Cooperative Bridges: Topology Control in Cooperative Wireless Ad Hoc Networks

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***Abstract*—Cooperative Communication (CC) is a technology that allows multiple nodes to simultaneously transmit the same data. It can save power and extend transmission coverage. However, prior research work on topology control considers CC only in the aspect of energy saving, not that of coverage extension. We identify the challenges in the development of a centralized topology control scheme, named *Cooperative Bridges*, which reduces transmission power of nodes as well as increases network connectivity. We observe that CC can bridge (link) disconnected networks. We propose two algorithms that select the most energy efficient neighbor nodes, which assist a source to communicate with a destination node; an optimal method and a greedy heuristic. In addition, we consider a distributed version of the proposed topology control scheme. Our findings are substantiated by an extensive simulation study, through which we show that the *Cooperative Bridges* scheme substantially increases the connectivity while consuming a similar amount of transmission power compared to other existing topology control schemes.**

***Index Terms*—Cooperative Communication; Topology Control; Connectivity**

I. INTRODUCTION

Wireless ad hoc networks are multi-hop structures, which consist of communications among wireless nodes without infrastructure. Therefore, they usually have unplanned network topologies. Wireless nodes need to save their power as well as sustain links with other nodes, since they are battery powered. Topology control deals with determining the transmission power of each node so as to maintain network connectivity and consume the minimum transmission power. Using topology control, each node is able to maintain its connection with multiple nodes by one hop or multi-hop, even though it does not use its maximum transmission power. Consequently, topology control helps power saving and decreases interferences between wireless links by reducing the number of links. As an example of topology control, the authors of [1-3] proposed a Minimum Spanning Tree (MST) based topology control algorithm in order to maintain the network connectivity and minimize the number of links.

Recently, a new paradigm named the Cooperative Communication (CC) [4] technique has emerged and single antenna devices can share the antennas of others that have spatial diversity such as the MIMO system. CC allows a source node and helper nodes to simultaneously transmit independent copies of analogous data to a destination node so that the destination node can combine partial signals of nodes and decode them [5-8]. One-hop neighbor nodes within the transmission range of a source node can be helper nodes. In other words, individual antennas on multiple nodes can work together to form an antenna array. There are extensive physical layer research efforts on the CC technique [9-11] and the importance of higher layer research is also being increasingly recognized. Since using CC results in robust connection, coverage extension, and power saving, CC can be applied to various areas such as topology control [12], broadcasting [5-7], and routing [8][13].

A topology control scheme [12] has been proposed for reduced power consumption using CC technology; however, it can be applied only when a strongly connected network topology is given at the initial step. A strongly connected network indicates a network where every node has a route to reach any other node. A wireless ad hoc network can be disconnected due to node mobility, low node density, and power constraint. The authors of [8][14][15] have shown that CC technology enhances connectivity among disconnected networks, but there has been no definitive answer given to topology control research considering coverage expansion with CC.

Therefore, we propose a centralized topology control scheme, which aims to increase network connectivity as well as reduce transmission power by minimizing the number of cooperative communication links (CC links) among disconnected networks. As a part of the proposed topology control scheme, we also suggest two helper decision algorithms to minimize transmission power for each CC link; an optimal method and a polynomial time heuristic algorithm. In addition,

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we also discuss how the proposed topology control scheme is performed in a distributed manner.

The main contribution of this paper includes the following aspects.

- To the best of our knowledge, we are the first to try topology control considering extended links with CC. While the existing topology control schemes preserve the given connectivity, we propose a new framework of topology control that increases connectivity. Moreover, the connectivity-power-ratio of cooperative bridges is similar to or higher than the existing algorithm. Our basic idea is based on a 2-layer MST structure. The MST-based methodology is not original but our problem formulation has novel elements.
- Several studies have been undertaken on helper selection algorithms considering the channel state in order to increase throughput [16]. However, the helper selection algorithm considering energy efficiency has not been identified by prior research. This paper describes the tradeoff between the power for a CC link and that for helper links that should be considered so that we can construct an energy efficient CC link. Furthermore, we propose two helper selection algorithms to minimize the power of nodes in order to participate in maintaining a CC link.

The rest of this paper is organized as follows. Section 2 reviews the related work. Section 3 describes the network model and formulates our problems. Section 4 proposes our topology control algorithm including helper decision algorithms. Section 5 discusses the distributed version. In section 6, the results of simulation are presented. Finally, section 7 concludes this paper.

II. RELATED WORK

In traditional multi-hop networks, intermediate nodes cooperate with a source node by forwarding the message to a destination node, which is performed on the network layer. Accordingly, the destination can receive only one copy of the message from the source or relay node. However, cooperative communication is different in that it originates from physical layer techniques; when a source node transmits a message, helper nodes around the source can overhear and retransmit it. There are two categories for this type of retransmission: *amplify-and-forward* and *decode-and-forward* [10]. Under amplify-and-forward, a helper node receives a noisy signal and amplifies it before retransmission. Under decode-and-forward, on the other hand, a helper node must firstly decode the signal and then retransmit the detected data. A destination node combines several copies of the signal from a source node and helper nodes, and obtains the advantage of spatial diversity. The concept of combining partial signals has been traditionally known as maximal ratio combining [17].

In order to adapt to various channel states among nodes and to increase throughput, a source node can decide whether it uses only one helper node or two helper nodes simultaneously [11]. It can even select no helper nodes for the same reason. MAC layer-based algorithms for such helper selection have been studied many times. For example, in CoopMAC [16], a source node records the channel state at each helper and selects the one that has the best state. Shi et al. [18] propose the optimal algorithm that selects each helper for every source-destination pair in the whole network. In this paper, we assume that a source node can choose one or several helpers considering node location, connectivity, and power consumption, which is similar to the assumption of [5-8].

Network layer research usually considers simple physical characteristics for CC instead of variations of channel state. In [5][6][12], a hitch-hiking model based on decode-and-forward and maximal ratio combining is employed, and [15] shows a simpler CC model. Our research is also based on a similar model. In [12] and [5], a topology control and broadcasting algorithm is proposed, respectively, which reduce average power consumption by utilizing the CC technique after a strongly connected network is given at the initial step. In [6], the proposed algorithm selects a smaller number of forwarding nodes for broadcasting by CC. Observing that the CC technique extends the transmission range and it can link disconnected networks, [15] analyzes the improvement of network connectivity via percolation theory when CC is applied. None of the existing topology control research acknowledges that coverage extension with CC results in linking disconnected networks. We propose a novel topology control algorithm that minimizes average transmission power as well as maximizes the connectivity of divided networks.

In general, topology control minimizes the total or maximum energy consumption per node. Sometimes it also has other objectives such as to increase the throughput or to meet QoS requirements. Finding a strongly connected topology that has the minimum total energy consumption is known as an NP-complete problem in [19]. Since [12] proved that the optimal topology control problem using CC is also NP-complete, we propose a heuristic algorithm for topology control.

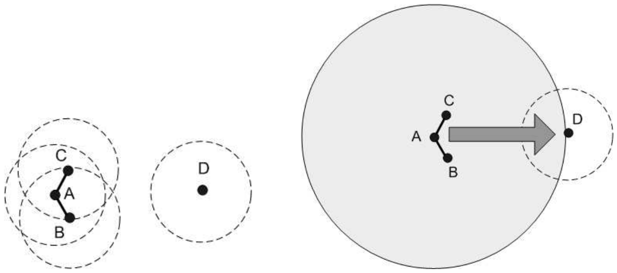
Minimum spanning tree (MST) preserves connectivity, and builds a sparse graph, therefore, it is a good approximation of the optimal solution to the topology control problem [20]. Ramanathan et al. [2] introduce the MST-based centralized algorithm and Gallager et al. [3] propose the distributed MST algorithm (DMST). The LMST algorithm [1] enables us to make a pseudo-MST by letting each node construct a localized MST. We also adapt the MST structure for the proposed topology control considering CC.

III. MODEL AND PROBLEM FORMULATION

In this section, we describe a cooperative communication model and a network model for our topology control scheme. In addition, we define two problems: 1) Topology Control considering Extended Links caused by CC and 2) Energy-Efficient Extended Link with CC.

A. Cooperative Communication Model

Our model is similar to those of [12][15]. Every node has a maximum transmission power limit P_{MAX}. P_i is the



(a) Direct links. (b) Cooperative link (CC link).

Fig. 1: Coverage Extension using CC.

transmission power of node i. α is the path loss exponent and τ is the minimum average SNR for decoding received data. d_{ij} is the distance between node i and node j. For a source node i to communicate with node j directly (figure 1(a)), they must satisfy

$$P_i(d_{ij})^{-\alpha} \geq \tau \qquad (P_i \leq P_{MAX}). \tag{1}$$

Ω denotes the set of a source node and helper nodes. If nodes in Ω transmit simultaneously, i.e., use cooperative communication, the following formula must be satisfied for correct decoding at destination node j.

$$\sum_{i \in \Omega} P_i(d_{ij})^{-\alpha} \geq \tau \qquad (P_i \leq P_{MAX}) \tag{2}$$

CC leads to extended transmission coverage. For example, in figure 1(a), node A cannot communicate with node D, since D is out of the maximum transmission range of A. On the other hand, in figure 1(b), node A can send a cooperation-request message and data to nodes B and C, and then the three nodes simultaneously transmit the data to D. Therefore, D can receive it due to the extended transmission range of nodes A, B, and C. The physical layer issues including synchronization for implementing the CC technique can be found in [8]. On the other hand, in figure 1(a), if node B uses CC with helper A in order to communicate with C, which is already reachable to B by direct links, the network can reduce the sum of node transmission power. Cardei et al. [12] focus their problem formulation on saving power with CC, not extended CC links.

B. Network Model

The wireless network topology is modeled as a 2-dimensional graph: graph $G = (V, E)$. $V = (v_1, ..., v_n)$ is a set of randomly distributed nodes and E is a set of pairs of nodes (v_i, v_j), with $v_i, v_j \in V$. The notations $V(G)$ and $E(G)$ are used for the vertex- and edge-set of G. The weight of a *directional link* from u to v is denoted as $w(u \rightarrow v)$. Edge (u, v) has weight, $w(u, v)$, which means the average power consumption for maintaining a *bi-directional link* (u, v). The average weight for bi-directional CC link, weight $w(u, v)$, is $(w(u \rightarrow v) + w(v \rightarrow u))/2$. $N(v)$ is the set of neighbor nodes within the maximum transmission range of node v. All elements in $N(v)$ are the candidate nodes, which are eligible as helper nodes for v. The power set of $N(v)$ signifies $\wp(N(v)) = \{X | X \subset N(v)\}$, which is the set containing all subsets of $N(v)$. Node v is able to communicate with its neighbors directly within 1 hop. $R(u)$ is the set of nodes which are reachable to node u by 1-hop or multi-hop, i.e., have a path to a node u. The term ‘connectivity’ used in this paper means reachability, not the degree of nodes.

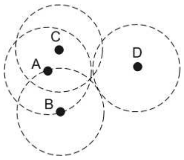


Fig. 2: A case that power required for helper links is higher than that for a CC link.

Definition 1 (Helper node set): $H(u)$ symbolizes the set including all helper nodes of a node u. $H(u) \subset N(u)$ and $H(u) \in \wp(N(v))$.

Definition 2 (Helper link): A helper link is a direct link between a source node and its helper node.

Definition 3 (Cluster): A *component* of a graph G is defined as a *maximal* connected subgraph of G [21]. In other words, in a network, it is the group of nodes which are mutually reachable by only direct links with P_{MAX}. For example, figure 1(a) has two components: One is the group of nodes A, B, and C, and the other is node D. A component is termed a *cluster* in this paper. Clusters cannot communicate due to the long distance if CC technology is not applied.

Definition 4 (Node connectivity): Given node u in network G, the node connectivity of u is the ratio of the number of reachable nodes of u to the number of all nodes, i.e.,

$$|R(u)|/|V|$$

Definition 5 (Network connectivity): Network connectivity is the average node connectivity of all nodes in the network G.

It is assumed that a unique ID is assigned to each node and each node knows its own location information. Node ID and the location information are exchanged among all nodes. The exchange among clusters is performed via CC technology with P_{MAX}. In the case of sensor networks, all location information is sent to a sink node which has sufficient resources for computation, and it performs computation for topology control.

C. Problem Formulation

The existing topology control [1][2][12] tried to minimize the transmission power of nodes and preserve the given connectivity. However, the goal of this paper is to minimize the transmission power while increasing the connectivity. We formally define this problem as follows.

Problem 1: (Topology Control considering Extended Links caused by Cooperative Communication) Given a wireless multi-hop network $G = (V, E)$, which can include clusters, with n nodes, assign a power level to every node such that the network connectivity of the induced graph is maximized by CC links, and the sum of power of all nodes, $\sum_{i \in V(G)} P_i$, is minimized.

As we mentioned in section 2, the optimal topology control problem with CC is NP-complete [12] and therefore, the above problem 1 is also NP-Complete. Thus, we propose a heuristic algorithm to solve it. In order to handle problem 1, we also need an energy-efficient algorithm that makes an extended link with CC. Let $P_u^d(i)$ be the minimum power of node u required for helper link (u,i), and $P_{u \cup h}^c(v)$ be that for CC link (u,v) with helper h. As the number of selected helper nodes increases, each node requires less $P_{u \cup h}^c(v)$. However, when the selected helper node h is relatively distant from source node u, $P_u^d(h)$ is greatly increased. For instance, in figure 1(a), neighbor nodes B and C are near source node A but destination node D is far from A. Assume that $\tau = 1, \alpha = 1, P_A(B) = d_{AB}$. In figure 1(a), d_{AD} is about three times as long as r (the radius of maximum transmission range of A), i.e., $d_{AD} = 3r$. Therefore, A should use B and C as helper nodes with maximum power. Then, it allows the value of $P_{A \cup \{B,C\}}^c(D)$ to be higher than $P_A^d(B)$ because $P_{A \cup \{B,C\}}^c(D) = P_{MAX}$ and $P_A^d(B) < P_{MAX}$. On the other hand, in figure 2, destination node D is relatively nearer to source node A ($d_{AD} = 2r$) but neighbor node B is at the boundary of the maximum transmission range of A ($d_{AB} = r$). The value of $P_A^d(B)$ becomes larger than $P_{A \cup \{B,C\}}^c(D)$ if A selects both B and C as helper nodes because $P_A^d(B) = P_{MAX}$ and $P_{A \cup \{B,C\}} < P_{MAX}$. Considering this tradeoff, we need the strategy that source node A selects helper nodes such that it minimizes the sum of transmission power of source node A and the helper nodes. Section 4 describes how to compute $P_A^d(B)$ and $P_{A \cup \{B,C\}}^c(D)$.

Problem 2: (Energy-Efficient Extended Link with Cooperative Communication) Given nodes u and v, (which belong to two different clusters and can mutually construct a bi-directional CC link because Eq. (2) is satisfied), find $H(u)$ and $H(v)$ such that $w(u,v)$ is minimized.

IV. PROPOSED TOPOLOGY CONTROL SCHEME

This section consists of five steps describing our centralized topology control algorithm with corresponding figures, which is the solution for problem 1. The proposed schemes for problem 2 are in the second step. We assume a central unit for the computation in this section. In the following subsections, graph G handles only direct links and G' deals with CC links. A graph G'' is transformed from G'.

A. Step 1: Construction of Clusters with P_{MAX} in G

Given graph G where $V(G) \neq \phi$, $E(G) = \phi$, edge (u,v) is constructed when there exists a direct path (i.e., without CC technology) between node u and v if the nodes operate with P_{MAX}. There exist at least two clusters in G when the network is disconnected. Figure 3 describes step 1. The same cluster ID is assigned to all nodes in the same cluster. The cluster ID is the ID of the node that has the highest ID value in the cluster. $C(u)$ is used to denote the ID of the cluster which node u belongs to.

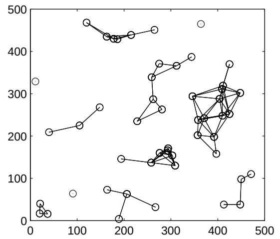


Fig. 3: Disconnected networks in step 1.

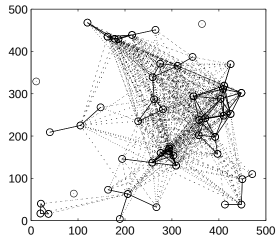


Fig. 4: Redundant CC links among clusters in step 2.

B. Step 2: Construction of Candidates of CC Links among Clusters in G'

Given graph G' where $V(G') = V(G)$ and $E(G') = \phi$, if $C(u) \neq C(v)$ and u and v mutually satisfy Eq. (2), a CC link (u,v) is constructed in G'. Consequently, G' becomes a bipartite graph [21] where $E(G')$ connects two nodes that belong to different clusters. This process is shown in figure 4. CC links in G' and direct links in G are shown as dotted and solid lines respectively. The elements in $E(G')$ will become the candidates for CC links connecting two separated clusters.

Given that Eq. (2) is satisfied where u is a source node and v is a destination node on edge (u,v) and vice versa, edge (u,v) becomes a bidirectional CC link. If any CC link is not bi-directional, which means that connectivity is not established even if CC technology is applied, the edge does not exist in G'. We do not consider directional edges, since these are not practical. If a link is indeed regarded as a bidirectional CC link, helper nodes and a weight are assigned to it.

The weight of a direct link (u,v) can be decided easily, since it is closely related to d_{uv}. However, for determining the weight of a CC link, we have to consider the location of helper nodes as well as d_{uv}. A new standard is necessary in order to compute the weight of the CC link and this problem has already been mentioned regarding problem 2 in section 3. Thus, we need a helper decision method to minimize the weight, namely the transmission power, considering the trade-off between the cost for a CC link and that for the helper links. The basic idea is to minimize the sum of power of a source node and the helper nodes. The following subsections introduce an optimal method and a greedy heuristic algorithm, which allocate the weight and the helper nodes for each CC link in step 2.

1) Optimal Method: A source node can use cooperative communication only after sending a request message to neighbor nodes via direct communication. The minimum transmission power of source node s, which consists of P^d and P^c for direct- and cooperative communication, is as follows.

$$\max_{i \in H(s)} P_s^d(i) = \frac{\tau}{(\max_{i \in H(s)} d_{si})^{-\alpha}} \tag{3}$$

$$P_{s \cup H(s)}^c(v) = P_\Omega^c(v) = \frac{\tau}{\sum_{i \in \Omega} (d_{iv})^{-\alpha}} \tag{4}$$

In (3), $\max_{i \in H(s)} P_s^d(i)$ is the transmission power required by source node s to establish a helper link to f, where f is the element of $H(s)$ located at the greatest distance from s. $P^c_{s \cup H(s)}(v)$ in (4) is the transmission power of s required to construct a CC link to destination node v with the assistance of helpers in $H(s)$. $\max_{i \in H(s)} P_s^d(i)$ and $P^c_{s \cup H(s)}(v)$ are derived from (1) and (2), respectively. The P^d of helper node h can be computed as follows.

$$P_h^d(s) = \frac{\tau}{(d_{hs})^{-\alpha}} \tag{5}$$

The helper link (s, h) is a bi-directional link and helper h needs $P_h^d(s)$ to maintain direct link (s, h). We assume that each node participating in cooperation, i.e., s and $H(s)$, pays the same power cost for simultaneous transmission to a destination node. Accordingly, the P^c of a helper node is given by (4).

The set of helper nodes, $H(u)$, and weight $w(u \rightarrow v)$ are assigned to a directional CC link from u to v. The optimal method takes into account all combinations of $H(u)$ and finds a pair of $H(u)$ and $w(u \rightarrow v)$ that can maintain a CC link with minimum transmission power. $H(u)$ and $w(u \rightarrow v)$ are determined by the following equation.

$$\begin{aligned}
&Minimize \quad w(u \rightarrow v) \\
&\qquad = P_u(v) + \sum_{i \in H(u)} P_i(v) = \sum_{j \in \Omega} P_j(v) \qquad (6) \\
&s.t. \\
&\Omega = H(u) \cup \{u\} \qquad \forall H(u) \in \wp(N(u)) \\
&\sum_{j \in \Omega} P_{MAX}(d_{jv})^{-\alpha} \geq \tau \qquad \forall H(u) \in \wp(N(u)) \\
&P_u = \max\{(\max_{i \in H(u)} P_u^d(i)), P_\Omega^c(v)\} \quad \forall H(u) \in \wp(N(u)) \\
&P_i = \max_{i \in H(u)} \{P_i^d(u), P_\Omega^c(v)\} \qquad \forall H(u) \in \wp(N(u))
\end{aligned}$$

This objective function finds a proper subset of helper nodes in all combinations of the helper set so that the sum of the power in source node u and its helper nodes $H(u)$ is minimized, which means it finds $H(u) = \arg\min\{P_u(v) + \sum_{i \in H(u)} P_i(v)\}$. Then it can determine $w(u \rightarrow v)$, the weight of the directional CC link, according to the sum of power. The first constraint means the construction of set Ω which is the union of the source node and the set of chosen helper nodes. In other words, Ω is the set of nodes that send the same message together using CC. In order to guarantee a CC link to connect source node u and destination v, the second constraint prevents the source node from selecting a low number of helper nodes. In the third constraint, P_u is the transmission power consumed by source node u and it is decided by the greater value of $\max_{i \in H(u)} P_u^d(i)$ and $P_\Omega^c(v)$. P_i, shown in the fourth constraint, is the transmission power of helper node i and it is the larger value of $P_i^d(u)$ and $P_\Omega^c(v)$. Therefore, for topology control, (6) becomes a mechanism which determines the weight for a directional CC link and selects a set of helper nodes for saving power. Then, the weight for bi-directional CC link, $w(u, v)$, is derived by the average of $w(u \rightarrow v)$ and $w(v \rightarrow u)$.

The computational complexity of comparing all combinations of $H(u)$ is 2^k where k is the number of neighbor nodes. However, it is exponential and thus impractical to compute in case of a large number of elements of $N(u)$.

2) Greedy Heuristic: In this subsection, we propose a greedy heuristic for selecting the helper set. When we add neighbor node i as a helper node, let b_i be the amount of power saving that a source node can obtain from adding helper node i in order to maintain a CC link, and let c_i be the cost that the source node communicates with i directly. Given source node u and destination node v, b_i and c_i can be obtained by the following equations:

$$b_i = P_u^d(v) - P^c_{u \cup i}(v) = \frac{\tau}{(d_{uv})^{-\alpha}} - \frac{\tau}{\sum_{\Omega \in \{u,i\}} (d_{\Omega v})^{-\alpha}} \tag{7}$$

$$c_i = P_u^d(i) = \frac{\tau}{(d_{ui})^{-\alpha}} \tag{8}$$

In (7), $P_u^d(v)$ is the power that source node u needs in order to communicate with destination node v directly. $P_u^d(v)$ is greater than P_{MAX} since u and v can be connected only with a CC link, not a direct link. $P^c_{u \cup i}(v)$ is the power of u when u uses a node i as a helper node in order to communicate with v using CC technology. Consequently, the difference of $P_u^d(v)$ and $P^c_{u \cup i}$, namely b_i, indicates how much power can be saved if u uses CC technology with a helper node i, compared to the case where CC technology is not applied. P_u^d and $P^c_{u \cup i}(v)$ can be obtained by modifying (1) and (2), respectively. In (8), c_i, viz. P_u^d , is the transmission power of u such that u can communicate with helper node i directly. $P_u^d(i)$ can be calculated based on (1).

In our heuristic, the source node adds neighbor nodes to helper node set H, in non-ascending order of $\frac{b_i}{c_i}$, checking whether the node satisfies (2) which is a necessary condition for establishing a CC link, and whether the transmission power is minimized. The following pseudo-code explains our heuristic in detail. Line 2 of the code sorts all of the neighbor nodes in non-ascending order of $\frac{b_i}{c_i}$. In the while statement of line 4, it selects individual nodes from the sorted list and adds each to the set of helper nodes until (2) is satisfied, which is the basic constraint to establish a CC link between source node u and destination node v. After satisfying (2), by the while statement of line 7, it continues adding a helper node until u and $H(u)$ has the minimum sum of power at the current iteration. If $H(u)$ has all neighbor nodes or the sum of power at the current iteration is less than that at the next iteration, it returns $H(u)$ and the corresponding power. Using the above pseudo-code, $w(u \rightarrow v)$ can be obtained, and the average of $w(u \rightarrow v)$ and $w(v \rightarrow u)$ is used to obtain $w(u, v)$.

C. Step 3: Reducing CC Link(s) in Graph G' and G''

G'' is generated from G' by converting every cluster of G' to $V(G'')$. CC links among clusters in G' also become $E(G'')$ which connects $V(G'')$. The number of CC links is reduced

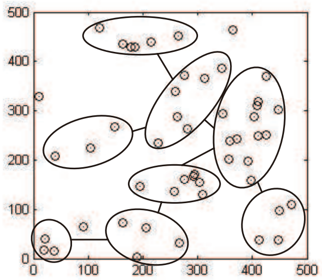


Fig. 5: Minimum Spanning Tree regarding clusters as nodes in step 3.

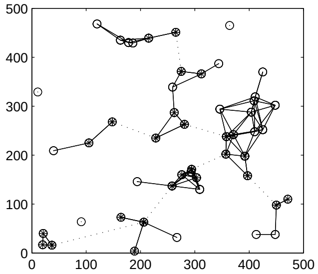


Fig. 6: G and G' in step 3.

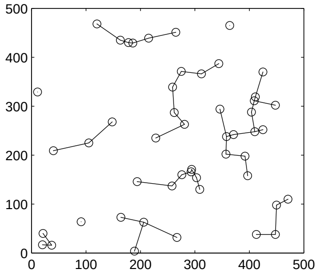


Fig. 7: Minimum Spanning Tree within Clusters in step 4.

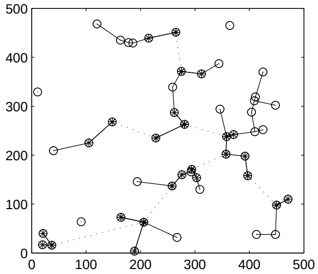


Fig. 8: Final Topology in step 5.

Algorithm 1 Greedy Helper Set Selection $(u, N(u), v)$

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$u$: a source node, $v$: a destination node
$A = \{b_{\pi(1)}/c_{\pi(1)}, b_{\pi(2)}/c_{\pi(2)}, ..., b_{\pi(n)}/c_{\pi(n)}\}$ includes all $b_i/c_i$ of every neighbor node sorted in non-ascending order. $i$: the ID of a node, $n$: the total number of neighbor nodes, $k$: the index number for the sorted elements, $\pi(k)$: the function returning ID $i$ corresponding to the $k$th element of list $A$, i.e., node $i$ having $b_{\pi(k)}/c_{\pi(k)}$
$H(u) \leftarrow \phi, \Omega \leftarrow u, k \leftarrow 0$
while $\sum_{i\in\Omega} P_{MAX}(d_{iv})^{-\alpha} < \tau$ do
    $k \leftarrow k + 1$
    $H(u) \leftarrow H(u) \cup \{\pi(k)\}$
    $\Omega \leftarrow \Omega \cup H(u)$
end while
while $k \leq n$ do
    if $k = n$ then
        Return $H(u), \sum_{i\in\Omega} P_i(v)$
    else if $\sum_{i\in\Omega} P_i(v) < \sum_{i\in\Omega\cup\pi(k+1)} P_i(v)$ then
        Return $H(u), \sum_{i\in\Omega} P_i(v)$
    else
        $k \leftarrow k + 1$
        $H(u) \leftarrow H(u) \cup \{\pi(k)\}$
        $\Omega \leftarrow \Omega \cup H(u)$
    end if
end while
```

by applying the minimum spanning tree (MST) algorithm to G''. In order to make MSTs, we use Kruskal's algorithm [22] that does not need to select a root node. Figure 5 describes G'' at step 3. The CC links that do not belong to MSTs in G'' are also eliminated from G'. G and G' at step 3 are shown in figure 6. Dotted and solid lines are drawn for CC links in G' and direct links in G, respectively. Source nodes and chosen helper nodes are marked with stars (*).

D. Step 4: Reducing Link(s) in Each Cluster of Graph G

Within each cluster of graph G, direct links, which do not apply CC technology and are not energy efficient, are discarded by using the MST algorithm again. However, if u maintains a CC link chosen as a link of MST in step 3 and v is selected as the helper of u (i.e., $v \in H(u)$), link (u, v) should not be discarded due to the constraint of the guarantee on CC links. Thus, all helper links are chosen as links of MST in advance, before the MST algorithm is applied. Accordingly, some clusters may not be constructed as a tree. The purpose of applying the minimum spanning tree algorithm for graph G is to reduce the overall power consumption in each cluster. The reason why we do not apply MST in step 1 in advance is that each node needs to consider all 1-hop neighbors as possible helper node candidates in step 2. Figure 7 shows G, the result of step 4. In addition, in order to achieve further power reduction in clusters, we can apply the DTCC algorithm [12] instead of the MST algorithm. The results of applying MST and DTCC to each cluster are compared in section 6.

E. Step 5: Combining Two Graphs, G and G′

At last, we combine the two graphs by adding $E(G')$ to G. In other words, the final topology is as follows: the connection among clusters becomes the MST of the CC links, while the topology within clusters is comprised of the MST of the direct links. The result is shown in figure 8. $E(G)$ and $E(G')$ is expressed by the solid and dotted lines, respectively. After the two topologies are combined, the power of each node i is decided by following equation.

$$P_i = \max\{\max_{(i,j)\in E(G)} P_i^d(j), \max_{(i,j)\in E(G')} P^c_{i\cup H(i)}(j)\} \qquad (9)$$

V. DISTRIBUTED ALGORITHM

In this section, we discuss how the proposed centralized algorithm works in a distributed fashion.

First, each node establishes links with neighbor nodes that belong to the same cluster using direct communication with the maximum transmission power. Each node measures the current position using GPS or localization methods and exchanges the position information with other nodes in the cluster. Each node also broadcasts its node ID to other nodes in the same cluster and if the delivered ID is bigger than that of a receiver node, the receiver node saves the received ID as its cluster ID.

After the construction of each cluster is over, with CC technology and P_{MAX}, each node transmits the request message to other nodes in different clusters by using all neighbor nodes as helper nodes. The result corresponds to figure 4. The message includes the position of a source node and the cluster ID of the source node. After receiving the request message, the node transmits the reply message except in the following cases:

- The cluster ID in a request message is the same as that of a receiver node.
- The cluster ID is different but successful CC transmission between a source node and a receiver node is impossible due to the lack of helper nodes.

In the above second case, the receiver node and its helpers cannot send a message to the source node, while the source node and its helpers can do so. In this case an asymmetric link can be made but the source node does not maintain the asymmetric CC link because there is no reply message from the receiver.

After generating CC links among clusters via the request and reply mechanism, each node determines its helper nodes and weight using the proposed algorithm in section 4(B). Then the node sends the following information 1) its ID, 2) the ID of the destination cluster and 3) the weight of the CC link to a representative node with the highest node ID in the same cluster.

Within each cluster, the representative node with the highest node ID applies the Distributed MST algorithm (DMST) [3] to the CC links between its cluster and neighbor clusters, regarding each cluster as a node. DMST is an algorithm which generates a MST in distributed fashion. Accordingly, the node can determine which CC links should remain and then it broadcasts the information of the final CC links, which includes the source nodes' IDs and the destination clusters' IDs, to every node in the same cluster. Finally, we can construct an MST where each link is a CC link and each node is a cluster. After that, each node can also apply DMST to the direct links within each cluster.

VI. SIMULATION RESULTS

We have proposed novel ideas, which ensure energy efficiency by assigning proper CC links, and which increase and maintain the network connectivity. In this section, we perform extensive simulations to compare the performance of the proposed energy-efficient topology controls using cooperative communication (Coop. Bridges, Coop. Bridges + DTCC) with other schemes. Coop. Bridges is the topology control applying the greedy heuristic in step 2 of section 4 and the MST algorithm within each cluster in step 4 of section 4. Coop. Bridges + DTCC is based on Coop. Bridges, but the DTCC algorithm [12] is used within each cluster in step 4 of section 4. The compared schemes are as follows: a scheme that maintains direct links to all neighbor nodes without using CC (Max-Power-w/o-CC) and a topology control scheme maintaining all possible direct links and CC links (Max-Power-w/-CC). In Max-Power-w/-CC, each source node selects all neighbor nodes as its helper nodes. In addition, DTCC [12] and a MST topology scheme without using CC (MST) are also compared. Since there is no existing topology control scheme using an extended transmission range with CC, we select MST and DTCC, which are common in topology control schemes without CC and with CC, respectively. The goal of topology control is to maintain the connectivity among as many nodes as possible while minimizing the power consumption of each node. Therefore, we use the average transmission power as the simulation metric for evaluation of energy efficiency. To evaluate the connectivity, we use the network connectivity which is defined in section 3. In addition, we also observe the connectivity-power-ratio (the ratio of network connectivity to average transmission power). In this simulation, 10-110 nodes are randomly arranged in a $500m \times 500m$ area. The path loss factor α is set to 2 and 4. The value of P_{MAX} is 4900 and 24010000 for each value of α so that the maximum transmission range for a direct link will always be 70 meters. For convenience, the SNR threshold τ is set to 1. In order to produce more reliable results, the data are generated by averaging the data from several random topologies. The number of types of random seed for node arrangement is 50. By fixing the network area to $500m \times 500m$ and adjusting the number of nodes in the simulation environment, we can generate clusters. Figure 9 shows the number of clusters generated according to the number of nodes. In figure 10, the greater the node density, the smaller the degree of network partitioning. The degree of network partitioning is defined as the ratio of the number of clusters to the number of nodes. The simulation results for the simulation metrics are described in the following three subsections.

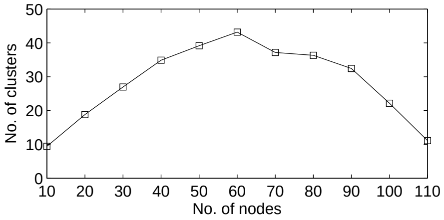

Fig. 9: No. of clusters.

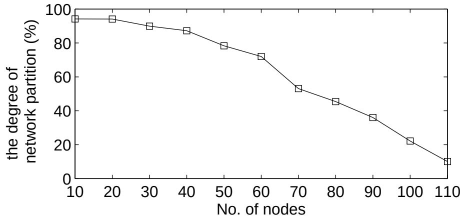

Fig. 10: Degree of network partitioning.

A. Comparison of connectivity

In figure 11 and 14, the network connectivity with respect to an increase in the number of nodes is compared. The path loss factor α is set to 2 and 4 in figure 11 and 14, respectively. It is observed that as the number of nodes (i.e., node density) increases, the network connectivity also increases. Since each node can communicate with more nodes via CC links among clusters, the network connectivity in Max-Power-w/-CC, Coop. Bridges and Coop. Bridges + DTCC has a greater rate of increase than that of MST, DTCC, and Max-Power-w/o-CC. When the node density is near the center, i.e., the number of nodes is between 40 and 90, there is a big difference (up to 2.6 times) between connectivity performance. On the other hand, the difference of performances in the other interval is reduced, because a smaller density yields few helper nodes and the distance among clusters is too long, while a larger density can be covered by direct links, in both cases where the number of generated CC links decreases. This difference of connectivity performance between schemes tends to be increased when α is 2 rather than 4. This phenomenon reflects the fact that the frequency of connecting clusters by CC is reduced if the path loss factor α is increased. On the other hand, Max-Power-w/o-CC, MST and DTCC show the same connectivity in both figure 11 and 14, since the maximum transmission range is fixed as 70m in case of direct communication, regardless of the path loss factor.

B. Comparison of transmission power consumption

Figure 12 and 15 compare the power consumption of the topology control mechanisms as the number of node increases. The value of α is 2 and 4 in figure 12 and 15 respectively. The power consumption of each scheme (in descending order) is as follows: Max-Power-w/-CC, Max-Power-w/o-CC, Coop. Bridges, Coop. Bridges + DTCC (or MST), and DTCC. The power consumption of Coop. Bridges and Coop. Bridges + DTCC is similar to or a little higher than that of MST but it is less than Max-Power-w/o-CC. Moreover, there is a case that the power consumption of Coop. Bridges + DTCC is less than MST. This shows that our algorithm does not require high power consumption compared to the schemes without CC. This is because the cooperative bridges algorithm selects the minimal number of CC links required for increased network connectivity, after transforming each CC link into an energy-efficient one.

When the number of nodes is 10, the power consumption is similar in all topology control schemes. This is because the node density is so low that there are not enough helper nodes and therefore, CC cannot be used in that case. When the number of nodes grows from 30 to 90, the number of nodes connected by CC or direct links is increased. Thus, the power consumption of all schemes tends to increase compared to the case that the density of nodes is extremely small or large. In case that the number of nodes ranges from 60 to 110, the energy efficient schemes such as Coop. Bridges, Coop. Bridges + DTCC, MST, and DTCC show a decreased power consumption. On the other hand, other schemes such as Max-Power-w/-CC and Max-Power-w/o-CC, which do not consider a MST, show the opposite phenomenon. When there are 110 nodes, since most nodes are connected via direct links, the performance enhancement is determined by the MST algorithm, which reduces the number of links, and by DTCC, which replaces direct links with CC links, not by CC. The difference between energy-efficient schemes and the other ones is more obvious in figure 15, where the path loss factor α is 4, than in figure 11, where α is 2.

C. Comparison of Connectivity-power-ratio

Figure 13 and 16 shows the connectivity-power-ratio of each algorithm, where α is 2 and 4, respectively. First, Coop. Bridges and Coop. Bridges + DTCC show higher performance than the other schemes in figure 13 ($\alpha = 2$). This means that the connectivity benefit from using the Coop. Bridges algorithm is much more than the increment of power consumption. However, in figure 16 ($\alpha = 4$), Coop. Bridges + DTCC and Coop. Bridges have a similar connectivity-power-ratio to DTCC and MST, respectively. This is because the increment of connectivity is reduced but the difference of power is not significantly reduced compared to the case that alpha is 2. However, since algorithms using Coop. Bridges have a high connectivity benefit, a similar performance in terms of connectivity-power-ratio can still be seen in the affirmative view.

D. Summary

- When α is 2, the suggested topology control schemes (Coop. Bridges and Coop. Bridges + DTCC) have higher (about 2.6 times stronger) network connectivity performance than the other topology control scheme that does not consider an extended transmission range with CC. However, they have marginally higher power consumption (1.28 times in Coop. Bridges and 1.19 times in Coop. Bridges + DTCC). The comparison of schemes in terms of connectivity-power-ratio shows that the suggested idea has the best performance among the considered topology control schemes.
- Especially, in case that the alpha value is low and the degree of network partitioning is at an intermediate level (or there are many clusters), the suggested idea (Coop. Bridges, Coop. Bridges + DTCC) outperforms the other algorithms in terms of network connectivity and connectivity-power-ratio.

VII. CONCLUSION

In this paper, we have proposed a novel centralized topology control scheme to minimize the transmission power of nodes and increase connectivity for separated networks, considering coverage expansion of cooperative communication technology. Our present study is the first to investigate this approach. Our solution constructs an MST-based network connectivity graph with minimal CC links selected from possible candidates of CC links to reduce transmission power. Furthermore, two helper-node selection schemes to maintain energy-efficient CC links were suggested; the optimal method and the greedy heuristic method. We also applied MST (or DTCC) to each cluster for direct links and it achieved further power reduction. Next, we discussed a distributed version of the proposed topology control scheme. Via simulations, we concluded that our algorithms lead to greater enhancements (up to 50%) in connectivity than other topology control schemes with

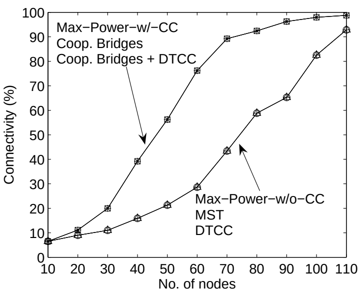

Fig. 11: Connectivity $(\alpha = 2)$.

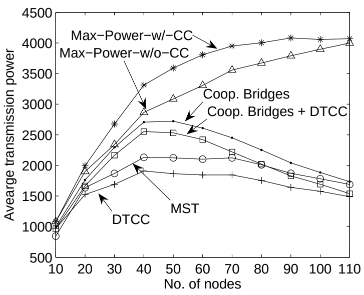

Fig. 12: Power consumption $(\alpha = 2)$.

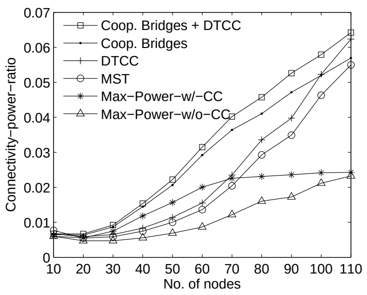

Fig. 13: Connectivity-power-ratio $(\alpha = 2)$.

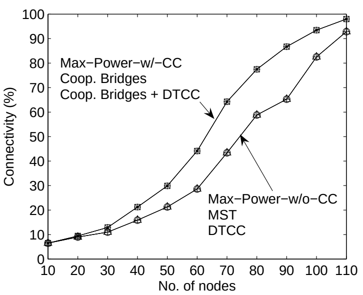

Fig. 14: Connectivity $(\alpha = 4)$.

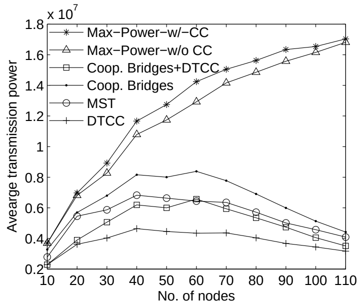

Fig. 15: Power consumption $(\alpha = 4)$.

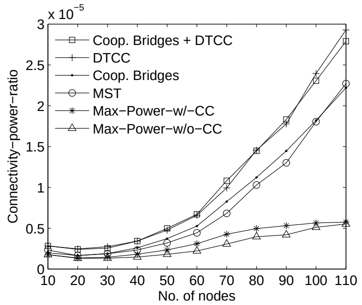

Fig. 16: Connectivity-power-ratio $(\alpha = 4)$.

tolerable increase of transmission power. The advantage of the proposed schemes is even bigger when the path loss exponent tends to be smaller and there are more disconnected networks. Our work can provide guidelines on how to construct energy-efficient CC links to extend network connectivity.

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