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Energy efficient cooperative communications using coalition formation games

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ABSTRACT

It is well-known that a single node in a network cooperates with one another employing cooperative communications can lead to transmission power saving. However, due to the additional processing power in receiving and retransmitting other's information, not all nodes and cooperative protocols can achieve energy efficiency. To ensure energy efficiency of a cooperative network, a novel merge process, consisting of transmission request stage, merge stage, and cooperative transmission stage, utilizing coalition formation games is proposed. The goal is to find a good cooperation structure, in which individual nodes in cooperative groups can achieve their own energy efficiency, thus resulting in energy efficiency of the cooperative network. The merge process is applied to a cooperative communication protocol, namely wireless network cocast (WNC), to demonstrate and validate its effectiveness. Simulations show that for the same network setting, the cooperative transmission networks can require 3.3 times less total power, accounting for both transmission and processing power, than the direct transmission networks to provide a comparable quality of service. The larger the network dimension is the larger the power saving for cooperative transmission over direct transmission. In addition, the cooperative networks achieve balanced power distribution, which helps improving the network lifetime. Comparing with an iterative merge-and-split process in coalition formation games, the simulations show that the iterative merge-and-split process should be only used in small-size networks while the proposed merge process has much more advantage in large-size networks.

1. Introduction

Cooperative communications have been attractive due to the ability of improving communication performance. Leveraging the broadcast nature of wireless communications, nodes in a network that overhear the transmitted information can help relay it to the intended destination. Cooperative communications thus form a virtual antenna array to combat channel fading through spatial diversity and can significantly improve communications in terms of throughput, reliability, range and coverage [1].

In military hand-held and man-packed applications as well as in commercial wireless sensor networks, where the devices rely on batteries for their operations, energy efficiency is an important factor of consideration. Energy efficiency in cooperative communications has been considered in the literature [2–4]. The power consumption at a node includes the transmission power consumption, which accounts for the energy efficiency of the power amplifier (PA) and the peak-to-average power ratio (PAPR), and the processing power consumption of the radio frequency (RF) components at the transmit and receive RF chains. In [2], single-antenna nodes in a group cooperate with each other in transmission to another group of single-antenna nodes using distributed multiple-input multiple-output (MIMO) techniques such as Alamouti's space-time block

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coding [5] or general space-time block coding [6]. The work in [3] extends the work in [2] by taking into account extra training overheads and the impact of the channel path loss exponent on the energy efficiency. In [4], a source node transmits to a destination node with the assistance of N relay nodes. Due to additional processing power consumption in reception and retransmission of information in cooperative communications, energy efficiency is not guaranteed at all times. The authors thus studied the energy efficiency over transmission distance and identified the conditions, at which cooperative communications should be employed. Common shortages of the previous works are that they only considered simplified network settings with the same distances among nodes in the network. In addition, they do not consider any protocol used to exchange and acquire channel state information, based upon which transmission power consumption can be computed.

In this work, we utilize coalition formation games to achieve energy efficiency of cooperative networks in dynamic settings. Coalition formation games have been applied in economics and political science [7]. Users in the games form cooperative groups to improve their own benefits. Recently, coalition formation games are also used to analyze performance of communication networks [8–13]. For example in [9], single-antenna user nodes in cooperative groups employ MIMO to send data to a multi-antenna base node to improve their capacity. In [10], secondary user nodes in cooperative groups cooperatively conduct spectrum sensing to achieve better sensing performance.

Coalition formation games consider the gain and the cost in cooperation. For energy efficient cooperative communications, nodes when forming cooperative groups achieve transmission power saving through spatial diversity while incurs additional processing power due to the reception and retransmission of overheard information. To find a good cooperation structure, merge and split rules were proposed in [14,15], and an iterative merge-and-split process was applied in [9,10], where the authors assume that channel state information is available at nodes. Considering implementation feasibility, we realize that information exchange also requires certain medium access control. In addition, the complexity of exchanging information in wireless networks and computation complexity of the merge-and-split process are too high, especially with large numbers of nodes. Therefore, we propose a heuristic time-division multiple access (TDMA)-based merge process in forming cooperative groups. The merge process includes three stages: transmission request, merge, and cooperative transmission. The condition for a merge is that the merge leads to power saving for the group without causing additional power burden for the individual members.

The merge process is applied to a cooperative communication protocol, namely wireless network cocast (WNC) [16], due to its ability to overcome the issues of imperfect frequency and timing synchronization caused by the asynchronous nature of cooperation. Nevertheless, the proposed merge process can be applied to other protocols in cooperative communications with expected minor changes. We characterize the power consumption for individual nodes in direct transmission (DTX) and in cooperative transmission (CTX). We then conduct simulations to evaluate the performance of the proposed merge process and compare the performance between the merge process and the iterative merge-and-split process.

Simulation results show that the proposed merge process ensures that nodes in CTX consume less or the same power in comparison with DTX for the same quality of service represented by a symbol error rate (SER). The larger the network dimension is the larger the power saving of CTX over DTX. In other words, for the same network setting, CTX networks with the merge process always achieve energy efficiency over DTX networks. In addition, the merge process results in balanced power consumption distribution, which helps improving the network lifetime.

The simulation results also show that the iterative merge-and-split process achieves higher power saving than the proposed merge process. However, the computation complexity, represented by a run time, of the iterative merge-and-split process is much higher than that in the proposed merge process. As a result, the iterative merge-and-split process should be only used in small-size networks while the proposed merge process has much more advantage in large-size networks.

The rest of this paper is organized as follows. After this introduction section, the system model for cooperative transmission is introduced in Section 2. The power consumption in DTX and CTX networks are characterized in Section 3. In Section 4, the merge process based on coalition formation games is proposed. Simulations illustrating the performance of the proposed merge process and comparing its performance with that of the iterative merge-and-split process are provided in Section 5. Lastly, we draw some conclusions in Section 6.

2. System model

As shown in Fig. 1, we consider N user nodes as $U_1, U_2, \ldots, U_N$ randomly distributed in a network. These nodes have their own information that need to be delivered to a common base node U_0. We assume that user nodes have a limited power source while the base node is power-abundant. For example as in WiMAX system [17], the user nodes are mobile devices relying on batteries while the base node can be a base station. For this assumption, we do not consider power consumption of the base node [3]; nevertheless, this power consumption can be incorporated into our model.

All nodes in the network are assumed to have a single antenna. The channels are modeled as narrow-band Rayleigh fading, whose variance between arbitrary nodes U_u and U_v is

$$\sigma_{uv}^2 = \kappa d_{uv}^{-\alpha}, \tag{1}$$

where d_{uv}, κ, α are the distance between U_u and U_v, the pathloss constant, and the pathloss exponent, respectively. From (1), a pair of nodes that are closer to each other, i.e. smaller d, would have a larger channel variance. The pathloss constant can be modeled as

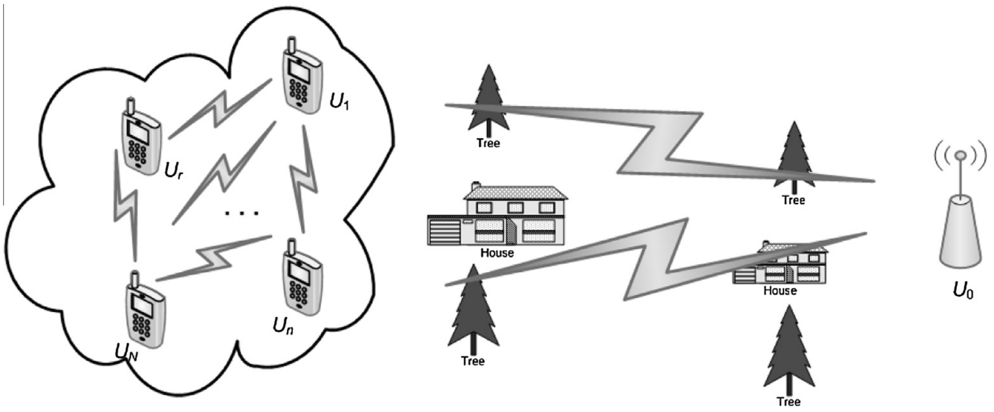

Fig. 1. A multi-source wireless network.

$$\kappa = \left(\frac{\lambda}{4\pi}\right)^2 \frac{G_t G_r}{N_f}, \tag{2}$$

where λ is the carrier wavelength, G_t and G_r are, respectively, the transmit and receive antenna gains, and N_f is the noise figure.

We consider two transmission architectures, denoted as DTX and CTX. Each user node in DTX directly transmits its own information to the base node while in CTX, the N user nodes are divided into cooperative groups using a proposed merge process that will be discussed in Section 4. The purpose of the proposed merge process is to ensure energy efficiency of CTX over DTX. Each cooperative group employs multipoint-to-point WNC scheme in [16] for the cooperation among the user nodes. We choose WNC protocol as an application of our proposed merge process because it can handle the issues of imperfect frequency and timing synchronization caused by the asynchronous nature of cooperation. Nevertheless, the proposed merge process can be applied to other protocols in cooperative communications with expected minor modifications.

The SER for transmitting information from U_n to U_0 in DTX using PSK modulation can be expressed as [18]

$$SER_n^D = F\left(1 + \frac{bE_{s,n}^D \sigma_{0n}^2}{N_0 \sin^2\theta}\right), \tag{3}$$

where $b = \sin^2(\pi/\mathcal{M})$ is a coefficient associated with $\mathcal{M}$-PSK modulation, N_0 is the thermal noise power spectral density (PSD), $E_{s,n}^D$ is the energy per symbol, and

$$F(x(\theta)) = \frac{1}{\pi}\int_0^{(\mathcal{M}-1)\pi/\mathcal{M}} \frac{1}{x(\theta)} d\theta. \tag{4}$$

When the SNR is high, the SER can be approximated as

$$SER_n^D \simeq \left(\frac{bE_{s,n}^D}{N_0}\right)^{-1} \frac{g(1)}{\sigma_{0n}^2}, \tag{5}$$

where $g(x) = \frac{1}{\pi}\int_0^{(\mathcal{M}-1)\pi/\mathcal{M}} [\sin(\theta)]^2 d\theta$.

As discussed in [16], the WNC protocol encompasses two phases, the source transmission phase and the relay transmission phase. In the first phase, each user node within a cooperative group takes turn to transmit its own information to the base node. Due to the broadcast nature of wireless communications, other user nodes that overhear the information can help relaying it to the base node in the later phase. In the relay transmission phase, each user node acting as a relay node constructs a unique signal in FDMA-like or CDMA-like manners. The signal is a combination of the overheard information previously received from the other $(\mathcal{N}-1)$ user nodes in the source transmission phase, where $\mathcal{N}$ is the number of nodes in the cooperative group. The base node U_0 jointly detects the transmitted information from the received signals in both source transmission phase and relay transmission phase.

We assume decode-and-forward protocol in cooperation, where a relay node decodes the overheard information and then re-encodes and transmits it to the base node if the decoding is correct. From [16], the exact SER expression associated with information from U_n for $\mathcal{M}$-PSK modulation is

$$SER_n^C = \sum_{S_n=0}^{2^{(\mathcal{N}-1)}-1} F\left(\left(1+\frac{bE_{s,nn}^C\sigma_{0n}^2}{N_0\sin^2\theta}\right)\prod_{\substack{r=1\\ r\neq n}}^{\mathcal{N}}\left(1+\frac{bE_{s,rn}^C\sigma_{0r}^2\beta_{rn}}{N_0\epsilon_n\sin^2\theta}\right)\right)\prod_{\substack{r=1\\ r\neq n}}^{\mathcal{N}} G(\beta_{rn}), \tag{6}$$

where $E_{s,nn}^C$ and $E_{s,rn}^C$ (for $r \neq n$) are, respectively, the energy per symbol allocated at the source node U_n and at the relay node U_r, ϵ_n is the interference impact due to the cross-correlations in forming the unique signal at a relay node, and $\beta_{rn} \in \{0,1\}$ for $r \neq n$ represents a detection state at U_r. When U_r detects U_n's information correctly, $\beta_{rn} = 1$; otherwise, $\beta_{rn} = 0$. All β_{rn}'s form the decimal number S_n in (6), i.e., $S_n = [\beta_{1n}, \ldots, \beta_{rn}, \ldots, \beta_{\mathcal{N}n}]_2$ that represents one of $2^{\mathcal{N}-1}$ network detection states associated with information from U_n. In (6), we also have

$$G(\beta_{rn}) = \begin{cases} 1 - SER_{rn} & \text{if } \beta_{rn} = 1 \\ SER_{rn} & \text{if } \beta_{rn} = 0 \end{cases}, \tag{7}$$

where

$$SER_{rn} = F\left(1 + \frac{bE_{s,nn}^C \sigma_{rn}^2}{N_0 \sin^2\theta}\right) \tag{8}$$

is the SER in detecting U_n's information at U_r. Note that the total symbol energy associated with U_n's information is $E^C_{s,n} = \sum_{r=1}^{\mathcal{N}} E^C_{s,rn}$. When the SNR is high, the approximate SER can be expressed as [16]

$$SER^C_n \simeq \left(\frac{bE^C_{s,n}}{N_0}\right)^{-\mathcal{N}} \times \frac{1}{\sigma^2_{0n}} \sum_{S_n=0}^{2^{(\mathcal{N}-1)}-1} \frac{g(1+|\Omega_{n1}|)[g(1)]^{|\Omega_{n0}|}}{\alpha_{nn}^{1+|\Omega_{n0}|}\prod_{r\in\Omega_{n1}}\alpha_{rn}\left(\frac{\sigma^2_{0r}}{\epsilon_n}\right)\prod_{r\in\Omega_{n0}}\sigma^2_{0r}}, \quad (9)$$

where $\alpha_{nn} = E^C_{s,nn}/E^C_{s,n}$ and $\alpha_{rn} = E^C_{s,rn}/E^C_{s,n}$, the fractions of the energy per symbol $E^C_{s,n}$ allocated at U_n and U_r, respectively, and Ω_{n0} and Ω_{n1} denote, respectively, subsets of indexes of relay nodes that decode U_n's information erroneously and correctly.

The transmission power for a given bit rate R_b and a constellation size $\mathcal{M}$ is

$$P_{s,n} = E_{s,n}(R_b/\log_2(\mathcal{M})), \quad (10)$$

where $E_{s,n}$ is the symbol energy associated with a given SER and can be computed exactly using (3) and (6) for DTX and CTX, respectively, or approximately using (5) and (9). As shown in (9), CTX provides a spatial diversity order of $\mathcal{N}$ for transmissions to the base node U_0 while DTX results in a diversity order of one. The spatial diversity in CTX is the source of transmission power saving of CTX over DTX [16,19]. However, due to the additional processing power in receiving and retransmitting information in CTX, not all nodes and cooperative networks result in energy efficiency over DTX [2–4]. In the next section, we characterize the power consumption in DTX and CTX networks, and in Section 4, we propose a merge process based on coalition formation games to form cooperative groups to ensure energy efficiency of a cooperative network.

3. Power consumption in DTX and CTX networks

Fig. 2 illustrates the transmitter and receiver chains of a single-antenna system. It can be assumed that all nodes in the network have identical transmitter and receiver chains. As modeled in [2,20], power consumption in a radio system includes two major parts: the transmission power consumption accounting for the PA efficiency as well as the PAPR and the processing power consumption of other RF components. In this work, we neglect the power consumption of the baseband signal processing blocks such as those to perform forward error correction and modulation and assume uncoded communication as in [2]. Nevertheless, the power consumption for these blocks [21] can be incorporated into the model.

3.1. Power consumption in DTX

In direct transmission, a user node U_n only transmits its own information. Thus its transmission power consumption is

$$P^D_{T,n} = \frac{\xi}{\eta}P^D_{s,n}, \quad (11)$$

where ξ is the PAPR, η is the PA efficiency, and $P^D_{s,n}$ is the required transmission power in DTX to achieve a given SER and can be computed as in (10). U_n also incurs a processing power due to the power consumption at the transmitter RF components as

$$P^D_{P,n} \approx P_{DAC} + P_{filt} + P_{mix} + P_{syn}, \quad (12)$$

where $P_{DAC}, P_{filt}, P_{mix}$, and P_{syn} are the power consumption at the digital-to-analog converter (DAC), the transmit filters, the mixer, and the frequency synthesizer, respectively. P_{filt}, P_{mix}, and P_{syn} can be modeled as constants [20] while P_{DAC} can be approximated as [20]

$$P_{DAC} \approx \left(\frac{1}{2}V_{dd}I_0(2^{n_1}-1) + n_1C_p(2B+f_{cor})V^2_{dd}\right), \quad (13)$$

where V_{dd} and I_0 are the voltage and current supplies, C_p is the parasitic capacitance, n_1 is the number of bits in the DAC, $B = R_b/\log_2(\mathcal{M})$ is the symbol bandwidth, and f_{cor} is the corner frequency. The total power consumption for U_n in DTX is

$$P^D_n = P^D_{T,n} + P^D_{P,n}. \quad (14)$$

3.2. Power consumption in CTX

In CTX, the N user nodes are divided into cooperative groups following the proposed merge process that will be described in the next section. Within each cooperative group S, whose size is $\mathcal{N}$, nodes cooperate following multipoint-to-point WNC protocol [16]. Node $U_n \in S$ transmits its own information in the source transmission phase and other nodes' information in the relay transmission phase. We assume equal power consumption strategy [19], which allocates one half of the required transmission power at the source node and equally divides the other half at the $(\mathcal{N}-1)$ relay nodes. Thus the transmission power consumption of node U_n is

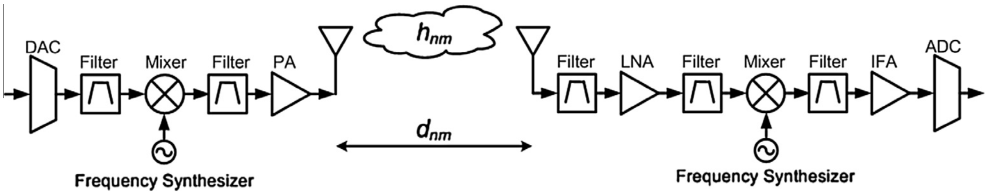

Fig. 2. Transmitter and receiver chains.

$$P^C_{T,n} = \frac{\xi}{\eta}\left(\frac{1}{2}P^C_{s,n} + \sum_{\substack{r=1\\ r\neq n}}^{\mathcal{N}} \frac{1}{2(\mathcal{N}-1)}P^C_{s,r}\right), \tag{15}$$

where ξ is the PAPR, η is the PA efficiency, and $P^C_{s,n}$ and $P^C_{s,r}$ are computed as in (10). In addition, U_n incurs a processing power consumption

$$P^C_{P,n} = P^C_{Ptx,n} + P^C_{Prx,n}, \tag{16}$$

where $P^C_{Ptx,n}$ and $P^C_{Prx,n}$ are the processing power at transmitter and receiver RF components, respectively. We have

$$P^C_{Ptx,n} = P^C_{Ptx,STP} + P^C_{Ptx,RTP}, \tag{17}$$

where $P^C_{Ptx,STP}$ and $P^C_{Ptx,RTP}$ are the power consumption at the transmitter RF components in the source transmission phase and the relay transmission phase, respectively. These power consumptions follow (12), in which P_{DAC} takes the form of (13) in the source transmission phase and

$$P_{DAC} \approx \left(\frac{1}{2}V_{dd}I_0(2^{n_1}-1) + n_1C_p(2(\mathcal{N}-1)B + f_{cor})V^2_{dd}\right) \tag{18}$$

in the relay transmission phase, where the factor of $(\mathcal{N}-1)$ in (18) is due to use of FDMA-like or CDMA-like techniques to relay overheard information in WNC. The processing power consumption at the receiver RF components can be expressed as

$$P^C_{Prx,n} \approx (\mathcal{N}-1)(P_{LNA} + P_{filr} + P_{mix} + P_{IFA} + P_{ADC} + P_{syn}), \tag{19}$$

where $P_{LNA}, P_{filr}, P_{mix}, P_{syn}, P_{IFA}$, and P_{ADC} are the power consumption at low-noise amplifier (LNA), the receive filters, the mixer, the frequency synthesizer, the intermediate-frequency amplifier (IFA), and the analog-to-digital converter (ADC), respectively. The factor of $(\mathcal{N}-1)$ in (19) is due to the fact that U_n receives $(\mathcal{N}-1)$ times in the source transmission phase. Like the transmitter RF chain, $P_{LNA}, P_{filr}, P_{mix}, P_{syn}$, and P_{IFA} can be modeled as constants [20] while P_{ADC} can be approximated as [20]

$$P_{ADC} \approx \frac{3V^2_{dd}L_{min}(2B + f_{cor})}{10^{-0.1525n_2+4.838}}, \tag{20}$$

where V_{dd}, B, and f_{cor} are defined as in (13), L_{min} is the minimum channel length in the complementary metal–oxide–semiconductor (CMOS) technology, and n_2 is the number of bits in the ADC. The power consumption at user node U_n in CTX, therefore, is

$$P^C_n = P^C_{T,n} + P^C_{P,n}. \tag{21}$$

4. Energy-efficient coalition formation game

4.1. Coalition formation game concept

Coalition formation games have been applied in economics and political science [7]. Recently, they are also used to analyze performance of communication networks [8–10]. Fundamentally, a coalition formation game consists of a three-tuple $(\mathcal{P}, v, \mathbf{x})$ [8], where $\mathcal{P} = \{1, 2, \ldots, N\}$ is a set of players who seek to form cooperative groups (or coalitions) to improve their positions in the games, v is a utility function that defines how the game would play, and $\mathbf{x}$ is a vector representing the payoffs the members would receive from the value v.

In this work, each node is treated as a player, who seeks partners to form a cooperative group to achieve power saving for itself and thus for the whole group. There is a tradeoff in power of CTX architecture when forming cooperative groups. Each node in a cooperative group achieves transmission power saving through spatial diversity while incurs additional processing power due to the reception and retransmission of overheard information. As a result, we define the utility function and individual payoff for CTX architecture as

$$v(S) = \sum_{U_n\in S}\left(P^D_{T,n} - P^C_{T,n}\right) - \sum_{U_n\in S}\left(P^C_{P,n} - P^D_{P,n}\right), \tag{22}$$

and

$$x_n(S) = \left(P^D_{T,n} - P^C_{T,n}\right) - \left(P^C_{P,n} - P^D_{P,n}\right), \tag{23}$$

respectively, where S denotes a cooperative group with members U_n's, $P^D_{T,n}$ and $P^C_{T,n}$ are the transmission power consumption in DTX and CTX, respectively, and $P^D_{P,n}$ and $P^C_{P,n}$ denote the processing power consumption in the respective transmission architectures. These power consumptions can be computed as shown in Section 3. Note when $S = \{U_n\}$, a single-member cooperative group, the power terms associated with CTX converge to those associated with DTX. In that case, $v(S) = x_n(S) = 0$.

In (22), the first summation is the transmission power saving while the second summation is the additional processing power. They represent the gain and the cost, respectively, in cooperation. As the size of the cooperative group increases, both the gain and the cost increase. The processing power, as seen in Section 3, linearly increases with the size of the cooperative group. However, the transmission power saving in cooperation gradually diminishes due to the nature of incremental diversity [22]. Therefore, user nodes at some point can no longer be added to the cooperative group since the extra gain of involving the nodes cannot cover the additional cost. This prevents CTX from forming the grand coalition [8], a coalition that includes all the user nodes in the network.

To find the optimal cooperative structure, merge and split rules were proposed in [15] as follows:

- **Merge Rule:** A merge of a set of cooperative groups $\{S_1, S_2, \ldots, S_k\}$ to $\bigcup_{j=1}^k S_j$ if $\sum_{j=1}^k v(S_j) < v\left(\bigcup_{j=1}^k S_j\right)$.
- **Split Rule:** A split of any cooperative group $\bigcup_{j=1}^k S_j$ to $\{S_1, S_2, \ldots, S_k\}$ if $v\left(\bigcup_{j=1}^k S_j\right) < \sum_{j=1}^k v(S_j)$.

In other words, using the merge and split rules iteratively would yield better coalition structures. It is shown in [14,15] that every iteration of the merge-and-split process terminates. The rules have been applied in cooperative communications for capacity improvement [9] and spectrum sensing [10].

The iterative merge-and-split process [9,10] is associated with the high complexity in exchanging information and high computation required in the split process, which requires a full search for all possible splits. Therefore, we propose a heuristic merge process to form cooperative groups in CTX. In the next section, we will compare the performance of our proposed merge process with the merge-and-split process through simulation. A merge between two cooperative groups S_1 and S_2 in our proposed merge process also follows the merge rule, i.e.,

$$v(S_1 \cup S_2) > v(S_1) + v(S_2) \text{ for } S_1 \cap S_2 = \emptyset. \tag{24}$$

This condition is to ensure that the network power saving of the merged group would be achieved. To avoid additional power burden to individual nodes when cooperating together, we impose the second condition as

$$x_n(S_1 \cup S_2) \geqslant x_n(S_i) \ \forall n, \tag{25}$$

for $i = 1$ or 2, the index of the cooperative group that U_n belongs to before merging S_1 and S_2 together. The condition in (25) is also called Pareto order [9]. Conditions (24) and (25) show that a merge happens if at least one user node is able to improve its energy efficiency without increasing other user nodes' power consumption.

We propose three stages for energy efficient cooperative communications, including transmission request, merge, and cooperative transmission. Since the merge requires the computation of each member's transmission power as in (3) and (6) (or in (5) and (9)), which needs the knowledge of the inter-user and user-base channel variances, i.e. $\sigma^2_{rn}, \sigma^2_{0n}$, and σ^2_{0r}, for all members in the group, we propose a TDMA-based merge process that ensures the information exchange among the members occur orderly.

4.2. Transmission request stage

In the first stage, the N user nodes send request-to-send (RTS) signals to the base node U_0. Each user node uses a maximum transmission power P_{max} so that other user nodes can estimate the inter-user channel variances. As modeled in (1), the larger the channel variance is the closer of the nodes. For two nodes that are not able to hear one another, the inter-user channel variance is assumed to be zero. After receiving all the RTS's, U_0 based on its estimated user-base channel variances determines a transmission order for the user nodes, starting from the farthest to the closest. Without loss of generality, we can number the user nodes in decreasing order of their distance to the base node. In this manner, U_1 and U_N are the farthest and the closest to U_0, respectively. U_0 then broadcasts the transmission order to the user nodes. Based on the broadcasting signal from U_0, the user nodes can also estimate the user-base channel variances. The inter-user and user-base channel variances will be used in the second stage, where the merge process takes place.

4.3. Merge stage

Based on the transmission order, starting from U_1 down to U_N, the merge process takes place to form cooperative groups. The purpose is to allow faraway nodes, which are disadvantageous in terms of transmission power consumption, receiving more assistance to lower their power burden. In the merge process, each node is allowed a maximum number of attempts, denoted as *Max*, which is used to control the overhead in forming cooperative groups. Note that larger *Max* values associate with larger overhead; however, the maximum size of the cooperative groups are governed by the conditions in (24) and (25). When these conditions fail, no node can be added into the cooperative group and further attempts are not helpful in improving power saving. Thus there is a need to obtain an optimal *Max* value for a network using CTX architecture. The impact of *Max* on the network power saving will be studied through simulation in the next section.

A merge schedule for the merge process is shown in Fig. 3(a), which is TDMA-based. Assume at present that we attempt to merge at user node U_n. If U_n already belongs to some cooperative groups due to previous merges at other user nodes, then U_n remains silent during its assigned $T_{n1}, T_{n2}, \ldots, T_{nMax}$ time slots. Otherwise, U_n begins to merge with other remaining nodes in the network. In this case, U_n is called the coalition head and its index n is used for the coalition index.

The merge at U_n happens as follows. Based on the inter-user channel variances that it has estimated in the transmission request stage, U_n derives a list of *Max* closest neighbors and attempts to merge with these neighbors. At the beginning, U_n broadcasts its user-base channel variance to its neighbors. A neighbor that has not merged in another cooperative group will save this information for future computation. Assume at present that U_n attempts to merge with U_r, its closest non-member neighbor. U_n first sends the indices of the members in its cooperative group to U_r and requests for a merge. U_r agrees to merge if the following three conditions are satisfied. Firstly, U_r does not belong to any cooperative group. Secondly, it has inter-user and user-base channel variances for all coalition members. This condition is to ensure full diversity for all user nodes in the cooperative group. Note that U_r obtains the inter-user channel variances during the transmission request stage and the user-base channel variances in the broadcasting signals from other members who already join the cooperative group. Lastly, conditions in (24) and (25), computed by U_r, are satisfied. If the three conditions are not satisfied, U_r remains silent and lets the time slot expire. When U_r agrees to merge, it acknowledges the agreement back to the members in the cooperative group, sends the

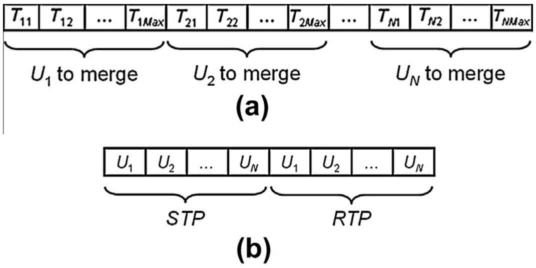

Fig. 3. (a) Merge schedule and (b) cooperative transmission schedule.

Table 1
Three stages for energy efficient cooperative communications.

Transmission request stage
1. Each user node sends a RTS to the base node
    1.1. Other user nodes estimate inter-user channel variances
    1.2. Base node determines a transmission order
2. Base node broadcasts the transmission order
    2.1. User nodes estimate user-base channel variances

Merge stage: For $n = 1, 2, \ldots, N$
1. U_n remains silent during $T_{n1}, T_{n2}, \ldots, T_{nMax}$ if it is already merged
2. Otherwise, U_n starts the merge process with *Max* attempts
    2.1. U_n follows the merge process in Section 4.3

Cooperative transmission stage
1. Each user node takes turn to transmit based on cooperative transmission schedule
    1.1. A node decodes and relays only for its cooperative members
2. Base node detects information based on the cooperative groups

transmission power requirements for each node in the cooperative group, and broadcasts its user-base channel variance. User nodes in range of U_r's transmission can record U_r's user-base channel variance for later computation when it is requested to merge. U_n then repeats its attempts to the next closest non-member node until there is no node available to merge or when U_n expires all its *Max* attempts.

Note that since the number of user nodes is finite and only the merge process is considered, the proposed heuristic algorithm is guaranteed to converge. However, there is no guarantee that the proposed algorithm will converge to Nash equilibrium of the origin coalition formation game since the proposed algorithm does not include the split process.

4.4. Cooperative transmission stage

After the cooperative groups have formed, cooperative transmissions take place. Each user node takes turn to transmit based on a cooperative transmission schedule in Fig. 3(b), which includes $2N$ time slots for the source transmission phase and the relay transmission phase. Note that the time slots in the merge schedule are much shorter than those in the cooperative transmission schedule. A user node only decodes and relays information for its members. The base node detects information of user nodes based on the cooperative groups formed by the merge process.

Table 1 summarizes the three phases of the energy efficient cooperative communications. In a mobile condition, this process can be repeated once in a while depending on the channel coherent time.

5. Simulations

We perform simulations to validate the proposed merge process for CTX architecture. The first metric is network power saving (NPS), defined as

$$NPS \triangleq \frac{\sum_{n=0}^{N} P_n^D}{\sum_{n=0}^{N} P_n^C} \text{ (times)}, \qquad (26)$$

where P_n^D and P_n^C follow (14) and (21), respectively, to show that total power saving of CTX over DTX resulted from the use of the proposed merge process. We expect that *NPS* is greater than or equal to unit throughout our simulations. In other words, the proposed merge process would result in a power consumption for CTX that is less than or the same with the power consumption for DTX. Note that *NPS* accounts for only the power consumption in the cooperative transmission stage. Although CTX consumes additional power for information exchange and computation in transmission request and merge stages, the power consumption in these stages is assumably negligible in comparison with that in the cooperative transmission stage.

To compare the performance between the proposed merge process and the iterative merge-and-split process [9,10], we use power saving ratio (PSR) and run time ratio (RTR). The power saving ratio is defined as a ratio of the network power saving resulted from the use of the iterative merge-and-split process over that resulted from the use of the proposed merge process. Similarly, the run time ratio (RTR) is defined as a ratio of the computation time required in the iterative merge-and-split process over that required in the proposed merge process. Note that the run time ratio does not account for the time to acquire the information for the computation.

For the simulation setup, the simulation parameters are listed in Table 2. We consider networks of N user nodes $U_1, U_2, \ldots, U_N$ uniformly distributed in a square area and the base node U_0 placed at the origin $(0, 0)$. In a center network, the user nodes are placed in a square area $\mathcal{A} = [-D, D]^2$ while in a corner network, they are distributed in $\mathcal{A} = [0, D]^2$, where D denotes the network dimension. It is purposefully to provide comparable power consumption for the two network types that have the same network dimension. The user nodes are numbered in decreasing order of their distance to the base node with U_1 and U_N being the farthest and the closest to U_0, respectively. As we presented in Section 4, the order is determined in the transmission request stage. In this section, we present mainly the performance associated with center networks; however, similar performance behaviors are found with corner networks.

In the first simulation, we examine the performance of the proposed merge process with various numbers of attempts *Max*. We consider center networks with $D = 500$ m. Fig. 4 presents the average network power savings versus various *Max* and N over 50 network realiza-

Table 2
Simulation parameters.

Transmission parameters	RF parameters [20]	Parameters for P_{DAC} and P_{ADC} [20]
$f_c = 400$ MHz	$\xi = 4$ dB (QPSK)	$V_{dd} = 3$ V
$\alpha = 3$	$\eta = 0.35$	$I_0 = 10$ μA
$G_t = G_r = 3$ dBi	$N_f = 7$	$C_p = 1$ pF
$N_0 = -174$ dBm/Hz	$P_{mix} = 30.0$ mW	$L_{min} = 0.5$ μm
$R_b = 10$ Kbps	$P_{filt} = P_{filr} = 2.5$ mW	$f_{cor} = 1$ MHz
$\mathcal{M} = 4$ (QPSK)	$P_{LNA} = 20$ mW	$n_1 = 16$ (16-bit DAC)
$\text{SER}_0 = 2\text{e}{-3}$ (equivalently $\text{BER}_0 = 1\text{e}{-3}$)	$P_{IFA} = 3$ mW	$n_2 = 14$ (14-bit ADC)
$\epsilon_n = 1$	$P_{syn} = 50.0$ mW	

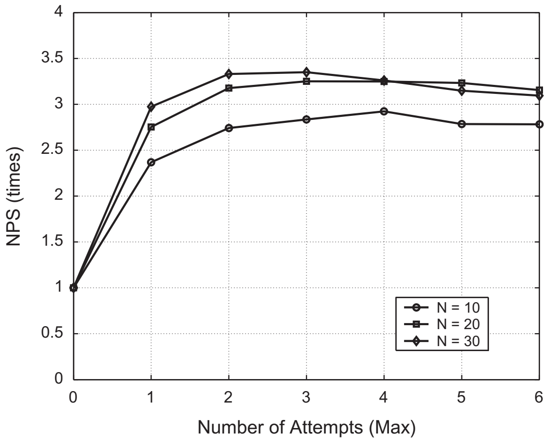

Fig. 4. Average network power saving versus various numbers of attempts (*Max*).

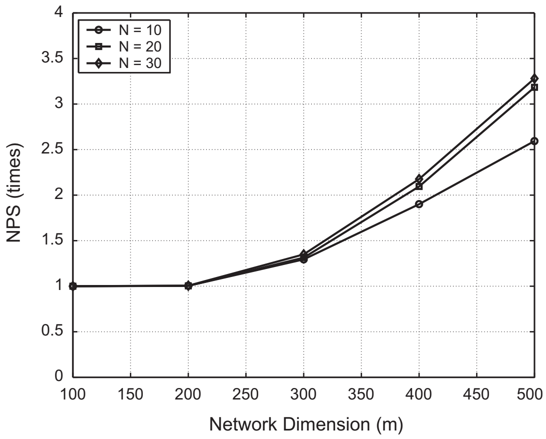

Fig. 5. Average network power saving versus various network dimensions and sizes for $Max = 2$.

tions. In the figure, $Max = 0$ associates with the use of DTX architecture and thus the network power saving takes a value of one. From the figure, as *Max* increases, the network power savings rapidly increase at first and then tend to be stable for large values of *Max*. The increment in network power savings for the first few of *Max* values is due to the large gain in transmission power saving of CTX over DTX. As *Max* continues increasing, more processing power is needed while the relative gain in transmission power reduces. For large values of *Max*, the cooperative groups are no longer able to accept new members due to the failure of conditions (24) and (25). As a result, the network power savings tend to be stable for large values of *Max* and further attempts are no longer necessary. In this particular setup, $Max = 4$, 3, and 2 are optimal for $N = 10$, 20, and 30, respectively.

Next, we consider the performance of the proposed merge process for various network sizes N and dimensions D. In this simulation, center networks are used and $Max = 2$. Fig. 5 presents the average network power savings for various N and D over 50 network realizations. From the figure, the average network power savings are greater than or equal to a unit for all the considered N and D. The simulation clearly shows that the proposed merge process provides energy efficiency in the network for CTX over DTX. As the network dimension increases, more power savings for CTX over DTX can be achieved, as shown in the figure, due to more saving in transmission power consumption. This suggests that for networks with large network dimensions, the proposed merge process should be used to form cooperative groups for energy efficiency over DTX.

Now, we examine the cooperation structures generated by the proposed merge process. In this simulation, we consider both center networks and corner networks with $N = 20, Max = 2$, and $D = 100$ m and 500 m. Fig. 6 shows the performance for the case of $D = 100$ m. The merge process produces only single-member cooperative groups as shown in the top subfigures. The reason for this outcome is due to the small network dimension, which leads to a transmission power saving that cannot compensate the large processing power required in cooperation. In such a case, all user nodes utilize direct transmission and result in the same power consumption for both CTX and DTX as shown in the bottom subfigures.

When the network dimension increases, more transmission power saving can be achieved to compensate the additional processing power consumption. Thus, the proposed merge process allows user nodes cooperating with each other to form multiple-member cooperative groups.

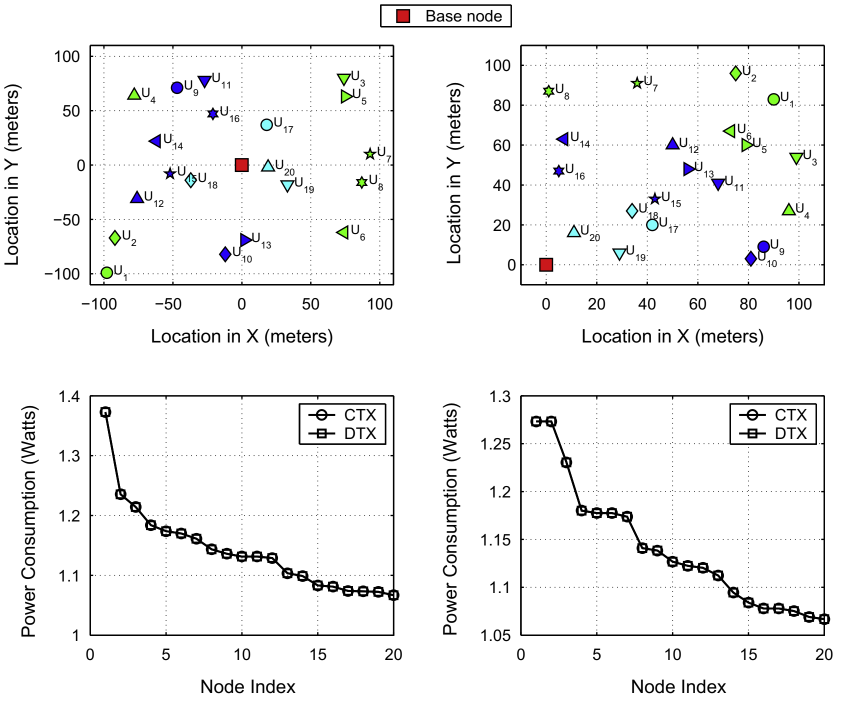

Fig. 6. Coalition structures (shape and color coded) and individual power consumption for center and corner networks of $N = 20$ and $D = 100$ m ($Max = 2$). With $D = 100$ m, the merge process produces only single-member cooperative groups. All nodes utilize direct transmission, and the same power consumption is for both CTX and DTX.

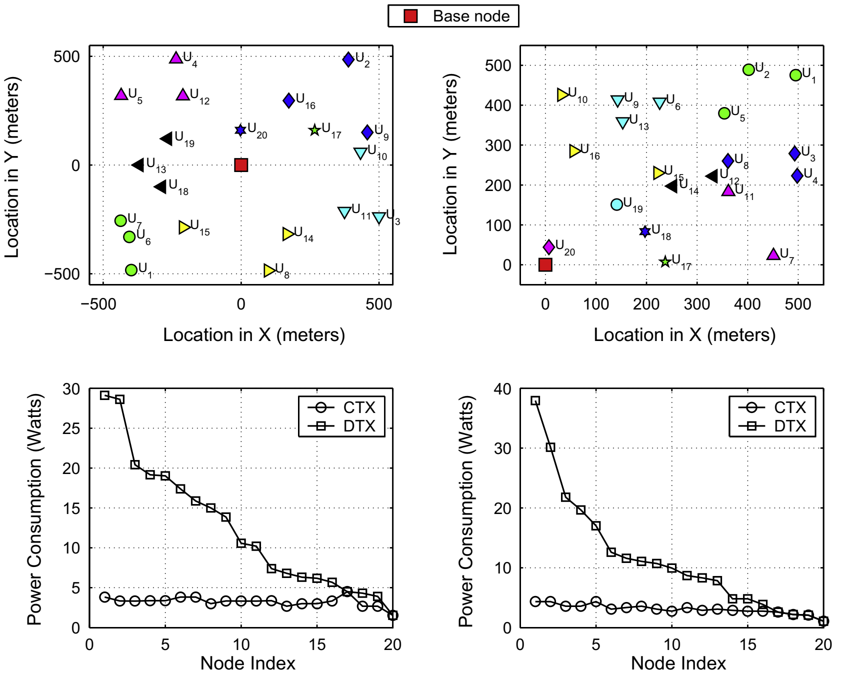

Fig. 7. Cooperation structures (shape and color coded) and individual power consumption for center and corner networks of $N = 20$ and $D = 500$ m ($Max = 2$). With $D = 500$ m, the merge process produces multiple-member cooperative groups. Since nodes cooperate in their transmission, substantial power reduction and balanced power consumption distribution can be achieved.

Fig. 7 shows the cooperation structures and individual power consumption for the case of $D = 500$ m. With $Max = 2$, the maximum size of the cooperative groups should be 3, i.e. $Max + 1$. A common point among the cooperation structures in the top subfigures is that some of user nodes stand by itself, creating single-member coalitions, for example $\{U_{17}\}$ and $\{U_{20}\}$ in the center network and $\{U_{17}\}, \{U_{18}\}, \{U_{19}\}$, and $\{U_{30}\}$ in the corner network. These nodes are in locations close to the base node and do not have large transmission power saving to compensate the additional processing power when cooperating with other nodes. The figure also shows that some cooperative groups, for example $\{U_7, U_{11}\}$ and $\{U_{12}, U_{14}\}$ in the corner network, do not have the full size. Although these cooperative groups welcome additional members since that would help reducing their power consumption, other nodes may not find the benefits to join due to the additional power burden to themselves, and thus larger cooperative groups could not be formed.

Fig. 7 also shows the actual power consumption for individual user nodes in DTX and CTX. From the bottom subfigures, the power consumption for all user nodes in CTX is always less than or equal to the power consumption in DTX. Together with the result shown in Fig. 5, the simulation results show that the proposed merge process achieves its objective, which is to provide energy efficiency for CTX over DTX without causing additional power burden to individual user nodes.

The bottom subfigures also show that high power consumption is required for distant user nodes in DTX. This is due to the dependency of the required transmission power on the transmission distance in direct transmission. In contrast, distant user nodes require much less power consumption in CTX. This is due to the cooperation among the user nodes that helps substantially reducing the required transmission power through the mean of spatial diversity. As a result, the power consumption profile in the CTX networks is very balanced with comparable power consumption for individual user nodes. Clearly, beside helping reducing network power consumption, the proposed merge process also help improving network lifetime, defined as the time until the first node in the network dies.

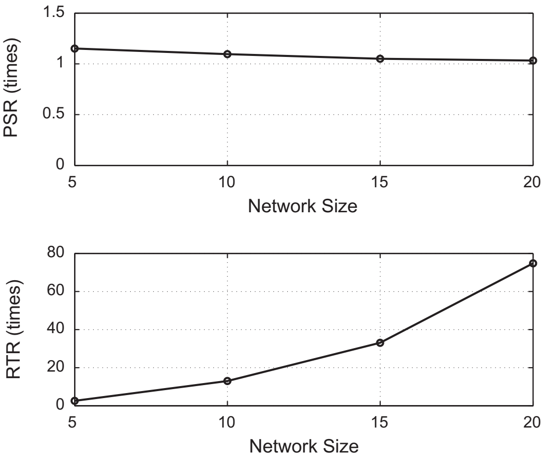

Fig. 8. Average power saving ratio and run time ratio associated with the proposed merge process ($Max = 2$) and iterative merge-and-split process for various network sizes with $D = 500$ m.

Lastly, we compare the performance between the proposed merge process and the iterative merge-and-split process [9,10]. Fig. 8 shows the power saving ratio and the run time ratio associated with the proposed merge process ($Max = 2$) and the iterative merge-and-split process for various network sizes. The simulation results were achieved over 50 network realizations. From the top subfigure, the power saving ratio is slightly greater than one, indicating the iterative merge-and-split process produces better network power saving than the proposed merge process, as expected. However, as shown in the bottom subfigure, the run time ratio, which represents the computation complexity of the merge-and-split process over the proposed merge process, on the other hands, tends to increase exponentially with the network size. Note that the run time ratio does not account for the time it takes to acquire information for the computation in these processes. Such time in the merge-and-split process is expectedly much higher than that in the proposed merge process. Considering both the additional network power saving and the run time ratio, as a result, the iterative merge-and-split process should be only used in small-size networks while the proposed merge process has much more advantage in large-size networks.

6. Conclusions

In this work, we proposed a novel merge process, consisting of transmission request stage, merge stage, and cooperative transmission stage, based on coalition formation games for energy efficiency in cooperative communications. It is well-known that cooperative communications can result in transmission power saving; however, due to the additional processing power in receiving and retransmitting each other information, not all nodes and cooperative protocols have energy efficiency. The merge process is used to find a cooperation structure that allows individual nodes to form cooperative groups to achieve their own energy efficiency, thus resulting in energy efficiency of the cooperative network. Simulations were conducted to show that the cooperative transmission resulted from the merge process always requires less total power, which include the transmission power and the processing power, than direct transmission to provide a comparable SER. The larger the network dimension is the larger the power saving for cooperative transmission over direct transmission. In addition, the merge process results in balanced power consumption distribution, which helps improving the network lifetime. Comparing with an iterative merge-and-split process in coalition formation games, the simulations showed that the iterative merge-and-split process should be only used in small-size networks while the proposed merge process has much more advantage in large-size networks.

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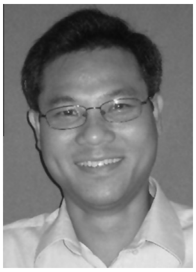

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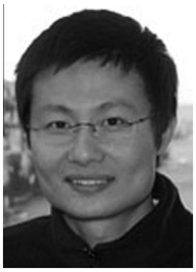

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