendix C)

$$P_k^{MMPA} = \max\left\{P_k^{RPA}, \hat{P}_k\right\} \quad (29)$$

where

$$\hat{P}_k : \Lambda_{\mathbf{w}}\left(\hat{P}_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right) = \hat{P}_k. \quad (30)$$

In other words, the estimated power $\hat{P}_k$ results in an iterative strategy to balance the SNRs $\bar{\gamma}_{k-1\to k+1}, \bar{\gamma}_{k\to k+1}$ (or equivalently, to minimize the spread) in order to exploit the cooperative diversity.

MRC
$\Lambda\left(P_k, A_{\mathcal{T}_{k+2}^{(2)},k+2}\right) \simeq \frac{\beta P_k^{MH}}{2A_{k,k+2}P_k}$
$\hat{P}_k \simeq \sqrt{\beta P_{k+1}^{MH} \ / \ (2A_{k,k+2})}$
EGC
$\Lambda\left(P_k, A_{\mathcal{T}_{k+2}^{(2)},k+2}\right) \simeq \frac{2\beta P_k^{MH}}{3A_{k,k+2}P_k}$
$\hat{P}_k \simeq \sqrt{2\beta P_{k+1}^{MH} \ / \ (3A_{k,k+2})}$
SC
$\Lambda\left(P_k, A_{\mathcal{T}_{k+2}^{(2)},k+2}\right) \simeq \frac{\beta P_k^{MH}}{A_{k,k+2}P_k}$
$\hat{P}_k \simeq \sqrt{\beta P_{k+1}^{MH} \ / \ A_{k,k+2}}$

TABLE II

MIN-MAX POWER ALLOCATION (30) WITH LARGE FADING MARGIN ASSUMPTION (15) AND $c = 1$.

Depending on the specific combining scheme (8), solution to equation (30) needs to be evaluated numerically. However, for $\mathcal{P}_{out} \ll 1$ and $A_{k,k+2}\hat{P}_k \gg \beta$ (large fade margin assumption) and for any of the combining schemes, the solution of (30) can be approximated in closed form. Power values are summarized in Table II and we refer to Sect. VII-B for their numerical validation.

A partial argument to support the min-max strategy (28), or equivalently (29), as energy savings with respect to the MH is that $\hat{P}_k < P_{k+1}^{MH}$. This inequality can be easily verified as: *i)* P_{k+1}^{MH} is never solution to (30), and *ii)* $\Lambda_{\mathbf{w}}\left(P_{k+1}^{MH}, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right) < P_{k+1}^{MH}$ as far as $P_{k+1}^{MH} > 0$. A numerical validation for the lifetime performance gains that can be achieved through MMPA strategy with respect to both MH and RPA is in Sect.VII-B.

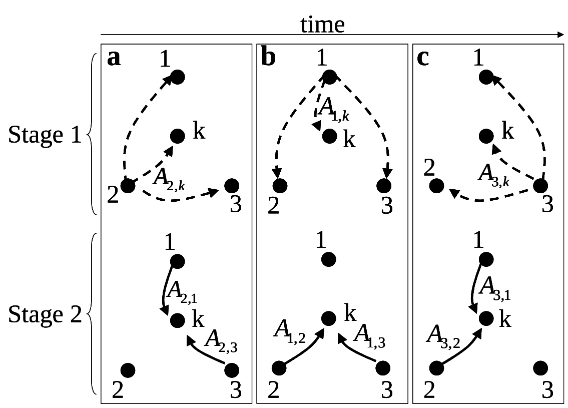


Fig. 3. Message exchange during link state estimation for 3 nodes that belong to the neighbor set $N_k = \{1, 2, 3\}$ of node k

VI. LINK-STATE ESTIMATION

For the case $c = 1$, power allocation schemes require that any node (say node $k \in \mathcal{R}$) has the knowledge of the following average (or slowly-varying) quantities: *i)* $\mathbf{A}_{\mathcal{T}_{k+1}^{(2)},k+1} = [A_{k-1,k+1}, A_{k,k+1}]$, and *ii)* $P_{k-1}^{RPA} = \bar{\gamma}_{k-1\to k}/A_{k-1,k}$. Average signal power $\bar{\gamma}_{k-1\to k}$ in *ii)* can be easily estimated from copies of the the received signal $y_{k-1\to k}(\bar{t}-1)$ over multiple frames. However, "one-hop" link states $[A_{k,k+1}, A_{k-1,k}]$ and the "two-hop" link state $A_{k-1,k+1}$ have to be known during the power allocation phase for the next hop. Here it is proposed a distributed signalling scheme that conveys the required estimates for $c = 1$, figure 3 illustrates the messaging for a 3 nodes neighborhood.

For clarity of exposition, let $\mathcal{N}(k)$ be the *open neighborhood* set that contains the set of the nearest terminals to kth node that fall within the maximum kth node *transmission range* $r_{\max}$; we also define the set $\mathcal{N}[k] = \mathcal{N}(k) \cup \{k\}$ as the *closed neighborhood*. From example in figure 3 it is $\mathcal{N}(k) = \{1, 2, 3\}$ and $\mathcal{N}[k] = \{k, 1, 2, 3\}$. In the following we assume that each k node has the knowledge of its open neighborhood set $\mathcal{N}(k)$.

According to figure 3, let node k start a link state estimation (or update) through a broadcast of a control message (i.e. a beacon frame [13] for beacon-enabled networks) to all $i \in \mathcal{N}(k)$, then there is a two-stage signalling scheme that have to be repeated for each node $i \in \mathcal{N}(k)$ (see sequences **a**, **b** and **c** in figure 3 for a three nodes neighborhood). By focusing on sequence **a**:

Stage 1: node $i = 2$ is the first node that receives and decodes the message, it sends a reply (echo) message (dashed arrows) with the (known) maximum power $P_{\max}$. Since all other nodes $m \in \mathcal{N}[k] \setminus \{i = 2\} = \{k, 1, 3\}$ that sense a busy channel are receiving, "one-hop" neighbor link state $A_{2,k} = \bar{\gamma}_{2\to k}/P_{\max}$ can be easily estimated at node k after some averaging over a time interval larger than fading coherency.

Stage 2: from the average SNR $\bar{\gamma}_{2\to m}$ received by all the $m \in \mathcal{N}(k) \setminus \{i = 2\} = \{1, 3\}$ nodes, link states $A_{2,m} = \bar{\gamma}_{2\to m}/P_{\max}$ can be similarly estimated and thus fed back to node k (solid arrows).

The same signalling scheme is repeated in sequences **b** and **c** for nodes $i = 1$ and $i = 3$, respectively.

A *proactive* link state estimation is thus performed (an equivalent *reactive* based version could be employed as well): all the "one-hop" link states $A_{k,i}$, $\forall i \in \mathcal{N}(k)$ and the "two-hop" one $A_{m,i}$, $\forall i, m \in \mathcal{N}(k)$, $i \neq m$ have to be stored at node k (in addition to the received values $\mathbf{y}_{k+1} = [y_{k\to k+1}(\bar{t}), ..., y_{k-c\to k+1}(\bar{t}-c)]^T$) and periodically updated. According to the setting in figure 3, Table III shows an example of the required link-states stored at k-th node and available at MAC layer for each route including k (notice that we assume channel reciprocity).

It may be noticed that for $c = 2$ the computation of the previous power assignments at node k, $\mathbf{P}_{(c)}^{RPA} =$

Next Hop	Previous Hop	Link States
1 | 2	2 | 1	$A_{1,k}, A_{2,k}, A_{1,2}$
2 | 3	3 | 2	$A_{2,k}, A_{3,k}, A_{2,3}$
1 | 3	3 | 1	$A_{1,k}, A_{3,k}, A_{1,3}$

TABLE III

MAC LAYER TABLE FOR LINK STATES AT NODE k

$\left[P_{k-2}^{RPA}, P_{k-1}^{RPA}\right]$, requires knowledge of the link states $\mathbf{A}_{\mathcal{T}_k^{(2)},k} = [A_{k-2,k}, A_{k-1,k}]$ that can be fed back to node k from $(k-1)$th node. Similarly, we may notice that MMPA scheme (Sect. V-B) requires the link states $\mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}$ to be available at kth node. Therefore, after each link updating phase the states $\mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}$ have to be fed back to node k from the neighbor $(k+1)$th node.

In general, both MMPA and RPA power allocation strategies with $c = 2$ require the estimated link states to be periodically exchanged between neighboring nodes.

VII. Network lifetime maximization using MCTC

Performance gains in terms of network lifetime using the MCTC scheme with respect to a MH based strategy are evaluated numerically. Since both approaches are independent on the above network layer, we compare the maximum lifetime results when assuming two different energy efficient routing algorithms: Minimum Total Transmission Power Routing [6] (MTPR) and the Optimum Link Cost (OLC) based routing algorithm proposed in [14]. Both these routing algorithms are briefly reviewed below to make the paper self-consistent.

A. Maximum battery life routing

Many energy efficient algorithms for routing that focus on network lifetime ΔT_{life} maximization have received considerable attention over the past few years [6]. Let T_i denote the lifetime of node $i \in \mathcal{G}$ (i.e., the time at which it runs out of energy), the network lifetime

$$\Delta T_{life} = \min_{i \in \mathcal{G}} (T_i) \tag{31}$$

is the time of the first node death, and it is equivalent to the earliest network partition time.

Due to its inherent low complexity, we focus on the class of maximum battery life non-cooperative routing algorithms [6] that can be solved by well-known standard shortest path algorithms such as Dijkstra or the distributed Bellman-Ford [15]. They need a link cost metric $C_{i \to j}$ among all links of the network $i, j \in \mathcal{G}$ that can be updated according to the time-varying topology of the network. The routing problem can be solved by finding the path that minimizes the sum of all link costs. In particular, for link $i \to j$ it is

$$C_{i \to j} = (A_{i,j})^{-x_1} \left(\frac{\bar{E}_i}{E_i} \right)^{x_2} \tag{32}$$

where the pair $\bar{E}_i$, E_i are the initial and residual energies of node i, respectively. The MTPR scheme is simply obtained for $x_1 = 1$ and $x_2 = 0$ in (32): the route paths are chosen based on the link states without any knowledge of the residual energy of each node. However, it has been shown that the Optimal Link Cost (OLC) metric (32) should account also for the residual energies at each node and thus one should maximize the network lifetime with respect to x_1 and x_2 (the solution can be numerically evaluated and it leads to $x_1, x_2 > 0$). Here the OLC based routing strategy has been used for $x_1 = 1$ and $x_2 = 30$ in (32). Of course, OLC comes at the expense of increased complexity with respect to MTPR as node residual energy information have to be frequently updated and transmitted among neighboring nodes (notice that routing might change according to the residual energy). As final remark, we may notice that, since both MTPR and OLC schemes are non-cooperative based routing algorithms, resulting paths for cooperative transmission are suboptimal since relay node selection should be accomplished through cross layer interaction between MAC and network layer [16] to design a "cooperative routing" scheme. Nevertheless, in numerical validation below it is shown that the resulting lifetime gains with respect to MH schemes justify the selection of reduced complexity routing strategies where node cooperation is attained entirely at MAC layer.

B. Numerical results

Simulation environment is based on 200 randomly generated network topologies; for each topology there are N nodes uniformly distributed within a square area $50m \times 50m$ of $A_r = 2500m^2$. Each node periodically sends a packet to the common sink node having an infinite power supply. The outlined setting is adopted from the standard IEEE 802.15.4 [13]: carrier frequency $2.45GHz$, maximum bit rate $250kbps$ and packet duration of $T_S = 1.93ms$ (resulting in a physical protocol data unit (PPDU) of 60 octets). Link quality requirements for the application at hand are $\beta = 7dB$ and $\mathcal{P}_{out} = 10^{-6}$.

To simplify the analysis, each node in the network has the same amount of initial energy $\bar{E}_i = n_o \bar{E}$ as a multiple n_o (here $n_o = 320$) of the maximum available energy consumption level $\bar{E} = T_s P_{\max}$ for a transmission with maximum power $P_{\max} = 0dBm$ of a packet to a node at the maximum distance $r_{\max} = 25m$ with path-loss vs distance d as d^{-4}. According to [17] the power consumption during receiving P_{RX} has been set 3dB higher than the minimal average (wrt random node distribution) power level (without fading) required for transmission to a neighbor node: $\beta E[d^4]$. For two dimensional networks, it can be shown that [18] $E[d^4] = 6/\pi^2 \left(A_r/N\right)^2$.

To ensure a fair comparison among different simulation environments, the network lifetime ΔT_{life} is normalized with respect to the initial energy resulting in $T_{life} = \Delta T_{life}/n_o$. Figures 4 and 5 show numerical evaluations of the CDF for the normalized network lifetime T_{life}. Some remarks are in order: *i)* the overhead of the power consumption for the signalling described in Section VI has been neglected; *ii)* since it is of interest here the comparison between two transmission schemes with the same link quality requirements, lifetime reduction due to retransmission after a link failure (equivalent to an outage event caused by fast fading) has been omitted; *iii)* MTPR based routing algorithm (solid lines) and OLC based strategy (dotted lines) are employed at the upper network layer so that performances using MCTC with Selection Combining (SC-MCTC in figure 4) and Maximal Ratio Combining (MRC-MCTC in figure 5) are compared with the MH scheme based on the same routing algorithms; *iv)* the case of $c = 1$ cooperating nodes (power values can be derived from (26) for the SC-MCTC and from (19) for the MRC-MCTC case) and $N = 20$ sensors is considered, in figure 6 results with higher c and N values are given for the case of SC-MCTC with

RPA strategy; *v)* although numerical techniques can be used to derive the exact power values for the Equal Gain Combining case, lifetime results are not considered herein.

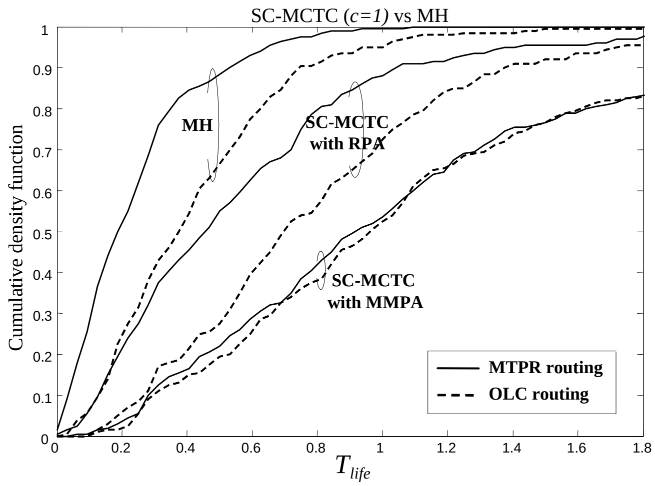


Fig. 4. Cumulative density function for the normalized network lifetime T_{life} for MTPR routing (solid line) and OLC strategy (dotted line) of the proposed MCTC with selection diversity (SC-MCTC) with recursive (RPA) and min-max (MMPA) power allocation schemes. The non-cooperative MH is shown as reference.

From figure 4 the normalized lifetime T_{life} for SC-MCTC shows a larger improvement with respect to non-cooperative MH when the routing is based only on the link states (MTPR strategy). When power allocation is based on the worst-case network topologies the benefits of more complex routing strategy as for OLC vanishes since the cooperative multihop with MMPA has practically the same performance for both routing algorithms considered here. In addition, performance of non-cooperative MH with OLC routing is comparable to the cooperative MCTC with simpler recursive power allocation (RPA) and MTPR routing. This conclusion holds true only for multihop diversity of order 2 while larger degree of cooperative diversity improves the benefits of the MCTC. As conclusion of this numerical analysis, the min-max power allocation in a cooperative transmission scheme has the advantage of reducing the complexity of routing algorithms with an increase of at least $2 \div 3$ times in the average lifetime with respect to MH.

Figure 5 shows the CDF of the normalized lifetime T_{life} of the cooperative multihop protocol MCTC with maximal ratio combining (MRC-MCTC). The use of this optimal combining scheme makes the lifetime almost independent on the two power allocation strategies proposed here and on the routing algorithm employed. However, this result is at the expenses of an higher hardware complexity due to channel estimation processing. MMPA strategy becomes effective when a sub-optimal SC combining scheme is used. Same performances could be obtained by the simpler SC-MCTC scheme with MMPA (Figure 4) and the MRC-MCTC strategy with RPA (figure 5): a trade off between sensor hardware complexity (due to the required channel estimation with MRC) and MAC

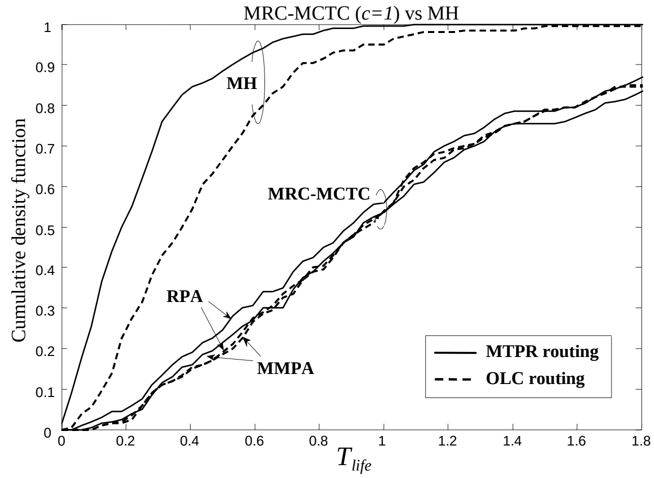


Fig. 5. Cumulative density function for the normalized network lifetime T_{life} for MTPR routing (solid line) and OLC strategy (dotted line) of the proposed MCTC with maximal ratio combining (MRC-MCTC) with recursive (RPA) and min-max (MMPA) power allocation schemes. The non-cooperative MH is shown as reference.

layer complexity (due to MMPA) has to be taken into account. Lifetime improvements of MMPA in conjunction with the optimum MRC combiner are marginal compared to the SC case. The latter result can be motivated by noticing that: *i)* as far as the transmit power level is reduced due to the MMPA strategy, the receiving power becomes crucial in determining the resulting network lifetime; *ii)* the SNR balancing effect (see Sect. V-B) due to the MMPA scheme substantially reduces the performance benefits of the MRC combiner compared to the SC scheme; in particular this holds whenever stringent demands of outage reliability are needed [11].

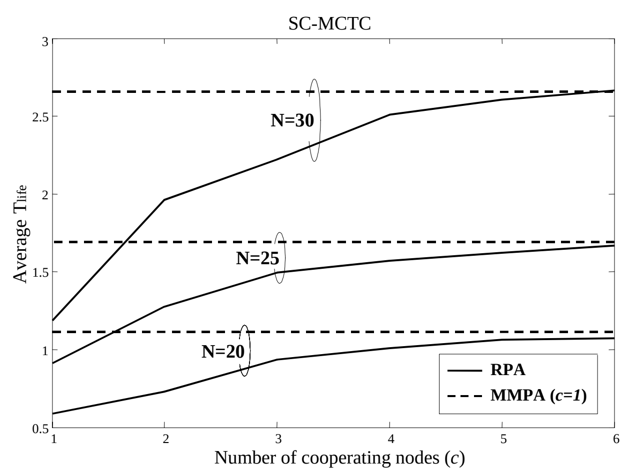


Fig. 6. Lifetime performances for varying number of nodes (N) of an SC-MCTC with RPA (solid lines) power allocation strategy with respect to the number of nodes (c) cooperating with the source. MMPA allocation with $c = 1$ is shown as reference (dashed lines).

For the RPA case, an higher degree of cooperation c is expected to increase the network lifetime. The average lifetime vs the degree of multihop diversity $c+1$ is shown in figure 6 when employing selection-diversity (SC-MCTC scheme) and increasing sensors' density featuring $N = 20$, 25 and 30 sensors in $A_r = 2500m^2$. MMPA strategy with $c = 1$ (dashed lines) is compared with the RPA (solid lines) for an increasing c value (power levels in Table I have been considered) and by assuming an MTPR routing algorithm at the network layer. When c is large enough (in our case $c \geq 6$), the average lifetime resulting from RPA coincides with the one resulting from MMPA with $c = 1$ as RPA allows a greater number of nodes to be involved in cooperation and thus a greater MAC layer complexity. When increasing the density of nodes (here $N = 30$) RPA derives a substantial benefit from an high number of cooperating nodes as path diversity can be better exploited.

VIII. Conclusion

The proposed hybrid multihop-cooperative transmission scheme (MCTC) takes advantage of cooperative and multihop diversity benefits with linear combining schemes. Two energy aware power allocation schemes have been tailored for MCTC to efficiently exploit the recursive structure with minimal signalling among neighbor nodes. Power values can be easily obtained at network setup (or during the updating) as they are based on the knowledge of the *average* attenuation for neighboring nodes. Through a proper design of the power allocation among cooperating nodes belonging to the primary route, we show that network lifetime performances can be considerably increased compared to the non-cooperative mutihop case. Moreover, considering a practical case where only $c = 1$ node along the route is cooperating and a simple selection combining scheme is used, the proposed min-max power allocation strategy (MMPA) exhibits similar lifetime performances to other more complex policies that allow a greater number of cooperating nodes, or combining schemes that require istantaneous channel estimates at the receivers.

As a final remark, the relaying nodes belonging to the route path and employing the MCTC protocol are selected without any cross layer interaction between MAC and network layer. Route selections based on different performance metrics [19] (i.e., end-to-end delay or packet throughput) rather than power consumption could be employed as well.

IX. Appendix

A. CDF $F_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}(\gamma)$ in (12)

The CDF (12) of $\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}$ refers to the istantaneous SNR at node $k+1$ after linear combination of the $c+1$ signal replicas, it can be written in terms of the instantaneous SNR $\gamma_{k+1} = [\gamma_{k \to k+1}, ..., \gamma_{k-c \to k+1}]^T$ as $\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1} = \mathcal{W}(\gamma_{k+1})$, where $\mathcal{W}(\cdot)$ depends on the combining scheme. Since Rayleigh fading is uncorrelated among different paths, the moment generating function of $\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}$ depends on $\bar{\gamma}_{k+1} = E[\gamma_{k+1}] = diag(\mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)}, k+1}) \cdot [\mathbf{P}_{(c)}^T, P_k]^T$, where we recall that $\mathbf{P}_{(c)} = [P_{k-c}, ..., P_{k-1}]^T$ relies on the (known) power assignments of the c previous nodes and $\mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)}, k+1} = [A_{k-c,k+1}, ..., A_{k,k+1}]^T$:

$$\Psi(s; \bar{\gamma}_{k+1}) = $$
$$= E[\exp(-\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1} s)] =$$
$$= \int\limits_{\gamma_{k+1} \succcurlyeq 0} \exp(-\mathcal{W}(\gamma_{k+1})s) \prod_{\ell=k-c}^{k} \frac{\exp\left(-\frac{\gamma_{\ell \to k+1}}{\bar{\gamma}_{\ell \to k+1}}\right)}{\bar{\gamma}_{\ell \to k+1}} d\gamma_{k+1} \tag{33}$$

(notice that all SNRs in vector γ_{k+1} have probability $\Pr(\gamma_{\ell \to k+1}) = \exp\left(-\frac{\gamma_{\ell \to k+1}}{\bar{\gamma}_{\ell \to k+1}}\right) / \bar{\gamma}_{\ell \to k+1}$, $\ell = k, ..., k-c$). Exploiting the Laplace inversion theorem [11] the CDF reduces to

$$\psi(\gamma; P_k, \mathbf{P}_{(c)}, \mathbf{A}_{\mathcal{T}_{k+1}^{(c+1)}, k+1}) =$$
$$= \frac{1}{2\pi j} \int_{a-j\infty}^{a+j\infty} \frac{\Psi(s; \bar{\gamma}_{k+1})}{s} \exp(\gamma s) ds, \tag{34}$$

as (12) in the main text (a is a real number so that the contour path of integration is in the region of convergence of $\Psi(s; \bar{\gamma}_{k+1})$).

B. Proof of eq. (27)

The energy-saving relationship of the MCTC $P_k^{RPA}(MRC) < P_k^{RPA}(EGC) < P_k^{RPA}(SC) < P_k^{MH}$ is proved for any degree of multihop diversity c by first deriving the ratios P_k^{RPA}/P_k^{MH} for different combining schemes and then by checking all the inequalities in the chain (27). Recall that herein the large fade margin assumption (15) is used.

- Derivation of $P_k^{RPA}(MRC)/P_k^{MH}$: From equation (19), for the case $c = 1$, it is enough to show that

$$\frac{\bar{\gamma}_{k-1 \to k+1} \Gamma\left(\frac{\beta}{\bar{\gamma}_{k-1 \to k+1}}\right)}{\beta} > 0 \tag{35}$$

  for any $\bar{\gamma}_{k-1 \to k+1} > 0$. The proof is straightforward since $\Gamma\left(\frac{\beta}{\bar{\gamma}_{k-1 \to k+1}}\right) > 0$ for $\forall \bar{\gamma}_{k-1 \to k+1} > 0$. In particular, it can be easily shown that when $\bar{\gamma}_{k-1 \to k+1} \simeq \beta$ the ratio $P_k^{RPA}(MRC)/P_k^{MH} \simeq 1/e$ or equivalently the power gain of the MRC is $4.3dB$. When the assumption in (15) holds true, the energy gain of an RPA power allocation strategy employing MRC with respect to MH can be written as a function of c

$$\frac{P_k^{RPA}(MRC)}{P_k^{MH}} \simeq \frac{\beta^c}{(c+1)! \prod_{\ell=k-c}^{k-1} \bar{\gamma}_{\ell \to k+1}}. \tag{36}$$

- Derivation of $P_k^{RPA}(EGC)/P_k^{MH}$: For large fade margin (15) the energy gain of the RPA strategy when employing EGC-MCTC with respect to MH can be written as a function of c:

$$\frac{P_k^{RPA}(SC)}{P_k^{MH}} \simeq \frac{[2(c+1)]^c}{(2c+1)!} \frac{\beta^c}{\prod_{\ell=k-c}^{k-1} \bar{\gamma}_{\ell \to k+1}}. \tag{37}$$

- Derivation of $P_k^{RPA}(SC)/P_k^{MH}$: From equation (26), for the case $c = 1$, since $\bar{\gamma}_{k-1 \to k+1} > 0$ it is

$\Gamma\left(\frac{\beta}{\bar{\gamma}_{k-1\rightarrow k+1}}\right) < 1$. As before, if $\bar{\gamma}_{k-1\rightarrow k+1} \simeq \beta$ it is $P_k^{RPA}(SC)/P_k^{MH} \simeq 1-1/e$ and thus there is $2dB$ power gain with respect to MH case. When assumption in (15) holds, energy gain of an RPA power allocation strategy employing SC-MCTC with respect to MH can be written as a function of c:

$$\frac{P_k^{RPA}(SC)}{P_k^{MH}} \simeq \frac{\beta^c}{\prod_{\ell=k-c}^{k-1} \bar{\gamma}_{\ell\rightarrow k+1}}. \qquad (38)$$

- Proof of $P_k^{RPA}(MRC) < P_k^{RPA}(EGC) < P_k^{RPA}(SC)$: From assumption in (15), and recalling (36), (38) and (37), the inequality is proved by checking that

$$\frac{1}{(c+1)!} < \frac{[2(c+1)]^c}{(2c+1)!} < 1. \qquad (39)$$

Left side inequality can be reduced to $\prod_{i=0}^{c-1}(2c+1-i) < [2(c+1)]^c$ and it is proved as $\prod_{i=0}^{c-1}(2c+1-i) < (2c+1)^c < [2(c+1)]^c$. Although the right side inequality in (39) can be numerically verified, proof for the case $c \rightarrow \infty$ can be easily dealt with by using the Stirling formula [20]: right inequality may be easily rewritten for $c \rightarrow \infty$ as

$$\frac{1}{2\sqrt{\pi c}\exp(-2c)\,(2c)^c} < 1, \qquad (40)$$

and this proves the inequality asymptotically.

C. Min-Max problem (28)

Let $\hat{P}_k$ be the solution of (30), when $P_k^{RPA} > \hat{P}_k$ the optimization (28) can be written as

$$P_k^{MMPA} = \arg\min_{P_k}[P_k] \qquad (41)$$
$$s.t.\ P_k^{RPA} \leq P_k \leq P_{\max}$$

and the solution is: $P_k^{MMPA} = P_k^{RPA}$. On the contrary, when $P_k^{RPA} \leq \hat{P}_k$ (28) can be decoupled into two problems

$$\begin{cases} P_k^{MMPA} = \arg\min_{P_k}\left[\Lambda_{\mathbf{w}}\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right)\right] \\ \qquad s.t.\ P_k^{RPA} \leq P_k \leq \hat{P}_k \\ P_k^{MMPA} = \arg\min_{P_k}[P_k] \\ \quad s.t.\ \hat{P}_k < P_k \leq P_{\max} \end{cases} \qquad (42)$$

the solution is $P_k^{MMPA} = \hat{P}_k$. Including both cases, solution to the original problem (28) reduces to the solution (29) in the main text.

REFERENCES

[1] V. Rodoplu, T. H. Meng, "Minimum energy mobile wireless networks," *IEEE Journal on Sel. Areas in Comm.* vol. 17, no. 8, pp. 1333-1344, Aug. 1999.

[2] R. Madan, C. Shuguang, S. Lall, A. Goldsmith, "Cross-layer design for lifetime maximization in interference-limited wireless sensor networks," in *Proc. of IEEE INFOCOM 2005*, vol. 3, pp. 1964-1975, Mar. 2005.

[3] M. Haenggi, "On routing in random Rayleigh fading networks," *IEEE Trans. on Wireless Comm.*, vol.4, pp.1553-1562, Jul. 2005.

[4] J. N. Laneman, D. N. C. Tse and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol.50, pp.3062-3080, Dec. 2004.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity, Part I: System description," *IEEE Trans. on Commun.*, vol. 51, pp 1927-1938, Nov. 2003.

[6] C. K. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," *IEEE Comm. Magazine*, pp.138-147, June 2001.

[7] M. O. Hasna, M. S. Alouini, "Optimal power allocation for relayed transmissions over Rayleigh-fading channels," *IEEE Trans. on Wireless Comm.*, vol. 3, no. 6, pp. 1999-2004, Nov. 2004.

[8] J. Boyer, D. D. Falconer, H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. on Comm.*, vol.52, pp.1820-1830, Oct. 2004.

[9] M. Haenggi, "Analysis and design of diversity schemes for ad hoc wireless networks," *IEEE Journal on Sel. Areas in Comm.*, vol. 23, no. 1, pp.19-27, Jan. 2005.

[10] P. Gupta, P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. on Inform. Theory*, vol.46, pp.338-404, March 2000.

[11] M. K. Simon, M. S. Alouini, *Digital Communication over Fading Channels*, Wiley Interscience, 2004.

[12] B. B. Barrow, "Diversity combination of fading signals with unequal mean strengths," *IEEE Trans. on Commun.*, vol. 11, no. 1, pp. 73 - 78, Mar 1963.

[13] Standard specifications 802.15.4-2003, available at *http://www.ieee802.org/15/pub/TG4.html.*

[14] J. H.Chang, L. Tassiulas, "Maximum lifetime routing in wireless sensors networks," *IEEE/ACM Trans. on Networking*, vol.12, no.4, pp.609-619, Aug. 2004.

[15] D. Bertsekas, R. Gallager, *Data Networks*, Prentice Hall Ed. 2002.

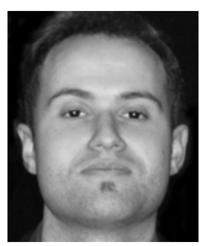
[16] Z. Yang, J. Liu, A. H. Madsen, "Cooperative routing and power allocation in ad-hoc networks," in *Proc. of IEEE GLOBECOM '05*, vol. 5, pp. 2730 - 2734 28 Dec. 2005.

[17] S. Basagni, M. Conti, S. Giordano and I. Stojmenovic, *Mobile Ad Hoc Networking*, IEEE Press 2004.

[18] M. Haenggi, "On distances in uniformly random networks," *IEEE Trans. on Inform. Theory*, vol.51, pp.3584-3586, Oct. 2005.

[19] E. M. Royer, C. K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Pers. Communic.*, pp. 46-55, Apr. 1999.

[20] M. Abramowitz, I. A. Stegun, *Handbook of Mathematical Functions*, ref. 6.1.39, 1970.



Stefano Savazzi (S'05) received the M.Sc. degree (with honors) from the Politecnico di Milano, Milan, Italy, in December 2004, where he is currently working toward the Ph.D. degree. From March to July 2005, he was a Visiting Researcher at the Signals and Systems department, Uppsala University, Sweden. He holds a patent on the work developed for his M.S. thesis. His current research interests include signal processing aspects for digital wireless communications and, more specifically, antenna array processing for MIMO systems, minimum energy design for wireless ad-hoc networks, wireless relay channels.

Umberto Spagnolini (SM'03) received the Dott.Ing. Elettronica degree (cum laude) from Politecnico di Milano, Milan, Italy, in 1988. Since 1988, he has been with the Dipartimento di Elettronica e Informazione, Politecnico di Milano, where he is Full Professor in Telecommunications. His general interests are in the area of statistical signal processing. The specific areas of interest include channel estimation and space-time processing for wireless communication systems, parameter estimation and tracking, signal processing and wavefield interpolation applied to UWB radar, geophysics, and remote sensing. Dr. Spagnolini serves as an Associate Editor for the IEEE Transactions on Geoscience and Remote Sensing.