On the Interplay between Clustering and Power Control in Multihop Wireless Networks

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Abstract—Topology control offers many advantages for wireless networks such as reduced energy cost, simplified communication graph and network-wide connectivity. There are mainly two methods for managing the network topology. In clustering, a hierarchy of backbone nodes is selected to improve on the systems scalability and network lifetime whereas in power control each node adjusts its transmission power to achieve certain desirable properties of the resulting topology. While the focus of the former approach is to find an ideal number of the backbone nodes, the main objective of the latter approach is to estimate a minimal power level which can solve multi-objective design problem. There have been several topology control protocols proposed however they miss the potential of combining both approaches. In this paper we propose Two-Tiered Topology Control (TTTC) protocol, a generic framework which combines the clustering and power control approach towards topology control and evaluate different conditions under which it performs well. TTTC operation is divided into two phases. During the first phase, a parameterized clustering algorithm is executed to obtain clusters of varying properties. At the end of first phase, the network is organized into two tiers. The backhaul-tier consists of cluster-head nodes while the connectivity-tier contains the cluster-members. In the second phase, each cluster-head runs a local MST-based power control algorithm. Simulation results show that proposed framework achieves efficient trade-off in terms of energy cost, neighbor count and hop count while maintaining fully connected network. Moreover, the framework relies on local available information with lower communication overhead.

I. INTRODUCTION

Data gathering is a primary task in many wireless ad hoc and sensor network deployments. The many-to-one is the most prevalent communication paradigm utilized in several data gathering applications. The data is collected from several sources and forwarded towards a single remote destination in a multi-hop fashion. The key challenge is to efficiently disseminate data by minimizing the energy cost and interference among the neighboring nodes while maintaining a fully-connected network topology. Fundamental to this challenge is the design of effective communication protocols and the controlling mechanisms of underlying network topology (also topology control) over which the protocols are implemented.

There are several taxonomies proposed for the topology control protocols [1] [2] in wireless networks. These taxonomies generally categorize protocols in to two classes [3]. The clustering approach allows the selection of a subset of nodes in the network to construct a connected backbone. The backbone nodes (also cluster-head) form a hierarchical structure such that they are either connected directly or via intermediate nodes while all other ordinary nodes (also cluster-member) are associated with them. The main objectives of the clustering approach are to reduce the complexity of the topology through organizing networks in to smaller manageable clusters, and thus to improve the system scalability as well as energy efficiency. However, finding an optimal set of backbone nodes is an NP-hard problem [3] and often assumes the availability of complete network information which is difficult to obtain. To account for this several heuristic-based and localized algorithms are proposed. Comparatively these distributed algorithms select sub-optimal number of backbone nodes and more likely to achieve only partial design objectives.

The second approach is based on power control where each node optimally adjusts the transmission power level. Power control algorithms have been proved to construct efficient network topologies i.e., fully connected, consume minimum energy, provide optimal hop stretch factor, and consist of bi-directional links among small number of direct neighbors. Moreover, the algorithm for constructing such network topologies must utilize local information only with lower communication overhead. However, these multi-objectives are often conflicting in nature where improving a certain performance metrics result in worsening of another [4] [5]. For example most of the existing power control algorithms idealize Minimum Spanning Tree (MST) [6] based topology construction which generates the sparsest topologies with lower energy cost however they also result in larger hop count among the
sources and a common destination. Moreover, the number of hops required to reach destination do not scale well with the growing network size [7]. Lower energy cost and interference is achieved at the expense of longer and inflexible or sub-optimal routing paths. Fig. 1 plots the average hop count and the total energy cost (i.e., sum of transmission power assigned to all nodes) for various network sizes. The results are obtained by applying the MST-based topology control protocol to various number of nodes randomly distributed over an area of $1000m^2$. The sink node is located at the center of the network field. We observe that the average hop count increases significantly as the network size increases. The total energy cost decreases with an average neighbor count of two nodes. Although MST-based topologies achieve connectivity, energy efficiency and lower nodal degree, the presence of multi-hop data traffic over such a large number of hops will produce significant overall interference and energy consumption[8].

Since, topology control is extremely relevant in context of resource-constrained and technologically feasible devices the focus of this paper is on hybrid approach towards topology control. The main idea is to combine the best from two approaches i.e., clustering and transmission power control to manage wireless network topologies. The proposed framework, named Two-Tiered Topology Control (or TTTC) works in two phases. In the first phase, a common destination node (e.g., a sink or base-station) initiates a distributed backbone selection algorithm. At the end of first phase, the network is organized into two tiers. The backhaul-tier would consist of cluster-head nodes while the connectivity-tier contains the cluster-members. In the second phase, each cluster-head executes a local MST-based topology control algorithm and assigns transmission power to their cluster-members according to the desired set of design goals. Heterogeneous transmission power levels are assigned to cluster-head and cluster-members separately, where backbone or cluster-head nodes are connected via long range backhaul links which significantly reduce the number of hops required to reach the destination. On the other hand, the cluster-members operate with relatively shorter ranges to conserve energy, maintain lower nodal degree thus reducing interference and improving the spatial reuse. Furthermore, by delegating the data collection task among cluster-heads and cluster-members along with the provision of rotating the cluster-head responsibility can potentially improves the network overall performance.

TTTC design significantly differs from existing hybrid topology control protocols such as Cluster-based Topology Control (CLTC) [9], and Multi-hop MST-based Topology Control (MMST) [10] in the following aspects. Firstly, unlike previous studies, we have utilized a fully distributed and parameterized clustering algorithm to study the impact of various backbone structures with different cluster properties on the resultant topology. By varying the number of cluster-head and cluster-members nodes we get further insight on the interplay between different backhaul-tier and its effect on the connectivity-tier. Secondly, the proposed work is not limited to run centralized power control protocols at the cluster-head node. Instead, based on the local information each node is capable of executing distributed power control protocols as well, which qualifies TTTC as generic framework. Finally, the previous works often assume global topology information and result in higher communication overhead. In contrast the proposed TTTC protocol operates on local information only and is communication efficient as well.

The rest of the paper is organized as follows. Section 2 introduces the proposed two-tiered framework for topology control. Section 3 presents extensive performance evaluation. Finally, conclusion is presented in Section 4.

II. TTTC: Two-Tiered Topology Control Protocol

The intuition behind two-tiered topology control protocol is to distribute 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 between cluster-head or backbone nodes which operate at relatively longer transmission ranges to reach more distant destinations e.g., the inter-cluster communications. Whereas cluster-member nodes in the connectivity-tier employ shorter transmission ranges to reach their respective cluster-head e.g., the intra-cluster communication. Particularly, in our proposed two-tiered topology control protocol, the nodes are classified into two categories based on the heterogeneous assignment of transmission power levels. The cluster-head nodes utilize maximum transmission power and send the collected aggregated data towards the distant sink node. An immediate consequence of this result in fewer number of hops count towards the sink node. Whereas, the cluster-members are allowed to use lower transmission power level resulting in lower energy cost and nodal degree. In the absence of the power control phase, the proposed scheme works like an efficient clustering algorithm.

A. The Backhaul-Tier

As the name implies, the backhaul-tier constructs the network backbone or core over which high level network control functions such as routing can be implemented. The backhaul-tier consists of all the backbone nodes in the network which are connected via maximum transmission power. In order to find such a subset of backbone nodes we propose to employ the Minimum Connected Domination Set (MCDS) [11] [12] of all the nodes in the network. More importantly a fully distributed and parameterized clustering algorithm is used with the following two desirable properties.

1) It enables a variety of clustering properties and thus versatile performance gains using a single clustering scheme only. In the previous studies [9] [10] several clustering schemes were implemented and tested in order to get the insight into their impact on the topology control performance. In contrast, only a single algorithm should dynamically adjusts the number of cluster-heads and the cluster sizes. Furthermore, this characteristic must be obtained at the expense of lower message exchanges per-node as the communication overhead. Lower overhead makes the approach energy efficient and
scalable for resource-constrained networks like wireless sensor networks (WSNs).

2) Generally, the cluster-head nodes are required to operate at transmission ranges comparatively higher than that of the cluster-members. Additionally, the cluster-heads are also supposed to run local topology control algorithm. These facts could possibly leads to shorten the network lifetime which is usually defined by the smaller number of cluster-heads. In order to improve on the network lifetime, the cluster-head responsibility must be rotated among all the neighboring nodes.

We used Budhaditya’s [11] [12] heuristic based algorithm as the basis for finding the set of nodes that constitute the backhaul-tier. This algorithm works on the concept of Virtual Dominating Set (VDS) to construct a connected dominating set of various densities. The parameter virtual range \( V_r \) controls the membership of this set (called Minimal Virtual Connected Dominating Set or MVCDS) and thus result in different clustering properties. In their algorithm, initially all nodes are marked with WHITE color. During the MVCDS construction phase, nodes are either marked BLACK or RED. BLACK nodes become cluster-head (or dominator) while the RED ones become cluster-members (or dominatee). The sink initiates construction of backhaul-tier by turning itself BLACK (i.e., cluster-head) and sending the control packet. On reception, a WHITE node marks itself RED (i.e., cluster-members) if it is within \( V_r \) distance otherwise it turns BLUE. The BLUE nodes compete, and the ones which can cover larger number of uncolored nodes wins. The selected BLUE node turns BLACK before disseminating the control packet further in to the network. The newly BLACK node becomes children of the previous BLACK node, thus making the dominating set connected during the process.

Previously, the utilizations of MVCDS include retrieving topology information at various details and node scheduling [11] [12]. However, in our paper we have used an extended version of this concept to tailor the scheme according to the aforementioned clustering properties. We extend the Budhaditya’s algorithm in two ways. Firstly, the algorithm now takes into account the residual energy while selecting the BLACK nodes. Second, during the BLACK node selection process all nodes receive information such as location and neighbor list from the immediate neighborhood which is included in the control packet. This information is then used by the subsequent power control algorithm running either at the cluster-head or distributed algorithm at each node to calculate the transmission power level according to the desired set of design objectives.

### B. The Connectivity-Tier

Once the cluster-head selection process is over, the cluster-head nodes either run a local power control algorithm within the cluster and let each cluster-members know their respective transmission power level or each cluster-member execute a distributed algorithm to decide upon its own transmission power level.

Algorithm 1 Two-Tiered Topology Control (TTTC)

**Initialization:**

1: \( \text{node}.Vr \) \( \triangleright \) Virtual Range
2: \( \text{node}.TX = TX_{\text{max}} \) \( \triangleright \) Maximum Power Level
3: \( \text{node}.\text{nblist} \) \( \triangleright \) Neighbor List
4: \( \text{node}.\text{energy} \) \( \triangleright \) Residual Energy
5: \( \text{node}.\text{color} = \text{white} \) \( \triangleright \) Initially all uncolored nodes
6: if sink is True then
7: \( \text{node}.\text{color} \leftarrow \text{black} \)
8: \( \text{BROADCAST}(Vr, TX, \text{nblist}, \text{energy}, \text{color}) \)
9: end if

**Phase 1 - Clustering (Backhaul-Tier)**

10: procedure \( \text{ReceiveBROADCAST}(Vr, TX, \text{nblist}, \text{energy}, \text{color}) \)
11: for each \( \text{node} \) do
12: if DistanceFromBlack \( \leq \) \( V_r \) then
13: \( \text{node}.\text{color} \leftarrow \text{red} \)
14: else
15: \( \text{node}.\text{color} \leftarrow \text{blue} \)
16: end if
17: for each \( \text{blue} \) neighbor \( v \) starting from the farthest do
18: for each \( \text{white} \) neighbor \( u \) of \( v \) do
19: \( u.\text{color} \leftarrow \text{blue} \)
20: if \( u \) has more uncoloredneighbors & energy then
21: \( u.\text{color} \leftarrow \text{black} \)
22: \( \text{BROADCAST}(Vr, TX, \text{nblist}, \text{energy}, \text{color}) \)
23: end if
24: end for
25: end for
26: end procedure

**Phase 2 - Power Control (Connectivity-Tier)**

27: for each \( \text{black} \) node \( i \) do
28: \( i.TX \leftarrow TX_{\text{max}} \)
29: for each \( \text{red} \) neighbor \( j \) associated with \( i \) do
30: \( TX_{\text{minimal}} \leftarrow \text{PRIMS}(i, j) \)
31: \( \text{UNICAST}(j, TX_{\text{minimal}}) \)
32: end for
33: end for
34: procedure \( \text{ReceiveUNICAST}(j, TX_{\text{minimal}}) \)
35: \( j.TX \leftarrow TX_{\text{minimal}} \)
36: end procedure

Since a cluster-head has to perform subsequent operations in a centralized manner it may introduce a single point of failure within a cluster. Being a framework for a hybrid topology control protocol, TTTC allows other alternatives such as a decentralized approach where information is distributed to all member nodes and each node is responsible for its transmission power assignment, hence the use of cluster-heads is not necessary. However, the two approaches are equivalent from the theoretical perspective and we chose to proceed with the centralized approach. For this purpose each clus-
head locally runs the Prim’s algorithm to construct Minimum Spanning Tree (MST). Using Prim’s algorithm, the cluster-head finds the minimal transmission power level for each of its cluster-member and convey it via a unicast packet. The resultant topologies are 1-connected because the previous studies found that requirements on 2-connected topologies results in significant increase in energy consumption. However, the idea here can easily be further extended for 2-connected topologies without any extra communication overhead. Algorithm 1 formally describes the sequence of operations carried out by the proposed TTTC protocol in more details.

We consider a 50 node network to exemplify the proposed TTTC protocol, given in Fig. 2. Fig. 2 (a) shows that among 50 nodes, 15 nodes are selected as the cluster-heads (represented by square shape), while remaining are the cluster-members (circle shape) associated with their respective cluster-head. Cluster-heads labeled CH1 through CH14 and a sink located at the center of the network field. The backhaul-tier is illustrated with solid darker lines connecting backbone nodes whereas the cluster-members association is shown using the dashed lines. Fig. 2 (b) shows the power-controlled network topology with the corresponding local minimum spanning tree represented as solid lighter lines.

III. PERFORMANCE EVALUATION

A. Simulation Environment

For performance evaluation of the proposed TTTC framework we conducted extensive simulation-based studies, using the NS-2 [13] simulator. In the first set of simulation results a comparison between the global MCDS algorithm and the proposed distributed MVCDS algorithm with various values of virtual range \( V_r \) is presented. In previous studies on hybrid topology control, either the network size is varied or several of the clustering algorithms are used to study the impact of different clustering properties on the performance. For instance in [9], the network size is varied to get clusters of different sizes and thus to fluctuate the degree with which both centralized and distributed parts of the hybrid scheme are applied. Similarly, in [10] several clustering schemes are implemented to yield a range of average cluster sizes so that their impact on the topology control can be evaluated. In our proposed the same effect can be repeated by simply varying the virtual range \( V_r \) while keeping the allowable maximum transmission power level and the network area constant. Following performance metrics are utilized to evaluate the clustering phase.

1) Total number of cluster-head nodes (or the cardinality of the dominating set).
2) Average number of cluster-members per cluster (or average cluster size).

The power control phase is evaluated using three performance metrics.

1) Total Energy Cost, is the sum of total transmission power level (in Watts) assigned to all of the nodes, obtained at the end of the TTTC protocol.
2) Average Transmission Range is defined as the ratio between the sum of all transmission ranges (in meters) and the network size.
3) Average Neighbor Count is defined as the ratio between total number of neighbors and the network size.
4) Average Hop Count, is defined as the ratio between total number of hop count from a node to the sink and the network size.

For a comparative study, we compared TTTC framework with two other protocols.

1) Global MST (referred as Global) produces the sparsest topology which consumes minimum energy. However, it assumes that each node knows the global position of all the other nodes in the network. There is no clustering performed during the Global MST algorithm, in other words these topologies represent flat network where all nodes have essentially the same role.
2) Local MST (referred as Local) produces efficient topologies where the backhaul-tier is obtained using Global MCDS algorithm, whereas the connectivity-tier utilize cluster-wide local MST algorithm.

The simulations are performed for different network sizes, ranges from 100 to 500 nodes. The nodes are randomly deployed over the terrain of size 1000m\(^2\), with sink node placed at the center of the network field. The maximum allowable transmission range is set to 250m and the virtual range \( V_r \) is selected from 50m, 100m, 150m, 200m and 250m.
Fig. 3. Backhaul-tier with 200 nodes: (a) Clustering using Global MCDS algorithm vs. MVCDS algorithm. (b) $V_r=100m$. (c) $V_r=200m$. (d) $V_r=250m$.

Fig. 4. (a) Number of cluster-heads vs. Network Size. (b) Average number of cluster-members vs. Network Size. For various Virtual ranges $V_r$.

In the simulations, the Two-ray ground reflection [14] is used as a radio propagation model and is assumed that each node is equipped with an omni-directional antenna. In this study, we convert the values from distances to power using Friis free space model and the Two-ray ground reflection models that are currently implemented in the network simulator NS-2. The free space propagation model assumes the ideal condition, thus it is useful for short distances. On the other hand, the Two-ray ground reflection model considers both the direct path and the ground reflection path. Therefore we considered the crossover point of two models i.e., if the distance is less than 86.14m then the Friis model is applied otherwise the Two-ray ground reflection model is used.

B. Simulation Study

1) Study of the clustering phase: Fig. 3 shows the sample topologies obtained as the result of the clustering phase. These network topologies consist of 200 nodes. Fig. 3 (a) shows the result of clustering performed by the global MCDS algorithm which assumes availability of network-wide topology information. Fig. 3 (b)-(d) illustrate the output of the enhanced MVCDS clustering algorithm for different values of the virtual range $V_r$. The black solid square and red circle represent cluster-head and cluster-member nodes, respectively. The black solid lines are the backhaul-tier links and the dashed lines shows the cluster-member association with their respective cluster-heads. Fig. 3 (b) (c) and (d) are the resultant
Fig. 5. Connectivity-tier with 200 nodes: (a) Power Control using Global MCDS Clustering and Local MST vs. MVCDS Clustering and Local MST. (b) \( V_r = 100 \text{m} \). (c) \( V_r = 200 \text{m} \). (d) \( V_r = 250 \text{m} \).

backhaul-tier constructed from applying the proposed MVCDS algorithm when the virtual range is set to \( V_r = 100 \text{m} \), 200m and 250m, respectively. These values of the virtual range correspond to the 40%, 80% and 100% of the maximum transmission range value. As illustrated in the figures, for different values of virtual range \( V_r \), the number of cluster-head nodes and cluster sizes adapt accordingly.

For all the given network sizes as the virtual range \( V_r \) increases the number of cluster-head nodes decreases and oppositely the cluster size increases. A smaller change in network density results in comparatively lower percentage increase in number of cluster-heads. For example, the transitions among sparse to slightly denser networks results in at most 20% increase in cluster-head count whereas the transition between slightly denser networks to highly dense network causes an average of 20% and 38% increase, respectively. Generally, the centralized clustering scheme gives least number of cluster-head for all simulated network sizes. Equally important is the effect of varying virtual range for a given network size. For all network sizes that we simulated, the switch among initial or lower virtual range values brings significant reduction in total number of cluster-head nodes. As shown is Fig. 4 (a), the percentage decrement in number of cluster-head nodes range between almost 40% and 60% for the first three virtual ranges. This is in contrast with the observation made for last two virtual range values which remain well below the 30%.

The cluster size fluctuates with varying 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 control phases are applied. The average number of nodes per cluster increases with the increase in virtual range values as given in Fig. 4 (b). For centralized clustering scheme, although the number of nodes has a slight effect on the MCDS size, but the resultant cluster sizes increase significantly. The percentage increment in cluster size among first three value of \( V_r \) (i.e., 50m, 100m and 150m) is substantial in comparison with the last two values (i.e., 200m and 250m). Moreover, as the network size grows this increment grows gradually. Thus, instead of applying various clustering algorithm, we have utilized a single algorithm with varying virtual range values to generate clusters of different sizes while limiting the communication overhead to a single message per-node.

The simulation setup consists of total 100 to 500 nodes in the network. The clustering algorithm is configured by adjusting virtual range values such that each cluster-member is only at one-hop distance from the cluster-head when it utilizes maximum transmission range. For example, for 200 nodes the average number of cluster-head nodes are 124, 62, 39, 28, and 23 and average cluster size obtained is 1.62, 3.3, 5.2, 7.3, and 8.94, when the virtual range is set to 50m, 100m, 150m, 200m and 250m, respectively. Whereas for the global MCDS clustering algorithm the average number of cluster-head nodes is 15 and the average cluster size is 14 nodes.
2) Study of the power control phase: Fig. 5 shows the sample network topologies produced at the end of the TTTC protocol. The sparsest of all these topologies is the one with fewer number of cluster-head nodes and with larger cluster sizes which is obtained by the global MCDS and local MST combination (Local) given in Fig. 5 (a). For the TTTC protocol, the parameter value $V_r$ determines the cluster-head count and the average number of cluster-members per cluster thus influences other topological parameters such as energy cost, hop count and nodal degree. As the value of $V_r$ grows, a sparser communication graph with minimal energy cost and shorter links starts to appear as shown in Fig. 5 (b), (c) and (d). For the lower values of $V_r$, the sub-optimal clustering algorithm results in higher number of cluster-head nodes and fewer number of associated cluster-members. Consequently, larger number of nodes tends to operate at maximum transmission power, resulting in fewer hops towards the sink at the cost of higher energy consumption. The average number of neighboring nodes tends to decrease with the increase in virtual range value. Intuitively, $V_r$ act as a control knob which can be used to tune various performance matrices such as energy cost, average hop count and nodal degree.

The global MST (Global) algorithm behaves as if the entire network is consists of a single cluster. The fact that a single node is aware of the network-wide node information (location or distance) resulted in overall best performance in terms of energy cost. Fig. 6 (a) illustrates the total energy cost in terms of power assigned (Watts). With lower values of virtual range the number of cluster-heads are the largest (consequently, with as few as two cluster-members), thus forcing most of the nodes to operate at maximum transmission range. However, the energy cost decreases gradually with the increase in the virtual range values. Recalling results from the previous subsection, the increment in virtual range value results in larger cluster-sizes. For a 200 nodes network, the trend start from an average of two nodes per cluster to almost 9 nodes per cluster and finally with the global clustering scheme it reaches 14 nodes per cluster. Applying a power control algorithm over a larger clusters causes more nodes to reduce their respective transmission ranges. In order to present a more realistic comparison from power consumption perspective, the energy cost is given in terms of Watts that NS-2 supports. In NS-2, a crossover point of Two-way ground reflection and Friss [14] is used as the radio propagation model. Moreover, Table I, provides the total energy cost for various values of path loss exponent $\alpha$. The value of path loss exponent is set to 2 (i.e., $\alpha=2$) and 4 (i.e., $\alpha=4$) to represent free space and city terrain with shadowing effects, respectively.

Similar trend can be observed in terms of transmission range assigned to nodes, as shown in Fig. 6 (b). With higher node densities, a connected topology is simply obtained by lesser distant neighboring nodes. The interference is often characterized by the number of neighbors. Overall, the neighbor count decreases with the increase in virtual ranges value as shown in Fig. 6 (c). Here it is worth mentioning that this topological parameters plays an important role in determining efficiency.
of any control protocol whether it is routing, channel access or scheduling. Higher number of neighbors results in potentially greater interferences while offering several redundant paths. Likewise a larger neighborhood requires larger amount of neighbor state information to be stored. Finally, Fig. 6 (d) shows that for the given $V_r$, the hop count increases with the increase in the network size. However, for the given network size the hop count decreases as the virtual range increases. Although the global MST topology conserves significant amount of energy, the final transmission ranges are just sufficiently long enough to ensure overall connected network. The fact that the MST algorithm favors the minimal length edges, resulted in larger hop distances from nodes to sink. The percentage decrease in terms of energy cost, neighbor count and hop count is substantial between initial two consecutive virtual ranges. However, the trend goes gradual for the later values of $V_r$.

In case of Global and Local MST algorithms, the obvious trade-off is the communication overhead associated with the network-wide global information collection at a single node and applying a centralized power control or clustering algorithm. Essentially, the TTTC operation takes two to three messages exchange per-node as compared to an average of four to six messages per-node required by similar genre of topology control protocols such as CLTC [9].

In summary, the lower values for $V_r$ result in higher number of cluster-heads or smaller cluster-sizes, therefore more nodes operate at the maximum transmission power level. Consequentially, in terms of energy the cost is higher whereas higher forwarding progress leads to fewer number of hop count towards the sink. The higher nodal degree potentially causes higher interferences among the neighboring nodes. Such parameter settings are more suitable for wireless mesh networks with mesh backbone where the destinations are farther and multi-hop is the usual mean to reach the distant information sink. Moreover, the backhaul-tier is used frequently i.e., mostly to transport the aggregated results. Similarly, higher values for $V_r$ produce lower number of cluster-heads or larger cluster-sizes, therefore more nodes tend to operate at minimal transmission power level. Under such circumstances, the energy cost is minimized and the shorter transmission ranges results in higher hop count value while the lower nodal degree brings higher spatial reuse. Such situations favor wireless sensor networks where energy and other resources are critical to the network lifetime longevity. Furthermore, the data updates are usually limited to immediate neighborhood only before it is aggregated and disseminated towards the final destination.

### IV. CONCLUSION

In this paper, we presented a two-tiered topology control protocol (TTTC) for multi-hop wireless networks which combines the best from two classes of topology control namely clustering and power control. The operation of TTTC is divided in to two phases. During the first phase we utilized a parameterized clustering algorithm whereas in the second phase, cluster-head nodes run a power control algorithm and assign minimum transmission power levels to their respective cluster-members. Since cluster-head are allowed to operate at maximum transmission power, the heterogeneous power levels assignment provide an efficient trade-off between clustering and other topological parameters such as connectivity, energy cost, number of neighbors and number of hops required to reach the final destination. Moreover, TTTC operation systematically discovers hierarchical routing paths from all the nodes towards a common sink. Effectiveness of TTTC has been assessed via extensive simulation studies. The results show that the proposed framework offers versatile performance in terms of energy cost, hop count and nodal degree while maintaining network-wide connectivity. In addition, TTTC operation takes at most three message exchange per-node as compared to an average of four to six messages per-node required by similar genre of topology control protocols.

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### REFERENCES


### TABLE I

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