Energy Aware Power Allocation strategies for Multihop-Cooperative transmission schemes

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***Abstract*— This paper deals with a cooperative decoded relaying scheme in multihop wireless network and the corresponding transmitters power allocation strategies for nodes belonging to a single primary route towards a destination. The proposed transmission strategy is referred as Multihop Cooperative Transmission Chain (MCTC). The MCTC is based on the relays of the same message by multiple previous terminals along the route and on their linear combination at the receiver 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 attenuation using a recursive power assignement that can be employed locally with minimal signalling exchange among nodes. In this paper the MCTC with selection combining strategy at receivers and power assignement that minimizee the maximum spread of received power (min-max strategy) is able to better exploit the multihop diversity. In addition, for ad hoc network where the energy of each node is an issue, the MCTC considerably increases the network lifetime when compared to non-cooperative multihop schemes.**

I. INTRODUCTION

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 multihop routing strategy together with energy preserving transmission techniques is a fundamental issue that involves at all layers of the communication system, from the hardware up to the applications [1].

In wireless networks channel fading is one of the main source of impairment that can 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 a meaningful energy savings and throughput enhancement [2].

In this paper we investigate the problem of allocating the transmit power among cooperative relaying nodes when the route has been optimized separately (e.g., by any energy aware routing algorithm [3]) and the network design is based on the outage probability. Conventional (non-cooperative) multihop (MH) transmission scheme is known to be an energy aware strategy that allocate the power on each independent hop according to the outage constraint [1]. A further reduction of energy consumption arises from MH transmission scheme that takes advantage of cooperative diversity when multiple previous nodes along the route cooperate to relay the same message to the receiving nodes in a so called *multihop diversity* [4]. Starting from the benefits established for the multihop diversity, in this paper we propose a transmission strategy 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. Power allocation for relayed transmission schemes have been dealt with in [5] by minimizing end-to-end outage probability subject to a power budget constraint, herein a different approach is considered where the minimum power assignment of MCTC is optimized in order to guarantee the end-to-end network constraint and maximize network lifetime. More specifically, it is proposed an incremental power assignment algorithm that adds the needed power on each hop to guarantee the end-to-end outage probability. The recursive power allocation at transmitter is based on the knowledge of the average (not instantaneous) attenuation (i.e., path loss and shadowing) and on the combining scheme at receiving node.

The paper is organized as follows: the system model is described in Sect.II while Sect.III gives an overview of the MH transmission scheme. Sect.IV illustrates the MCTC strategy and sheds a light on its energy savings potentialities. Two recursive power allocation techniques for MCTC scheme employing the selection combining (SC-MCTC) are proposed in Sect.V together with a specific signalling protocol that conveys the required estimates at the cooperating nodes. Sect.VI shows the performance comparison of SC-MCTC and MH in terms of network lifetime for settings with randomly placed nodes of limited battery energy supply (routing is optimized according to [3]). In summary, SC-MCTC with diversity order of 2 (i.e., one cooperating node) has an average lifetime that is at least 3 times the one for MH.

II. NETWORK AND LINK MODEL

A wireless ad hoc network is 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 *source* node (S) generates a data stream for a *destination* node (D). Let us assume that an optimal unicast route path $\mathcal{R} \subset \mathcal{G}$ from node S to D has been established from the network layer and it is composed by a set $\mathcal{R}$ of $|\mathcal{R}| = M$ of nodes ordered according to some optimum criterion to relay the data stream to node D, let the ordering be labelled as $\mathcal{R} = \{S, 1, 2, ..., M-2, D\}$. Nodes that do not belong to the route $\mathcal{G} \setminus \mathcal{R}$ are kept into a sleep mode by the power management system. To avoid any interference, it is assumed that transmission strategy is based on time division.

Let the relay processing be characterized by the Decode and Forward (DF) strategy: if node $k \neq D$ has relaying capabilities, it first decodes and then retransmits the same message to the next scheduled node in the route. When active, the kth node transmits to the mth node with a power P_k and it is not able to receive simultaneously (half duplex constraint). 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. The signal received by node m with node k relaying the source message $x_S(t)$ during the time slot t is

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

where the instantaneous received power $\gamma_{k \to m} = \bar{\gamma}_{k \to m} |h_{k,m}|^2$ has been decoupled into a fluctuating term $h_{k,m} \sim \mathcal{CN}(0,1)$ that accounts for Rayleigh fading and the average power

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

The message $x_S(t)$ is a sequence of complex data symbols drawn from a unit energy constellation and AWGN $n_m(t) \sim \mathcal{CN}(0,1)$ has unit power. Since $|h_{k,m}|^2 \sim \chi_2^2$, it is exponentially distributed and, 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* [6] 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 $P_{out} = prob(\gamma_{k \to m} < \beta)$ while the probability of successful reception is thus $1 - P_{out}$. To simplify, we assume that each hop of the primary route has the same outage probability so that to ensure the end-to-end outage probability P_{EE} each hop is constrained to have $P_{out} = 1 - (1 - P_{EE})^{\frac{1}{M-1}}$. This choice guarantees a fair comparison of any power allocation strategy when evaluated in term of global performance as network lifetime.

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] and [7]), 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 $F_{k \to k+1}(\gamma) = prob(\gamma_{k \to k+1} \leq \gamma)$, by introducing a link quality requirement in terms of the pair (β, P_{out}) the power P_k^{MH} follows from the constraint

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

where $\Gamma(\alpha) = 1 - \exp(-\alpha)$ as

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

Thus in MH transmission a fade margin of $1/\ln(1 - P_{out})^{-1}$ is added to the minimal required transmitting power $\beta / A_{k,k+1}$ in order to cope with channel impairments. In the following all the power assignments will be scaled with respect to the MH assignment (4).

IV. MULTIHOP COOPERATIVE TRANSMISSION CHAIN (MCTC)

Enabling cooperation among transmitting nodes guarantees to exploit more power efficient strategies. 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, P_{out}) as for MH (Sect.III), here we propose a simple repetition based cooperative scheme where a $c+1$ copies of each message to be transmitted to terminal $k+1$ are transmitted over $c+1$ orthogonal (on non-interfering) subchannels characterized by statistically independent fading, multihop diversity up to degree $c+1$ can be obtained by the receiver depending on the specific combining technique. In the following we consider a time division based scheme with $c = 1$ as the extention to larger degree of cooperation ($c > 1$) and to frequency division sub-channelling is straightforward.

The MCTC scheme is illustrated in figure 1. For each transmitting node $k \in \mathcal{R} \setminus S$ there are 2 subsequent nodes $k+1, k+2$ (solid and dashed arrows in figure 1 at slot t) in the route that are receiving. From receiving link, the $(k+1)$th receiver has 2 copies of the same message during 2 subsequent time slots $t-1$ and t that can be combined to exploit the multihop diversity order of 2, the cooperative set of nodes is thus $\mathcal{T}_{k+1} = \{k-1, k\} \subset \mathcal{R}$. Received signals can be collected into 2×1 vector $\mathbf{y} = [y_{k \to k+1}(t), y_{k-1 \to k+1}(t-1)]^T$ and these are characterized by the average SNRs for each time slot $\{\bar{\gamma}_{k \to k+1}, \bar{\gamma}_{k-1 \to k+1}\}$. At time slot t the only power allocation that is to be assigned is the one of kth node P_k that has to be constrained so that the instantaneous SNR at node $k+1$ after the combination of the received copies of the message $\mathbf{y}$ is larger than the threshold β with probability at least $1 - P_{out}$. Here we consider a linear combining technique from the cooperative transmitting set $\mathcal{T}_{k+1}$ as

$$y_{\mathcal{T}_{k+1} \to k+1}(t) = \mathbf{w}^H \mathbf{y} \tag{5}$$

where $\mathbf{w} = [w_0, w_1]^T$ is the unit-norm combining vector (i.e., $\mathbf{w}^H \mathbf{w} = 1$) evaluated from any known combining scheme. Of course, the $(k+1)$th receiver has to know the

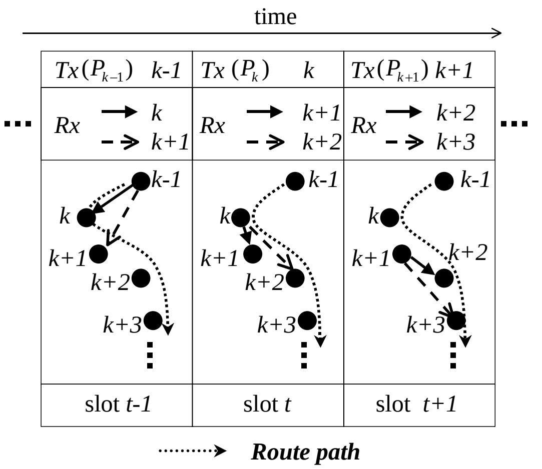

Fig. 1. Multihop Cooperative Transmission Chain time division structure for the case $c = 1$

instantaneous channel state for all the set $\mathcal{T}_{k+1}$ while the power allocation at the transmitter k is based on knowledge the *average* attenuation $A_{k,k+1}$ only.

V. POWER ALLOCATION FOR MCTC

MCTC protocol is intrinsically recursive, this reflects in the power allocation as we can restrict the power assignment only to the previous hop to guarantee the hop-by-hop outage constraint P_{out}. In this section we propose two energy efficient power allocation strategies tailored for MCTC scheme with selection combining (SC-MCTC), other combiners in (5) that require *instantaneous* channel state information at each receiver are not discussed in this paper due to lack of space. However, some numerical evaluation for maximal ratio combiner is compared to SC-MCTC in Sect.VI.

A. Recursive Power Allocation (RPA)

Although for any linear combining technique the analytical derivation of the CDF $F_{\mathcal{T}_{k+1}\rightarrow k+1}(\gamma) = prob(\gamma_{\mathcal{T}_{k+1}\rightarrow k+1} \leq \gamma)$ of the instantaneous SNR $\gamma_{\mathcal{T}_{k+1}\rightarrow k+1}$ at node $k+1$ after the combiner is intractable, this can be described as

$$F_{\mathcal{T}_{k+1}\rightarrow k+1}(\gamma) = \Psi\left(\gamma; P_k, P_{k-1}, \mathbf{A}_{\mathcal{T}_{k+1},k+1}\right), \qquad (6)$$

in terms of the (known) power assignment of the previous node P_{k-1}, the (unknown) power allocation (P_k) of node k, the link states $\mathbf{A}_{\mathcal{T}_{k+1},k+1} = [A_{k,k+1}, A_{k-1,k+1}]^T$ between each node belonging to the cooperative set $\mathcal{T}_{k+1}$ and $k+1$. The Recursive Power Allocation (RPA) scheme can be obtained by assigning to each node the minimum power level P_k^{RPA} in order to achieve the link quality requirement P_{out}. Differently from (3) the power allocation P_k^{RPA} can be reduced by taking advantage of power assignment for previous node P_{k-1}^{RPA}. Power P_k^{RPA} is obtained by solving with respect to P_k

$$\Psi\left(\beta; P_k, P_{k-1}^{RPA}, \mathbf{A}_{\mathcal{T}_{k+1},k+1}\right) = P_{out} \qquad (7)$$

for each $k \in \mathcal{R} \diagdown \{S, D\}$. The solution can be found if $\mathbf{A}_{\mathcal{T}_{k+1},k+1}$ is assumed to be known by kth node. Similarly to MH (4), for any pair (β, P_{out}) the power level P_k^{RPA} depends on the power assignment for the previous nodes in the route according to the function $\Lambda(\cdot)$ as

$$P_k^{RPA} = \Lambda\left(P_{k-1}^{RPA}, \mathbf{A}_{\mathcal{T}_{k+1},k+1}\right), \qquad (8)$$

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 node k is aware of the power P_{k-1}^{RPA} as it estimates the SNR $\bar{\gamma}_{k-1\rightarrow k}$ and the link state $A_{k-1,k}$ (see Sect.V-C)

1) Selection combining MCTC: In selection combining (SC) scheme the receiver chooses (and decodes) from vector $\mathbf{y}$ the received signal with the largest SNR. The instantaneous SNR at node $k+1$ reads

$$\gamma_{\mathcal{T}_{k+1}\rightarrow k+1} = \max\left\{\gamma_{k-1\rightarrow k+1}, \gamma_{k\rightarrow k+1}\right\}, \qquad (9)$$

thus the optimization problem can be stated as in (7) where the CDF $F_{\mathcal{T}_{k+1}\rightarrow k+1}(\gamma)$ follows from the product $F_{\mathcal{T}_{k+1}\rightarrow k+1}(\gamma) = \Gamma\left(\frac{\gamma}{A_{k-1\rightarrow k+1}P_{k-1}^{RPA}}\right)\Gamma\left(\frac{\gamma}{A_{k\rightarrow k+1}P_k}\right)$. Power allocation for the kth node in the route can be easily found as

$$P_k^{RPA} = P_k^{MH} \cdot \Gamma\left(\frac{\beta}{A_{k-1,k+1}P_{k-1}^{RPA}}\right) \qquad (10)$$

A proof of the energy gain with respect to MH case is straightforward as the second term in (10) is strictly lower than 1.

B. Min-Max Power Allocation (MMPA)

Although multihop diversity yields to a substantial energy savings with respect to MH, the RPA scheme is sub-optimal as the power allocation for a kth node relies on power assignment for the previous $(k-1)$th node and it coincides with the minimum power level in order to meet the link quality requirements for the hop $k \rightarrow k+1$. However, the analysis of the solution (10) shows 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.

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 $P_{k+1}^{RPA} = \Lambda\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right)$. By allowing the kth node to be aware of the link states $\mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2} = [A_{k+1,k+2},\ A_{k,k+2}]$ 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

$$P_k^{MMPA} = \arg\min_{P_k \in \mathcal{I}_k}\left[\max\left\{\Lambda\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right), P_k\right\}\right] \qquad (11)$$

where the power is constrained to be within the support: $\mathcal{I}_k = [P_k^{RPA}, P_{\max}]$ and $P_k^{RPA} = \Lambda\left(P_{k-1}^{MMPA}, \mathbf{A}_{\mathcal{T}_{k+1}^{(2)},k+1}\right)$.

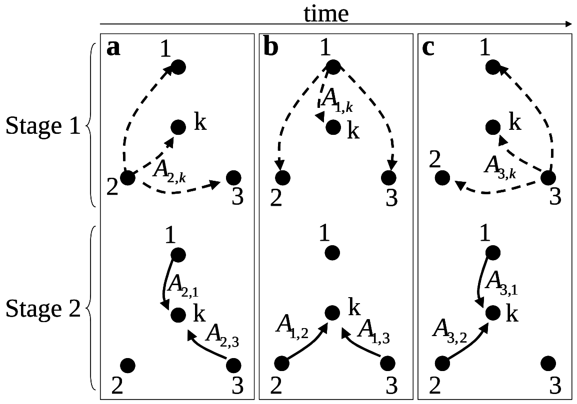

Fig. 2. Message exchange during link state estimation, 3 nodes belong to the neighbor set $N_k = \{1, 2, 3\}$ of node k

Solution for problem (11) can be reduced as (Appendix C)

$$P_k^{MMPA} = \max\left\{P_k^{RPA}, \hat{P}_k\right\} \tag{12}$$

where

$$\hat{P}_k : \Lambda\left(\hat{P}_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right) = \hat{P}_k. \tag{13}$$

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.

Depending on the specific combining scheme (**??**), solution to equation (13) 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 (13) can be approximated in closed form. Power values are summarized in Table **??** and we refer to Sect. VI-B for their numerical validation.

A partial argument to support the min-max strategy (11), or equivalently (12), 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 (13), and *ii)* $\Lambda\left(P_{k+1}^{MH}, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right) < P_{k+1}^{MH}$ 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.VI-B.

C. Link state estimation

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)* $\mathbf{A}_{\mathcal{T}_{k+1},k+1} = [A_{k,k+1}, A_{k-1,k+1}]$, 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 the received signals over several slots $\{y_{k-1\to k}(t-1)\}$. 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. Herein it is proposed a distributed signalling scheme that conveys the required estimates as outlined in figure 2 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 2 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 2, let node k start a link state estimation (or update) through a broadcast of a control message 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 boxes **a**, **b** and **c** in figure 2 for a three nodes neighborhood). By focusing on box **a**:

Stage 1: node $i = 2$ is the first node that sense a free carrier (assuming to employ a carrier sense multiple access as in standard IEEE 802.15.4 [8]) and thus it sends a reply (echo) message (dashed arrows) with a known maximum power level $P_{\max}$. All other nodes $m \in \mathcal{N}[k] \setminus \{i = 2\} = \{k, 1, 3\}$ are receiving. At this time "one-hop" neighbor link state $A_{2,k} = \bar{\gamma}_{2\to k}/P_{\max}$ can be easily estimated at node k.

Stage 2: from the average SNR $\bar{\gamma}_{i\to m}$ 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 estimated and feed back to node k (solid arrows).

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

All the "one-hop" link states $A_{k,i}$ for $\forall i \in \mathcal{N}(k)$ and the "two-hop" $A_{m,i}$ for $\forall i, m \in \mathcal{N}(k)$, $i \neq m$ have to be stored at node k and periodically updated. The minimum number of required estimates reduces to $\binom{|\mathcal{N}[k]|}{2}$, where $|\mathcal{N}[k]|$ refers to the cardinality of the closed neighborhood set (i.e., $|\mathcal{N}[k]| = 4$ for the case illustrated in figure 2).

Notice that MMPA scheme (Sect. V-B) requires that the link states $\mathbf{A}_{\mathcal{T}_{k+2},k+2}$ are available at kth node as a result of the previously outlined signalling scheme. Therefore, after each link updating phase the states $\mathbf{A}_{\mathcal{T}_{k+2},k+2}$ have to be feedback to node k from $(k+1)$th node. In general, MMPA strategy requires that the estimated link states are periodically exchanged between neighboring nodes.

VI. 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 [3] (MTPR) and the Optimum Link Cost (OLC) based routing algorithm proposed in [9].

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 [3]. Let T_i denote the lifetime of node $i \in \mathcal{G}$, (i.e. the time at which it runs out of

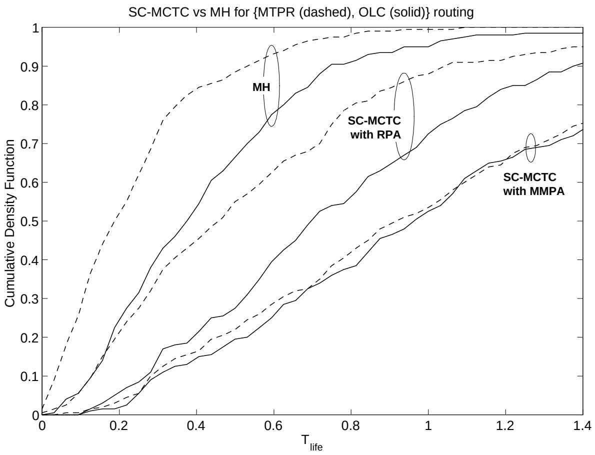

Fig. 3. Cumulative density function for the normalized network lifetime T_{life} for MTPR routing (dashed line) and OLC strategy (solid line) of the proposed MCTC with selection diversity (SC-MCTC) with recursive (RPA) and min-max (MMPA) power allocation schemes. The non-cooperative MH is shown as reference.

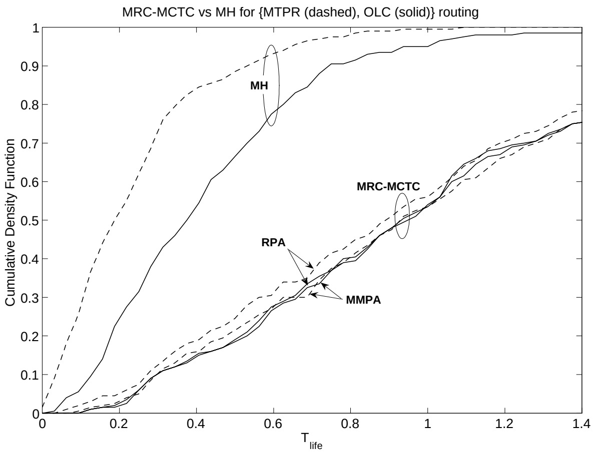

Fig. 4. Cumulative density function for the normalized network lifetime T_{life} for MTPR routing (dashed line) and OLC strategy (solid line) of the proposed MCTC with maximal ratio combining (MRC-MCTC) with recursive (RPA) and min-max (MMPA) power allocation schemes. The non-cooperative MH is shown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

energy), the network lifetime

$$\Delta T_{life} = \min_{i \in \mathcal{G}} (T_i) \tag{14}$$

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

Here we focus on the class of maximum battery life routing algorithms [3] that can be solved by a standard shortest path algorithm such as Dijkstra or the distributed Bellman-Ford [10] and thus it needs 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 best path which minimizes the sum of all link costs. In particular, for link $i \to j$ it is

$$C_{i \to j} = (A_{i,j})^{-x_1} \left(\frac{\bar{E}_i}{E_i} \right)^{x_2} \tag{15}$$

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 (15): route paths are chosen based on the link states without any knowledge of the residual energy of each node. However, in [9] it has been shown that the Optimal Link Cost metric (15) should account also for the residual energies at each node and thus it 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 obtained by choosing $x_1 = 1$ and $x_2 = 30$ in (15). 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).

B. Numerical results

Simulation environment is based on 200 randomly generated network topologies, for each topology there are $N = 20$ nodes uniformly distributed within a square area of $A_r = 250m^2$. Each node periodically sends a packet to a common sink node with infinite power supply. The outlined setting is suited for the standard IEEE802.15.4 [8] at a carrier frequency of $2.45GHz$, maximum bit rate of $250kbps$ and a packet duration of $T_S = 1.93ms$. Link quality requirements for the application at hand are $\beta = 7dB$ and $P_{out} = 10^{-6}$.

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 ref.[11] the power consumption during receiving P_r 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 [12] $E[d^4] = 6/\pi^2 \left(A_r/N\right)^2$.

To ensure a fair comparison among different simulation environments, the network lifetime ΔT_{life} is normalized with respect to the initial energy resulting in $T_{life} = \Delta T_{life}/n_o$. Figure 3 shows 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 V-C in 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 (dashed lines) and OLC based strategy (solid lines) are employed at the upper network layer so that performances using MCTC with Selection Combining (SC-MCTC) are compared with the MH scheme based on the same routing algorithms.

From figure 3 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 as for the min-max strategy MMPA the benefits of more complex routing strategy as for OLC vanishes as the cooperative multihop with MMPA has practically the same performance for both routing algorithms considered here. In addition, non-cooperative MH with OLC routing has similar performance as 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. In summary, 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.

For the sake of comparison (a detailed analysis is not carried out in this paper) figure 4 shows the CDF of the normalized lifetime T_{life} of the cooperative multihop scheme 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. However, this result is at the expenses of a larger signalling among nodes to update the instantaneous link state.

VII. CONCLUSION

The hybrid multihop-cooperative transmission scheme (MCTC) proposed here takes advantage of cooperative and multihop diversity benefits with linear combining schemes. The two energy efficient power allocation schemes tailored for the MCTC increase the network lifetime at least $2 \div 3$ times compared to non-cooperative multihop. Power assignment is recursive and is based on the knowledge of the average attenuation for neighboring nodes, this is easily obtained at network setup (or during the updating). Even if the paper is focused on a practical case with $c = 1$ cooperating node along the route, results indicate that a meaningful energy savings can be obtained at the price of a reasonable Medium Access Control (MAC) layer complexity. As a final remark, the relaying nodes of MCTC protocol belonging to the route path are selected without any cross layer interaction between MAC and network layer. Route selections based on different performance metrics (i.e., end-to-end delay or packet throughput) rather than power consumption could be employed as well.

VIII. APPENDIX-A: MIN-MAX PROBLEM (11)

Let $\hat{P}_k$ be the solution of (13), when $P_k^{RPA} > \hat{P}_k$ the optimization (11) can be written as

$$\begin{aligned} P_k^{MMPA} &= \arg\min_{P_k} [P_k] \\ s.t.\ P_k^{RPA} &\leq P_k \leq P_{\max} \end{aligned} \tag{16}$$

the solution is straightforward: $P_k^{MMPA} = P_k^{RPA}$. On the contrary, when $P_k^{RPA} \leq \hat{P}_k$ (11) can be decoupled into two problems

$$\begin{cases} P_k^{MMPA} = \arg\min_{P_k} \left[\Lambda\left(P_k, \mathbf{A}_{\mathcal{T}_{k+2}^{(2)},k+2}\right)\right] \\ \qquad s.t.\ P_k^{RPA} \leq P_k \leq \hat{P}_k \\ P_k^{MMPA} = \arg\min_{P_k} [P_k] \\ \quad s.t.\ \hat{P}_k < P_k \leq P_{\max} \end{cases} \tag{17}$$

the solution is $P_k^{MMPA} = \hat{P}_k$. Including both cases, solution to original problem (11) reduces to the solution (12) in the main text.

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