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A Coalitional Graph Game Approach for Minimum Transmission Broadcast in IoT Networks

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ABSTRACT In this work, we consider the broadcast mechanisms for both reliable links and unreliable links in the Internet of Things (IoT) networks. Focusing on the minimum transmission broadcast (MTB) problem, we propose an efficient algorithm, termed as the Connected Dominating Set Algorithm based on Coalitional Graph Game (CDSA-CGG), to find the minimum connected dominating set (MCDS). Distinct from related work in the literature which adopts a non-cooperative game approach and assumes the interaction among nodes is limited to neighboring nodes, we formulate the interaction and cooperation among nodes over reliable links and over unreliable links as a connected forwarding graph based on coalitional graph game. We prove that the forwarding graph constructed by CDSA-CGG is a Nash network. In addition, we also prove that the final resulting graph is pairwise stable. The simulation results show that the proposed coalition graph game-based algorithm performs well in terms of the number of transmissions, convergence rate, and lifetime of nodes.

INDEX TERMS Coalitional graph game, IoT, minimum transmission broadcast, connected dominating set, pairwise stability.

I. INTRODUCTION

In the past few years, with the rapid development of network infrastructure and mobile devices, IoT applications have been rapidly deployed in various fields of people's lives, such as healthcare, environmental monitoring, smart factories, smart home, intelligent transport, *etc.*, [1]–[4]. The potential economic impact of IoT is expected to bring many business opportunities and to accelerate the economic growth of IoT-based services. According to the Gartner's report [5], up to 8.4 billion IoT devices will be in connected through machine-to-machine (M2M) by 2017 and this number will reach 20.4 billion by 2020. One way to construct an IoT network is with the help of the wireless sensor networks [6]–[8], consisting of a lot of randomly distributed, low-cost, and low-power tiny sensor nodes.[1] The sensor nodes are responsible for collecting the sensed data and then periodically transmit the sensed data to the sink node for communicating with each other. With the multiple diversity of IoT applications and the rapid increasing number of smart devices, the network system becomes more and more complex. Thus, how to disseminate real-time sensing data to their nearby applications in local IoT networks for lowering service latency is critical to the success of IoT networks, where the efficiency of the routing search is highly dependent on how efficiently this dissemination is implemented [9]–[15]. In the traditional broadcasting schemes, flooding is the simplest broadcasting scheme. In a simple flooding scheme, every node simply rebroadcasts a newly received data packet to all nodes in the networks. Thus, this scheme is easy to be

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[1]In this paper, sensor nodes are represented by nodes.

implemented in resource-constrained wireless nodes and adaptive to the dynamic network topology of IoT nodes. However, the flooding scheme not only is costly, involves excessive power consumption, but also causes the broadcasting storm problem [16]–[18]. To avoid the problem of broadcasting storm, developing a broadcast scheme with the minimum number of transmissions is a crucial issue. The problem is referred to as the minimum transmission broadcast (MTB) problem [19]. More specifically, the MTB problem deals with the selection of intermediate relaying nodes by which the whole network can be covered. In other words, starting from the source node, the data are able to reach all nodes of the network through these selected nodes. Thus, determining how to reduce the number of transmissions and improve efficiency is of great importance and has drawn much attention in the past decade [19]–[27].

In [19], Hong *et al.* developed the MTB strategy to improve transmission efficiency. In the MTB problem, two link models are considered: the reliable-link model and the unreliable-link model. Packets under the reliable-link model are guaranteed to be received without error, whereas those under the unreliable-link model will be received correctly with some probabilities. In the case of the reliable-link model, the MTB problem can be considered as the Minimum Connected Dominating Set (MCDS) problem [21] or the Maximum Leaf Spanning Tree (MLST) problem [22]. To minimize the number of forwarding nodes and solve the MTB problem, *virtual backbone* structures have been proposed [23], [24], and nodes in the virtual backbone help forward packets. However, these works did not take interaction among users into account [20].

To take nodes' interaction into consideration, [20] first proposed a broadcast strategy based on noncooperative game theory. The *Game-Based Broadcast Tree Construction (GB-BTC)* algorithm [20] was proposed to solve the MTB problem and construct a broadcast tree for both reliable and unreliable links. The utility of each player takes both the number of children and the reception probability into consideration. The GB-BTC algorithm is capable of obtaining the optimal broadcast schemes by formulating the MTB problem over reliable and unreliable links as two mixed integer linear programming (MILP) problems for small-scale networks and by achieving the Nash equilibrium for large-scale networks with a distributed game-based algorithm. However, since the interaction in the method is limited to two adjacent users only in which each user focuses on maximizing its own profit due to the inherent characteristic of noncooperative game [28]–[30], it will lead to the hotspot problem. Thus, fewer suitable nodes can be chosen as the forwarding nodes while the selected nodes become hot spots, which reduces the network lifetime.

Since both the interaction and the cooperation among nodes over the reliable and unreliable link models have not been well studied in the aforementioned work, we are therefore motivated to investigate efficient and reliable broadcasting schemes using the coalitional graph game. In our previous work [31], we have successfully proposed a coalitional broadcasting graph game to take both the interaction and the cooperation among nodes into account. However, only the reliable-link model was considered.

In this work, we complete the investigation of the MTB problem by including the theoretical game formulation in the case of the unreliable-link model. Furthermore, unlike [31], we provide theoretical investigations regarding whether the proposed CDSA-CGG converges to a local Nash network [32], [33] and whether the converged broadcasting tree is pairwise stable [34]–[36]. The main purpose of the work is to minimize the number of forwarding nodes while simultaneously extending the overall lifetime of the IoT network. The interaction and cooperation among nodes depend on the game-induced graph and the topological structure of nodes in the network, whereas [20] considered only the topological structure. This helps avoid the occurrence of hot spots, extend the lifetime of the network, and ensure the minimal number of forwarding nodes possible. The utility of the proposed CDSA-CGG accounts for the joint coverage of a node and its parent and the number of hop counts from the origin of the information source in the case of the reliable-link model. On the other hand, in the case of the unreliable link model, we consider a more robust design by incorporating the reception probability into the utility function. Through an extensive computer simulation, we demonstrate that the proposed CDSA-CGG outperforms GB-BTC in terms of the number of forwarding nodes, maximum latency, and network lifetime in the case of reliable links. In the case of unreliable links, the proposed CDSA-CGG has a similar performance to GB-BTC in terms of the number of forwarding nodes and maximum latency, but has a longer network lifetime than GB-BTC. The main contributions of this work are summarized as follows.

- We consider a novel broadcasting scheme of IoT networks in which broadcasting nodes form a cooperative coalition in order to minimize the number of forwarding nodes while simultaneously extending the overall lifetime of the IoT networks. To the best of our knowledge, this paper presents the first study that applies the coalitional graph game to model the cooperation and the topological structure among nodes as a coalitional broadcasting graph.
- We propose a new coalitional graph game-theoretic framework to analyze the interaction and cooperation among nodes in an IoT network. We apply the equilibrium concepts of the Nash and the pairwise-stability, respectively, to characterize the convergence and stability of the final connected network among nodes.
- We develop a method based on the coalitional graph game by considering both the cooperation and the topological structure of nodes to construct the connected dominating set over the reliable and unreliable links for avoiding the hot spot problem and, as a result, extending the lifetime of the network with the minimal number of forwarding nodes.

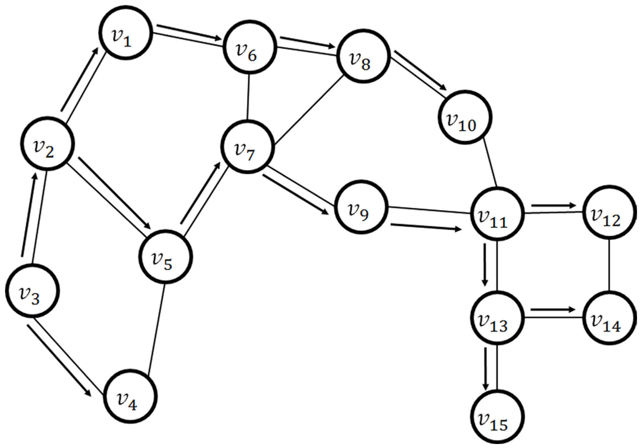


FIGURE 1. An arbitrary network topology.

- We demonstrate that the formulated coalitional graph game will converge to a local Nash network. In addition, we prove that the final resulting graph will be pairwise stable.
- We conduct numerical analyses to verify the benefits of forming a coalitional broadcasting graph among nodes resulting from the proposed CDSA-CGG algorithm. An simulative example is also given to illustrate the constructed topologies based on the proposed approach.

The remainder of this work is organized as follows. Section II presents the system model in detail. In Section III, the proposed coalitional graph game methods are introduced. In Section IV, the corresponding algorithms are proposed. In addition, the proof of the stability of the methods is presented. In Section V, the simulation results of comparing our methods with related works under both the reliable-link model and the unreliable-link model are shown. Finally, concluding remarks are given in Section VI.

II. SYSTEM MODEL

In this work, we consider a network where nodes are uniformly distributed over an area. The set of nodes in the networks is denoted by $\mathcal{P}$ and each node is aware of the one-hop information through the exchange of periodic hello messages with its neighbors. Let node v be a node in the network. We denote the set of neighboring nodes of node v by $\mathcal{N}(v)$. For example, as shown in Fig. 1, the set of all nodes in the network is $\mathcal{P} = \{v_1, \ldots, v_{15}\}$, and $\mathcal{N}(v_1) = \{v_2, v_6\}$.

Assuming that the source node is v_3, we aim to find the set of forwarding nodes to help broadcast the messages of v_3 such that all nodes in the network can receive these messages. To simplify the search of the forwarding nodes, each node is assumed to be connected to the source node by one path at most to avoid receiving duplicates of the same messages. An example is illustrated in Fig. 1, where the arrows indicate the broadcasting direction with respect to these messages sent from the source node v_3.

In this work, two link models are considered: The reliable-link model and the unreliable-link model. In the reliable-link model, packets transmitted over any reliable link are always delivered successfully. In contrast, packets transmitted from one end to the other over any unreliable link are delivered with probability in the unreliable-link model. In this work, we assume that the messages will be rebroadcast until all the receivers have received the messages successfully. The successful reception probability of the packets between node i and its neighboring node j is denoted by p_{ji} for $j \in \mathcal{N}(i)$.

In the following section, a coalitional broadcasting graph game will be proposed to construct the connected dominating set as the virtual backbone to solve the MTB problem under the reliable-link and unreliable-link models.

III. COALITIONAL BROADCASTING GRAPH GAME FORMULATION FOR CONNECTED DOMINATING SET CONSTRUCTION

In the context of broadcasting, fewer redundant broadcasting packets is a major design consideration [37]–[39]. Thus, the MTB problem aims to find a broadcasting scheme with the minimum number of transmissions while guaranteeing the full delivery of packets. With game theory, the interplay among nodes can be better understood, which helps design a suitable broadcasting scheme [20]. Unlike the noncooperative game theory adopted in [20], we resort to the coalitional graph game in cooperative game theory [29], [30] to model the cooperation among nodes. The main difference between the proposed approach and the work [20] lies in the fact that, in addition to the interaction among nodes, the cooperation suggested by the game-induced graph plays another major role in the construction of the broadcasting tree. By additionally considering the cooperation among nodes, the proposed broadcasting scheme can achieve fewer transmissions and lower latency than the broadcasting scheme in [20] under the reliable-link model, whereas the proposed broadcasting scheme performs similarly to [20], but has a longer lifetime.

We will start with the definition of the proposed coalitional broadcasting graph game.

A. THE DEFINITION OF THE COALITIONAL BROADCASTING GRAPH GAME

In this work, the proposed CDSA-CGG is based on the coalitional graph game. The conventional coalitional graph game cannot be directly applied to the design of the broadcasting strategies [28] due to the possible formation of loops in the resulting graph. Proper modifications are needed. In this work, we propose a new game model called the coalitional broadcasting graph game, which is defined as follows:

Definition 1: The coalitional broadcasting graph game is given by $\langle \mathcal{T}, \mathcal{P}, \mathcal{G}, \mathcal{S}, \succeq \rangle$, where

- $\mathcal{P} = \{1, 2, \cdots, P\}$ is the set of players, i.e., the set of nodes in the network.
- $\mathcal{T}$ is the topology structure of players in $\mathcal{P}$.
- s_i is the set of strategies of player i and $\mathcal{S}$ is the set of strategies of all the players in the networks; that is $\mathcal{S} = \{s_1, s_2, \cdots, s_P\}$.

- $\mathcal{G}$ is the collection of all possible directed connecting graphs without loops, which is represented by $\mathcal{G} = \{G_1, G_2, \cdots\}$, in which G_i represents the broadcasting tree [40]–[42].
- $\succeq = \{\succeq_1, \succeq_2, \cdots, \succeq_P\}$ is the set of preference relations, where $\succeq_i$ is the preference of player i over the distributions of payoffs of graphs in $\mathcal{G}$. For example, if player i prefers G_j than G_k, then it can be represented in the form of $G_j \succeq_i G_k$. ■

It is worth noting that the strategy of a player in CDSA-CGG is the selection of another player as its parent in the broadcasting tree. The main purpose of the proposed coalitional broadcasting graph game is to obtain a stable, directed connecting graph G^*, in which no players can unilaterally deviate from the formed coalition to gain more benefits. In addition, the stable graph G^* will not result in the loop problem; this means that each node has only one upstream node in the resulting graph G^*. Note that in the following sections, node i and vertex i are both referred to as player i.

B. UTILITY DEFINITION IN THE RELIABLE-LINK MODEL

In the reliable-link model, since the links among nodes in the network are error-free, finding fewer forwarding nodes and achieving less latency (which is defined as the time gap between the starting time of broadcasting and the time when the last node receives the broadcasting messages) correlates with the coverage of the forwarding nodes. When the nodes with larger coverage are selected as the forwarding nodes, we can expect that fewer forwarding nodes will be needed to cover all nodes in the network and lower latency can be achieved. In this work, two structures are used to define the coverage of nodes: the physical topology, $\mathcal{T}$, which represents the physical connections among nodes, and the directed connecting graph G formed by the proposed game.

We assume that a node only has one-hop information. Given the formed directed connecting graph G, when the adjacent nodes are i, j in $\mathcal{T}$ and node i wants to choose node j as its parent in G, we define the coverage of the nodes as

$$C_G(i,j) = |N_{\mathcal{T}}(i) \cup Ch_G(j)|,$$

where $|\cdot|$ is the cardinality, $N_{\mathcal{T}}(i)$ is the set of neighboring nodes of node i in $\mathcal{T}$ and $Ch_G(j)$ are the children of node j in G. $C_G(i,j)$ considers the role of j in graph G and the possible downstream nodes of node i in $\mathcal{T}$. We rewrite $C_G(i,j)$ as

$$\begin{aligned} C_G(i,j) &= |N_{\mathcal{T}}(i)| + |Ch_G(j)| - |N_{\mathcal{T}}(i) \cap Ch_G(j)| \\ &= |N_{\mathcal{T}}(i)| + |\{Ch_G(j)/N_{\mathcal{T}}(i) \cap Ch_G(j)\}|. \end{aligned}$$

Given the two possible candidates for the parents of node i, node j and k, when $C_G(i,j) > C_G(i,k)$, this implies that

$$|Ch_G(j)/\{N_{\mathcal{T}}(i) \cap Ch_G(j)\}| > |Ch_G(k)/\{N_{\mathcal{T}}(i) \cap Ch_G(k)\}|.$$

$Ch_G(j)/N_{\mathcal{T}}(i) \cap Ch_G(j)$ can be viewed as the additional coverage provided by node j if node i chooses node j as its parent in graph G. Thus, $C_G(i,j) > C_G(i,k)$ means that for node i, choosing node j as the parent node is more beneficial than choosing node k since more nodes can be in the coverage. This could lead to fewer nodes in the network being selected as the forwarding nodes and achieving higher broadcasting efficiency [38].

Another consideration in the design of an efficient broadcasting scheme is the broadcast latency. The broadcast latency is represented by the time required for all the nodes in the network to receive the broadcasting messages. In this work, the broadcast latency is defined as the number of hops required for the broadcasting messages sent from the source node to the last receiving node in the formed graph. In this definition, the processing delay and propagation delay are ignored. With defined joint coverage and broadcast latency, if node i chooses node j as its parent node in graph G, the utility of node i is defined by

$$U_G(i,j) = C_G(i,j) - \alpha h_G(j) + \lambda, \tag{1}$$

where $h_G(j)$ is the distance, which is the number of hops between node j and the source node in G, and α is a constant value.

C. UTILITY DEFINITION IN THE UNRELIABLE-LINK MODEL

In the unreliable-link model, the links among nodes are error-prone and each link has its own probability of errors. Apart from the coverage and hop count, the link quality is another key factor that affects the broadcast latency and number of forwarding nodes. To save the number of forwarding nodes, it is also desirable for a node to choose another node as a parent if the link quality between them is optimal. That is, suppose that the current constructed graph is G, given two possible parents of node i, say node j and node k, when $C_G(i,j) = C_G(i,k)$ and $h_G(j) = h_G(k)$, node i would prefer j over k if

$$p_{ji} > p_{ki}.$$

Thus, in the unreliable-link model, if node i chooses node j as its parent, the utility of node i is modified to

$$U_G(v,j) = C_G(i,j) - \alpha_1 h_G(j) - \alpha_2 \frac{1}{p_{ji}} + \lambda, \tag{2}$$

where α_1 and α_2 are two constants in the current constructed graph G, to embrace the impact of the link quality. As will be demonstrated, adopting the utility function in (2) can prolong the lifetime of the network while providing similar latency and number of forwarding nodes to GB-BTC [20].

In both link models, each node in the network seeks to choose the parent that is the most beneficial in the current formed graph G such that the utility in (1) can be maximal. That is,

$$j = \arg \max_{\ell \in N_{\mathcal{T}}(i) \cap G} U_G(i,\ell). \tag{3}$$

In the case of the reliable-link model, the proposed coalitional broadcasting graph game can build a broadcasting tree with fewer forwarding nodes and shorter broadcast latency

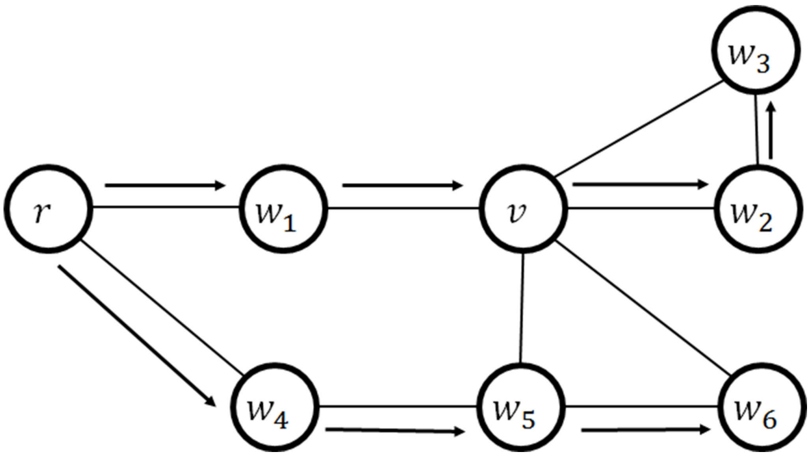


FIGURE 2. An illustrative example of how a loop can form if proper care is not taken.

whereas in the case of the unreliable-link model, the stability of a link is additionally taken into account.

IV. GAME THEORETIC FORMULATION AND ANALYSIS

A. THE CONSTRAINTS OF THE PROPOSED GAME

In general, each player tends to maximize its payoffs in a strategic game. However, if the players only consider how their payoffs are maximized, this will result in that some players choose the descendants to be their parents. Thus, the connected graph will be disconnected. For instance, as shown in Fig. 2, node r is the source node and the neighboring node of node v is represented by $\mathcal{N}(v) = \{w_1, w_2, w_3, w_5, w_6\}$. The source node r broadcasts the messages to all the nodes, where the solid arrow in Fig. 2 represents the transmission direction of messages. From the figure, we can see that node v first receives messages from node w_1, and then, transmits the messages to node w_2. Thus, nodes w_2 and w_3 are the descendants of node v. However, if node v only considers maximizing its own utility, and disregards the relationships among nodes, it may choose one of its original descendants to be the parent node. Thus, the graph will be disconnected at node v.

To prevent the nodes from choosing their descendants in a graph to be their parents, two constraints must be imposed:

- For any node i, it cannot choose its children in the graph to be the parent nodes.
- For any node i, let j be the possible candidate of its parent node. This requires that $h(i) \geq h(j) - 1$, where $h(i)$ is the hop count of this node from the source in the graph.

With the first constraint, the disconnected problem of the graph can be avoided. The second constraint ensures the chosen parent of node i is closer to the source, which can help reduce latency, and this chosen parent is unlikely to be the descendant of its descendants.

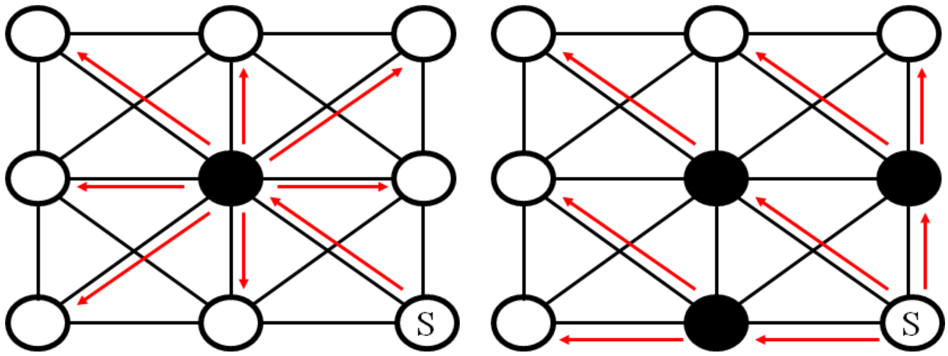
B. THE PROPOSED ALGORITHM

In this section, we will propose an algorithm, called the Connected Dominating Set Algorithm based on the Coalitional Graph Game (CDSA-CGG), to address the MTB problem based on the coalitional broadcasting graph game. The proposed algorithm for the construction of the broadcasting tree is presented in Algorithm 1 and will be called the CDSA-CGG algorithm for simplicity hereafter.

In Algorithm 1, the initial graph G_0 is firstly constructed by using the Dominating Sets and Neighbor Elimination-Based Broadcasting algorithms, breadth-first search, or a random graph. The purpose of the initial graph is to determine the parent descendent relation among nodes. Upon initialization, each node in the network tried to connect to the node in the current graph, which is most beneficial to the collective utility. Then, each node sends a hello message to exchange information. After completion of the first message exchange, each node can update its strategy to maximize its payoff, if possible, until all nodes converge to the steady state. In addition, some notations in Algorithm 1 are stated as follows:

- $Ch_{G_k}(i)$ represents the children of node i in a given network G_k.
- $h(i)$ represents the hop count of this node from the source in the current graph.
- κ represents the κth iteration in the generating process of coalitional network graph. Its initial value is set to be -1.
- $U_{G_k}(i, j)$ represents the utility of node i if node i chooses node j as its parent node in a network graph G_k.
- s_i represents the strategy of node i and is one of the parent nodes of node i in the current graph. The algorithm is to seek an advantageous s_i such that the utility of node i can be large as possible.

The illustration of the CDSA-CGG and GB-BTC algorithms under the reliable-link model is shown in Fig. 3, where the solid black circle represents the forwarding node, the circle with "S" means the source node, and the red arrows indicate the directions of packet forwarding. This illustrative example reveals the advantage of adopting CDSA-CGG to select the forwarding node. With the proposed CDSA-CGG,



(a) CDSA-CGG in reliable-link model

(b) GB-BTC in reliable-link model

FIGURE 3. Illustrating example of CDSA-CGG and GB-BTC.

Algorithm 1 The Proposed Algorithm for Broadcasting Tree Construction Based on CDSA-CGG

Input: s: the source node; G_0: an initial graph; κ: is defined to present the κth iteration; s_i: the strategy of node i;
Output: the converged graph G^*;
$\kappa = -1$;
while (true) **do**
  $\kappa = \kappa + 1$;
  for each node $i \in \mathcal{P}$ in a given network G_κ **do**
    if node i receives a HELLO message **then**
      update the $N(i)$ information;
    else if node i receives a JOIN message **then**
      update the $Ch_{G_\kappa}(i)$ information;
    else if node i receives a LEAVE message **then**
      update the $Ch_{G_\kappa}(i)$ information;
    end if
    $s_{TMP} \leftarrow s_i$;
    for each node $j \in N(i)$ **do**
      if $U_{G_\kappa}(i,j) > U_{G_\kappa}(i, s_i)$ and $h(i) \geq h(j) - 1$ **then**
        $s_i \leftarrow j$;
      end if
    end for
    if $s_i \neq s_{TMP}$ **then**
      node i sends a JOIN message to node s_i;
      node i sends a LEAVE message to node s_{TMP};
      $G_{\kappa+1} \leftarrow G_\kappa + ij - is_i$;
    else if $s_i = s_{TMP}$ **then**
      $G_{\kappa+1} \leftarrow G_\kappa$;
    end if
  end for
  if $G_{\kappa+1} = G_\kappa$ **then**
    output G^*;
    break;
  end if
end while

the inter-relationship among nodes in the graph is taken advantage of and the number of forwarding nodes can be reduced. In this example, the number of forwarding nodes chosen by GB-BTC is three, whereas only one forwarding node is required in CDSA-CGG.

In the followings, we will prove the convergence of the proposed algorithm and the stability of the resulting graph.

C. ANALYSIS OF CONVERGENCE

We assume that the proposed CDSA-CGG algorithm converges to the final resulting graph G^*. We first would like to show that the constructed final graph G^* is a tree rooted at the source.

Theorem 1: The final stable network graph G^* resulting from the CDSA-CGG algorithm for any initial graph is a directed connecting tree structure rooted at the source node.

Proof: Consider a network graph G in which a node i is disconnected from the graph. In other words, no communicating path exists between node i and the source node directly or through a multipath. In this case, from the defined utility function, the node will receive a negative payoff, $-\lambda$. As a result, node i has no incentive to disconnect itself from the network and chooses to be part of the graph to improve its situation. Furthermore, since each node is connected to the source via one path at most, together with the fact that no loops have formed, the resulting graph obtained by Algorithm 1 is a directed connecting tree structure rooted at the source node. ■

Next, we will prove the CDSA-CGG algorithm converges and G^* is a local Nash network. First, we define $U_i(G_{s_i,s_{-i}})$ as the utility of node i in the current graph, $G_{s_i,s_{-i}}$, when its strategy is s_i and all other nodes' action profile is s_{-i}. $G_{s_i,s_{-i}}$ explicitly emphasizes the dependence of the graph on the strategies taken by all nodes in the network. Given a network graph G, for any node $i \in \mathcal{P}$, given the set of feasible strategies $\mathbb{S}_i$, the best response of node i is defined as follows [32]:

Definition 2: For any player $i \in \mathcal{P}$, a strategy $s_i^* \in \mathbb{S}_i$ is defined as a local best response if $U_i(G_{s_i^*,s_{-i}}) \geq U_i(G_{s_i,s_{-i}})$, $\forall s_i \in \mathbb{S}_i$, where s_{-i} is the collection of the strategies of the other players.

From Definition 2, the best response of a player is correlated with the constructed graph and the strategies of other players. The cooperation of players derives from the fact that the chosen strategy of each player is related to others through the constructed graph. This differentiates the cooperative game from a noncooperative one. In addition, the proposed CDSA-CGG algorithm is a myopic algorithm [34]. Based on the current graph constructed in the previous iteration, the set of feasible best responses of each node is formed and each node chooses one from this set to improve its utility in the current iteration. After all nodes make their decisions in this iteration, a new graph is constructed, which will be utilized to build new sets of feasible best responses of nodes in the next iteration. Due to the iterative nature of the proposed CDSA-CGG algorithm, two questions naturally arise:

- Will the CDSA-CGG algorithm converge?
- If the CDSA-CGG algorithm does converge, will the converged graph be a Nash network [32]?

We first answer the question of convergence by proposing the following theorem.

Theorem 2: With our proposed CDSA-CGG algorithm, for an initial network graph G_0, it will converge to a final network graph G^* after T iterations, where T is finite.

Proof: We can view the graphs obtained by iterations from a sequence of graphs. That is, let G_t be the graph obtained in the tth iteration. $G_1, G_2, \cdots, G_t, \cdots$ forms a sequence. According to Definition 2, each player will choose the best feasible strategies in each iteration. Consequently, the utility of each player never decreases from one iteration to another. Since each term in the utility function defined in either (1) or (2) is finite, the utility of each player cannot be infinite. Therefore, the utility of each player converges, and together with the fact that the number of possible graphs is finite, the graph converges. That is,

$$G_1 \rightarrow G_2 \rightarrow \cdots \rightarrow G_t \rightarrow \cdots G^* \tag{4}$$

■

To answer the second question, we have to define the Nash network adopted from [32] below.

Definition 3: A network graph G is a Nash network if no node i can improve its utility by unilaterally changing its current feasible strategy $s_i \in \mathbb{S}_i$ without degrading the utility of others.

Based on Theorem 2, we propose the following theorem:

Theorem 3: The final graph G^* resulting from the proposed algorithm is a local Nash network.

Proof: In the proposed CDSA-CGG algorithm, each node only cares about how to maximize its own utility in a graph, which reflects the relationship among nodes. Therefore, each node changes its strategy in a graph if its utility can be better off and the collective utility can be improved as well[2]. As mentioned above, when the proposed algorithm converges to a final graph G^*, the strategy taken by any player in G^*, s_i^*, must be a local best response. Thus, $U_i(G_{s_i^*,s_{-i}^*}) \geq U_i(G_{s_i,s_{-i}^*})$, $\forall s_i \in \mathbb{S}_i$ holds and no player can be better off by deviating unilaterally from the current strategy s_i, $i \in \mathcal{P}$. As a consequence, the final graph G^* is a local Nash network. ■

D. ANALYSIS OF GRAPH STABILITY

In this section, we will discuss the pairwise stability of the final graph G^*. Pairwise stability has been a major concept of stability [43], which was originally defined as follows.

Definition 4: A network G^* is pairwise stable with respect to a profile of utility functions U if (i) for all i and $ij \in G$, $U_i(G) \geq U_i(G - ij)$ and $U_j(G) \geq U_j(G - ij)$, and (ii) for all $ij \notin G$, $U_i(G + ij) > U_i(G)$ and $U_j(G + ij) < U_j(G)$.

The pairwise stability in Definition 4 mainly addresses two key points:

1) No node gains from severing a link.
2) No pair of disconnected nodes can benefit by forming a new connection.

However, when applied to the broadcasting problem, the original pairwise stability is not sufficient. In the context of the broadcasting problem, the formation of loops is not allowed and the second criterion in Definition 4 does not seem to be suitable. Due to the utility defined in either (1) or (2), the player always has to participate in the formation of the broadcasting tree, and hence, the resulting graph formed by CDSA-CGG contains all the players; thus, the fact that two disconnected players form a connection would introduce a loop in a broadcasting tree formed by the CDSA-CGG algorithm, which is not allowed in the context of broadcasting. To tackle this problem, the pairwise stability is modified and defined in the following definition.

Definition 5: A network G^* is pairwise stable with respect to a profile of utility functions U if (i) for all i and $ij \in G$, $U_i(G) \geq U_i(G - ij)$, and (ii) for all $ij \in G$, $ik \notin G$, $U_i(G - ij + ik) < U_i(G)$.

Next, we will show that the final graph G^* is pairwise stable, as defined in Definition 5.

Theorem 4: The final graph G^* resulting from the CDSA-CGG algorithm is a pairwise stable network.

Proof: Due to Theorem 3, G^* is a Nash network and each player's strategy is their best response in G^*. Any deviation from their current strategy results in a decrease in their utility. Therefore, no player will gain from severing the current connection unilaterally and no two disconnected players will deviate from their current strategies and form a new connection. ■

V. SIMULATION RESULTS

In this section, numerical results are presented to illustrate the benefits gained from cooperation. We simulate a scenario where the number of nodes in the network is from 40 to 140. These nodes are distributed uniformly over a 1km×1km square region. Two cases are considered in our simulation: a reliable-link model and an unreliable-link model. To demonstrate the merits and demerits in this simulation, we compare the results of some performance metrics of the proposed approach against the Dominating Sets and Neighbor Elimination-Based Broadcasting

[2]We will delay the prove of the improvement of collective utility until Theorem 4.

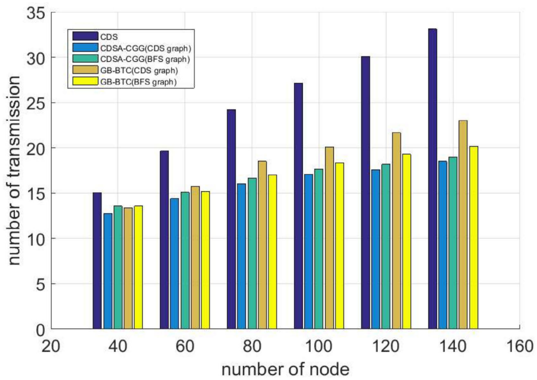


FIGURE 4. **The comparison results with respect to the number of forwarding nodes in the case of the reliable-link model for $D_{th} = 250$.**

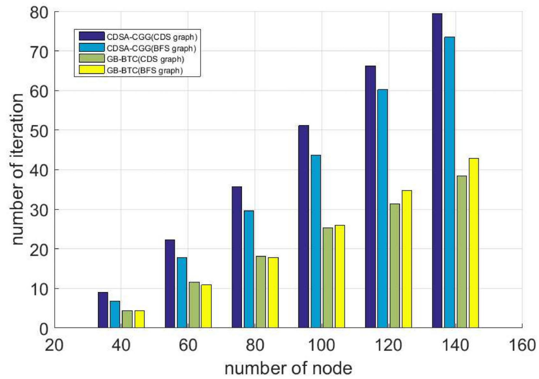


FIGURE 6. **The comparison results of the convergence rate in the case of the reliable-link model for $D_{th} = 250$.**

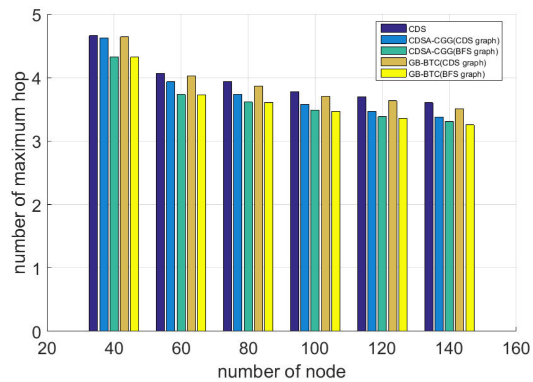


FIGURE 5. **The comparison results of latency in the case of the reliable-link model for $D_{th} = 250$.**

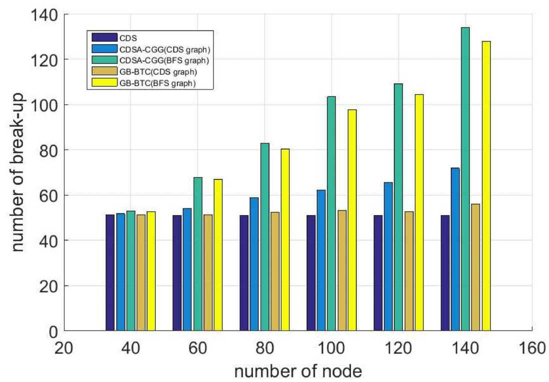


FIGURE 7. **The comparison results with respect to the lifetime of nodes in the case of the reliable-link model for $D_{th} = 250$.**

Algorithms (DSNEB) [21], which are labeled respectively as "CDS" and "GB-BTC" [20]. These performance metrics for the comparison include the average number of transmissions to cover all nodes, the average latency, the average rate of convergence, and the average lifetime, which is the time when the first node runs out of battery. Since the proposed approach and the GB-BTC algorithm need an initial graph to start with, two initial graphs, namely the CDS graph and BFS graph, are constructed by the CDS and the Breadth-First Search (BFS), respectively. We will start with the case of the reliable-link model.

A. SIMULATION RESULTS UNDER THE RELIABLE-LINK MODEL

Under this model, as long as two nodes are neighbors, packets will be received correctly. During the simulation, two nodes are considered neighbors if the distance between them is smaller than D_{th} meters.

Fig. 4 shows the comparison of the average number of transmissions required to cover all the nodes in the network among the proposed approach and two other approaches. In the case of the reliable-link mode, the average number of transmissions to cover all nodes in the network is the same as the average number of selected forwarding nodes. As shown in Fig. 4, the average number of forwarding nodes of the pro-

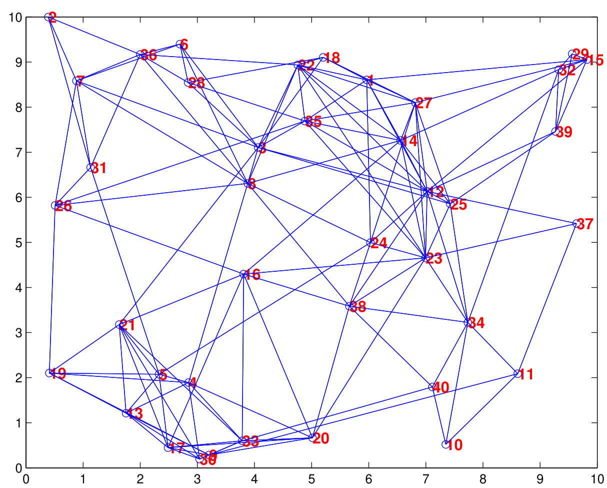
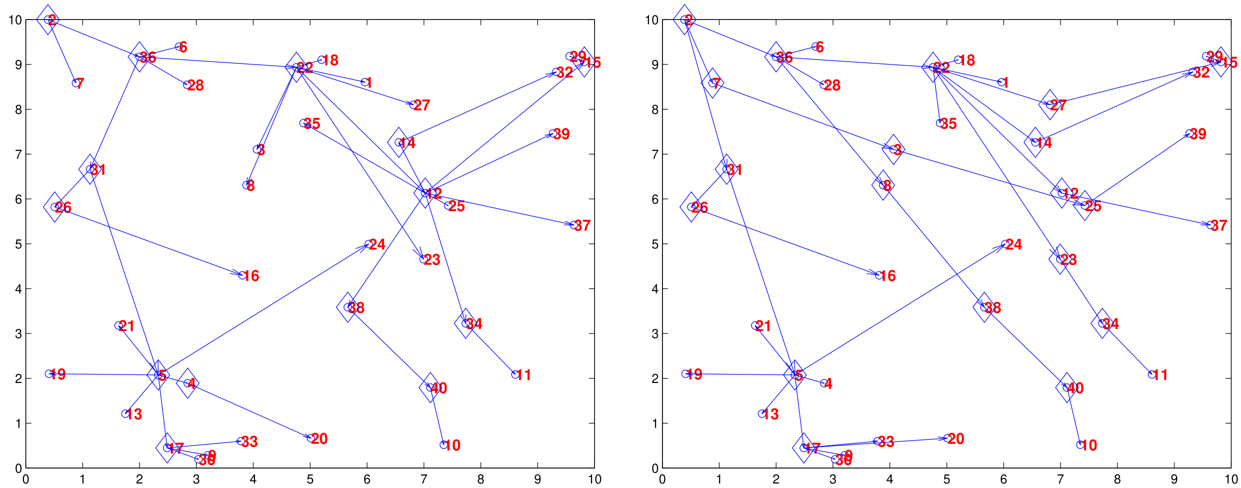


FIGURE 8. **The topology in the simulative example.**

posed approach is the smallest among all approaches. As the density of the number of nodes increases, the gap between the proposed approach and GB-BTC becomes more noticeable when the CDS graph is adopted as the initial graph in the case of the reliable-link model. This is due to the fact that the proposed approach takes the joint coverage of a node and its



(a)
CDSA-CGG under reliable-link model

(b)
GB-BTC under reliable-link model

FIGURE 9. An one-shot simulative example.

children into account when selecting the forwarding nodes. However, GB-BTC considers only the children of nodes and ignores the interaction between a node and its neighbors. This results in more unnecessary forwarding nodes in GB-BTC.

Fig. 5 illustrates the comparison of the average number of hops from the source node to the farthest forwarding node. This can be seen as the latency of the broadcasting. As shown in Fig. 5, the latency of the proposed approach is always better than that of DSNEB, which is labeled "CDS". However, the proposed approach has better latency performance than GB-BTC in the CDS graph and performs worse than GB-BTC in the BFS graph. This phenomenon illustrates that both the proposed approach and GB-BTC are affected by the initial graph.

In order to analyze the rate of convergence, only one player is allowed to deviate from its current strategy in each iteration. The comparison results of the convergence rate between our approach and GB-BTC are shown in Fig. 6. As can be seen clearly, the GB-BTC approach has better convergence rate than that of our approach. Even though our approach has worse convergence rate, each node in our approach only changes its strategy to a new one no more than once on average.

Figure 7 depicts the comparison results of the lifetime of nodes among the proposed approach and others. The lifetime means the time that the first node in the network runs out of its battery [44]. The proposed approach can achieve better performance in lifetime. The reason behind the longer lifetime of the proposed approach lies in the capability of distributing forwarding nodes more evenly than GB-BTC. As shown in Fig. 4, the proposed approach finds less forwarding nodes than GB-BTC. If the chosen forwarding nodes are not distributed evenly across the network, the hop spots are easier to occur in the proposed approach than GB-BTC. Furthermore, GB-BTC focuses more on the number of the children of a node. This will lead to higher likelihood of the node with more children to be selected as the forwarding node. On the contrary, the proposed approach takes both the number of the children and the coverage of a node into consideration. Thus, the proposed approach weighs both factors to make decision and is more likely to avoid creating hot spots than GB-BTC.

Next, we will show one simulative example of the chosen forwarding nodes under the topology shown in Fig. 8 when node 2 is the source, which is located in the upper-left corner. The graphs constructed by CDSA-CGG and GB-BTC are shown in Fig. 9. The total number of forwarding nodes of CDSA-CGG is 14 whereas that of GB-BTC is 19 in this example.

B. SIMULATION RESULTS UNDER THE UNRELIABLE-LINK MODEL

In the unreliable-link model, each node decides its neighboring node based on the received SNR, which is presented by

$$SNR_r = \left[\left(g\sqrt{d^{-\alpha}}\right)\sqrt{SNR_t}\right]^2, \quad (5)$$

where SNR_t represents the transmission SNR, SNR_r represents the received SNR, g represents the fading gain, d represents the distance between any two nodes in the network topology, and α represents the environment variable. Two nodes are considered to be neighbors when $SNR_r \geq SNR_{th}$, where SNR_{th} is the SNR threshold. In addition, we assume that Binary phase-shift keying (BPSK) modulation is utilized and a packet contains L symbols. Thus, bit error rate (BER) of a BPSK signal transmitted from node v to w [45] is

$$BER_{vw} = Q\left(\sqrt{2SNR_r^{vw}}\right),$$

and the probability of successful reception of a packet transmitted from node v to w is

$$p_{wv} = (1 - BER_{vw})^L.$$

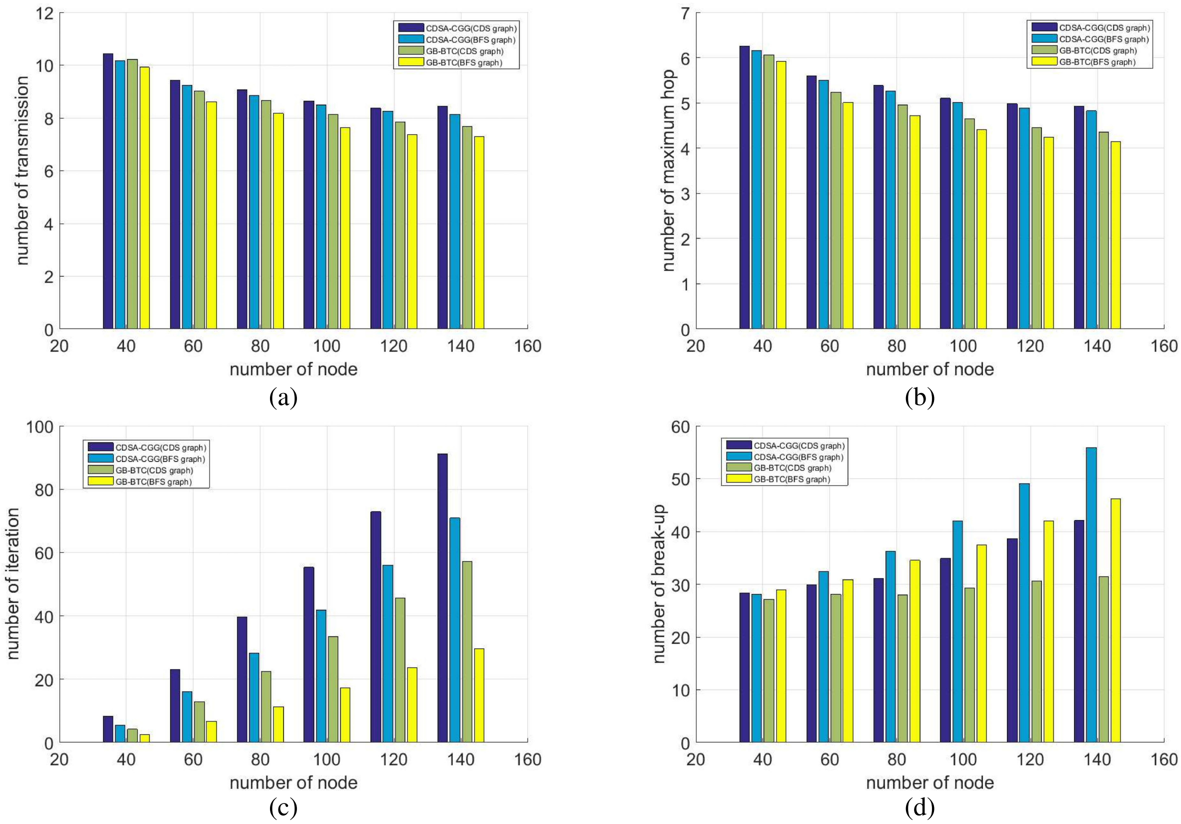


FIGURE 10. Comparisons between the proposed approach and GB-BTC in the case of unreliable link model when $SNR_{th} = 0.4$ and $L = 1$.

Note that in this part, we only compare our proposed approach and the GB-BTC. It is worth noting that both our proposed approach and the GB-BTC guarantee full delivery due to the retransmission mechanism as mentioned in [20].

From Fig. 10(a), we see that the number of transmissions of GB-BTC used to cover all the nodes in the network is smaller than that in our proposed approach in the CDS graph and BFS graph. However, the respective differences between the two approaches are within one on average. The comparison results with respect to latency, as shown in Fig. 10(b), illustrate the differences in latency between both approaches in the CDF graph and BFS graph are small. However, when we look at the comparison results of lifetime, as shown in Fig. 10(d), the proposed approach has much better lifetime performance than that of GB-BTC in both the CDF graph and BFS graph, especially when the number of nodes is large.

VI. CONCLUSION

In this paper, we have proposed a fully distributed algorithm, which was called the CDSA-CGG algorithm, based on the coalitional graph game to solve the MTB problems under the reliable-link model and under the unreliable-link model. The proposed approach based on coalitional graph game by considering both the cooperation and the topological structure of nodes was used to build the connected dominating set over the reliable and unreliable links in an IoT network. In addition, with the proposed approach, the overall lifetime of IoT network was extended with the minimal number of forwarding nodes. We used the Nash equilibrium and the pairwise-stability solution concept to characterize the convergence and stability of the final connected network among nodes, respectively. The analytical arguments were verified by simulation, where the benefits of forming a coalitional broadcasting graph among nodes resulting from the proposed algorithm were visually presented in terms of the number of transmissions, convergence rate, and lifetime of nodes.

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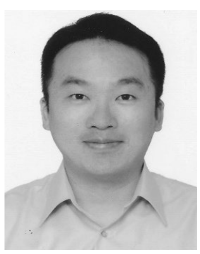

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