A multihop-cooperative transmission protocol for energy limited WPAN systems

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***Abstract*— This paper deals with power allocation strategies in a wireless personal area network (WPAN) supporting the IEEE 802.15.4 standard for low power transmission. The proposed transmission strategy for nodes belonging to a single primary route towards a destination is referred as Multihop Cooperative Transmission Chain (MCTC). The MCTC is based on the relays of the same message by multiple 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 exploiting the link quality (LQ) measurements available at each 802.15.4 compliant device. The proposed power assignement is recursive and can be employed locally with minimal signalling exchange among nodes. For WPAN networks where energy consumption reduction and throughput enhancement are main design challenges, the proposed MCTC scheme increases the network lifetime with respect to non-cooperative schemes by guaranteeing specific end-to-end delay (and throughput) requirements.**

I. Introduction

Wireless personal area networks (WPANs) are used to convey information over relatively short distances. The main objectives of an WPAN are quick deployment, reliable data transfer, short-range operation, extremely low cost devices, and a reasonable battery life, still maintaining a simple and flexible protocol that involves little or no infrastructure. Our analysis has been focused on an ad hoc peer-to-peer topology conforming to the IEEE 802.15.4 standard [1] where wireless devices can communicate with any other device as long as they are in range of one another or if other devices are able to relay their packets. Designing energy preserving power allocation techniques as well as specific communication protocols that maximize the overall system throughput are fundamental issues that involves all layers of the communication system: from the hardware up to the applications [2].

In wireless environments the problem of a reliable data transfer arises as fading impairments cause random power fluctuations of the received signal. If decoding errors at the receiver occur, (e.g. due to a deep received signal fade), the data can reach the destination without errors by means of a MAC layer automatic repeat request (ARQ) algorithm. In this scheme, correct received data packets are signalled by the receiver to the sender by positive acknowledgement (ACK frame), whereby corrupted packets are signaled by negative acknowledgements (NACK frame). For low power devices, such as ZigBee motes [3], this protocol (herein referred to MH), is energy efficient but results in a high overhead due to the large number of required retransmissions that substantially decrease system throughput. Fading impairments, that cause corrupted packets at the receiver, can be mitigated by means of a “fading margin” term that increases transmit power according to received signal fluctuation statistics. As show in [2], power allocation can be increased on each hop in order to guarantee an outage probability on each link and thus reduce the NACK signalling overhead. This approach, herein referred to as MH-Fm (Fading margin) enhances the overall system throughput (i.e. in terms of average end to end packet delay reduction), but it substantially limits the network lifetime [4]. Herein, by introducing the Multihop-Cooperative Transmission Chain protocol (MCTC in [5]) together with a power allocation strategy that takes advantage of the cooperative diversity benefits [6], we show that enabling cooperation among the nodes belonging to the route guarantees a better trade off between energy consumption reduction and throughput enhancement with respect to both MH and MH-Fm schemes. Power allocation is based on the knowledge of the average (not instantaneous) attenuation (i.e., path loss and shadowing) that can be easily derived from the link quality (LQ) measurements [1] that are available at each device.

The paper is organized as follows: the system model is described in Sect.II while Sect.III gives an overview of the MH and MH-Fm transmission schemes. Sect.IV illustrates the MCTC strategy and sheds a light on its energy savings potentialities. A recursive power allocation technique (RPA) for MCTC scheme is proposed in Sect.V, power levels are computed in case selection combining (SC-MCTC) and maximum ratio combining (MRC-MCTC) are employed. Sect.VI shows the performance comparison of SC-MCTC with both MH and MH-Fm in terms of network lifetime and end-to-end delay performances for settings with randomly placed nodes of limited battery energy supply.

II. Network and Link model

In our framework 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. Let us assume that an optimal unicast route path $\mathcal{R} \subset \mathcal{G}$ from node S (*source* device) to node D (*destination* node) 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 this ordering be labelled as $\mathcal{R} = \{S, 1, 2, ..., M-2, D\}$.

Terminals that do not belong to the route $\mathcal{G} \setminus \mathcal{R}$ are kept into a sleep mode by the power management system. A slotted version of the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) algorithm is employed at the MAC layer during the contention access period (CAP) [1] to avoid mutually interfering transmissions.

Let the relay processing be characterized by the Decode and Forward (DF) strategy: if node $k \in \mathcal{R}$ 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-quality* (LQ) $L_{k,m}$ that accounts for path loss and shadowing. The signal received by node m with node k relaying the source message x_S during the time slot t is

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

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

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

The message x_S 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 $\left|h_{k,m}\right|^2 \sim \chi_2^2$, 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* [7] 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 $\mathcal{P}_{out} = prob(\gamma_{k\to m} < \beta)$ while the probability of successful reception is thus $1-\mathcal{P}_{out}$. Notice that β relies on the hardware receiver sensitivity [3] and on the required BER (bit error rate) performance (see Sect. VI-B). To simplify, when power allocation is based on a fading margin term, we assume that each hop of the primary route has the same outage probability. To ensure the end-to-end outage probability P_{EE} each hop is constrained to have the same value of $\mathcal{P}_{out} = 1 - (1-P_{EE})^{\frac{1}{M-1}}$.

III. Multihop (MH) transmission

A. Multihop transmission without fading margin (MH)

When low power devices such the ZigBee compliant motes [3] are employed, transmit power is obtained by assigning the minimum power level to each node in the route so as the average SNR measured at each receiver is at least equal to the threshold β. Recalling the channel model introduced in the previous Sect. II, the minimal required transmitting power at node k towards node $k+1$ reads:

$$P_k^{MH} = \beta / L_{k,k+1} \tag{3}$$

Assuming that corrupted packets are signalled by negative acknowledgements (NACK frames), this protocol is energy efficient but it results in a high overhead due to the large number of required retransmissions that substantially increase the end-to-end packet delay (and therefore it limits the overall system throughput).

The average number of retransmissions $E[N_r]$ required by the MH scheme to achieve an overall outage probability $\mathcal{P}_{out}$ can be written as: $E[N_r] \geq \log_{\Gamma(1)}(\mathcal{P}_{out})$, where $\Gamma(\alpha) = 1 - \exp(-\alpha)$ and equality holds under the assumption of uncorrelated fading during each retransmission. The average power consumption for a reception of a packet with outage probability $\mathcal{P}_{out}$ can be simplified as $E[N_r]P_k^{MH}$.

B. Multihop transmission with fading margin (MH-Fm)

Multihop relaying can be based on the design of the transmission power level P_k^{MH-Fm} at node k for the link $k \to k+1$ to account for the fade margin in order to cope with the Rayleigh fading and to reduce the probability of a NACK signalling. In order to review the basics of MH-Fm with an outage constraint (see e.g., [2]), let us refer to the channel model introduced in the previous Sect. II. In a fading environment, 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 an outage probability requirement in terms of the pair $(\beta, \mathcal{P}_{out})$, the required power P_k^{MH-Fm} follows from the outage constraint

$$F_{k\to k+1}(\beta) = \Gamma\left(\frac{\beta}{L_{k,k+1}P_k^{MH-Fm}}\right) = \mathcal{P}_{out} \tag{4}$$

where $\Gamma(\alpha) = 1 - \exp(-\alpha)$ and thus

$$P_k^{MH-Fm} = \frac{P_k^{MH}}{\ln(1-\mathcal{P}_{out})^{-1}} \tag{5}$$

In MH-Fm transmission a fade margin of $1/\ln(1-\mathcal{P}_{out})^{-1}$ is added to the minimal required transmitting power $P_k^{MH} = \beta/L_{k,k+1}$ in order to cope with channel impairments. Energy savings of the MH scheme with respect to the MH-Fm strategy, $E[N_r]P_k^{MH} \leq P_k^{MH-Fm}$, can be partially proved by noticing that when $\mathcal{P}_{out} < \Gamma(1)$, it is

$$E[N_r] < \frac{1}{\ln(1-\mathcal{P}_{out})^{-1}}, \tag{6}$$

where we recall that $E[N_r] = \log_{\Gamma(1)}(\mathcal{P}_{out})$ holds when fading is uncorrelated among each retransmission.

IV. Multihop Cooperative Transmission Chain (MCTC)

MCTC protocol requires some devices along the route to cooperate to relay the same message over independent fading channels. Moreover the receiving node linearly combines all these contributions. The power among each transmitting node can be recursively allocated by adding the needed power on each hop to guarantee the end-to-end outage probability [5]. 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-Fm 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. A simple repetition based

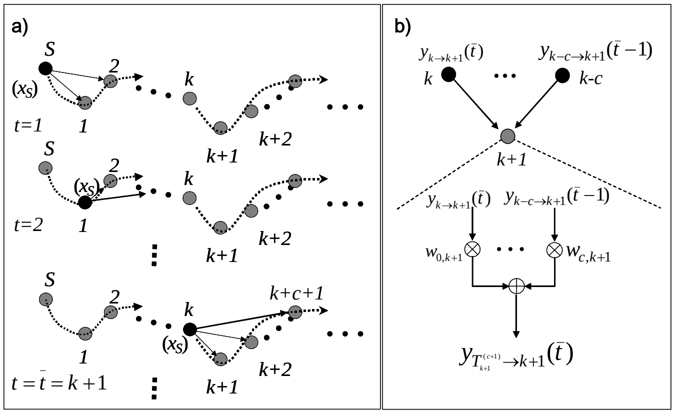

Fig. 1. a) Multihop Cooperative Transmission Chain time division structure b) Cooperating set of nodes relaying copies of the message x_S and the linear combining at the $(k+1)$th node.

cooperative scheme is herein proposed: $c+1$ 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, cooperative diversity up to degree $c+1$ can be obtained by the receiver according to the specific combining technique. As orthogonal subchannelling, here we consider a time division based scheme, the extension to frequency division is straightforward.

The MCTC protocol is illustrated in figure 1-a. 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 1-b), 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: $\mathcal{T}_{k+1}^{(c+1)} = \{k-c,...,k\} \subset \mathcal{R}$. Received signals can be collected into $(c+1)\times 1$ vector $\mathbf{y}_{k+1} = [y_{k\to k+1}(\bar{t}),...,y_{k-c\to k+1}(\bar{t}-c)]^T$ and these are characterized by the average SNRs for each time slot $\{\bar{\gamma}_{k\to k+1},...,\bar{\gamma}_{k-c\to k+1}\}$. 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 illustrated in figure 1-b we consider a linear combining technique from the cooperative transmitting set $\mathcal{T}_{k+1}^{(c+1)}$ as

$$y_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(t) = \sum_{i=0}^{c} w_{i,k+1}^{*} y_{k-i\to k+1}(t-i) = \mathbf{w}_{k+1}^{H}\mathbf{y}_{k+1} \quad (7)$$

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

V. Recursive Power allocation for MCTC

In this section we briefly review power allocation results proposed in [5] tailored for the MCTC scheme with selection combining (SC-MCTC) and we extend those results to maximum ratio combining (MRC-MCTC) case and to $c>1$.

Once defined the LQ measurements vector $\mathbf{L}_{\mathcal{T}_{k+1}^{(c+1)},k+1} = [L_{k,k+1},...,L_{k-c,k+1}]^T$ between each node belonging to the cooperative set $\mathcal{T}_{k+1}^{(c+1)}$ 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 outage probability requirement $\mathcal{P}_{out}$. Differently from (4) the power allocation P_k^{RPA} can be reduced by taking advantage of power assignment for previous nodes $P_{k-1}^{RPA},...,P_{k-c}^{RPA}$. Power P_k^{RPA} is obtained by solving with respect to P_k (for each $k \in \mathcal{R} \diagdown \{S,D\}$)

$$\Psi_{\mathbf{w}}\left(\beta; P_k, P_{k-1}^{RPA},...,P_{k-c}^{RPA}, \mathbf{L}_{\mathcal{T}_{k+1}^{(c+1)},k+1}\right) = \mathcal{P}_{out} \quad (8)$$

where function $\Psi(\cdot)$ is the CDF $F_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(\gamma) = prob(\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} \leq \gamma)$ of the instantaneous SNR $\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}$ at node $k+1$ after the combiner. The solution can be found if $\mathbf{L}_{\mathcal{T}_{k+1}^{(c+1)},k+1}$ is assumed to be known by kth node. Similarly to MH-Fm (5), for any pair (β, $\mathcal{P}_{out}$) the power level P_k^{RPA} depends on the power assignment for the previous nodes in the route according to the function $\Lambda_{\mathbf{w}}(\cdot)$ as

$$P_k^{RPA} = \Lambda_{\mathbf{w}}\left(P_{k-1}^{RPA},...,P_{k-c}^{RPA}, \mathbf{L}_{\mathcal{T}_{k+1}^{(c+1)},k+1}\right), \quad (9)$$

recursive structure has now been made explicit. Of course, for the source $k=S$ there is no cooperation to be exploited and $P_S^{RPA} = P_S^{MH-Fm}$. Notice that, when $c=1$, node k is aware of the power P_{k-1}^{RPA} and it can estimate the SNR $\bar{\gamma}_{k-1\to k}$ and the LQ $L_{k-1,k}$ with the aim of the signalling scheme proposed in [5]. The case $c=2$ requires the estimated link states to be periodically exchanged between neighboring nodes.

A. Selection Combining case

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

$$\gamma_{\mathcal{T}_{k+1}^{(c+1)}\to k+1} = \max\left\{\gamma_{k-c\to k+1},...,\gamma_{k\to k+1}\right\}, \quad (10)$$

thus the optimization problem can be stated as in (4) where the CDF can be written as: $F_{\mathcal{T}_{k+1}^{(c+1)}\to k+1}(\gamma) = \prod_{\ell=k-c}^{k}\Gamma\left(\frac{\gamma}{\bar{\gamma}_{\ell\to k+1}}\right)$. Power allocation for the kth node in the route can be easily found as

$$P_k^{RPA}(SC) = P_k^{MH-Fm} \cdot \prod_{\ell=k-c}^{k-1}\Gamma\left(\frac{\beta}{L_{\ell,k+1}P_\ell^{RPA}}\right). \quad (11)$$

B. Maximal Ratio Combining Case

MRC is known as the optimum combining scheme in AWGN that requires a full CSI at the receiver [8]. 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

$$w_{i,k+1} = \sqrt{\frac{P_{k-i} L_{k-i,k+1}}{\sum_{i=0}^{c} \gamma_{k-i \to k+1}}} \cdot h_{k-i,k+1}, \tag{12}$$

for $i = 0, 1, ..., c$. Being the total SNR at the decision variable $\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1} = \sum_{\ell=k-c}^{k} \gamma_{\ell \to k+1}$, then, from equation 14.5.26 in [9], the CDF of $\gamma_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}$ reduces to:

$$F_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}(\gamma) = \sum_{i=0}^{c} A_i \cdot \Gamma\left(\frac{\gamma}{\bar{\gamma}_{k-i \to k+1}}\right) \tag{13}$$

where $A_i = \left(\prod_{\ell \neq i}^{c} \frac{\bar{\gamma}_{k-i \to k+1}}{\bar{\gamma}_{k-i \to k+1} - \bar{\gamma}_{k-\ell \to k+1}}\right)$. Power values for any c value can be found by substituting $\gamma = \beta$ and $F_{\mathcal{T}_{k+1}^{(c+1)} \to k+1}(\gamma) = P_{out}$ into (13) and rewritting (13) in the form of (9). Assuming $\mathcal{P}_{out} \ll 1$ and $\Gamma\left(\frac{\gamma}{\bar{\gamma}_{k \to k+1}}\right) \simeq \frac{\gamma}{\bar{\gamma}_{k \to k+1}}$, power assignment for the case $c = 1$ is:

$$P_k^{RPA}(MRC) \simeq$$
$$\simeq P_k^{MH-Fm} \left(1 - \frac{L_{k-1,k+1} P_{k-1}^{RPA} \cdot \Gamma\left(\frac{\beta}{L_{k-1,k+1} P_{k-1}^{RPA}}\right)}{\beta}\right), \tag{14}$$

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

VI. End-to-end delay and lifetime performances using MCTC

Performance gains in terms of lifetime and end-to-end delay using the MCTC scheme with respect to a MH and MH-Fm strategies are evaluated numerically. Since all approaches are independent on the above network layer, we compare the end-to-end delay and lifetime cumulative density function results when assuming the same Minimum Total Transmission Power Routing [10] (MTPR) to be employed at the network layer.

A. Maximum battery life routing

Many energy efficient algorithms for routing that focus on network lifetime T_{life} maximization have received considerable attention over the past few years [10]. 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, $T_{life} = \min_{i \in \mathcal{G}}(T_i)$, is the time of the first node death, and it is equivalent to the earliest network partition time.

Herein we focus on the class of maximum battery life routing algorithms [10] that can be solved by a standard shortest path algorithm such as Dijkstra or the distributed Bellman-Ford [11] and thus it needs a link cost metric among all links of the network that can be updated according to the time-varying topology of the network. In MTPR (Minimum Total transmission Power Routing) route paths are optimally chosen based only on the LQ measurements, other power efficient algorithms may be similarly employed (i.e. accounting for node residual energies as in [4]).

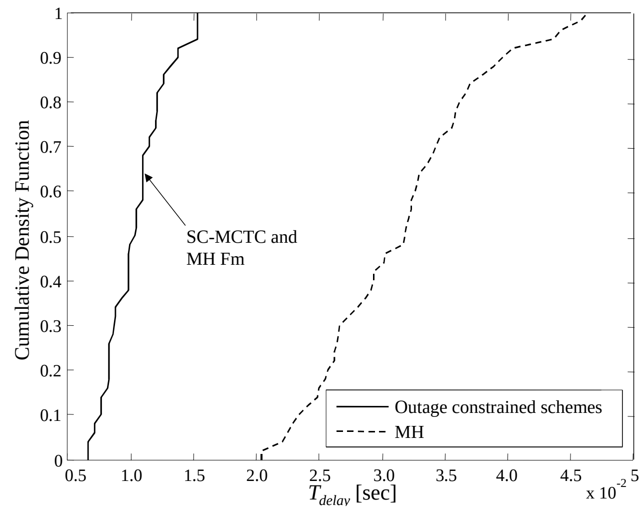

Fig. 2. Cumulative density functions for the average end-to-end delay T_{delay} when MTPR routing is employed at the network layer. MH scheme performances are compared to the proposed outage constrained schemes. (MH-Fm and SC-MCTC).

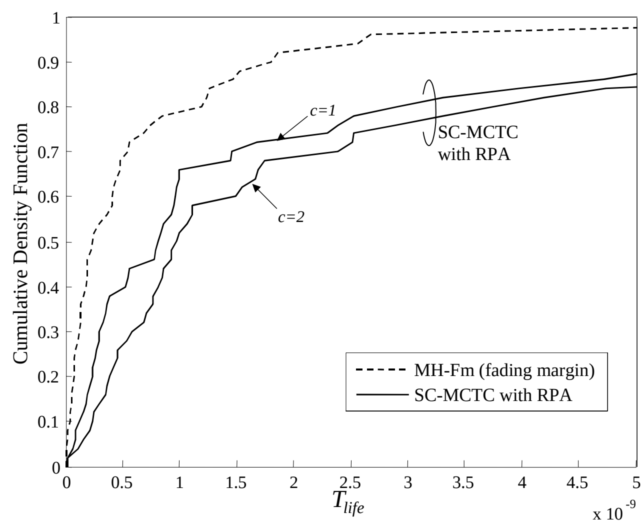

Fig. 3. Cumulative density function for the network lifetime T_{life} for MTPR routing of the proposed SC-MCTC with a recursive power alloaction strategy, $c = 1$ and $c = 2$. The non-cooperative MH-Fm (dashed line) is shown as reference.

B. Numerical results

Simulation environment is based on 50 randomly generated network topologies, for each topology there are $N = 8$ nodes uniformly distributed within a square area of $A_r = 8m \times 8m$. Each node periodically sends a packet to a common sink node that has no energy limitation (i.e., with infinite power supply). As specified in [1], for a bit rate of $250kbps$ a physical protocol data unit (PPDU) of 60 octets for a total packet duration of $T_S = 1.93ms$ has been chosen. Under the receiver sensitivity restrictions specified in [1], to guarantee a bit error rate of at least 10^{-3} with QPSK modulation, the resulting SNR threshold β is $7dB$. Fading margin term is design so as the probability of a packet retransmission due to

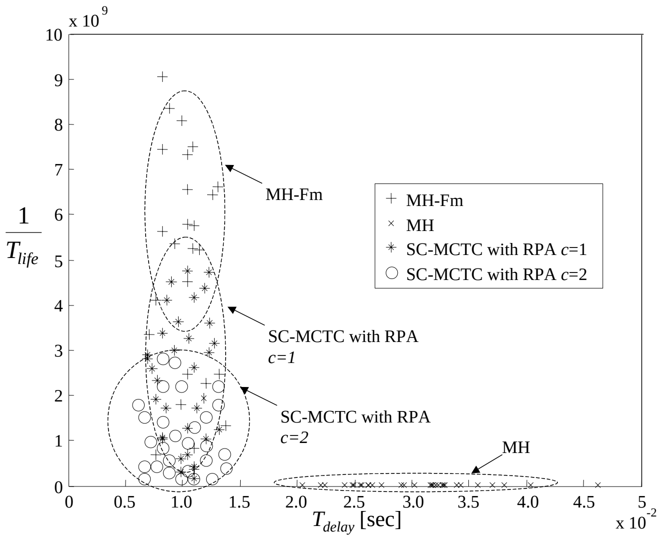

Fig. 4. Network lifetime and end-to-end packet delay performance tradeoff: each marker corresponds to a random network topology and specifies a lifetime ($1/T_{life}$) and an average end-to end packet delay realization. Different marker shapes have been used so as to assess all cases: MH (cross markers $\times$), Mh-Fm (plus markers $+$), SC-MCTC with $c = 1$ (star markers $*$) and SC-MCTC with $c = 2$ (circular markers $\circ$).

an outage event is reduced to a minimum, thus $\mathcal{P}_{out} = 10^{-6}$. According to the parameters specified by MicaZ devices [3] the available power levels are ranging from $-25dBm$ to $P_{\max} = 0dBm$. Moreover, by assuming path-loss vs distance d as d^{-4}, $r_{\max} = 10m$.

In figure 2 network performances in terms of end-to-end packet delay are analyzed by comparing the MH scheme with the outage constrained based MCTC and MH-Fm schemes. For each randomly generated network topology, an end-to-end average packet delay value T_{delay} is computed by averaging the end-to-end delays (i.e. the time between a packet transmission from the source and the successful decoding at the destination node D) for each source node in the network. A cumulative density function is thus calculated from the available average delay realizations. In figure 3 network lifetime T_{life} cumulative density function for SC-MCTC with $c = 1$ and $c = 2$ are computed for each random network topology and compared with the lifetime obtained through an MH-Fm strategy, higher degrees of cooperation (higher $c > 2$ values) do not provide significant performance gains as, according to the proposed simulation environment, the average number of nodes belonging to a route is limited to 4. When fading margin is accounted for (as in MH-Fm and MCTC schemes with recursive power allocation), the end-to-end delay T_{delay} is substantially reduced (up to 3 times in our case) with respect to MH as a substantial reduction of the NACK signalling probability can be accomplished (see figure 2). The proposed MCTC protocol substantially enhances network lifetime (figure 3) with respect to the non-cooperative MH-Fm scheme and guarantees the same outage performances (and thus the same average end-to-end packet delay). Therefore, by maximizing the overall system throughput with respect to MH scheme without limiting network lifetime as for MH-Fm, the protocol is expected to achieve a better trade off between energy consumption reduction and throughput maximization.

Figure 4 aims to bring further insight to network lifetime T_{life} and end-to-end packet delay T_{delay} performance. Each marker corresponds to a random network topology and specifies a lifetime ($1/T_{life}$ values are herein considered) and an average end-to end packet delay realization according to the selected power allocation scheme and the transmission protocol. Different marker shapes have been used so as to compare the MH schemes with the outage constrained schemes (MH, SC-MCTC with $c = 1$ and $c = 2$). The best trade off between end-to-end packet delay and lifetime performances is achieved by the SC-MCTC scheme with $c = 2$ as the corresponding markers are located within a tight region where both highest T_{life} and lowest T_{delay} values are attained.

VII. Conclusion

The transmission scheme (MCTC) proposed here takes advantage of cooperative and multihop diversity benefits with linear combining schemes. Power assignment is recursive and it is based on the knowledge of the average attenuation for neighboring nodes, this is easily obtained at network setup (or during the updating). When fading margin is accounted for (as in MH-Fm and MCTC schemes), the normalized end-to-end delay is substantially reduced with respect to MH resulting in an overall throughput enhancement. Moreover, the proposed cooperative transmission scheme limits the required fading margin level with respect to conventional outage constrained non-cooperative power allocation schemes (MH-Fm) so as to enhance lifetime. Higher perfomance gains can be attained at the price of an increased Medium Access Control (MAC) layer complexity [5], or employing optimum maximum ratio combining at the receivers. In summary, by limiting the end-to-end packet delay and improving network lifetime, the protocol is shown to achieve an optimal trade off between energy consumption reduction and throughput maximization.

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