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Towards Energy-Efficiency in Selfish, Cooperative Networks

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Abstract Cooperative communication has been proven effective in enhancing the performance of wireless networks, and a variety of techniques have been investigated to exploit the spatial diversity gain to provide reliable physical layer communications with multiple quality-of-service (QoS) requirements. In this paper, we propose an adaptive multi-relay selection with power allocation mechanism to offer energy fairness at each node for a cooperative network. Unlike traditional approaches where all nodes are considered to transmit in a collaborative manner, we explicitly consider the situation where nodes exhibit some degree of selfish behavior. Specifically, we introduce a novel concept of the *selfishness index* and incorporate it into a utility function which denotes the degree a node can benefit from cooperative transmission. Theoretical analysis and extensive simulation results are supplemented to show advantages in maximizing the network lifetime and guaranteeing the QoS in realistic wireless environments. We also consider the practical situation when nodes consume energy in mode switching, and carefully study the behavior of inter-cluster relay switching and the trade-off among network lifetime, switching cost and switching frequency.

Keywords cooperative communications · energy-efficiency · fairness · selfishness

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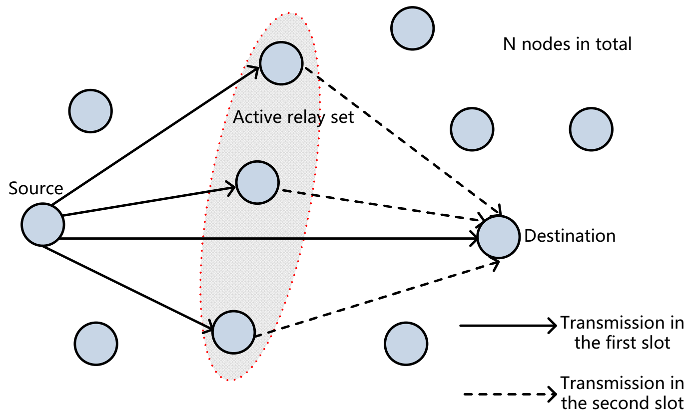

Fig. 1 Cooperative transmission model with multiple relays.

1 Introduction

Future wireless communication networks are expected to support the mixture of real-time applications, such as voice-over-IP and multimedia teleconferencing, and non-real-time data applications, such as web browsing, messaging and file transfers. Compared with wired environments, the error prone nature of the associated communication channels and traffic patterns in mobile wireless networks are more unpredictable. Therefore, their stringent and diversified quality-of-service (QoS) requirements cannot be easily and satisfactorily addressed through traditional approaches. Correspondingly, there have been increasing interests recently in protocol designs for wireless networks to enhance the performance of wireless ad-hoc and sensor networks; nevertheless, unpredictable variables like node mobility, node density and network dimensions make the diverse and stringent wireless QoS requirements extremely difficult to satisfy.

Due to the unreliability of wireless links, it has been of significant interests to study the impacts of physical-layer techniques on the design of upper-layers. Among many candidate techniques, the multiple-input multiple-output (MIMO) receives significant attention this far, which can provide spatial diversity and hence represents a powerful technique for interference mitigation and reduction [1]. Cooperative communication [2–4] provides an alternative way to achieve spatial diversity. The key feature of cooperative transmission is to encourage single-antenna devices to cooperatively share their antennas such that a virtual antenna array can be constructed and, hence significantly boosting reception reliability.

There are three main categories of cooperative communications, namely, amplify-and-forward (AF, [5]), decode-and-forward (DF, [2]), and coded cooperation (CC, [6]). Under AF, the cooperative relay node performs a linear operation on the signal received from the information source before forwarding it to the destination node. Whereas in DF, the cooperative relay node decodes the received signal, and re-encodes it before forwarding it to the destination node. CC integrates cooperation into channel coding, by sending different portions of each user's code word via independent fading paths. Although the idea of cooperative communication has been proposed for almost a decade, there are still fundamental issues to be considered from theoretical analysis perspectives. For example, physical layer researchers aim to develop different cooperative strategies for AF, DF or CC, to improve the reception reliability [7, 8], reduce power consumption [9, 10] and increase spectrum efficiency [11]. Moving up to the MAC layer, existing literatures are focusing on the scheduling issues, i.e., when to use cooperation, whom to cooperate with, and how to select cooperating nodes. On the network layer, however, studies consider to define an efficient cooperative routing protocol to deliver data packets between source and destination nodes.

In this paper, we consider the DF cooperative communication, as shown in Fig. 1. The packet transmission from a source (S) to a destination (D) is aided by (multiple) relay(s) (R). While there are variants of cooperative communication, depending on how the relays cooperate to the source's transmission, R's action in DF is to overhear the packet transmitted by S, decode it, and retransmit it to D, improving the reception quality of the (combined) signal at D. This cooperative scheme lends itself to a relatively easy implementation in hardware and software. Moreover, it is shown in [2] that such a cooperative scheme can achieve full second-order diversity and therefore provides significant improvement to the reception reliability.

In this paper, we explicitly focus on the fundamental issue of multiple relay selection, while considering the impact of selfish behaviors and exploring an effective mechanism to achieve both the energy efficiency and fairness. Particularly, we would like to answer the following questions:

1. Consider the selfishness nature of wireless nodes, what are impacts on the willingness of cooperation and the resulted overall network performance in terms of goodput, QoS outage, and energy-efficiency?
2. By considering such selfish behaviors, how to optimally select and allocate the power of the source and relays to achieve energy efficiency, fairness and extended network lifetime?
3. What are the impacts of MAC layer protocols/scheduling algorithms on the PHY layer cooperation and how to further improve the inter-layer cooperation?
4. In practical scenarios where energy costs in mode switching are explicitly considered, how to optimally select the set of relays for power efficiency?

More specifically, we propose a cooperation scheme to jointly consider relay selection and power allocation by incorporating fairness and selfishness natures of wireless nodes. We capture the selfish behavior in wireless networks by introducing a *selfishness index* which represents the selfish level of each node, and incorporate this index into a novel *utility* function which denotes the net payoff of a node from cooperative transmission. Higher utility denotes more responsibility in the cooperative transmission; while for the purpose of decreasing power consumption, a node with lower utility can show some degree of selfishness to reserve energy. In the proposed approach, only relays with non-negative utility and longest estimated network lifetime meets the relay selection criterion. On the other hand, the power allocation issue is considered to be an optimization problem which aims to minimize the sum of weighted power while satisfying a given outage probability threshold. Extensive simulation results confirm that, by using the proposed method, the selected relay set achieve the goals of transmission power efficiency and energy consumption fairness.

To summarize, the contribution of the paper is four-fold:

1. We explicitly derive a closed-form solution for the outage probability of a multi-relay cooperation scheme employing repetition-coded Decode-and-Forward (DF) strategy.
2. We incorporate a novel concept of *selfishness index* into a utility function to uniquely capture and regulate the selfish behavior of a node in the proposed relay selection strategy.
3. We propose a two-step relay selection mechanism covering all aspects of power efficiency, energy consumption fairness and network lifetime, and bring forward a "channel-aware packet selection" approach which can successfully combat realistic channel variations.
4. We extend our contribution to the scenario of explicitly considering the energy cost in switching mode, and extensively study the trade-off between the node power consumption and network lifetime, and the relationship between switching cost and switching frequency.

The remainder of this paper is organized as follows. Section 2 reviews the main previously reported relay selection schemes. In Section 3, we present the system model, derive the closed-form expression of outage probability for multiple simultaneous relays under repetition-coded Decode-and-Forward (DF) cooperation, and define the utility parameter with selfishness index. The proposed approach of relay selection and power allocation is introduced in Section 6 and 7, respectively. Extensive simulation results are shown in Section 8, followed by the practical considerations on switching mode in Section 9. Finally, concluding remarks are given in Section 10.

2 Related Work

The concept of cooperative communication can be traced back to the pioneering work done by Van Der Meulen [12] and Cover and El Gamal [13]. In [12], Van Der Meulen first introduces the three-terminal communication channel (or a relay channel) and gives capacity bounds for various ways of sending information on this channel. Cover and El Gamal [13] study general relay channel and establish an achievable lower bound. These early investigations on relay channels laid the foundation for cooperative communication, and a large body of research community are interested in cooperative communication whose main goal is to devise optimal resource (e.g., power, channel, relay, etc.) allocation schemes according to an objective function as well as the constraints of the underlying system. Optimal relay selection is one of such problems which is of great importance in cooperative wireless networks.

In the existing literatures, there are many different schemes for single relay selections. In [14], Zhao *et.al.* select the neighbor node with the maximum SINR as the best relay, while in [15] Sadek *et.al.* consider that the node nearest to the base station should be used in cooperation. In [16], Pandana *et.al.* propose a single relay selection and power allocation scheme based on channel condition and the residual energy. In [17], Sheng *et.al.* propose to minimize the total transmission power consumption of a single relay case, given only the outage probability satisfies a accepted level. Other single relay selection schemes can also be found in [18–21]. Although the best single-relay selection can improve system performance, the selected relay is likely to have heavy load, thereby resulting in imbalance of resource utilization.

There are also some studies on multiple relay selection [22–27]. Dan *et.al.* in [22] define the "emergence" diversity by employing multiple relays and propose a multi-relay selection scheme by incorporating instant channel state information and residual energy. In [23], Vardhe *et.al.* propose a multi-relay selection scheme, given the channel capacity can achieve a lower bound threshold. In [24], Liu *et.al.* propose a multi-relay selection scheme to maximize network lifetime. However, the number of selected relays is fixed in the algorithm and the authors have not considered to optimize the relay numbers. In [25], Li *et.al.* propose a dynamic relay selection scheme aiming at minimizing the long-term average cost while considering user mobility and satisfying the QoS requirement.

Unfortunately, existing literatures rarely consider relay selection with the selfish behavior. In [28], Liu *et.al.* discuss the selfish issue in cooperative networks and point out the importance to consider selfish behaviors. Furthermore, in [29] Hassan *et.al.* investigate the relay selection problem in the presence of malicious relay nodes and show that the malicious behavior of relay nodes harms the throughput performance. Motivated by the recent research activities on the study of the inherent loss of efficiency caused to a system by the participant selfishness, we would like to consider the impact of selfish behavior on relay selection and explore an effective mechanism to achieve the energy fairness.

3 System Model

We consider a wireless cooperative, relay network consisting of N nodes $\mathcal{N}$, where $\mathcal{N} \triangleq \{i = 1, 2, \ldots, N\}$. Each node operates independently and is associated with a set of attributes, denoted as the tuple:

$$\Big\langle E_i, \bar{E}_i(t), G_i(t), L_i(t), \gamma_i(t), U_i(t), w_i(t), S_i(t) \Big\rangle, \quad \forall i \in \mathcal{N} \tag{1}$$

and explained as follows. First, all nodes possess the same initial energy reserve, denoted as E_i, and its residual energy at time t is denoted as $\bar{E}_i(t), \forall i \in \mathcal{N}$. $G_i(t)$ and $L_i(t)$ are the introduced *Gain* and *Loss* of node i from cooperative transmission at time t, while $\gamma_i(t)$ is the time-varying *selfishness index*. $U_i(t)$ is the utility of node i, derived from $G_i(t)$, $L_i(t)$ and $\gamma_i(t)$ all together. The detailed definitions of above symbols are described in Section 5. $w_i(t)$ is the weight of node i in power allocation, defined in Section 6. We also assume that each node switches between two operational modes: `ON` (active mode) and `OFF` (sleeping mode), according to the outcome of relay selection, i.e., if node i acts as the source or relay at time t, $S_i(t) = 1$, and $S_i(t) = 0$ otherwise. State changes between `ON` and `OFF` would cause certain power consumption P_0; and studied in Section 9.

We assume a discrete system operation where time is divided into discrete time slots, and at any time slot, we assume only one source-destination node pair can be active, and thus co-channel interference from other sources are not considered. In the MAC layer, TDMA is used to provide collision-free transmissions from the source and relays. Besides, full channel state information is assumed to be available at source, where centralized relay selection and power allocation is performed (as the focus of this paper is not to study from the protocol perspectives, but fundamental design issues). Relay transmissions are assumed to be half-duplex such that they cannot send and receive packets simultaneously. All channels exhibit Additive White Gaussian Noise (AWGN). Finally, the fading is assumed to be stationary, with frequency non-selective Rayleigh block fading between any pair of nodes in the network.

As shown in Fig. 1, we conduct an investigation into the two-time-slot implementation of repetition-coded DF relaying strategies. The task of relay selection is as follows. At time t, a source s intends to send a message to a destination d. Other nodes are considered to be the candidate relays. In the first time slot, the source selects K nodes from the candidate relays to form an active relay set $\mathcal{K}_s$. Then, it broadcasts its packets to both the active relays and the destination. In the second time slot, the active relays in $\mathcal{K}_s$ retransmit the received packets, operating in a perfect synchronous manner to obtain the "emergence" diversity gain [22]. Hence, the destination receives multiple independent copies of the same packets transmitted through different wireless channels, and cooperative diversity gain can be achieved.

4 Theoretical Analysis on Multi-Relay Aided Cooperation

4.1 Direct Transmission

For sake of completeness, we start with direct transmission. According to the system model assumptions, the channel model incorporates path loss and Rayleigh fading. The channel gain $\mathrm{a}_{s,d}$ between the nodes s and d is modeled as $\mathrm{a}_{s,d} = h_{s,d}/d_{s,d}^{\alpha/2}$, where $d_{s,d}$ is the Euclidian distance between the nodes s and d, α is the path-loss exponent[1], and $h_{s,d}$ captures the channel fading characteristics.

The mutual information of the cooperative link is a random variable denoted by I. For a targeted data rate R, $I < R$ represents the outage events, and we use $\epsilon^{out} \triangleq \Pr\{I < R\}$ to denote its outage probability [2]. Then, the mutual information between source s and destination d is:

$$I_{s,d} = \log(1 + P_s^D |\mathrm{a}_{s,d}|^2), \quad \forall s, d \in \mathcal{N}, \tag{2}$$

where P_s^D is the normalized transmission power of source s, and for Rayleigh fading, $|\mathrm{a}_{s,d}|^2$ is exponentially distributed with parameter $d_{s,d}^{\alpha}$. Therefore, the outage probability satisfies:

$$\begin{aligned} \epsilon^{out} &= \Pr\Big\{ I_{s,d} < R \Big\} = \Pr\Big\{ |\mathrm{a}_{s,d}|^2 < \frac{2^R - 1}{P_s^D} \Big\} \\ &= 1 - \exp\left(- \frac{(2^R - 1) d_{s,d}^{\alpha}}{P_s^D} \right) \approx d_{s,d}^{\alpha} \left(\frac{2^R - 1}{P_s^D} \right), \end{aligned} \tag{3}$$

[1] The path loss exponent α is experimentally determined, and is typically in the range of 2 to 5 depending on propagation environment. For example, $\alpha = 2.0$ is for free space, $2.5 \sim 3.0$ for rural areas, $3.0 \sim 4.0$ for urban areas, and $4.0 \sim 5.0$ for dense urban areas.

under the condition of large P_s^D, and R is the desired data rate in bit/s/Hz, which can be defined by specific QoS requirements, e.g., the routing demand or throughput requirement.

Then, we write the normalized transmission power for direct transmission, as:

$$P_s^D = d_{s,d}^{\alpha} \frac{2^R - 1}{\epsilon^{out}}. \tag{4}$$

4.2 Cooperative Transmission With Multiple Simultaneous Relays

For a given active relay set $\mathcal{K}_s$, the maximum average mutual information between source s and destination d for repetition-coded DF [2, 30] can be shown as:

$$I_{s,d} = \min\{I_{s,\mathcal{K}_s}, I_{\mathcal{K}_s,d}\}, \tag{5}$$

where $I_{s,\mathcal{K}_s}$ and $I_{\mathcal{K}_s,d}$ are the mutual information in the first and second time slot, respectively, defined as:

$$\begin{aligned} I_{s,\mathcal{K}_s} &= \frac{1}{2}\log\left(1 + P_s^C|\mathsf{a}_{s,\mathcal{K}_s}|^2\right), \\ I_{\mathcal{K}_s,d} &= \frac{1}{2}\log\left(1 + P_s^C|\mathsf{a}_{s,d}|^2 + \sum_{i\in\mathcal{K}_s} P_i^C|\mathsf{a}_{i,d}|^2\right). \end{aligned} \tag{6}$$

P_s^C is the normalized power of source s in cooperative transmission, P_i^C is the normalized power of active relay $i \in \mathcal{K}_s$, $\mathsf{a}_{s,\mathcal{K}_s} = \sum_{i\in\mathcal{K}_s} \mathsf{a}_{s,i}/K$ is the average source-relay channel gain. It is worth noting that the factor 1/2 captures the fact that communication is performed in two time slots.

To simplify the discussion, we assume that each of the selected relays working under the DF protocol has higher signal-to-noise ratio (SNR) than the threshold, and can decode successfully [22]. Based on this assumption, we can conclude that the mutual information bottleneck between s and d is the second term in (6), namely: $I_{\mathcal{K}_s,d}$. Then, we formulate the outage event given by $I_{s,d} < R$ and the outage probability, as:

$$\begin{aligned} \epsilon^{out} &= \Pr\{I_{s,d} < R\} = \Pr\{I_{\mathcal{K}_s,d} < R\} \\ &= \Pr\left\{\frac{1}{2}\log(1 + P_s^C|\mathsf{a}_{s,d}|^2 + \sum_{i\in\mathcal{K}_s} P_i^C|\mathsf{a}_{i,d}|^2) < R\right\} \\ &= \Pr\left\{P_s^C|\mathsf{a}_{s,d}|^2 + \sum_{i\in\mathcal{K}_s} P_i^C|\mathsf{a}_{i,d}|^2 < 2^{2R} - 1\right\}. \end{aligned} \tag{7}$$

Theorem 1 *For multiple simultaneous relays, the outage probability under repetition-coded DF cooperation is given by:*

$$\epsilon^{out} \approx \frac{(2^{2R} - 1)^{K+1}}{(K+1)!} \prod_{i\in\{s\}\cup\mathcal{K}_s} \frac{d_{i,d}^{\alpha}}{P_i^C}. \tag{8}$$

Proof : In [31], Laneman *et.al.* proposed an approximation for (7) but with the assumption that each node has the same normalized power. We extend its result to the scenario where the normalized power of each node P_i^C ,$\forall i \in \{s\} \cup \mathcal{K}_s$ can be different. Take one item from (8) and let $\delta = 2^{2R} - 1$, $\rho_i s = P_i^C$, then we have:

$$\begin{aligned}
&\lim_{s\to\infty} s \cdot \Pr\{P_i^C |\mathsf{a}_{i,d}|^2 < \delta\} \\
&= \lim_{s\to\infty} s \cdot \Pr\left\{\rho_i s |\mathsf{a}_{i,d}|^2 < \delta\right\} = \lim_{s\to\infty} s \cdot \Pr\left\{|\mathsf{a}_{i,d}|^2 < \frac{\delta}{\rho_i s}\right\} \\
&= \lim_{s\to\infty} s \cdot \frac{\delta}{\rho_i s} d_{i,d}^{\alpha} = \frac{\delta}{\rho_i} d_{i,d}^{\alpha}.
\end{aligned} \tag{9}$$

We also apply Theorem 1 in [31]: let u_s and v_s be two independent random variables with the property that,

$$\lim_{s\to\infty} s \cdot \Pr\{u_s < t\} = f(t), \quad \lim_{s\to\infty} s^d \cdot \Pr\{v_s < t\} = g(t),$$

where $f(t)$ and $g(t)$ are monotone increasing and integrable, and $f'(t)$ is integrable. Then

$$\lim_{s\to\infty} s^{d+1} \cdot \Pr\{u_s + v_s < t\} = \int_0^t g(t-x) f'(x) dx. \tag{10}$$

The result (9) being utilized K times, yields the approximation:

$$\begin{aligned}
\epsilon^{out} &= \Pr\left\{P_s^C |\mathsf{a}_{s,d}|^2 + \sum_{i\in\mathcal{K}_s} P_i^C |\mathsf{a}_{i,d}|^2 < 2^{2R} - 1\right\} \\
&\approx \frac{(2^{2R}-1)^{K+1}}{(K+1)!} \prod_{i\in\{s\}\cup\mathcal{K}_s} \frac{d_{i,d}^{\alpha}}{P_i^C}.
\end{aligned} \tag{11}$$

□

From (8), it is clear that the outage probability is closely related to the transmission power P_i^C, number of selected relays K, desired data rate R, path-loss exponent α and the distance between nodes $d_{i,d}$.

Theorem 2 *Based on the previous system model assumption, given K relays, the cooperative scheme can achieve the spatial multiplexing gain $r = 1/2$ and diversity gain $d = K+1$, and $\epsilon^{out}(\mathsf{SNR}) \doteq \mathsf{SNR}^{-(K+1)}$.*

Proof : Recall the definition of the multiplexing gain r and diversity gain d in [32],

$$\lim_{\mathsf{SNR}\to\infty} \frac{R(\mathsf{SNR})}{\log(\mathsf{SNR})} = r, \quad \text{and} \quad \lim_{\mathsf{SNR}\to\infty} \frac{\log \epsilon^{out}(\mathsf{SNR})}{\log(\mathsf{SNR})} = -d. \tag{12}$$

Assume that the normalized transmission power of each node is the same, denoted as SNR. Then, (8) can be written as:

$$\epsilon^{out} \approx \frac{(2^{2R}-1)^{K+1}}{(K+1)!} \prod_{i\in\{s\}\cup\mathcal{K}_s} \frac{d_{i,d}^{\alpha}}{\mathsf{SNR}}. \tag{13}$$

And thus, the diversity gain can be derived as:

$$\begin{aligned} d &= -\lim_{\mathsf{SNR}\to\infty} \frac{\log \epsilon^{out}(\mathsf{SNR})}{\log(\mathsf{SNR})} \\ &= -\lim_{\mathsf{SNR}\to\infty} \frac{\log\left(\frac{(2^{2R}-1)^{K+1}}{(K+1)!}\prod_{i\in\{s\}\cup\mathcal{K}_s}\frac{d_{i,d}^{\alpha}}{\mathsf{SNR}}\right)}{\log(\mathsf{SNR})} \\ &= -\lim_{\mathsf{SNR}\to\infty} \frac{\log\frac{(2^{2R}-1)^{K+1}}{(K+1)!} + \sum_{i\in\{s\}\cup\mathcal{K}_s}\log d_{i,d}^{\alpha} - \sum_{i\in\{s\}\cup\mathcal{K}_s}\log(\mathsf{SNR})}{\log(\mathsf{SNR})} \\ &= \lim_{\mathsf{SNR}\to\infty} \frac{\sum_{i\in\{s\}\cup\mathcal{K}_s}\log\mathsf{SNR}}{\log(\mathsf{SNR})} \\ &= K+1. \end{aligned} \tag{14}$$

Note that the desired data rate R can be derived from (13),

$$R = \frac{1}{2}\log\left(1+\left(\epsilon^{out}(K+1)!\prod_{i\in\{s\}\cup\mathcal{K}_s}\frac{\mathsf{SNR}}{d_{i,d}^{\alpha}}\right)^{\frac{1}{K+1}}\right), \tag{15}$$

Then, we obtain the multiplexing gain as:

$$\begin{aligned} r &= \lim_{\mathsf{SNR}\to\infty}\frac{R(\mathsf{SNR})}{\log(\mathsf{SNR})} \\ &= \lim_{\mathsf{SNR}\to\infty}\frac{\frac{1}{2}\log\left(1+\left(\epsilon^{out}(K+1)!\prod_{i\in\{s\}\cup\mathcal{K}_s}\frac{\mathsf{SNR}}{d_{i,d}^{\alpha}}\right)^{\frac{1}{K+1}}\right)}{\log(\mathsf{SNR})} \\ &= \lim_{\mathsf{SNR}\to\infty}\frac{\frac{1}{2}\log\left(1+\left(\frac{\epsilon^{out}(K+1)!}{\prod_{i\in\{s\}\cup\mathcal{K}_s}d_{i,d}^{\alpha}}\right)^{\frac{1}{K+1}}\cdot\mathsf{SNR}\right)}{\log(\mathsf{SNR})} \end{aligned} \tag{16}$$

Let $\eta = \left(\frac{\epsilon^{out}(K+1)!}{\prod_{i\in\{s\}\cup\mathcal{K}_s}d_{i,d}^{\alpha}}\right)^{\frac{1}{K+1}}$, then:

$$r = \lim_{\mathsf{SNR}\to\infty}\frac{\frac{1}{2}\log(1+\eta\mathsf{SNR})}{\log(\mathsf{SNR})} = \lim_{\mathsf{SNR}\to\infty}\frac{1}{2}\cdot\frac{\eta\mathsf{SNR}}{1+\eta\mathsf{SNR}} = \frac{1}{2}. \tag{17}$$

We use $\doteq$ to denote the exponential equality [33]. $f(x)$ is said to be exponentially equal to x^d, denoted as $f(x)\doteq x^d$, when $\lim_{x\to\infty}\frac{\log[f(x)]}{\log(x)} = d$. From the definition of diversity gain, we can obtain:

$$\epsilon^{out}(\mathsf{SNR}) \doteq \mathsf{SNR}^{-(K+1)}. \tag{18}$$

□

5 Utility Function and Selfishness Index

To achieve the fairness in relay selection and power allocation, we associate each node with a *utility* representing its net payoff (or the actual benefit) received from cooperative transmission. Existing literatures have shown that by using relaying, a source node can gain a certain degree of power saving. However, if a node serves as a relay, it contributes its own resource to help others. Given the non-uniform packet arrival process at each node in the network and some specific MAC scheduling algorithm is employed, some nodes act more as the source while others may serve more as the relay. Therefore by introducing the utility, we aim to balance the power saving and loss of each node and offer a certain degree of fairness.

We use parameter *gain*, denoted as G, to represent the power saving of a source from cooperative communication. The instantaneous gain of node i at time t is defined as the difference between the direct transmission and cooperative relaying:

$$G_i(t) = G_i(t-1) + \Delta G_i(t), \tag{19}$$

and,

$$\Delta G_i(t) = \begin{cases} P_i^D(t) - P_i^C(t), & i = s, \\ 0, & \text{others.} \end{cases} \tag{20}$$

It is clear that only the source can accumulate a certain amount of gain, but not the relays.

Next, we introduce a parameter *loss*, denoted as L, representing the power spending of a relay from cooperative communication. The instantaneous loss of node i at time t is defined as:

$$L_i(t) = L_i(t-1) + \Delta L_i(t), \tag{21}$$

and,

$$\Delta L_i(t) = \begin{cases} P_i^C, & \forall i \in \mathcal{K}_s, \\ 0, & \text{others.} \end{cases} \tag{22}$$

At time t, only relays would accommodate certain amount of loss as they are helpers to the source and make a sacrifice in relaying packets. Since gain and loss are time-accumulative parameters, it is obvious that both $G_i(0)$ and $L_i(0)$ equals to zero, and if a node does not transmit any packets at time t, its gain and loss remain unchanged.

We use utility $U_i(t)$ to denote the actual benefit node i retains at time t and more benefit means more responsibility in transmission. One straightforward method to define utility is to subtract the loss from gain. Meanwhile, considering the selfish behavior of nodes, we incorporate a *selfishness index*, denoted as $\gamma_i(t) \in [0,1]$, into the utility function to make it more rational. Then, the utility $U_i(t)$ of each node i at time t can be formulated as:

$$U_i(t) = \gamma_i(t)\Big(G_i(t) - L_i(t)\Big), \quad \forall i \in \mathcal{N}. \tag{23}$$

It is worth noting that γ can be arbitrarily chosen where value "0" represents extremely selfish behavior and "1" indicated highly generous. If considering the energy reserve of the node at any time, we further quantify γ as:

$$\gamma_i(t) = \frac{\bar{E}_i(t)}{E_i}, \quad \forall i \in \mathcal{N}. \tag{24}$$

We argue that selfish behaviors can be fully captured in the parameter γ and utility function (23). First, if we denote the difference between the gain and loss as the *primal* utility, then "selfishness" means that a node is not willing to cooperate so as to take less responsibility in relay selection and power consumption. Examining (23), we see that the time-varying selfishness index $\gamma_i(t)$ reflects the percentage of utility (or net payoff) discount of each node. For instance, in (24), at the initial phase all nodes have full energy reserve and thus $\gamma_i(0) = 1, \forall i$, and more generous behavior is expected. When nodes participate in the cooperative transmission, they would spend more energy, and thus the lower value of the selfishness index and net payoff; as a result, higher degree of selfish behavior may exhibit. Given two nodes with the same primal utility, it is obvious that the one with less residual energy would have a lower utility and thus take less responsibility in helping others.

Furthermore, we associate the utility with a transmission "responsibility" in two ways: one is in relay selection process, where only nodes with non-negative utility have the opportunity to be selected as active relays; second is in power allocation process, where the power of a node is proportional to its instantaneous utility value. In the next section, we will show how the fairness factor performs in the proposed optimal power allocation.

6 Optimal Fair Power Allocation

Since relay selection criteria and power allocation rules are highly inter-related, we start with assumption that the active relay set $\mathcal{K}_s$ is given and illustrate the mechanism to find the most appropriate K members.

At time t, for given K relays, we propose an optimal power allocation scheme as a constrained optimization problem aiming at minimizing the sum of weighted transmission power under a given outage probability threshold ϵ_0. In order to derive a reasonable result, we scale the utility U into a value range of [0,1], denoted as $\dot{U}$. Then, the weight of node i is defined as:

$$w_i(t) = g(\dot{U}_i(t)), \quad \forall i \in \mathcal{N}, \tag{25}$$

where $g(\dot{U})$ is a generic non-increasing function of the normalized utility value $\dot{U}$, and one of its realization can be $g(\dot{U}) = \exp(-\beta\dot{U})$, where β is a constant.

Now, we formally introduce the optimization problem, as:

$$\begin{aligned} &\{P_i^C(t)\}_{i\in\{s\}\cup\mathcal{K}_s} = \underset{P_i^C(t)}{\operatorname{argmin}} \sum_{i\in\{s\}\cup\mathcal{K}_s} w_i(t) P_i^C(t), \\ &s.t. \quad \epsilon^{out} \le \epsilon_0. \end{aligned} \tag{26}$$

According to Theorem 1, let Q be a constant,

$$Q = \frac{(2^{2R}-1)^{K+1}}{(K+1)!} \prod_{i \in \{s\} \cup \mathcal{K}_s} d_{i,d}^{\alpha}, \tag{27}$$

where R, K and $\mathcal{K}_s$ are given; then ϵ^{out} can be rewritten as,

$$\epsilon^{out} = Q / \prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t). \tag{28}$$

Hence, the optimization problem (26) becomes:

$$\begin{aligned} &\{P_i^C(t)\}_{i \in \{s\} \cup \mathcal{K}_s} = \underset{P_i^C(t)}{\operatorname{argmin}} \sum_{i \in \{s\} \cup \mathcal{K}_s} w_i(t) P_i^C(t), \\ &s.t. \quad \prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t) \geq \frac{Q}{\epsilon_0}. \end{aligned} \tag{29}$$

It is a classic constrained optimization problem, which could be solved by Lagrangian multipliers; and thus we form a Lagrangian problem with multiplier λ as:

$$F = \sum_{i \in \{s\} \cup \mathcal{K}_s} w_i(t) P_i^C(t) - \lambda \Bigg(\prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t) - \frac{Q}{\epsilon_0} \Bigg). \tag{30}$$

The first order (necessary) optimality condition for (30) is:

$$\nabla F = 0 \text{ and } \lambda \Bigg(\prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t) - \frac{Q}{\epsilon_0} \Bigg) = 0. \tag{31}$$

Since the constraint is binding, $\lambda \neq 0$ and $\prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t) - \frac{Q}{\epsilon_0} = 0$, the first part of (31) becomes:

$$\nabla F = 0 \Leftrightarrow P_i^C(t) w_i(t) = \frac{\lambda Q}{\epsilon_0}, \quad \forall i \in \{s\} \cup \mathcal{K}_s, \tag{32}$$

or equivalently,

$$P_i^C(t) = \frac{\lambda Q}{\epsilon_0 w_i(t)}, \quad \forall i \in \{s\} \cup \mathcal{K}_s. \tag{33}$$

In other words, the instantaneous power consumption of node i is inversely proportional to its weight $w_i(t)$. It is worth noting that from (25) we define $w_i(t)$ as a non-increasing function of the normalized utility $\dot{U}_i(t)$, and more importantly, it can be concluded that the optimal power consumption for node i is proportional to its instantaneous utility.

Next, we put (33) into the constraint $\prod_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t) = Q/\epsilon_0$, and we have:

$$\lambda = \sqrt[K+1]{\frac{\prod_{i \in \{s\} \cup \mathcal{K}_s} w_i(t)}{(Q/\epsilon_0)^K}}. \tag{34}$$

Therefore, the closed-form representation of optimal transmission power for each node is formulated as:

$$P_i^C(t) = \sqrt[K+1]{\frac{Q}{\epsilon_0}} \cdot \frac{\sqrt[K+1]{\prod_{i\in\{s\}\cup\mathcal{K}_s} w_i(t)}}{w_i(t)}, \quad \forall i \in \{s\} \cup \mathcal{K}_s. \tag{35}$$

From (35), it is clear that higher utility values result in higher optimal power allocation, when a node benefits more from the help of other relay cooperations or it has more residual energy. While for those who contribute more frequently as relays or have less energy reserve, they exhibit different degrees of selfish behaviors. Hence, by minimizing the sum of weighted power of each node, optimal power efficiency and certain degree of energy consumption fairness can be jointly achieved.

7 Lifetime-Aware Two-Step Relay Selection

This section aims to find the most appropriate K nodes to form relay set $\mathcal{K}_s$, given that the transmission power of these K relays can already been optimally allocated in (35). The selection mechanism should allow the selected relays achieve high degree of power efficiency. Furthermore, as the benefit of each node receiving from the cooperative transmission is different, be fair and equitable, nodes with negative benefit from cooperative transmission will be removed from relay selection. Moreover, since most terminals are battery-powered, it should balance the energy consumption of each node as much as possible to maximize network lifetime, which, in this paper, is defined as when the first node runs out of energy. In the following discussions, we shall illustrate how we cover these aspects of power efficiency, cumulative benefits, energy consumption fairness and network lifetime all together in relay selection.

At time t, we denote the nodes with non-negative utility as a set $\mathcal{M} \triangleq \{m = 1, 2, \ldots, M\}$, where $U_m(t) \in \mathbb{R}^+, \forall m \in \mathcal{M}$. Then, the active relay set $\mathcal{K}_s$ with variable size K is a subset of $\mathcal{M}$ and $K = 1, 2, \ldots, M$. To this end, by performing exhaustive search over all possible decoding sets, we have $\sum_{K=1}^{M} \binom{M}{K}$ different combinations, or optimization iterations. We next separate this exhaustive search into two steps. Step-1 takes power efficiency and energy consumption fairness into consideration by using (35) to optimally allocate transmission power, and Step-2 covers the aspect of network lifetime.

Step-1: we choose the most appropriate relay set for each $K = 1, 2, \ldots, M$, and for the totally $\binom{M}{K}$ potential options, we calculate the power as in (35) and find the set which minimizes the objective function, the result of which is denoted as $\mathcal{K}^* \mid_K$,

$$\begin{aligned} &\mathcal{K}^* \mid_K = \underset{\mathcal{K}^j\mid_K}{\operatorname{argmin}} \sum_i w_i(t) P_i^C(t), \\ &\forall i \in \{s\} \cup \mathcal{K}^j \mid_K, \quad \forall j \in \left\{1, 2, \ldots, \binom{M}{k}\right\}, \end{aligned} \tag{36}$$

where $\mathcal{K}^j \mid_K$ represents the *j*-th subset of $\mathcal{M}$ with its size $|\mathcal{K}^j| = K$. Then, we calculate the estimated network lifetime T of set $\mathcal{K}^*|_K$ as:

$$T(\mathcal{K}^* \mid_K) = \min_i \frac{\bar{E}_i(t)}{P_i^C(t)}, \quad \forall i \in \{s\} \cup \mathcal{K}^* \mid_K . \tag{37}$$

Algorithm 1: Proposed Power Allocation and Relay Selection Approach

1 $\mathcal{M} = \emptyset$;
2 **foreach** $i \in \mathcal{N}$ **do**
3   **if** $i \neq s$ *and* $i \neq d$ *and* $U_i(t) \in \mathbb{R}^+$ **then**
4         $\mathcal{M} = \mathcal{M} \cup \{i\}$;
5   **end**
6 **end**
7 $M = |\mathcal{M}|$;
8 **for** $k = 1$ **to** M **do**
9   **for** $j = 1$ **to** $\binom{M}{k}$ **do**
10   set $\mathcal{K}^j\mid_K$ as the *j*-th subset of $\mathcal{M}$ with size K;
11   calculate the power of each node i as (35), $\quad \forall i \in \{s\} \cup \mathcal{K}^j\mid_K$;
12   **end**
13   calculate $\mathcal{K}^*\mid_K$ as in (36);
14   calculate $T(\mathcal{K}^*\mid_K)$ as in (37);
15 **end**
16 $\mathcal{K}_s = \mathrm{argmax}_{\mathcal{K}^*|_K} T, \quad \forall K \in \{1, 2, \ldots, M\}$;
17 calculate the power of each node i as in (35), $\quad \forall i \in \{s\} \cup \mathcal{K}_s$.
18 **if** $P_s^D > \sum_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t)$ **then**
19   cooperative transmission with $\mathcal{K}_s$;
20 **else**
21   direct transmission;
22 **end**

Following the same steps above, we are able to further obtain M sets $\{\mathcal{K}^*|_{K=1,2,\ldots,M}\}$.

Step-2: from the previous obtained M optional sets, we select the one with the longest estimated network lifetime as the active relay set $\mathcal{K}_s$:

$$\mathcal{K}_s = \operatorname*{argmax}_{\mathcal{K}^*|_K} T, \quad \forall K \in \{1, 2, \ldots, M\}. \tag{38}$$

Through the two-step relay selection, we are able to obtain the active relay set $\mathcal{K}_s$ and the power of each node. Note that cooperative transmission is not always the best solution, and in particular when the source and destination are very close to each other. Therefore, for sake of power efficiency, we use cooperative relaying if and only if:

$$P_s^D > \sum_{i \in \{s\} \cup \mathcal{K}_s} P_i^C(t). \tag{39}$$

Algorithm 1 shows the pseudo-code of the proposed power allocation and relay selection algorithm. At time t, given the source s, destination d and the candidate relays, we run this algorithm to generate the active relay set $\mathcal{K}_s$ and calculate the power of source and active relays, then select direct transmission or cooperative transmission based on power efficiency consideration. From line 1-6, we select the relays with non-negative utilities to form a set $\mathcal{M}$. Line 8-15 show the exhaustive search over all possible decoding sets, where the internal iteration is the Step-1 of relay selection and external iteration is the Step-2 of relay selection, as stated above. Finally, we get the active relay set $\mathcal{K}_s$ at line 16 and calculate the power of each node at line 17. Line 18-22 is the transmission scheme selection process. Cooperative transmission will be utilized only if it can achieve power saving compared with the direct transmission scheme.

8 Performance Evaluation

In this section, we first provide extensive numerical results by using two different network settings to investigate the impact of selfish behavior on power consumption, the relationship between node utility and power allocation, and demonstrate the superiority of our proposed approach in power saving and allocation fairness. Then, we study the achieved QoS outage of the proposed approach under the realistic environment, and further propose an improvement “channel-aware packet selection” approach, which can significantly lower the QoS outage and increase the network goodput.

8.1 A Five-Node Network Example

In this scenario, five nodes are randomly deployed in an area of $100 \times 100\text{m}^2$ region (the edges of the region are wrapped (toroid) to eliminate edge effects). Throughout the simulation, we set the path-loss exponent $\alpha = 3$, expected data rate $R = 1$ bps/Hz and targeted outage $\epsilon_0 = 0.01$, all as constants. Furthermore, we use $g(\dot{U}) = \exp(-\dot{U})$. At each time t, a packet is transmitted by a randomly selected source and received by a randomly selected destination. Other three nodes are treated as candidate relays from which the source generates the active relay set $\mathcal{K}_s$. A total of 1000 packets are simulated within the network and all nodes have adequate energy reserve being alive after the simulation.

We run our proposed approach in four different parameter settings. In the fully generous condition, $\gamma_i = 1, \forall i, t$, representing that none of them behave selfish at any time. In the second and third conditions, we partially assign nodes $i = 3$ and $i = 5$ as selfish nodes with $\gamma_{3,5}(t) = \{0.5, 0.1\}, \forall t$, respectively, while for other nodes we set $\gamma_{1,2,4}(t) = 1, \forall t$. Finally, in the energy-aware selfish condition, all nodes exhibit time-varying selfish behavior proportional to the percentage of remaining energy, i.e., $\gamma_i(t) = \bar{E}_i(t)/E_i, \forall i, t$.

It is observed in Fig. 2(a) that power consumptions of selfish nodes 3,5 are much smaller than the fully generous case (as shown by the arrows), and their total amount of power saving increases when selfishness index γ changes from 0.5 to 0.1. Meanwhile, for the rest of generous node 1, 2 and 4, their power consumptions would have to increase to complement the more selfish behaviors of other nodes to guarantee the requested QoS parameter R and ϵ_0.

Fig. 2(b) shows the total power consumption with different numbers of selfish nodes assigned in the afore-mentioned partial selfishness case. In contrast to the fully generous setting, partial selfishness leads to more energy consumption and this gap becomes even larger when γ reduces significantly from 1 to 0.1, showing that the total network consumption and network lifetime sacrifices although selfish nodes save their own energy. However, it is very interesting to observe that when all nodes exhibit energy-aware selfishness the network energy consumption achieves the least,

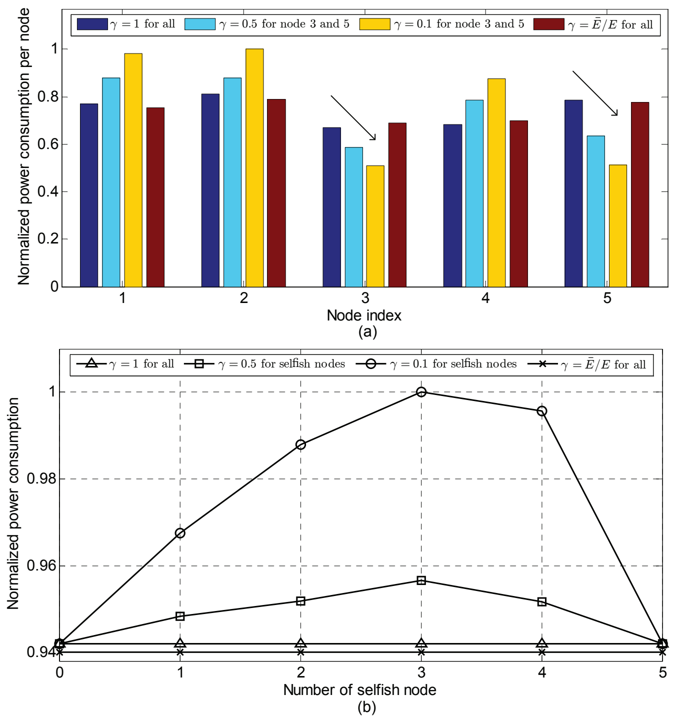

Fig. 2 Simulation results for selfishness impact in four different conditions: fully generous case, partial $\gamma = 0.5$ selfishness, partial $\gamma = 0.1$ selfishness, and all energy-aware selfish case. (a) Normalized power consumption. (b) Total power consumption vs. the number of selfish nodes.

resulting in an optimum. This is because by the rational energy-aware selfishness, power consumption is well balanced and no one is excessively depleted at any time.

Therefore, the simulation results of five-node example firmly demonstrate that our proposed approach captures the selfish behavior in an appropriate way, and the all energy-aware selfish condition achieves the best power saving, thus paving the way for its superior performance under a more practical and complex environment.

Next, we carefully examine the system behavior in detail, focusing to study the relationship between node utility and power allocation. Recall that in Section 5 we demonstrate the use of node utility to represent the actual benefit obtained from cooperative transmission and offer a certain level of fairness in power allocation. In order to understand the change of utility values and the result of power allocation, we consider the all energy-aware selfish condition and plot the power and utility change of each node over time, as shown in Fig. 3 and Fig. 4, respectively. From Fig. 4(a) we observe that since nodes are randomly selected as the source, their utility values increase when time evolves, and they converge quickly in about 25 time slots. With reference to Fig. 3(a) where power is allocated proportional to the utility, it also converges in the fast pace.

We zoom in the initial time period before convergence and obtain Fig. 3(b) with reference to Fig. 4(b). It is clear to verify the relationship between two parameters.

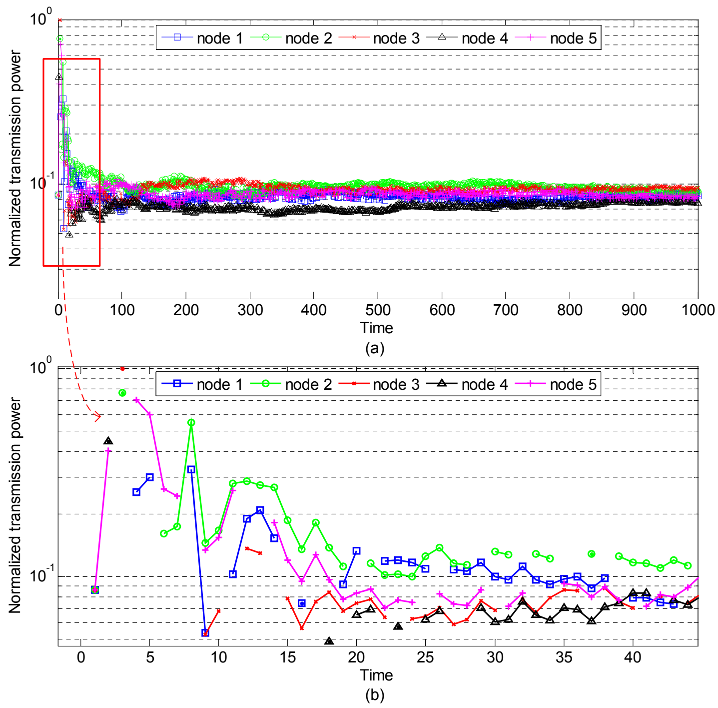

Fig. 3 Power allocation vs. time. The disconnected points are the time when a particular node does not participate in cooperative transmission.

Take $t = 19$ as an example. At $t = 19$, node 1 is the source while node 3 and 5 serve as relays. Because of $U_1(19) > U_5(19) > U_3(19)$, we derive $P_1^C(19) > P_5^C(19) > P_3^C(19)$. Examining Fig. 4(b), we can also figure out the role of each node at time t, since the source utility would increase, relay utility decreases and all other nodes unchanged. For example, node 2 is the source and the active relay set consists of node 3-5 at $t = 20$.

8.2 A Complete Network Setting

In this scenario, we place N (varied between 5 and 10) nodes at uniformly random locations in a $100 \times 100\text{m}^2$ region. A total of $1000 \times N$ packets are transmitted, and at each time t, a packet is transmitted by a randomly selected source and a randomly selected destination. The simulation result is averaged over 100 runs for each N. We use the all energy-aware selfish condition and the weight is also chosen as $g(\dot{U}) = \exp(-\dot{U})$. We aim to investigate the average power consumption for each node of our proposed approach under different parameter settings, i.e., by varying the path-loss exponent, outage probability threshold and desired data rate, to compare its performance with direct transmission and random relay selection approach. The random relay selection applies the same power allocation scheme as our proposed approach, but selects relay set randomly.

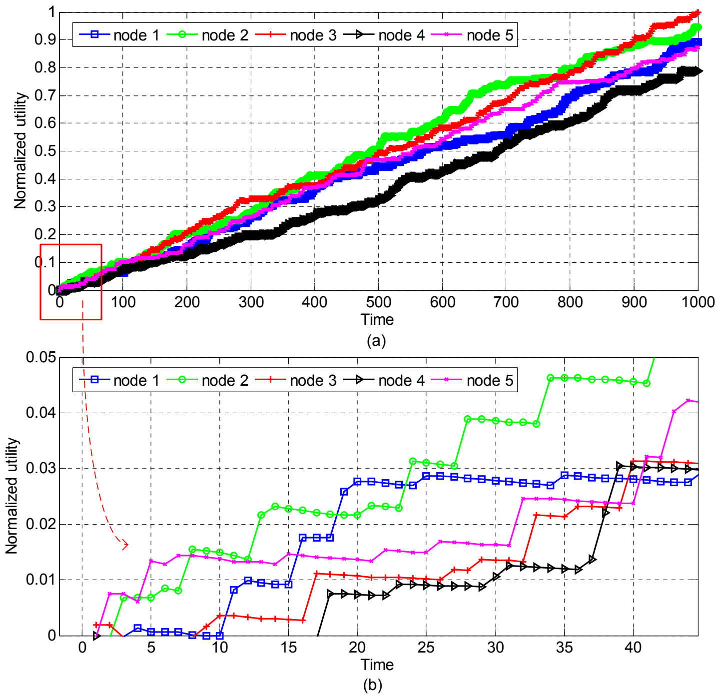

Fig. 4 Node utility vs. time.

Fig. 5 shows the average normalized power consumption with respect to (w.r.t.) different network sizes and α. We observe that our proposed approach consumes less energy than both the random relay selection approach and direct transmission by a factor of 1/2 and 1/9 when $N = 5$, respectively; and this gain becomes larger when N increases. Furthermore, as the network density increases, both the average energy consumption of the proposed approach and random relay selection approach decrease significantly since nodes in the nearby proximity can be leveraged as relays. With the increase of α, it is not surprising the network would spend more energy to combat the large scale fading factor. The effects of different ϵ_0 and R can be seen in Fig. 6 and Fig. 7 , where overall one can observe the similar trends that lower outage probability threshold and higher data rate (more stringent QoS requirements) eventually lead to higher power consumption; however the proposed approach always outperform the other two schemes.

Table 1 illustrates the fairness performance by applying Jain's fairness index to relay's power in the proposed approach when setting network parameter $\epsilon_0 = 0.01, R = 1$. This index is defined by $\sum(P_i^C)^2/\big(N\sum(P_i^C)^2\big), \forall i \in \mathcal{K}_s$. The result ranges from $\frac{1}{N}$ (worst case) to 1 (best case). The larger the index is, the better fairness that we can achieve.It can be seen that the power allocation between multiple relays reaches a relatively high level of fairness and does not change dramatically over different large scale fading factor α. This is achieved by the proposed utility function

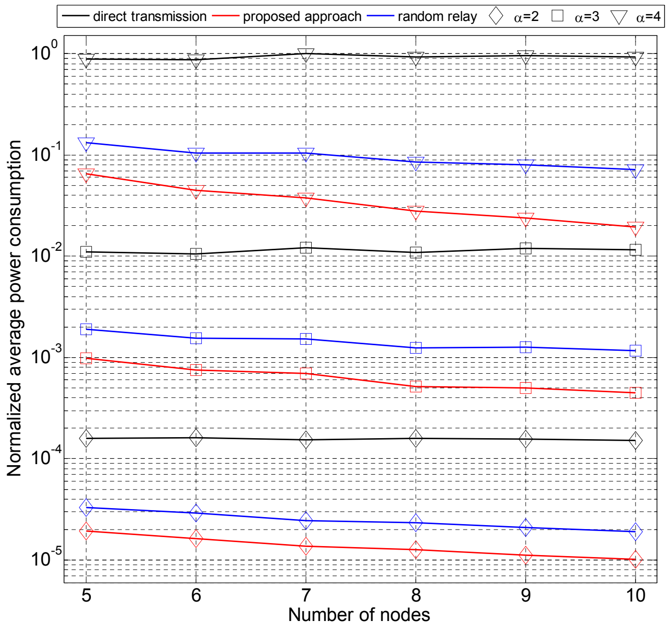

Fig. 5 Normalized average power consumption vs. the number of nodes, $\alpha = \{2, 3, 4\}$, $\epsilon_0 = 0.01$, $R = 1$.

Table 1 Fairness index (Jain's) among the relay power.

	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$
$N = 5$	0.9484	0.9485	0.9457
$N = 8$	0.9478	0.9421	0.9465
$N = 10$	0.9443	0.9450	0.9473

and the two-step relay selection algorithm on balancing the energy consumption of each node at each packet transmission.

8.3 Channel-Aware Approach

From our proposed approach, we are able to find the optimal active relay set $\mathcal{K}_s$ and allocate power of each node to achieve a high degree of fairness and energy efficiency. Nevertheless, the question still remains since results are statistically correct for Rayleigh fading channel, but how can we guarantee the low QoS outage from time slot to time slot? QoS outage events are mainly caused by the deep fading channel when a pair of source-destination nodes are randomly chosen (as simulated above). From (6), we observe that when the channel fading is severe, the mutual information obtained by the proposed approach tends to be small, thus having higher probability to be less than the desired data rate. Therefore, in order to lower the QoS outage, we use the channel state of previous time slot to aid the decision-making of relay selection for the current node pair. We call a channel between a specific source-destination

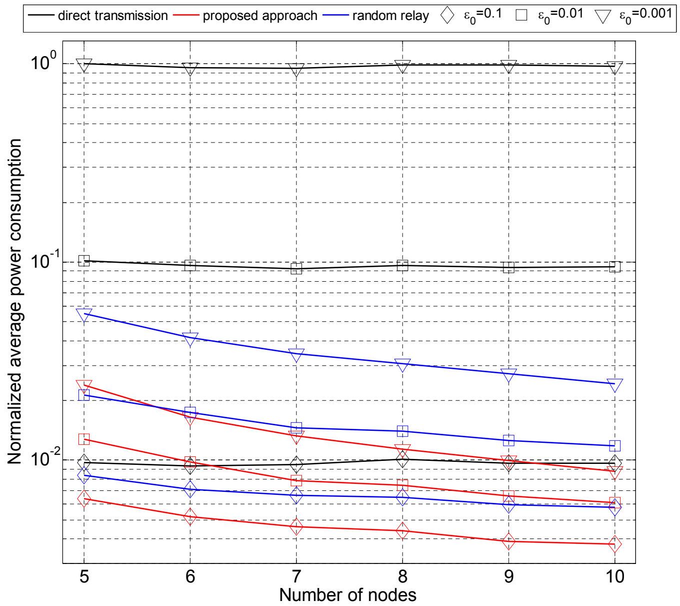

Fig. 6 Normalized average power consumption vs. the number of nodes, $\alpha = 3$, $\epsilon_0 = \{0.1, 0.01, 0.001\}$, $R = 1$.

pair with relay set $\mathcal{K}$ is "good" channel if,

$$\sum_{i \in \{s\} \cup \mathcal{K}} P_i^C(t) \frac{|h_{i,d}(t-1)|^2}{d_{i,d}^{\alpha}} > \sum_{i \in \{s\} \cup \mathcal{K}} P_i^C(t) \frac{\xi^2}{d_{i,d}^{\alpha}}, \tag{40}$$

satisfies, where ξ is a tunable threshold to judge the channel condition to be "good" in the next time slot t. The higher values of ξ indicates more stringent QoS requirements.

The purpose of this section is not to propose any novel MAC protocols/scheduling algorithms, but study the impact of different realistic channel conditions on the performance of our proposed relay selection scheme. Towards this end, without loss of generality, we also assume traffic arrive at each node independently and each node has a separate queue buffering these packets. We further assume that the queueing packets and channel conditions between any pair of source-destination node are known to the relay selection algorithm. It is worth noting that this assumption does not necessarily mean a centralized scheduling algorithm, but can be realized by distributed solutions like in [34] that exploits the multi-user diversity gain while satisfying the long-term throughput requirement.

We improve our previous "proposed approach", referred as "channel-aware: packet selection" scheme. It works as follows. At each time slot, a packet arrives at the buffer of the randomly selected source, intended to be transmitted to the randomly chosen destination. After the **Step-1** of Algorithm 1, based on the previous time slot channel information, the network evaluates the channel condition of the source-destination pair, and the ones between M obtained relay sets $\{\mathcal{K}^*|_{K=1,2,\ldots,M}\}$ and the destination as in (40). The relay sets with "good" channel condition will be passed to the

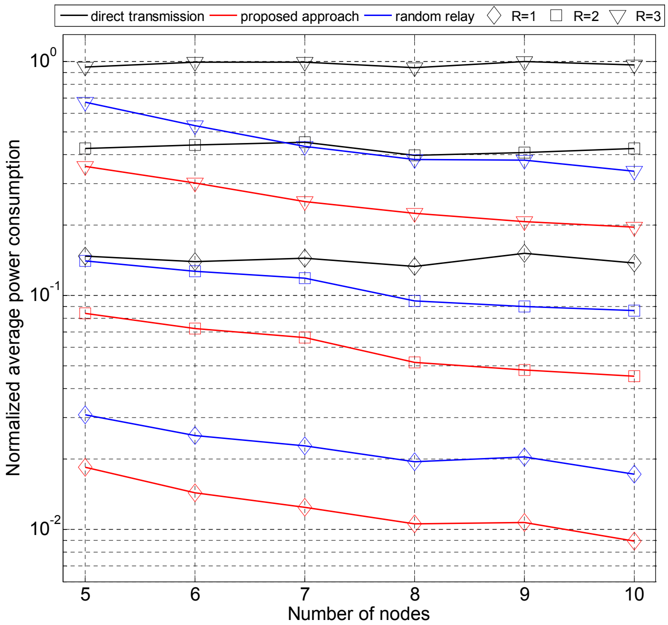

Fig. 7 Normalized average power consumption vs. the number of nodes, $\alpha = 3$, $\epsilon_0 = 0.01$, $R = \{1, 2, 3\}$bps/Hz.

Step-2 of Algorithm 1, the relay selection phase. However, if no relay sets exist after the channel evaluation, this transmission will be suspended and the network will follow the same procedure to examine the next communication pair until the packet with good transmitting channel is found. In the extreme condition where no communication pair in the network is associated with good channel, the cooperative relaying will be suspended and wait for next time slot. It is worth noting that the network remembers the packet arrival sequence, so that they are handled in a FIFO manner. Therefore, through packet selection, cooperative relaying happens only under *satisfactory* channel conditions for each time slot, and thus the QoS outage can be lowered at a maximum extent, but with the sacrifice of packet delay. Fig. 8 shows the revised system flow of channel-aware packet selection approach.

To assess its performance in terms of QoS outage, goodput (defined as the average number of transmitted packets without QoS outage per time slot), and power consumption, we still use the topology of five randomly deployed nodes in an area of $100 \times 100\text{m}^2$ region, and vary ϵ_0 as 0.1 and 0.01. A total of 20,000 packets are simulated, and the result is averaged for 100 runs. Data rate R is set to 1 bps/Hz. The selfishness index and weight function are the same as the one used in Section 8.2. Table 2 shows the practical simulation parameters including the channel and antenna model, and modulation and coding scheme. We compare the “channel-aware: packet selection” approach with the previously “proposed approached” in Section 7, and we investigate their performance by varying ϵ_0 and the doppler frequency. ξ is set to 0.3 and 0.18 for $\epsilon_0 = 0.1$ and $\epsilon_0 = 0.01$, respectively.

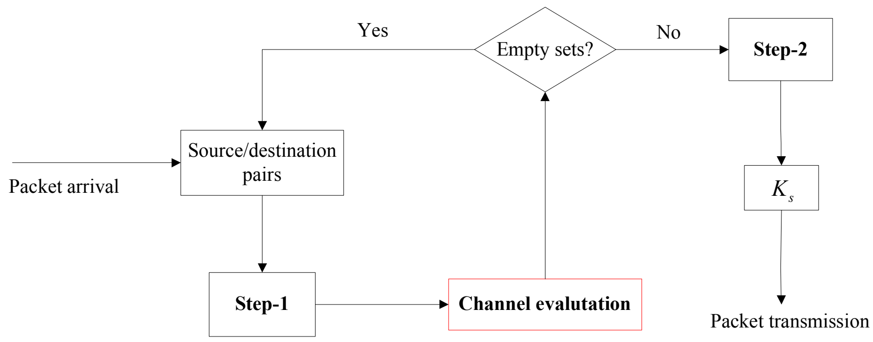

Fig. 8 System flow of the channel-aware packet selection approach.

Table 2 Simulation parameters

Parameter	**Value**
Channel Model	Rayleigh fading, Jake's Model [35]
Path-loss Exponent	2
System Bandwidth	50MHz
Time Slot Duration	81.92μs
Doppler Frequency	50, 60, 70, 80, 90, 100 Hz
Packet Length	512 bytes
Modulation and Coding	BPSK-1/1
Antenna Model	Omnidirectional

Fig. 9 shows that when the targeted outage probability $\epsilon_0 = 0.1$, the proposed approach suffers from average QoS outage 0.2 due to the potential deep fading between the randomly selected source-destination node pair. However, the channel-aware approach can successfully lower the outage close to the targeted ϵ_0. When $\epsilon_0 = 0.01$, the QoS outage under channel-aware approach is nearly zero.

Fig. 10 shows the trend of network goodput w.r.t. the doppler frequency. Since BPSK 1/1 is used in the PHY layer and the duration of the time slot is set to the length of transmitting one packet only, the upper-bound maximum goodput is 1. We can see that the goodput under channel-aware approach is higher than that under channel-unaware approach, and in particular, when $\epsilon_0 = 0.01$, the goodput under channel-aware approach is nearly 1. This is because the QoS outage is very low and the packet delay is well acceptable.

Table 3 shows the average packet delay of the channel-aware packet selection approach. When $\epsilon_0 = 0.1$, due to the higher possibility of deep fading, the average delay is higher if compared with the one when $\epsilon_0 = 0.01$. We also observe that this value experiences a decreasing trend with the increase of the doppler frequency. Note that "proposed approach", unaware of the channel conditions, provides the average packet delay equals to 1 slot. With reference to Fig. 9 and 10, it is interesting to highlight the trade-off between goodput/QoS outage and packet delay.

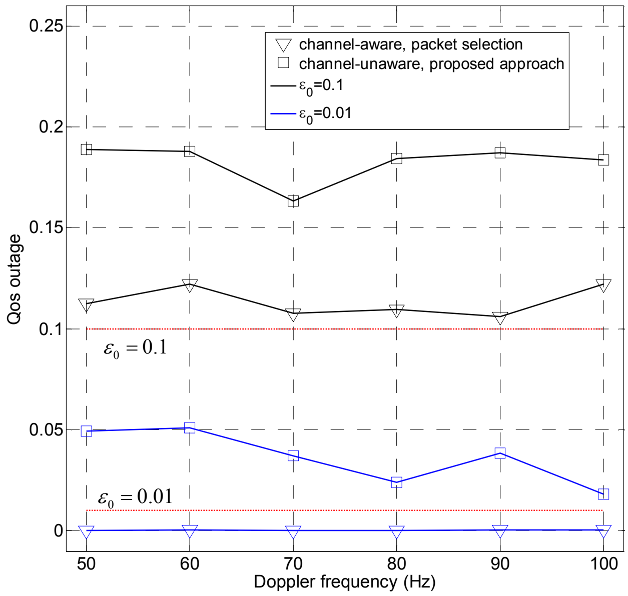

Fig. 9 QoS outage vs. doppler frequency.

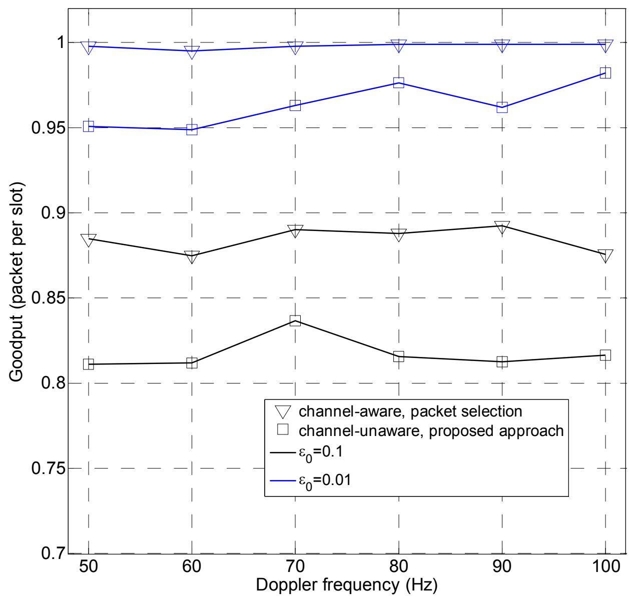

Fig. 10 Goodput vs. doppler frequency.

Fig. 11 demonstrates the power consumption of two approaches, where the newly proposed packet selection scheme does not yield extra energy usage, but its consumption is very close to the original approach.

Table 3 Average packet delay (in time slots) w.r.t different doppler frequencies and targeted ϵ_0 under the channel-aware packet selection approach

	50Hz	60Hz	70Hz	80Hz	90Hz	100Hz
$\epsilon_0 = 0.1$	44.5652	49.8665	38.4855	36.5292	31.7008	31.8160
$\epsilon_0 = 0.01$	36.6310	26.6589	32.3046	19.3332	19.6480	10.8629

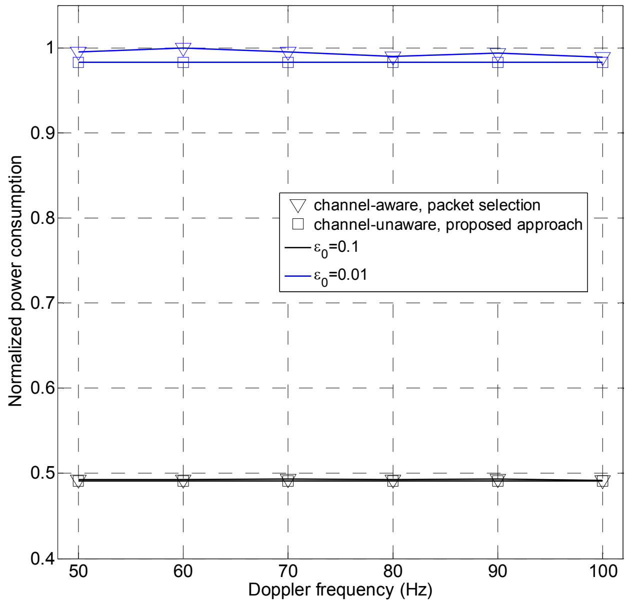

Fig. 11 Normalized power consumption vs. doppler frequency.

9 Practical Consideration: Mode Switching

In this section, we investigate our proposed approach in a more practical scenario, considering the energy cost in `ON`(active)/`OFF`(sleeping) mode switching. In practice, nodes may operate under certain duty cycles, and MAC protocols may enforce to wake up/sleep a set of nodes for the next time frame, according to the output of the relay selection algorithm. Towards this end, not all nodes in the network are available for relay selection. And even so, the energy cost of switching mode according to the selection decision may sometimes larger than transmitting one single packet to the nearby neighbor, and thus potentially significantly impact on the overall network lifetime. As far as the authors' knowledge, this is the first piece of research investigating this factor explicitly in the relay selection problem.

Towards this end, our focus in this section is to study the impact of energy cost in switching mode, and we assume that each node i is associated with a state $S_i(t)$, and if it acts as the source or relay, $S_i(t) = 1$; otherwise $S_i(t) = 0$. We use $P_i^{\text{switch}}(t)$ to denote the amount of energy cost when switching the mode between `ON` and `OFF`, whenever the previous state is different from the current one. Then, we re-formulate

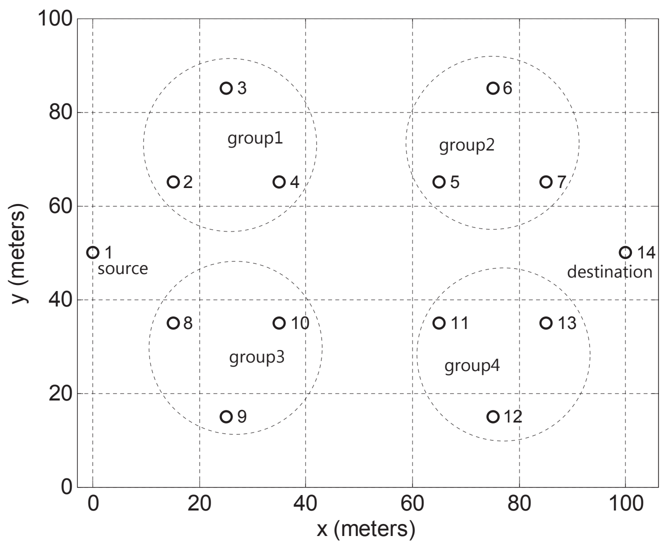

Fig. 12 Switching mode topology. Four relay groups and one permanent source-destination pair.

the optimization problem in (29), as:

$$\begin{aligned} \{P_i^C(t)\}_{i\in\{s\}\cup\mathcal{K}_s} &= \underset{P_i^C(t)}{\operatorname{argmin}} \sum_{i\in\{s\}\cup\mathcal{K}_s} w_i(t)P_i^C(t) + \sum_{i\in\mathcal{N}} P_i^{\text{switch}}(t), \\ s.t. \quad &\prod_{i\in\{s\}\cup\mathcal{K}_s} P_i^C(t) \geq \frac{Q}{\epsilon_0}. \end{aligned} \tag{41}$$

where

$$P_i^{\text{switch}}(t) = \begin{cases} P_0, & \text{if } S_i(t) \neq S_i(t-1), \\ 0, & \text{if } S_i(t) = S_i(t-1). \end{cases} \tag{42}$$

Accordingly, the estimated network lifetime calculated in (37) in relay selection process is rewritten as:

$$T(\mathcal{K}^* \mid_K) = \min_i \frac{\bar{E}_i(t)}{P_i^C(t) + P_i^{\text{switch}}(t)}, \quad \forall i \in \{s\} \cup \mathcal{K}^* \mid_K . \tag{43}$$

where the denominator denotes the total amount of energy usage considering the switching mode energy cost. The above optimization problem can be solved by many well-known method, like the projected subgradient algorithm [36].

To better demonstrate the effect of P_0 on relay selection, we use a scenario where node 1 and 14 always serve as the source-destination node pair, while 12 other nodes are grouped into four clusters located from the neighborhood of the source to the far end of it, as shown in Fig. 12. For simplicity reasons, in this section, we do not study the intra-cluster relay selection (i.e., which subset of nodes within a cluster are selected, but assuming their homogeneous operations). Nevertheless, we here focus on the *inter*-cluster selection, given that the relaying behaviors over time of these four

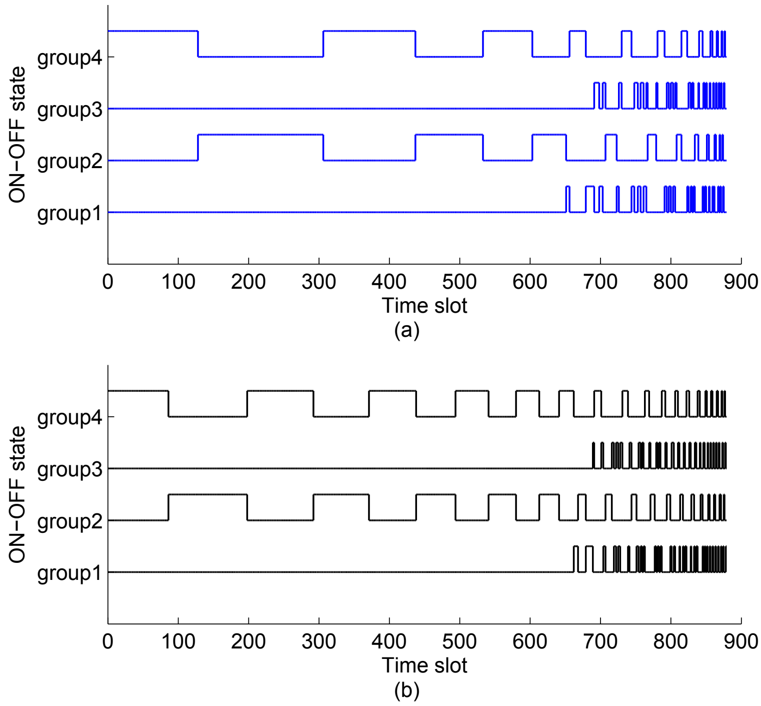

Fig. 13 The effects of energy cost when switching modes among four groups at different locations, where (a) `ON`/`OFF` energy cost: $2P_0$ (b) `ON`/`OFF` energy cost: P_0. P_0 equals to the direct transmission power where the distance is 10 meters.

groups at different locations may inter-relate with the amount of `ON`/`OFF` energy cost. We denote the four relay groups as $\mathcal{G}_i, \forall i \in \{1,2,3,4\}$ and the selected active relay group as $\mathcal{G}^*$.

At time t, by solving the optimization problem in (41), we obtain the power of each node in every candidate relay group. Then, we calculate the estimated network lifetime of each group. Here we exclude the source in network lifetime calculation because we assume the source to be equipped with sufficient energy supply. Finally, the group with the longest estimated lifetime is selected as the active relay group $\mathcal{G}^*$:

$$\mathcal{G}^* = \operatorname*{argmax}_{\mathcal{G}_i} \min_{j} \frac{\bar{E}_j(t)}{P_j^C(t) + P_j^{\text{switch}}(t)}, \quad \forall j \in \mathcal{G}_i, \quad i = \{1,2,3,4\}. \tag{44}$$

Fig. 13 shows the effect of extra power consumption when a group of nodes switch modes. In Fig. 13(b), we set the extra power consumption as P_0 with its value equivalent to the direct transmission power when the distance is 10 meters, and $2P_0$ in Fig. 13(a). The simulation initializes with all relays having different but limited residual energy supply and sufficient utility values, to avoid the problem of negative utility values in (25). As shown in Fig. 13(a), for the former 650 time slots, group 2 and group 4 are chosen as the candidate relay sets, alternating to service the packet transmission, due to their relatively shorter distances towards the destination; and thus, the lower power consumption per transmission, and longer network lifetime are expected, if compared with using group 1 and 3. Interestingly, the length of this "alternating period" is highly related to P_0, as higher energy cost ($2P_0$ in Fig. 13(a) and P_0 in Fig. 13(b)) makes the network reluctant to activate another group for service, until the gap is large enough to accommodate this energy cost for the purpose of extending the network lifetime. With the passage of time, the `ON` period becomes shorter, and even replaced by group 1 and 3 after time slot 650. This is because as more energy is consumed, the relative benefit of using the nearby relays becomes weak, and even though activating the sleeping group 1 and 3 may incur extra energy cost, its contribution to the overall network lifetime extension worth performing the switching decision. Nevertheless, even though group 1 and 3 are chosen for service nearly at the end of simulation, nearby groups 2 and 4 sometimes are also activated and back to service due to their relatively smaller energy consumption per transmission. Towards this end, we see how the network balances the switching cost and network lifetime (transmission power consumption).

The same effects become even clearer when considering the smaller energy cost when switching the mode, as shown in Fig. 13(b). Hence, it is very clear to see that higher energy cost in mode switching leads to a lower switching frequency.

10 Conclusion

In this paper, we investigated the problem of relay selection in cooperative communication, focusing on multiple simultaneous relays. We first derived a closed-form expression of the outage probability under repetition-coded DF cooperation. Then, we introduced the novel concept of selfishness index to capture the selfish behavior in cooperative transmission and incorporated it into a novel utility parameter representing the attained net payoff. After that, we proposed a two-step relay selection mechanism covering all aspects of power efficiency, energy fairness and network lifetime, by using the utility function that makes the process reasonable and rational. Extensive simulation results with different network sizes and QoS parameters showed that our scheme outperforms both the direction transmission and random relay selection scheme by a factor of 1/2 and 1/9 in power saving, respectively, when five nodes are randomly deployed. Furthermore, we evaluated our approach under realistic wireless environments and improved the proposed approach by considering the channel information in the previous time slot. This approach successfully lowers the QoS outage with tolerable delay penalty. Finally, we considered the practical situation when nodes consume energy in mode switching, and reformulated the power allocation optimization problem. We also have studied the behavior of inter-cluster relay switching and the trade-off among network lifetime, switching cost and switching frequency.

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