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Collaborative Topology Control for Many-to-One Communications in Wireless Sensor Networks

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ABSTRACT Topology control is relevant in wireless sensor network because of two reasons, namely minimal sensor coverage and power constraints. The former condition is typically satisfied by high-density deployment, whereas the latter mainly concerns with the control protocol design that is adaptable. Controlling communication topology is at the center of the efforts to optimize network performance while improving energy conservation. A dense topology often results in high interference and lower spatial reuse thus reduced capacity, while sparse topology is susceptible to network partitioning and sub-optimal path selection from the routing layer. Topology control has been extensively studied in both flat and hierarchical network by mean of power adjustment and clustering, respectively. Despite a common goal of making the topology less complex both techniques differ in their approach. While the focus of clustering is to form a connected backbone which consists of a minimum subset of nodes, i.e., dominating set, power adjustment focuses on minimizing energy consumption. Combining both approaches remains a relatively lesser explored area. We proposed a hybrid framework called collaborative topology control protocol, which combines dominating set-based clustering and transmission power adjustment. The protocol operates in two stages. During the first stage, a parameterized minimum virtual connected dominating set algorithm is executed to obtain clusters of various desirable properties. In the second stage, each cluster-head executes a distributed power adjustment algorithm. The simulation results show that the proposed topology control framework is capable of versatile performance in terms of transmission range/energy cost, the number of neighbors, edges, and hop distance. Moreover, the topology construction process uses the locally available information only with minimal communication overhead.

INDEX TERMS Wireless sensor networks, topology control, clustering, many-to-one communication, dominating set.

I. INTRODUCTION

Smart cities are built around people, leveraging technology to serve them. Remote sensors connected in a network are at the core of smart cities. These sensors can monitor and gather vast amounts of data about surrounding conditions like air quality, temperature, noise, water levels and upload information to a central base-station. Collecting and converting data into useful information help in optimizing resources and managing infrastructure cohesively. Thus, promoting sound and sustainable development making cities more livable.

Wireless sensor networks (WSNs) utilize several of the communication models such as converge-cast, broadcast, unicast, multicast, anycast, and geo-cast to collect and disseminate data from the physical environment. The converge-cast uses many-to-one communication model where a single remote destination (also sink or base-station) collects data from several sources in a multi-hop fashion. A node uses broadcast to reach all the other nodes in the network, i.e., one-to-many. The unicast (also one-to-one) method is used to transmit data from one node to a single specific recipient. Any-cast, multicast, and geo-cast are the variants of a one-to-many pattern where a source sends data packets towards any (nearest), several or geographical located group of potential destinations, respectively. One of the key challenges is to efficiently distribute data with the minimal energy cost and interferences while maintaining a fully-connected network topology. Fundamental to this challenge is to develop an adaptive controlling mechanism of the underlying network topology (also topology control) over which different communication models can be implemented.

An "*efficient*" network topology is fully-connected, consumes minimal energy, provides shortest paths, confines interference and promotes higher spatial reuse by carefully selecting some links. Moreover, it consists of symmetry or bi-directional links with a smaller number of neighbors or nodal degree. Another important requirement is that the topology construction algorithm utilizes local information only and effectively communicate it among the neighboring nodes. There are mainly two approaches to managing a network topology. Firstly, topology control by mean of transmission power adjustment that constructs network topologies with several desirable yet conflicting design objectives. Often improving a certain design goal results in worsening of another [1], [2]. For example, the Minimum Spanning Tree (MST) [3] based topology control protocols generate sparsest topologies. The fully-connected, low-cost topologies consisting of fewer symmetric links that are obtained at the expense of longer and sub-optimal routing paths between the data sources and a sink. While the energy cost decreases, the MST does not scale well in path length as the network size increases [4]. Therefore, the presence of excessive multi-hop traffic will result in significant overall interference and energy consumption [5]. Conversely, in the case of denser topologies generated by the k-Neighbor protocol the estimated number of neighbors (i.e., $k = 9$) to obtain a fully connected network is too large to minimize energy cost. While the energy cost decreases as the network size grows, is still significantly higher than the MST-based protocol. Moreover, in the presence of broadcast traffic, the higher number of links will increase the level of interference among the neighboring nodes. Typically, the data gathering applications utilize several of the communication models. While many-to-one is the predominant model, control packets such as a neighbor or route discovery, interest messages, and location updates are broadcasted either locally or globally, i.e., network-wide. Therefore, it is critical to constructing network topologies that not only efficiently address a large number of design objectives but also adapt itself to various types of communication models.

Secondly, the clustering approach hierarchically organizes the nodes. Each node either acts as a leader (also cluster-head) or cluster-member. All the cluster-members are said to be associated with their respective cluster-head in a parent-child relationship. The key motivation behind such an arrangement is to divide complexity of a network among a subset of nodes. The main focus of this work is on a hybrid approach towards topology control. The idea is to combine the best from two approaches, i.e., clustering and transmission power adjustment to manage wireless network topologies. The proposed framework named "*Collaborative Topology Control Protocol*" (or CTCP) operates in two stages. In the first stage, a common destination node (e.g., a sink or base-station) initiates a parameterized and distributed backbone selection algorithm. At the end of the backbone construction stage, the network is organized into two tiers. The *backhaul-tier* would consist of cluster-heads while the *connectivity-tier* contains the cluster-members. In the second stage, each cluster-head executes a localized transmission power adjustment algorithm and decides on the transmission power level for each cluster-members. We proposed a novel cluster-based transmission power adjustment algorithm and compared it against local MST, global MST, k-Neighbor and Cooperative Nearest Neighbor (CNN) topology control protocols.

The resultant topologies are fully connected, and heterogeneous transmission power levels are assigned to cluster-heads and cluster-members separately. The backbone nodes or cluster-heads are connected via long-range backhaul links which significantly reduce the hop distances between the source-destination pairs. Conversely, the cluster-members utilize relatively shorter transmission ranges to conserve energy, maintain lower nodal degree, and fewer symmetric links. Thus, a sparser network graph reduces interference and improves the spatial reuse. Moreover, by assigning the data collection task among cluster-heads and cluster-members along with the provision of rotating the cluster-head responsibility can potentially improve the overall network performance.

The rest of the paper is organized as follows. Section 2 describes the related work. Section 3 introduces the proposed collaborative clustering and transmission power adjustment framework for topology control. Section 4 presents an extensive simulation-based performance evaluation. Finally, a conclusion with a detailed perspective on results is given in Section 5.

II. RELATED WORK

Several taxonomies have been proposed for the topology control protocols [6], [7] in wireless networks. These taxonomies categorize protocols into four classes [6]. The first approach adjusts transmission power at each node to certain optimal level with different design objectives such as network-wide connectivity with reduced energy cost [8]–[10] or interference-based in delay constrained environment [11]. The second type of techniques (also power mode based) converse energy by periodically switching radio state between on and off [12], [13] or sleep scheduling [14]. The third type is clustering [15], in which a connected backbone is constructed by selecting a subset of nodes in the network. These backbone nodes (also cluster-head) form a tree-like hierarchical structure in such a way that they are connected with other ordinary nodes (also cluster-member) either directly or via intermediate nodes. The main objective of the clustering approach is to improve network scalability and performance which is achieved by reducing the complexity of the topology through logically organizing networks into smaller manageable groups. However, finding an optimal subset of nodes that form a fully-connected backbone is a well-known NP-hard problem [16]. The centralized clustering algorithms achieve a near optimal number of clusters but assume the availability of complete network-wide topological information such as location. Obtaining up-to-date information at a certain central entity incurs excessive communication overhead. To account for this heuristic-based and localized algorithms are highly sought-after. Comparatively, these distributed algorithms select sub-optimal number of backbone nodes and more likely to achieve only partial design objectives. Finally, the fourth category is a hybrid approach, which combines the best from other three approaches. The unified solution achieves further performance improvement by joining clustering with either power adjustment or power mode [17]. In this paper, we focused on a hybrid protocol which integrates clustering with the power adjustment approach.

Narayanaswamy *et al.* [18] and Shen *et al.* exploited the potential of combining clustering with routing and power control. To improve network capacity and energy conservation, they proposed two approaches. The approaches named COMPOW and CLUSTERPOW dealt with homogeneous and non-homogeneous node dispersion, respectively. In COMPOW every node transmits with the same minimum power level which ensures connected network topology consisting of bi-directional links. However, a single distant node resulted in higher power level. To overcome this limitation, CLUSTERPOW formed clusters by selecting the optimum minimum power levels and managed routes for each power level separately. CLUSTERPOW incurs significant communication overhead for computing routes per power level.

Zhao and Lloyd [20] proposed Cluster-based Topology Control (CLTC) framework, which operates in three phases. Phase 1 implements any distributed clustering algorithm while Phase 2 and 3 executes Intracluster and Intercluster topology control algorithms, respectively. The topology control algorithms use localized information, based on two optimization criteria MINMAX and MINTOTAL. Phase 1 and Phase 3, incur significant communication overhead, i.e., the average number of message exchange per node in CLTC is reported to be six. Although the operations of the subsequent two phases do not depend on the specific clustering algorithm used in the cluster formation phase, the overall effectiveness of topology control depends on the characteristics of resulting clusters. To study the impact of different clustering algorithms Liang and Errol proposed Multi-hop MST-based clustering algorithm for ad Hoc networks (MMST) [21]. In MMST several clustering algorithms were implemented along with topology control based on two different optimization criteria (i.e., Minmax and Mintotal). According to their findings, clusters with smaller sizes incurs lower communication overhead while larger cluster sizes result in the more efficient network topology. Earlier in [22], we studied the impact of parameterized clustering on the subsequent power-controlled wireless topologies. For this purpose, we utilized a centralized Minimum Spanning Tree (MST) based algorithm for transmission power selection. The preliminary results indicate that varying network and cluster size result in significantly different topological properties in terms of transmission power, neighbor, and edge count. In this paper, we proposed and implemented a novel collaborative topology control algorithm where cluster-heads and cluster-member collaborate to decide on their transmission range based on a localized and distributed algorithm without incurring additional communication overhead.

While CLUSTERPOW works with implicit clustering without cluster-head, the design of CTCP algorithm considerably differs from previous cluster-based topology control protocols such as Cluster-based Topology Control (CLTC) [20], and Multi-hop MST-based Topology Control (MMST) [21] in four features. Firstly the CTCP design employs a parameterized clustering algorithm to study the impact of different clustering properties on the final resultant topologies. Moreover, a novel power adjustment scheme is proposed that exploits local interaction among the neighboring nodes to decide upon the transmission power level for each node without incurring additional communication overhead. Secondly, in CTCP both clustering and power, adjustment stages are independent of each other, which qualifies CTCP as a generic framework. Therefore, the cluster-head can choose to execute any centralized power adjustment protocol locally. Alternatively, each cluster-member can also run a distributed power adjustment algorithm based on the local information. Thirdly, the previous works often assume global topology information and result in higher communication overhead. In contrast, the proposed CTCP protocol operates on local information only and is communication efficient as well. Finally, none of the related studies provided insight on the path length or data traffic pattern aspect of topology control, where reducing energy cost and connectivity were the foremost concerns.

III. CTCP: COLLABORATIVE TOPOLOGY CONTROL PROTOCOL

The intuition behind CTCP is to bifurcate the data gathering process between the backhaul-tier and the connectivity-tier of the network. The backhaul-tier allows nodes to use the backhaul links among cluster-heads. The cluster-heads forms the connected backbone by utilizing relatively longer transmission ranges to reach more distant destinations, e.g., the inter-cluster communications. Whereas cluster-member in the connectivity-tier employs shorter transmission range to reach their respective cluster-head, e.g., the intra-cluster communication.

A. THE CLUSTERING STAGE - BACKHAUL-TIER

The backhaul-tier establishes the connected network backbone or core over which MAC and routing networking functions can be implemented. The backhaul-tier consists of all the backbone nodes in the network which are connected via relatively higher transmission power level. We employed a Minimum Connected Domination Set (MCDS) based clustering algorithm. More importantly, a *fully distributed* and *parameterized* clustering algorithm is used with the following two desirable properties.

1) Clustering must exhibit versatile performance that enables logical grouping with varying properties using

a single algorithm. In the previous studies, [20], [21] several clustering algorithms were implemented and tested to get an insight into their impact on the topology control performance. Conversely, a parameterized clustering algorithm should be utilized to adjust different clustering properties such as the number of cluster-head and cluster size. Additionally, another desirable characteristic is to obtain efficient clustering at the expense of minimal control packet exchange, i.e., lower communication overhead. Lower overhead makes the algorithm energy efficient and scalable for resource-constrained networks like wireless sensor networks (WSNs).

2) The cluster-heads and cluster-members play different roles. Mostly cluster-member gathers information and broadcast data without maintaining complex routing states. Cluster-heads, on the other hand, are required to perform functions such as running local centralized algorithms, data aggregation, and routing. Moreover, cluster-heads often operate at heterogeneous transmission power levels. All these factors could lead to reducing the network lifetime which is often defined by fewer nodes in the network. Therefore, it is also desirable that the clustering approach must incorporate a simple yet effective mechanism through which cluster-head responsibilities could be rotated to increase network lifetime.

We used Minimum Connected Dominating Set (MCDS)-based clustering algorithm to construct the backhaul-tier which mainly consists of cluster-heads establishing a connected backbone. The idea is based on the algorithm proposed by Deb and Nath [23], [24]. The algorithm utilizes the notion of Virtual Dominating Set (VDS) to find the minimum subset of dominating nodes (or cluster-heads) with different cardinalities. The parameterized algorithm depends on the value of Virtual Range V_r which controls the membership of Minimal Virtual Connected Dominating Set (MVCDS). By varying the value of V_r, clustering with various properties can be obtained. The algorithm starts with marking all the nodes with WHITE color. During the execution, nodes can take on any of the three colors, i.e., BLACK, BLUE and RED.

At the start, a central entity (i.e., sink node) initiates the backbone construction process by first turning itself BLACK (also dominator or cluster-head) and broadcasting the control packet. On receiving the control packet, nodes which found themselves within the V_r range turn RED (also cluster-member) otherwise they turn BLUE. The BLUE nodes compete, and the one that is the farthest from the previous BLACK node wins. The winner BLUE node mark itself BLACK before further broadcasting the control packet into the immediate neighborhood. Each newly marked BLACK node establish a direct link with the previous BLACK node. The purpose is bi-fold, firstly the dominating set becomes connected, and secondly, a backward path is created towards the sink.

Earlier in [23], [24], Deb and Nath proposed a parameterized and distributed algorithm based on the MVCDS concepts. The algorithm retrieves topological information at various granularities based on the application requirements. However, in this paper, we have applied the MVCDS concepts to obtain clustering with the desirable properties mentioned above. For this purpose, we extend the Budhaditya's algorithm in two ways. Firstly, the tailored algorithm now takes into account the residual energy while selecting the BLACK or cluster-head nodes. In our enhancement, the selection of BLUE nodes to turn BLACK is based on the *Selection Criteria Index (SCI)*, calculated as following,

$$SCI = E_r * distance(BLACK, BLUE)/TX_{max} \quad (1)$$

Where, E_r is the residual energy (%) of the BLUE node, $distance(BLACK, BLUE)$ is the distance between a BLUE node and the previous BLACK node, and TX_{max} is the maximum transmission range. Secondly, during the dissemination of control packets, each node includes its current location and one-hop neighbor information. The information is then utilized by the subsequent power adjustment stage. The power adjustment stage can either execute a centralized algorithm locally at each cluster-head or each cluster-member calculates its transmission power level in a distributed manner depending upon the design objectives. For this purpose, each node maintains a soft state regarding 2-hop neighbor information by overhearing the control packets it received. Algorithm 1, formally presents the extended MVCDS algorithm in more details.

B. THE POWER ADJUSTMENT STAGE - CONNECTIVITY-TIER

On completion of the first stage, the network is now divided into cluster-head and cluster-members. There are two alternatives to execute the power adjustment stage, i.e., either in a centralized or distributed fashion. In the former case, each cluster-head would execute a power adjustment algorithm based on the local topological information. Once the cluster-head selects the power level of each of its cluster-member, it conveys these settings to their cluster-members. Whereas in the latter case each cluster-member decides on its transmission power distributively. As for the proposed CTCP, we opted for the first option.

Each cluster-head draws a complete topology map of its immediate neighborhood. This topological map consists of two levels of details, the immediate neighboring nodes that form the *direct view* and the neighbors of the immediate neighbors that form the *indirect view*. For cluster-heads (BLACK), the direct view mainly formed by the associated cluster-members (RED). The indirect view consists of the neighboring nodes of the cluster-member. For each cluster-member, its neighbor list is sorted in non-decreasing order of its distance from it. Next, it is checked whether the neighboring node belongs to the same cluster or not. Among all those neighbors that are associated with the same cluster-head, the closer then itself is selected as the next hop towards

Algorithm 1 Collaborative Topology Control Protocol

```
Initialization:
node.TX ← TX_max                                  ▷ Maximum Power Level
node.V_r ← % of TX_max                            ▷ Virtual Range
node.nbList ← UPDATENBRLIST(());                  ▷ Neighbor List
node.E_r ← UPDATERESIDUAL(());                    ▷ Residual Energy
node.color ← White                                ▷ Initially all uncolored nodes
if sink is True then
    node.color ← Black
    BROADCAST(Vr, nbList, E_r, color)
end if

Stage 1 - MVCDS-based Clustering (Backhaul-Tier)
procedure RECEIVEBROADCAST
        nbr.Vr, nbr.TX, nbr.nbList, nbr.E_r, nbr.color
    my.nblist ← UPDATENBRLIST(nbr.nbList)
    if (nbr.color = Black & my.color = White) then
        if DISTANCE(my, nbr) ≤ V_r then
            my.color ← Red
        else
            my.color ← Blue
        end if
    else if (nbr.color = Black & my.color = Blue) then
        if DISTANCE(my, nbr) ≤ V_r then
            my.color ← Red
        else if DISTANCE(my, nbr) > V_r then
            if MAX(FINDSCI(my.E_r, my.nbList)) then
                my.color ← Black
                BROADCAST(Vr, nbList, E_r, color)
            end if
        end if
    else if (nbr.color = Red||Blue) & (my.color =
White) then
        my.color ← Blue                           ▷ Compete to turn Black
    end if
end procedure
```

Algorithm 2 Collaborative Topology Control Protocol

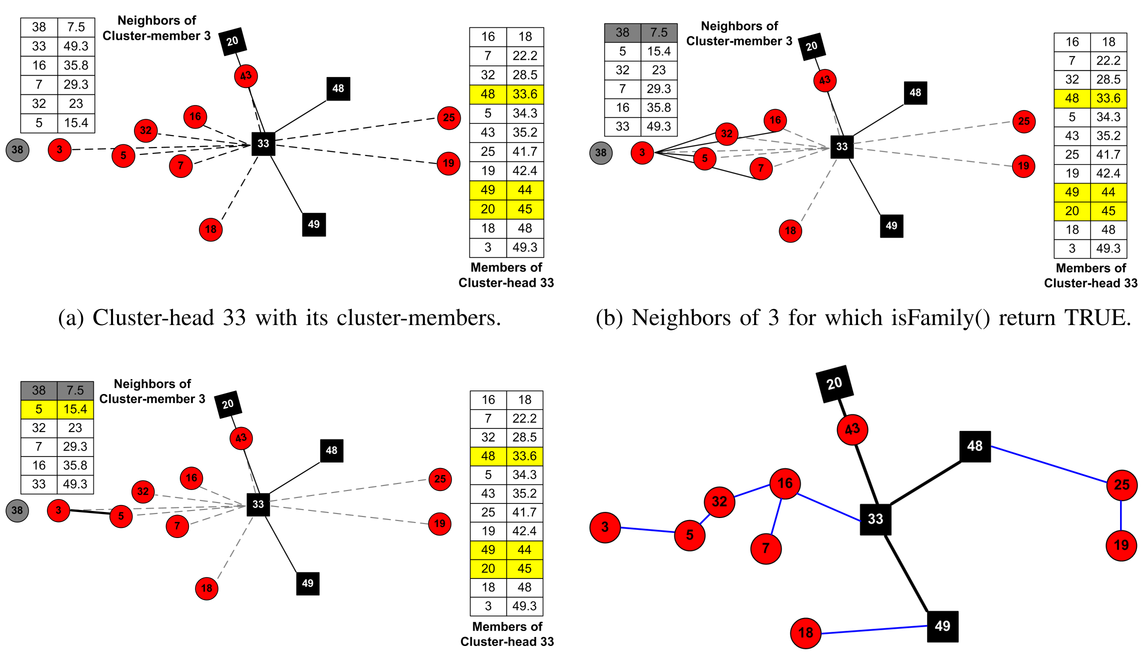
```
Stage 2 - Power Adjustment (Connectivity-Tier)
for each Black node i do
    i.TX ← TX_max
    for each Red neighbor j associated with i do
        sort(nbList, ASC)
        for each neighbor k of j starting from closest do
            if (ISFAMILY(i, j, k)) then
                if (ISCLOSEST(i, j, k)) then
                    G ← SUBGRAPH(j, k)
                    j.nextHop ← k
                    j.TX ← DISTANCETOPOWER(j, k)
                    BROADCAST(j, j.nextHop, j.TX)
                end if
            end if
        end for
    end for
end for
procedure RECEIVEBROADCAST(node, nextHop, TX)
    if (my.id = node) then
        my.nextHop ← nextHop
        if (my.TX < TX_max) then
            my.TX ← MAX(my.TX, TX)
        end if
    end if
end procedure
```

its cluster-head. Algorithm 2 formally describes the sequence of operations carried out by the proposed CTCP protocol in more details. Initially, all cluster-heads (BLACK) i operate at maximum transmission power. Then, for each cluster-member (RED) j associated with i, it sorted neighbor list is checked for two conditions.

1) *isFamily*(): This function checks whether the neighboring node k of j belongs to the same cluster i or not.
2) *isCloser*(): This function returns TRUE if the neighbor k is not the cluster-head (i.e., $i \neq k$) and if it is less distant to cluster-head then myself j.
3) *subgraph*(): A node creates a link with a neighboring node that can satisfy the two conditions mentioned above and select that node as an immediate next hop towards its cluster-head.
4) *BROADCAST*(): The selected power level information is transmitted to the cluster-members that finally adjust their respective transmission ranges accordingly.

The remaining lines of the pseudo-code make sure that each node is linked symmetrically with any other node which has selected this node as its next hop.

To exemplify the proposed algorithm we consider a cluster as shown in Fig. 1 (a). The cluster-head 33 finds the transmission power level of cluster-member 3. In Fig. 1 (b), among ten direct neighbors of node 3, four of them (16, 7, 32 and 5) satisfy the *isFamily*() condition, i.e., they belong to the same cluster. Next, in Fig. 1 (c), the four short-listed nodes, i.e., 5, 32, 7, and 16 are ordered in non-decreasing distance from node 3, and the least distant node is selected which satisfies the *isClosest* condition. Finally, a communication link between node 3 and 5 is added to the simplified topology graph while node 5 is also marked as the next hop towards the cluster-head. Here, it is noteworthy that the node 3 can choose to select a node based on other cost criteria such as link quality or closest neighbor from the cluster-head (thus to reduce the hop distance count). The cluster-head decides an efficient transmission power level and assigns it to its cluster-members using information available in both direct and indirect views. The final topologies are k-connected where k=1. Nevertheless, the proposed scheme can easily be extended to achieve higher values of k (i.e., 2-connected topologies) without additional communication overhead. However, earlier studies reported that higher values of k cause a significant increase in energy cost. Fig. 1 (d), shows the final topology.



(a) Cluster-head 33 with its cluster-members.

(b) Neighbors of 3 for which isFamily() return TRUE.

(c) Neighbor of 3 for which isClosest() returns TRUE.

(d) Final link selection.

FIGURE 1. CTCP: (a), (b) and (c) Link selection procedure for cluster-member 3 within cluster-head 33. (d) Final topology of a cluster.

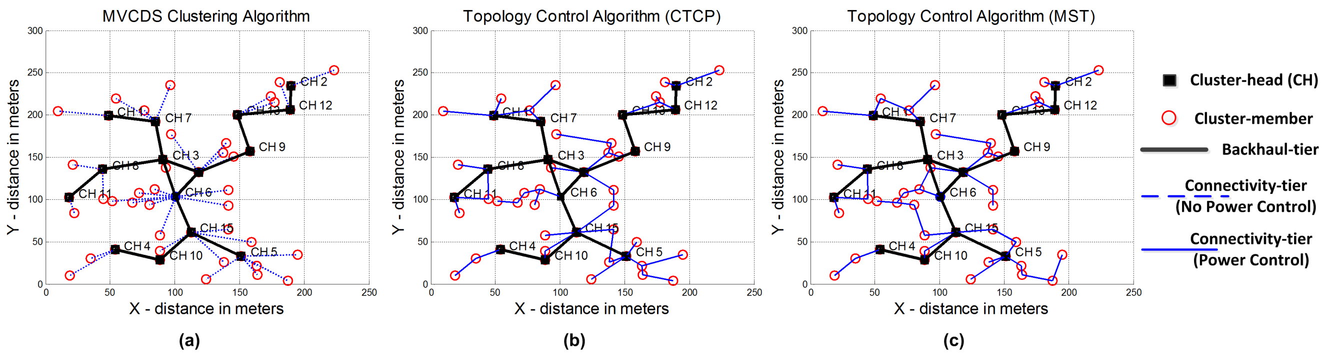


FIGURE 2. (a) Output of the MVCDS-based clustering stage with backhaul-tier and connectivity-tier. (b) Collaborative topology control protocol (CTCP). (c) Minimum spanning tree (MST).

We consider a 50 node network, given in Fig. 2. Fig. 2 (a) shows that among 50 nodes, 15 are selected as the cluster-heads (represented by black colored square shape), while remaining are the cluster-members (red colored circle shape) associated with their respective cluster-heads. Cluster-heads are labeled CH1 to CH14 while a data sink is positioned at the middle of the network area. Solid black lines are used to illustrate the back-haul tier links whereas the association between cluster-member and cluster-head is shown using the dashed blue lines. The final communication links are represented as solid blue lines. For comparison, we implemented Minimum Spanning Tree (MST), where each cluster-head locally runs the Prim's algorithm to construct a connected topology. Using Prim's algorithm, the cluster-head finds the minimum transmission power level for each of its cluster-members and convey it via local broadcast packet. Algorithm 3, presents MST in more details. Fig. 2 (b) and Fig. 2 (c) and shows the power-controlled network topologies for the proposed Collaborative Topology Control Protocol (CTCP) and the local Minimum Spanning Tree (MST) algorithm [22], respectively.

IV. PERFORMANCE EVALUATION

A. SIMULATION ENVIRONMENT

For performance evaluation of the CTCP framework, we conducted extensive simulation-based studies, using the ns-2 [25] simulator. Simulations are conducted by varying the total number of nodes in the network from 100 to 500 node to emulate sparser and denser deployment scenarios. The nodes are placed randomly over the network area of $1000m^2$, while the data sink is located in the middle of the network field. Each node antenna operates in an omnidirectional mode at

Algorithm 3 Multihop Minimum Spanning Tree

Stage 2 - Power Adjustment (Connectivity-Tier)

```
for each Black node i do
    i.TX ← TX_max
    for each Red neighbor j associated with i do
        G ← SUBGRAPH(i, j)
    end for
    j.TX ← PRIMS(G)
    BROADCAST(j, j.TX)
end for
procedure ReceiveBroadcast(node, TX)
    my.TX ← TX
end procedure
```

TABLE 1. Simulation parameters and their values.

Parameters	Values
Network Simulator	ns-2
Network dimension	1000mx1000m
Number of nodes	100,150,200,250 and 500
Virtual Range	50, 100, 150,200 and 250m
Maximum Transmission Range	250m
Maximum Transmission Power	0.2818W
Antenna Gain (Transmitter)	1
Antenna Gain (Receiver)	1
Antenna Height (Transmitter)	1.5m
Antenna Height (Receiver)	1.5m
RXThresh	4.46E-10
Bandwidth	1Mbps
System Loss	1
Frequency	2.4GHz

transmission range of 250m (or 0.2818W). The value of V_r is also varied between 50m to 250m with an increment of 50m. The values of the Virtual Range V_r correspond to the 20%, 40%, 60%, 80% and 100% of the maximum transmission range.

Two-ray ground reflection model [26] is utilized as a channel propagation model. A cross-over between Friis free space model and the Two-ray ground reflection models is used to obtain transmission power (W) from the transmission range (m). The implementation is part of the network simulator ns-2 where the cross-over distance is set to 76.14m. If the given distance between two nodes is less than 76.14m, then the Friis mode is used. Otherwise, the Two-ray ground reflection model is utilized. Table 1 shows the parameters and their values set during the simulations. At first, a comparative study between MVCDS and Global MCDS-based clustering algorithm yielding a near optimal number of clusters is presented. Since MVCDS is a parameterized algorithm, we include simulation results for different values of virtual range V_r. Previous studies on hybrid topology control protocols either implemented various clustering techniques [21] or change the number of nodes in the network [20] to produce clusters of different sizes. The idea was to understand the impact of different clustering properties on the resultant topologies. In proposed CTCP the same effect can be achieved by varying the Virtual Range, V_r. In our simulation studies, we kept the maximum transmission range and the network area constant. Following performance metrics are utilized to evaluate the clustering stage.

1) A total number of cluster-heads (or the cardinality of the dominating set).
2) An average number of cluster-members per cluster (or average cluster size).

In the second set of simulation results, the power adjustment stage is evaluated using five performance metrics.

1) Energy Cost is the ratio between the sums of transmission power levels (in Watts) assigned to all of the nodes and network size, obtained at the end of the power adjustment stage.
2) Transmission range (m) is given as the sum of transmission ranges assigned to all nodes, averaged over the network size.
3) Neighbor count, defined as the ratio between the total number of direct neighbors with symmetric (or bi-directional) links and the network size.
4) Edge count is defined as the ratio between the total number of asymmetric links (or uni-directional) and the network size. In several topology control studies, the number of edges reflects the level of interference caused by the nodes that are not the direct neighbors [27].
5) Hop distance is given as the total hop distance a packet has to traverse to reach the destination (i.e., sink) from a node, averaged over the network size. The hop distance value is obtained by executing the Breadth First Search (BFS) algorithm over the final topology controlled network.

For a comparative study, we compared CTCP framework with four other topology control protocols.

1) The Global MST algorithm produces the sparsest topologies. However, the minimal energy cost is achieved at the expense of excessive communication overhead. During the simulations of Global MST algorithm, no clustering was performed thus topologies represent the flat network.
2) Multi-hop MST (MMST) produces efficient topologies where the backhaul-tier is obtained using global MCDS-based clustering algorithm, whereas the connectivity-tier utilize cluster-wide local MST algorithm based on Prim′s algorithm.
3) k-Neighbor: In the k-Neighbor protocol, all nodes are connected to their k least distant neighbors. Using empirical and analytical studies, Blough *et al.* [5] found the value of k to be 6 and 9.
4) Cooperative Nearest Neighbor (CNN): Similar to k-Neighbor, neighbors cooperate to resolve the network partitioning problem at the lower value of k, i.e., k=5.

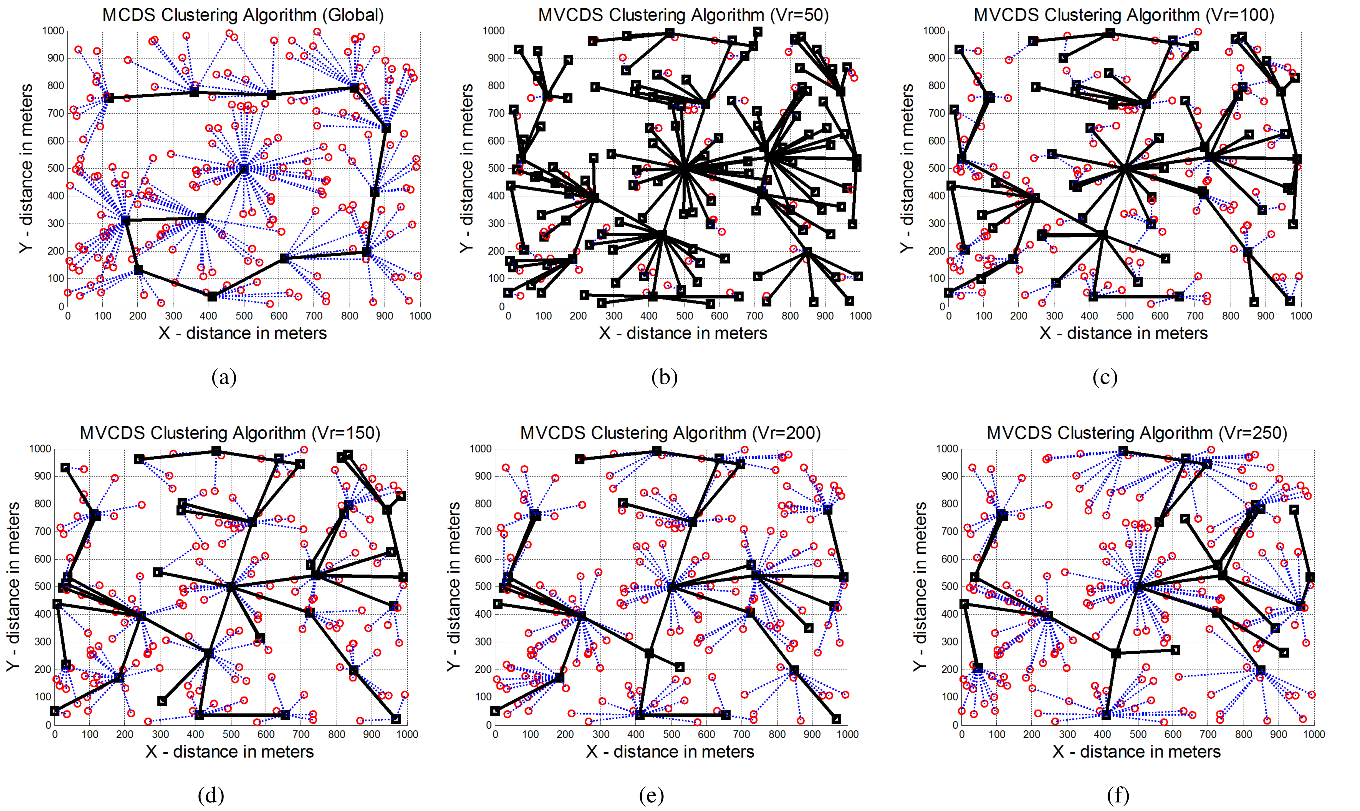


FIGURE 3. Output of MCDS and MVCDS-based clustering algorithms for network size of 200 nodes and various values of virtual ranges V_r. (a) Global MCDS. (b) MVCDS with $V_r = 50$m. (c) MVCDS with $V_r = 100$m. (d) MVCDS with $V_r = 150$m. (e) MVCDS with $V_r = 200$m. (f) MVCDS with $V_r = 250$m.

B. STUDY OF THE MVCDS-BASED CLUSTERING STAGE

Fig. 3 shows the sample topologies obtained as the result of the clustering stage. These network topologies consist of 200 nodes. Fig. 3 (a) shows the result of clustering performed by the global MCDS algorithm which assumes the availability of network-wide topology information. Fig. 3 (b)-(f) illustrates the output of the enhanced MVCDS clustering algorithm for different values of the virtual range V_r. The solid black squares and red circles represent cluster-heads and cluster-members, respectively. The solid black lines are the backhaul-tier links, and the dashed blue lines show the cluster-member association with their respective cluster-heads. Fig. 3 (b), (c), (d), (e), and (f) are the resultant topologies obtained at the end of MVCDS algorithm. For each instance, the virtual range is set to $V_r = 50$m, 100m, 150m, 200m, and 250m, respectively. As illustrated, it is evident that varying the values of virtual range V_r results in clusters with different properties, i.e., the number of cluster-head and cluster sizes.

For all the simulated network sizes, as the parameter V_r value increases, the number of cluster-heads decreases as shown in Fig. 4 (a). The initial changes in network size bring lower (i.e., up to 20%) percentage increase in the number of BLACK nodes (i.e., cluster-heads). Between highly dense networks the percentage increase is comparatively higher (i.e., up to 37%). For any given network size, the impact of varying V_r has a considerable impact as well. For lower values of V_r the higher (between 40% to 60%) percentage decrease in the number of BLACK nodes is observed. However, for the higher values of V_r, the lower (below 30%) percentage decrease in the number of BLACK nodes is observed. For all simulated network sizes, the global MCDS-based clustering algorithm resulted in the least number of cluster-heads.

The cluster size varies by changing the virtual range, as well. In the previous work, this factor is much of importance because it determines the degree with which both clustering and power adjustment stages are applied. The average number of nodes per cluster increases with the increase in virtual range values as given in Fig. 4 (b). For global MCDS-based clustering algorithm, although the network size has a relatively slight impact on the number of clusters, the cluster sizes increase considerably. The percentage increment in the number of cluster-members per cluster among lower values of V_r is large in comparison with the higher values. Furthermore, the increment grows gradually as the network size increases. We exploited the impact of varying V_r on clustering properties to obtain clusters of various sizes. Therefore instead of applying several clustering algorithms, we were able to use a single parameterized clustering algorithm at the expense of lower communication overhead, i.e., single control packet per-node.

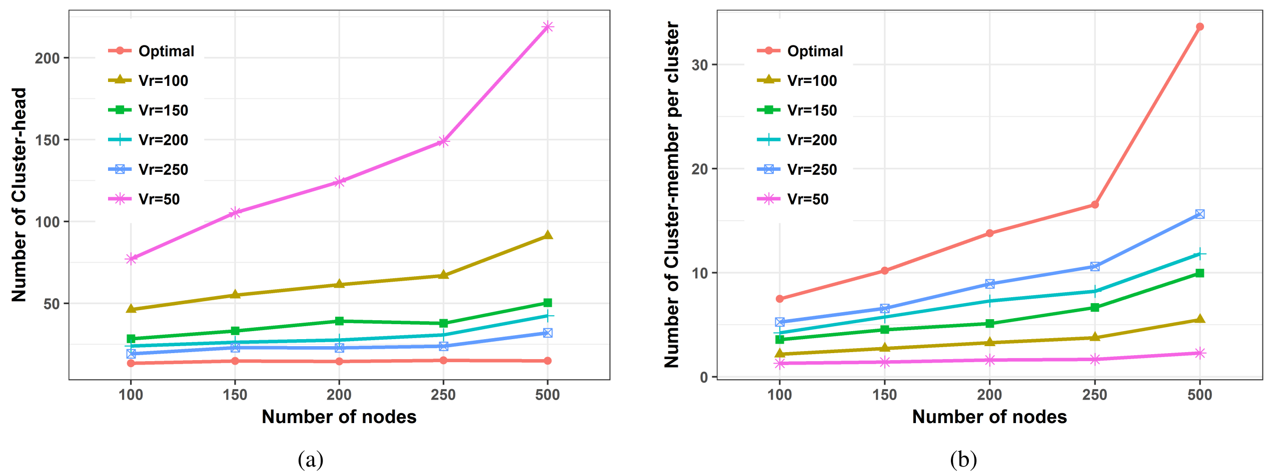


FIGURE 4. **(a) Number of cluster-heads. (b) Average number of cluster-members per cluster for various network sizes and virtual ranges V_r.**

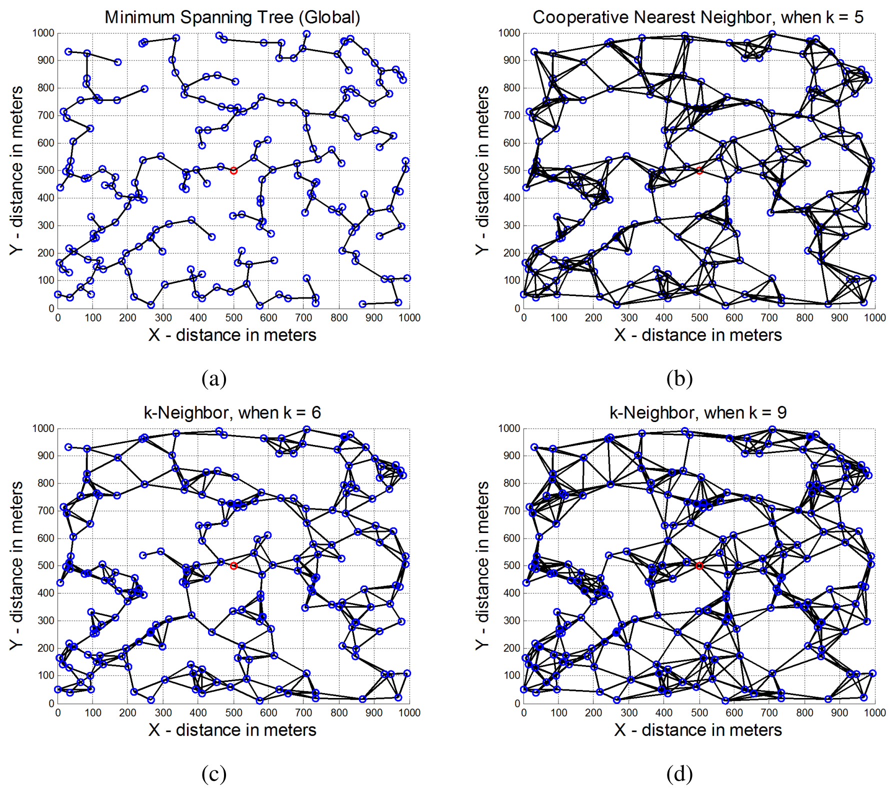


FIGURE 5. **Sample topology instances with 200 nodes: (a) Global MST. (b) CNN with k=5. (c) k-Neighbor with k=6. (d) k-Neighbor with k=9.**

In experiments, the number of nodes is varied between 100 to 500. For the network size of 200 nodes, the virtual range is varied between 50m and 250m with an increment of 50m. In MVCDS-based clustering algorithm, the average number of cluster-heads are 124, 62, 39, 27, and 23. Where the average cluster size obtained is 1.62, 3.3, 5.2, 7.3, and 7.94. As for the global MCDS-based clustering algorithm, the average cluster size is 14 nodes while the number of cluster-heads is 15.

C. STUDY OF THE POWER ADJUSTMENT STAGE

Fig. 5 shows the instance of topologies produced at the end of several competent topology control protocols. Among them, Global MST Fig. 5 (a) generates the sparsest while the neighbor-based such as CNN Fig. 5 (b), k-Neighbor Fig. 5 (c) and Fig. 5 (d) result in denser network topologies. As for the cluster-based topology control protocols, the sparsest topologies are the one which constitutes a smaller number of cluster-heads or in other words larger cluster sizes. Conversely,

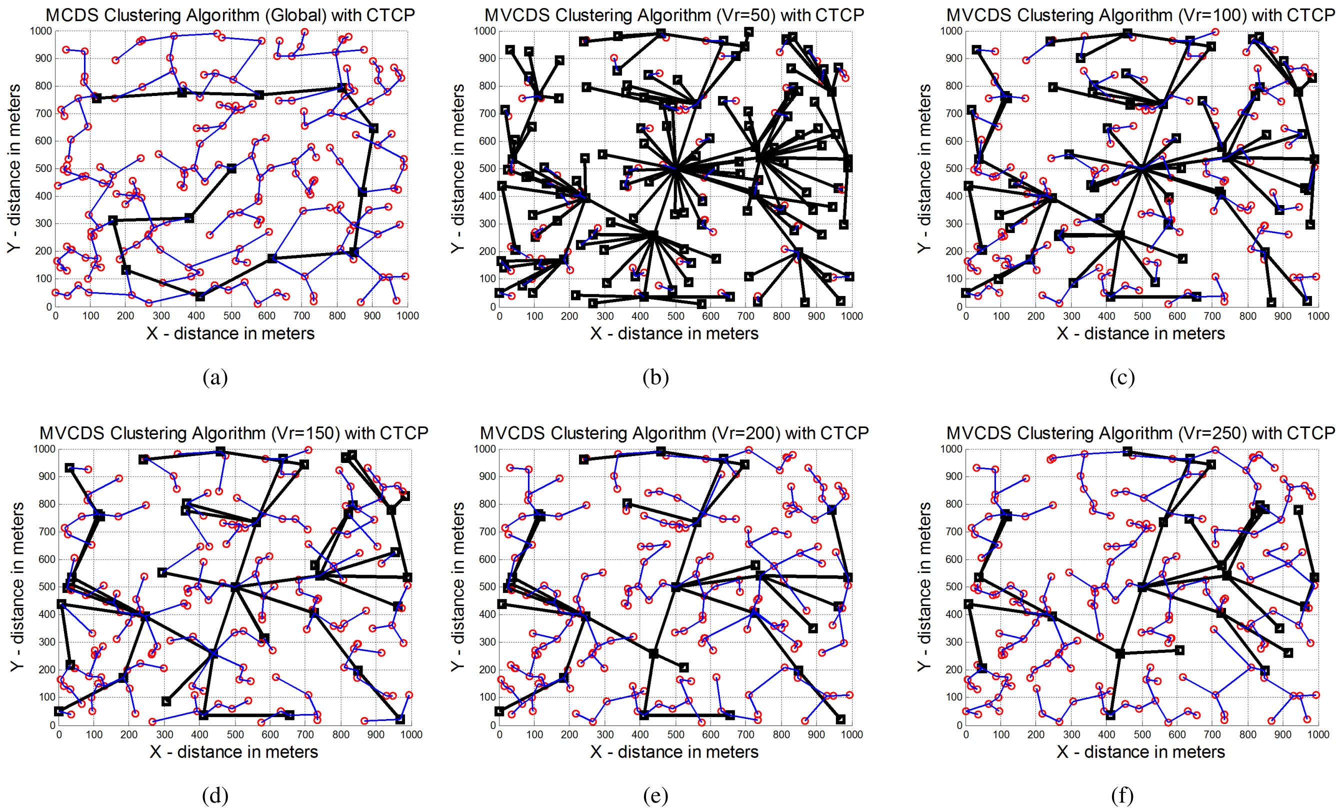


FIGURE 6. Sample topology instances with 200 nodes: (a) CTCP with Global MCDS-based clustering. (b)-(f) CTCP with MVCDS-based clustering for various virtual ranges V_r.

a higher number of cluster-heads with smaller cluster sizes result in dense topologies. Fig. 6 (a)-(f) illustrate and compare the final topologies which are obtained by the CTCP with global MCDS-based and with MVCDS-based clustering for various values of virtual range V_r.

1) IMPACT OF VIRTUAL RANGE ON THE TOPOLOGY CONTROL PERFORMANCE

The performances regarding different metrics, such as transmission range, energy cost, number of neighbors, edges, and hops for each protocol is discussed next.

Fig. 7 (a) shows the transmission range (m)/energy cost for the cluster-based topology control protocols. For the proposed algorithm, the simulations were conducted with varying virtual range values. The Global MST algorithm operates over a flat network (i.e., no clustering) as if a single cluster consists of all the nodes in the network. The assumption that the centralized algorithm has network-wide node information results in best performance regarding several performance metrics.

For the cluster-based protocols CTCP, the virtual range parameter value V_r is varied to measure the impact of parameterized clustering algorithm on the performance of topology control protocols. The MMST and CTCP (Optimal) used global MCDS-based clustering algorithm. Recalling from our previous discussion, the number of cluster-heads decreases as the virtual range increase with a corresponding increase in an average number of cluster-members per cluster. As the value of V_r grows, a sparser communication graph starts to appear. The network topology largely consists of shorter transmission links which lead to minimal energy cost. In CTCP, higher values of V_r result in larger cluster sizes. Applying the topology control algorithm over larger clusters causes more nodes to reduce their respective transmission ranges thus lowering the average transmission range/energy cost. Moreover, the fewer number of cluster-heads are required to maintain higher transmission power. As for the MMST, the result shows comparable performance when CTCP operating at higher (i.e., $V_r = 200$ and $V_r = 250$) values of the virtual range. However for lower (i.e., $V_r = 50$, $V_r = 100$ and $V_r = 150$) CTCP results in significantly higher transmission range/energy cost. For the lower values of V_r, the sub-optimal clustering algorithm results in higher number of cluster-heads and fewer number of associated cluster-members.

Fig. 7 (b) shows the contribution of each type of node towards overall trend regarding transmission range/energy cost. The transmission range/energy cost increases as the V_r increases for both types of nodes. Nevertheless, the transmission range selection of cluster-heads dominates the energy cost. Moreover, an increase in V_r value required both types of nodes to connect with more distant next hop towards the sink, bi-directionally. However, it is the number of each node type that would decisively impact the average transmission range and energy cost of the network. Cumulatively, the

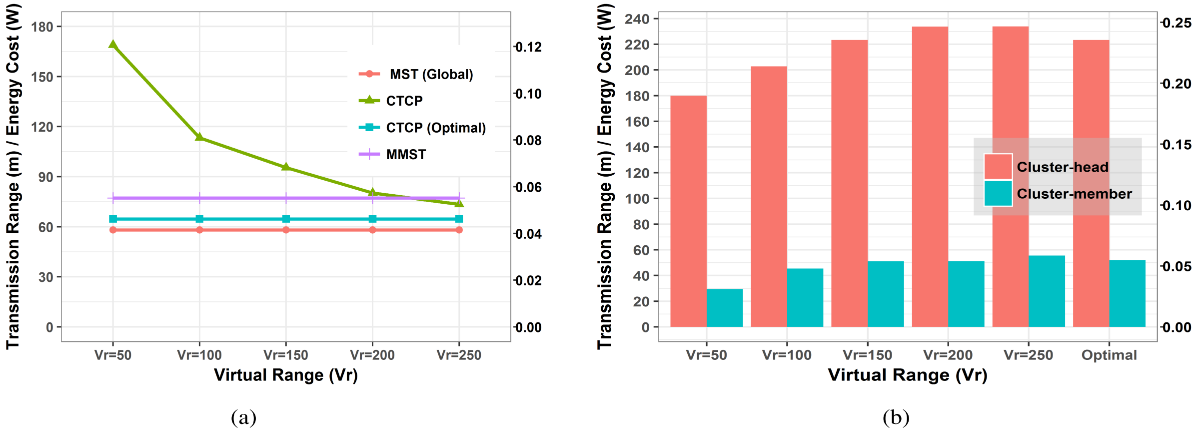


FIGURE 7. **Transmission range/Energy cost with 200 nodes for various values of virtual ranges V_r. (a) Transmission range/Energy cost. (b) Cluster-head vs. Cluster-member.**

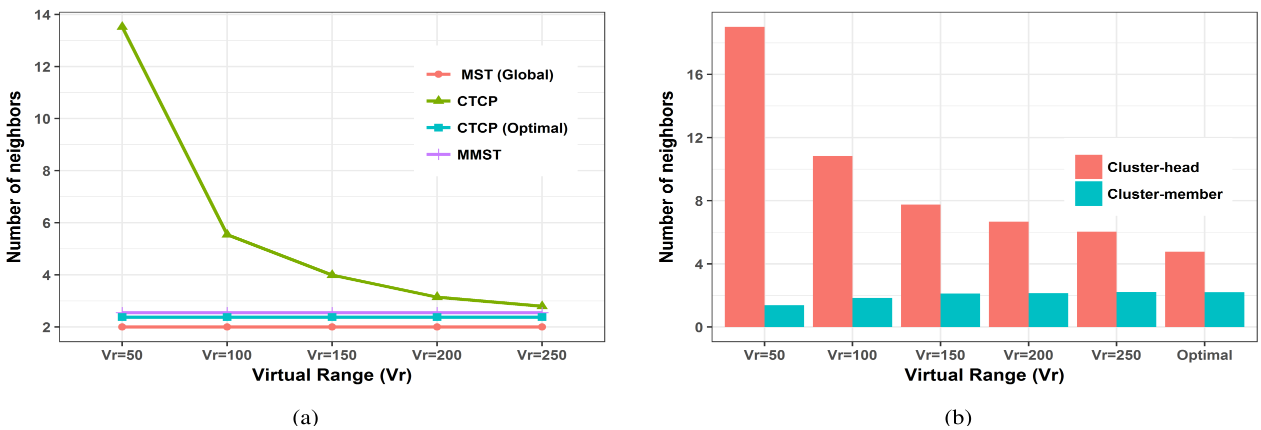


FIGURE 8. **Number of neighbors with 200 nodes for various virtual ranges V_r. (a) Number of neighbors. (b) Cluster-head vs. Cluster-member.**

decrease in a number of cluster-heads with higher transmission ranges and the corresponding increase in cluster-members with lower transmission range resulted in overall lower average transmission range and energy cost as the virtual range increases.

Fig. 8 (a) compares the cluster-based topology control protocols regarding the number of neighbors. The global MST resultant topologies are the sparsest with an average of two neighbors per node. In the proposed CTCP, increase in V_r causes lower transmission range, consequently the fewer number of neighbors with bi-directional links. MMST and CTCP approach with global clustering and higher values of virtual ranges performed comparably. However, for lower values of the virtual range, CTCP results in a considerably higher number of neighbors. Fig. 8 (b) the number of neighbors for cluster-head and cluster-member. Operating closely to the maximum transmission range causes cluster-heads to have a large number of neighbors. As V_r increases, the neighbor count decrease considerably for the cluster-heads. Conversely, there is a slight increase in the number of neighbors for the cluster-members.

Fig. 9 (a) shows the impact of V_r on the average number of edges. Increasing V_r values was the reason for reduced transmission range, thus a fewer number of neighbors with uni-directional links. In the case of an optimal number of cluster-heads, the CTCP performed slightly better as compared with MMST. Global MST results in the least number of edges in the final network topology. Fig. 9 (b) shows, overall the smaller virtual ranges result in larger number of edges. Especially in the cluster-head cases, an excessively large number edges results in a substantially dense topological graph. Since cluster-member are required to connect to nearest neighbor towards their corresponding cluster-head only, they tend to have a fewer number of links.

Fig. 10 (a) shows the Global MST topologies conserve energy at the cost of higher hop distances among the data sources and the common destination. Although CTCP and MST with global MCDS-based clustering approach performed well regarding other performance metrics, the number of hops required to reach sink is significantly higher. The main contributing factor is the lack of directed paths which the MVCDS algorithm creates explicitly during the execution of the first stage. In the global MCDS-based clustering algorithm, since the objective is to optimize the number of cluster-head in the network, usually longer and sub-optimal routing paths are selected. This impact can be witnessed by

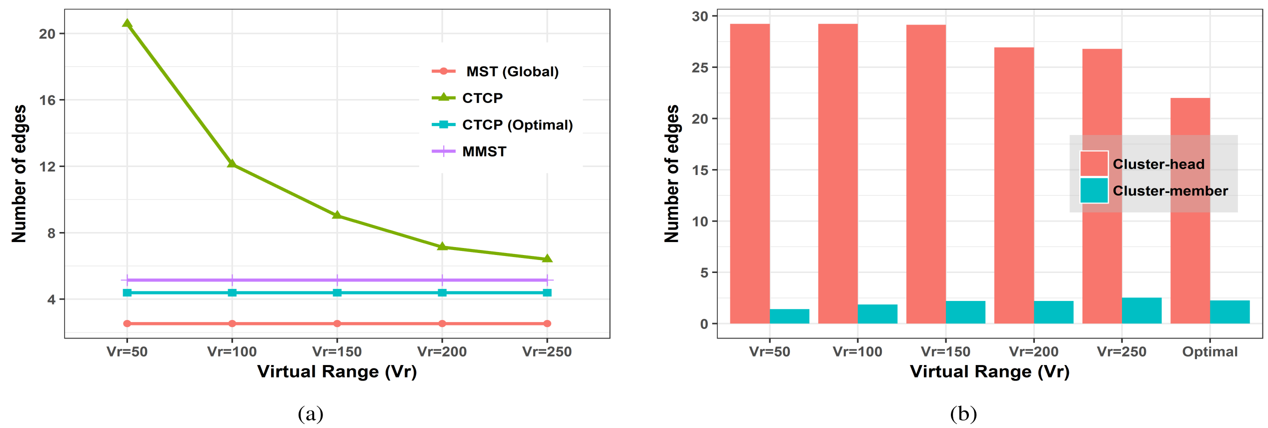


FIGURE 9. Number of edges with 200 nodes for various virtual ranges V_r. (a) Number of edges. (b) Cluster-head vs. Cluster-member.

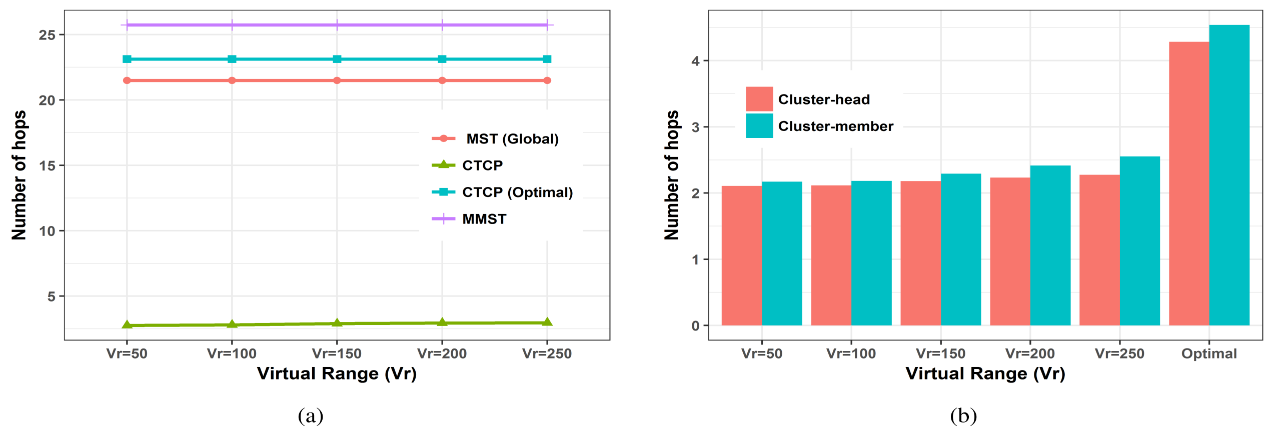


FIGURE 10. Number of hops with 200 nodes for various virtual ranges V_r. (a) Number of hops. (b) Cluster-head vs. Cluster-member.

carefully examining the Fig. 6. As for the proposed CTCP, the heterogeneous transmission power selection results in a lower number of hops. The number of hops increases as the virtual range (V_r) increases, mainly because higher V_r values cause larger cluster sizes, consequently larger hop distances between the cluster-members and their corresponding cluster-heads. Fig. 10 (b) shows that the immediate impact of reducing the number of links over which data can be communicated between both cluster-head and cluster-members is a slight increase in hop count. The shorter transmission range resulted in higher hop distances for the cluster-members.

2) IMPACT OF NETWORK SIZE ON THE TOPOLOGY CONTROL PERFORMANCE

For the next set of simulation results, the number of nodes in the network is varied to measure the impact of node density on the performance. In the plots, we included only two representative values for V_r, i.e., 100 and 250 and compared against several other competitive topology control protocols. We skipped other values to improve the readability of the plots.

Fig. 11 (a) shows the impact of varying network size on transmission range/energy cost. As for all the simulated network sizes, cluster-based topology control protocols such as Global MST, MMST, and CTCP (except for the lower value of V_r) result in lower transmission range/energy cost. As for the neighbor-based topology control protocols such as k-9 and CNN-5, the fully connected topologies are achieved at the expense of highest transmission range/energy cost among the competing topology control protocols. The k-6 protocol costs comparatively lower, however, the final topology is susceptible to the disconnected network. The transmission range/energy cost decreases as the network size increases, mostly due to the higher node density. As the network size grows, it becomes easier to obtain a connected network topology by establishing links with nearby neighbors only.

The impact of transmission range selection is quite evident on the number of neighbors and edges. Higher transmission range leads to a higher nodal degree and denser network topological graph. Overall, the number of neighbors and edges decreases with the increase in virtual ranges value as shown in Fig. 11 (b) and Fig. 11 (c). Here it is worth mention-

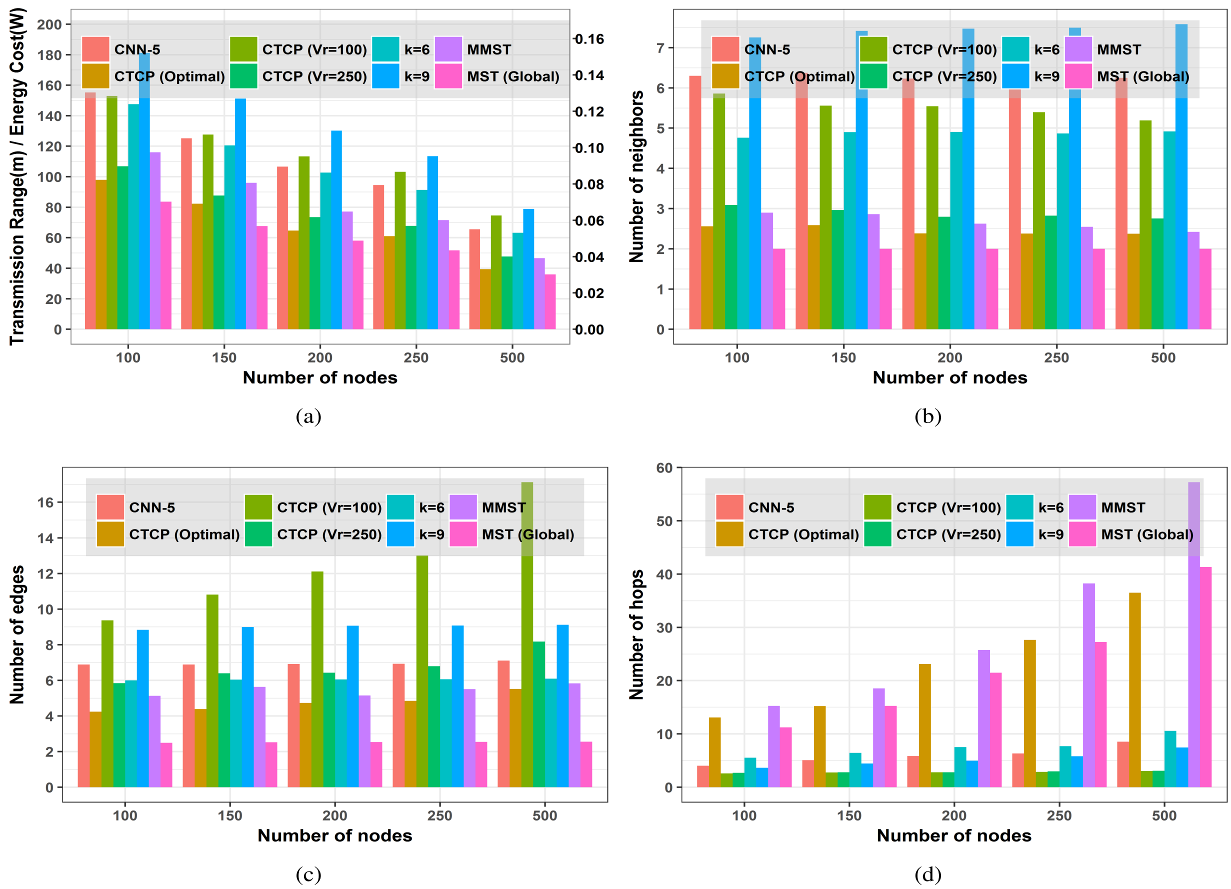


FIGURE 11. **(a) Transmission range/Energy cost. (b) Number of neighbors. (c) Number of edges. (d) Number of hops with network sizes of 100, 150, 200, 250 and 500 nodes.**

ing that the topological parameter plays an important role in determining the efficiency of any control protocol whether it is routing, channel access or scheduling. A higher number of neighbors or edges results in potentially greater interferences while offering several redundant paths. Likewise, a larger neighborhood requires a larger amount of neighbor state information to be stored and maintained.

Due to lower transmission range, as the network size grows the number of hops between the source-destination pair increases, as shown in Fig. 11 (d). In Global MST, each node is assigned a transmission range that is sufficiently large enough to guarantee a fully-connected network topology. Therefore, topologies generated by the Global MST algorithm result in the least energy cost. However, due to limited forward stretch factor, the hop distance between source-destination pair increases significantly. As for the MST and CTCP with global MCDS-based clustering, good performance regarding transmission power cost and interference friendly resultant topology is completely offset by significantly large of hop distances. The proposed CTCP result in topologies that are connected with a fewer number of hops to traverse between the data source and sink. However, the hop distance slightly increases as the virtual range (V_r) and network size increases. Neighbor-based topology control protocols performed well because of the longer forward stretch. Thus packets traverse fewer hops between a source and the destination.

V. CONCLUSION AND PERSPECTIVES

In this paper, we presented Collaborative Topology Control Protocol (CTCP), a hybrid approach for controlling communication topology in wireless sensor networks. CTCP combines the best from two categories of topology control, i.e., dominating set based clustering and transmission power adjustment. In CTCP, the nodes are classified into two categories based on the heterogeneous assignment of transmission power levels. The cluster-head operates at higher transmission range and sends the collected aggregated data towards a distant sink. An immediate consequence is lower hop distances between information sources and sink. Whereas, the cluster-members are allowed to use lower transmission ranges thus resulting in fewer neighbors and edges. For this purpose, a parameterized clustering algorithm is utilized based on the concept of virtual range V_r, which results in clustering with varying properties. For lower values of V_r, clusters with smaller cluster sizes are obtained with a large number of cluster-heads. Since most cluster-heads comparatively operate at larger transmission range, the energy cost is higher. Consequently, longer forwarding progress leads to higher interference with fewer hops to traverse between the source-destination pairs. These setting are more favorable for establishing the backhaul/backbone links in multihop wireless mesh networks, where the gateway/mesh and source nodes are located at farther distances and multihop is the way to reach the distant sink. Furthermore, the backbone is used less frequently, i.e., to transmit the aggregated information only.

As for the higher values of for V_r sparser topologies are obtained. Most of the nodes set their power level to a minimum because of larger cluster sizes and fewer cluster-heads. Therefore, the energy cost is minimized with a smaller nodal degree and slightly longer hop distances. Moreover, establishing links with fewer selected neighboring nodes result in lower interference and higher spatial reuse. These topologies support several of the requirements for energy and resource constrained wireless ad hoc and sensor networks where network lifetime longevity is of the foremost concern. In such network, the data updates are locally broadcasted before it is aggregated at the cluster-head and forwarded towards the final information sink. Moreover, the operation of CTCP explicitly discovers hierarchical routing paths from all the nodes towards a common sink. Most data gathering applications in wireless sensor networks employ many-to-one traffic paradigm in addition to the local broadcast. Therefore, constructing single structure topologies which make services like converge-cast and aggregation efficient for better network performance is always desirable. Intuitively, V_r act as a control knob which can be used to tune various performance matrices such as transmission range/energy cost, the number of neighbors, edges, and hops.

In MST, MMST, and CTCP with global MCDS-based clustering algorithms, the obvious trade-off is between performance and communication overhead. It requires excessive control message dissemination to acquire the network-wide global information at a central node and executing a centralized clustering and power adjustment algorithms. Essentially, the CTCP operation takes 2 or 3 message exchange as compared to an average of four to six messages required by other cluster-based topology control protocols such as CLTC [20]. As for the neighbor-based topology control algorithms, the communication overhead is low. However, the resultant topologies are dense with higher transmission range/energy cost. The lower hop distances are achieved at the cost of a higher number of neighbors and edges.

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