Topology design for wireless ad-hoc networks with backbone support

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Abstract —

A backbone-based hybrid network architecture has the potential to enhance the connectivity and throughput capacity of wireless ad-hoc networks. A fundamental problem for this hybrid network architecture is designing the optimal network topology under certain topological constraints. In this paper, this problem is formulated as a generalized optimal geometric Steiner network problem with minimum number of Steiner nodes under the various practical constraints. In this new problem formulation, the backbone (Steiner) nodes have two heterogeneous transmission ranges, one for connecting to the terminal nodes and the other for connecting to other backbone nodes. The overall network and the backbone subnetwork are both connected. We also consider the case when the number of hops from a terminal node to its closest backbone node is constrained. As the problem is NP-hard, we propose a multiple-step solution approach, compare several heuristic algorithms by a comprehensive simulation study and identify some critical topological characteristics. The results show that a highly scalable backbone network can be built for a large number of terminal nodes.

Keywords — **Wireless multi-hop networks, backbone topology design.**

I. INTRODUCTION

An ad-hoc wireless network is traditionally a self-organizing and rapidly deployable network which does not rely on any fixed infrastructure and data can only be forwarded by the nodes in a multi-hop fashion. Previous studies on ad-hoc wireless networks considered a homogeneous architecture where each node has a common and fixed transmission range. Several efficient protocols have been developed to deal with routing, topology control, location management, and power control problems for ad-hoc wireless networks. However, such an architecture without an infrastructure support becomes unscalable as the number of nodes per unit area becomes large [4]. Consequently, hybrid network models have attracted considerable attention [1] [2] [3]. In general, a hybrid network consists of a limited number of special nodes (i.e., backbone nodes) in addition to ordinary wireless nodes[1] to support the data communication between the terminal nodes. In this hybrid architecture, two terminal nodes can communicate either using multi-hop forwarding through an ad-hoc route, (*i.e.,* a set of other terminal nodes), or using the backbone infrastructure. This way, more efficient routing and topology control mechanisms can be designed that can enhance the connectivity, capacity, and lifetime of the entire network.

The backbone nodes can be connected to each other either by a wired network as in the case of wireless cellular networks [1], [5] or by wireless communication links [2], [3]. Wireless backbone networks have been considered in the literature under different models. In a group of work, backbone nodes are assumed to have the same capabilities as terminal nodes (*e.g.,* transmission range, battery life, processing power) and used solely as relay nodes in order to increase connectivity and support routing between the terminal nodes [10]. Under such a setting, it is not required to form a connected backbone subnetwork among the backbone nodes. In a similar work, it is assumed that the backbone nodes have the same transmission capacity as the terminal nodes. In addition, the location and the number of backbone nodes as well as the terminal nodes are fixed. Since any two nodes within each other's transmission range can potentially form a link, it is possible to map the problem to a regular graph and formulate it as the well-known dominating set problem [11]. The dominating set itself can be either connected or disconnected.

In another line of work, the backbone nodes are assumed to have higher capabilities such as longer transmission range, higher energy resources and higher processing capabilities. In addition, backbone nodes are required to constitute a connected subnetwork between each other. This latter hybrid model, which will also be the focus of this paper, has several application areas, *e.g.,* (1) wireless sensor ad-hoc networks: In addition to the role of information sink, the backbone subnetwork also plays the role of information exchange and aggregation. (2) Last mile wireless broadband networks with a free space optic (FSO) backbone [3]. (3) unmanned aerial vehicles (UAV) can form such a backbone network, as the central monitoring, processing, and communication backbone network to serve the terminals over a large battlefield. [2].

In this paper, we consider such hybrid networks and study the optimal network topology design problem. We assume that the backbone nodes are in general more capable than the terminal nodes with respect to transmission range and power supply and they are required to form a connected backbone subnetwork. Specifically, we study the problem of finding the minimum number of backbone nodes and their locations in order to have a connected network topology.

¿From a graph theory point of view, this fundamental problem can be formulated as a constrained geometrical Steiner network problem [13], where backbone nodes are equivalent to the Steiner points. It is proved in [7] that the Steiner tree problem with minimum number of Steiner points and bounded edge-lengths is NP-hard. Hence, the authors present a minimum-spanning-tree based heuristic, which has an approximation ratio that is equal to four [6], [8]. However, in their work, the Steiner nodes are not required to form a connected subnetwork.

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[1] From now on, we will denote such ordinary nodes, which have limited transmission range and power, as terminal nodes.

Our work differs from the existing solutions in several ways. First of all, the transmission range between backbone nodes is much larger than the transmission range between terminal nodes[2]. This results in a heterogeneous edge-length constraint which is not considered by the previous Steiner tree problem definitions. Secondly, in addition to the connectivity of the overall network, the subnetwork formed by the backbone nodes is also required to be connected. Finally, we will also consider the case where the number of hops from a terminal node to its closest backbone node is constrained. As the problem is NP-hard, we compare several heuristic algorithms by a comprehensive simulation study and obtain the important topological characteristics.

In this paper, we only consider the two-dimension Euclidean space, though we believe the insights obtained can be extended to higher dimensional spaces.

The paper is organized as follows. We formally define the network topology design problem in Section II. In Section III we present a number of heuristic algorithms. Section IV presents the simulation results and Section V concludes the paper.

II. Problem definition

Let $N = \{t_1, t_2, \cdots, t_n\}$ denotes the set of terminal nodes that are deployed in a two dimensional Euclidean plane $\mathbb{R}^2$. All terminal nodes have a fixed and common transmission power (range). On the other hand, backbone nodes have two sets of wireless transceivers working on two different wireless channels, one for the communication with the terminal nodes, and the other for the communication with other backbone nodes (that has a longer transmission range). We assume that a link is established between two nodes as long as the distance between the nodes is smaller than the corresponding transmission range. Then, let $G(N, E_N)$ denotes the corresponding topology while E_N represents the set of links that exists between the nodes in N. Note that, $G(N, E_N)$ is not necessarily a connected topology. Our objective is to find the minimal superset of N, denoted by P such that $G(P, E_P)$ as well as $G(P \setminus N, E_{P \setminus N})$ are connected. Note that the nodes in $P \setminus N$ (*i.e.,* the nodes in P other than those in N) constitute the set of backbone nodes M. In addition, we have the additional constraint that the maximum number of hops allowed for a terminal node to reach to the closest backbone node is limited by ρ. Figure II describes the algorithmic structure of the problem defined above. A

Input:

1) N: Set of terminal nodes.

2) (x_i, y_i): The geometric position of terminal node i, $\in N$.

3) δ: The maximum transmission range of a terminal node.

4) Δ: The maximum transmission range of a backbone node.

5) ρ: The maximum number of hops allowed for a terminal node.

Output:

1) P: The minimal superset of N.

1) $M = P \setminus N$: The set of backbone nodes.

2) The connected overall network topology $G(P, E_P)$.

3) The connected backbone network topology $G(M, E_M)$.

4)(x_j, y_j): The optimal position of the backbone node j, $j \in M$.

Figure 1: Algorithmic structure of the connectivity problem.

III. Solution Approaches

As discussed in the Introduction, the basic problem, bounded edge-length Steiner trees with minimum number of Steiner points, and its associated basic solution approach do not exactly match the topology design problem considered in this paper, especially due to the additional connectivity requirement of the backbone subnetwork as discussed in last section. The specific problem considered here is the Steiner tree problem with minimum number of "connected" steiner points and non-uniformly bounded edge-lengths. Given the fact that the basic problem is already NP-hard, we propose a heuristic algorithm that consists of the following three steps to solve the general problem:

Step 1:

- Solve the standard bounded edge-length Steiner tree problem. Recall that M denotes the set of backbone nodes and $G_b(M, E_M)$ is the corresponding backbone topology. Note that at this step $G_b(M, E_M)$ may not be connected.

Step 2:

- If there is a constraint on the maximum hop count from any terminal node to its closest backbone node, add new backbone nodes to the set M as necessary so that the hop constraint denoted by ρ is not violated.

Step 3:

- Add new backbone nodes to the set M as necessary such that the backbone subnetwork $G_b(M, E_M)$ becomes connected.

Suppose there exists an algorithm, *Alg-basic (n, r, R)*, to solve the basic bounded edge-length Steiner tree problem, where n is the set of nodes that needs to be connected by a Steiner tree, r and R are the respective edge-length bounds of terminal nodes and backbone nodes. Then solution $M =$ *Alg-basic* (N, δ, Δ) will give us the set M of the initial Steiner nodes (*i.e.,* backbone nodes) when the set of terminal nodes is given as the input to the algorithm. At this step, note that the overall network is connected but the backbone subnetwork $G_b(M, E_M)$ may not be a connected network with the edge-length bound Δ. In the second step, we need to associate each of the terminal nodes to a backbone node via the minimum number of ad-hoc hops. In order to avoid undesirably large number of ad-hoc hops from a terminal node to its closest backbone node, it is necessary to have a bound ρ on it. However this bound may require extra backbone nodes to be added to the network. For this purpose, we use a simple algorithm denoted as $C =$ *Alg-hop*(N, M, ρ) to fulfill the task above. Specifically, this algorithm does a depth-first search on the Steiner tree, counts the number of hops from the current terminal node to the closest backbone, adds an additional backbone node in the proximity of this terminal node if the bound is exceeded.

In the final step, in order to make $G_b(M, E_M)$ connected, we call the *Alg-basic* algorithm again but with a different

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[2] We assume that transmission range between backbone nodes and terminal nodes is equal to the one between the terminal nodes.

set of inputs. Specifically, we replace the terminal node set with the backbone node set obtained from the previous steps and look for additional backbone nodes to connect them when all nodes have the same transmission range Δ. Then, the solution $m = \textit{Alg-basic}(M,\ \Delta,\ \Delta)$ gives us the additional backbone nodes m that will be added to the backbone node set M in order to make the backbone network connected.

A. Algorithms for the bounded edge-length Steiner tree problem: (Alg-basic (n, r, R))

There are a few heuristic algorithms proposed for the bounded edge-length Steiner tree problem with a good approximation ratio [6], [7], [8]. However, as discussed before these heuristics does not consider the heterogeneous transmission ranges of terminal and backbone nodes. For this purpose, we have extended the existing solutions to consider this heterogeneity as described below.

1. *Minimum Spanning Tree (MST) heuristic* :
   This algorithm has two steps. In the first step, it generates a minimum spanning tree to connect all the $|N|$ terminal nodes. Then, in the next step, it inserts Steiner nodes (as many as needed) along the edges whose distance exceeds the transmission bound δ. Note that, along such an edge, the distance between the end terminal node and its neighboring Steiner node should be smaller than δ, but the distance between two neighboring Steiner nodes should be smaller than Δ.

2. *Shortest path tree (SPT) heuristic* :
   The algorithm starts from a terminal node as the initial subtree. Let us denote the terminal nodes that are currently not included in the subtree as free terminal nodes. It then iteratively updates the subtree by adding a randomly selected free terminal node at a time. The new terminal node is connected to the subtree either (1) directly if the *smallest* Euclidean distance between the free terminal node and the nodes in the subtree is within the δ constraint; or (2) by adding new Steiner nodes along the new edge if the distance exceeds the δ constraint.

3. *Shortest shortest path tree (S-SPT) heuristic* :
   Similar to the SPT, this algorithm also starts from a terminal node as the initial subtree. However, instead of picking up a random free terminal node, it calculates the shortest distance from every free terminal node to the current subtree and picks up the one closest to the subtree to form the new subtree. Again, the new node will be connected to the subtree either directly or by adding extra Steiner nodes along the new edge under the transmission range constraints.

IV. NUMERICAL RESULTS

In order to gain more insight on the problem and verify the performance of the algorithms above, we present results from comprehensive simulation studies on a large range of different design parameters. In all simulations, the terminal nodes are randomly distributed in a 12000 × 12000 two-dimensional plane. The default maximum transmission ranges of backbone nodes and terminal nodes are 2500 and 500 respectively.

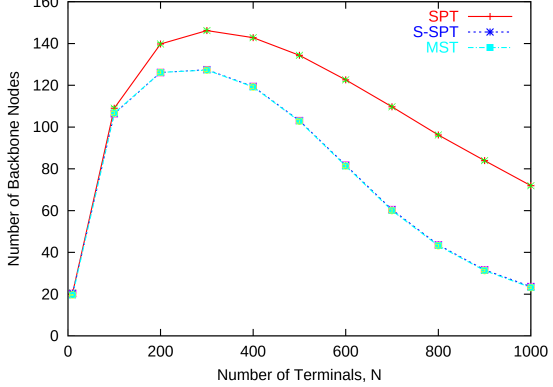

Figure 2: Backbone nodes M vs. Terminal nodes N, δ=500, Δ=2500

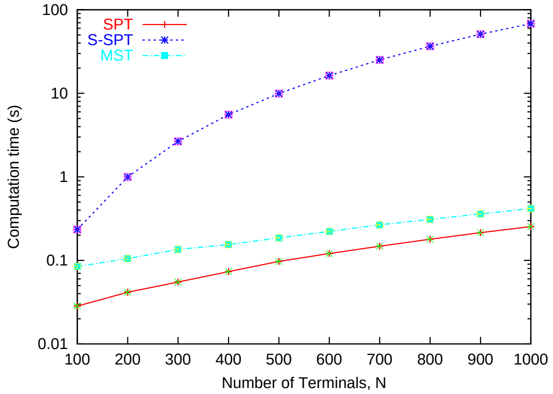

Figure 3: Computation time vs. Terminal nodes N, δ=500, Δ=2500

The results are averaged over 300 independent simulation runs and presented with the 95% confidence interval, where each simulation is obtained from a different random terminal node distribution.

Figure 2 shows how many backbone nodes are needed for different number of terminal nodes. In the first set of experiments, we did not put any constraint on the number of hops for the terminal nodes to reach to the backbone, *i.e.*, $\rho = \infty$. For small number of terminal nodes, in all three algorithms we need more backbone nodes to make the network connected as we increase the number of terminal nodes. However, after a certain point (roughly 300 in this result), the number of backbone nodes required begin to decrease sharply. This is due to the fact that more terminal nodes are within each other's transmission range and therefore connectivity is achieved without the help of extra backbone nodes. This result clearly demonstrates the scalability of backbone-based wireless ad-hoc network with large number of terminal nodes. Note that in general, the performance of S-SPT is at least as good as MST or better. This is due to the fact that MST adds the backbone nodes after the spanning tree is completed. On the other hand, S-SPT adds the backbone nodes during the calculation of the steiner tree. This actually, allows free terminal nodes to connect to the backbone nodes in the current subtree in addition to the terminal nodes in the subtree, and therefore increases the possibility of having a lower cost tree. However, it does not bring in much gains in terms of number of backbone nodes as we can see from Figure 2.

Another point we would like to point out is that the 95%

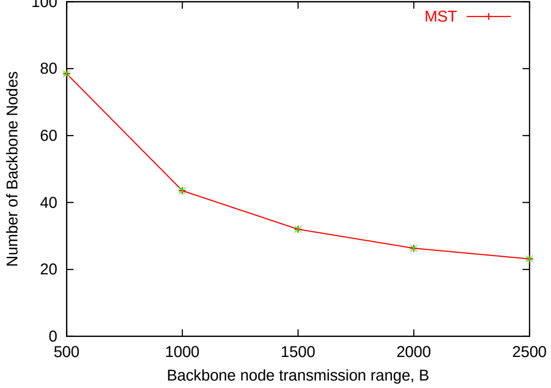

Figure 4: Backbone nodes M vs. Backbone node transmission range Δ, N=1000, δ=500

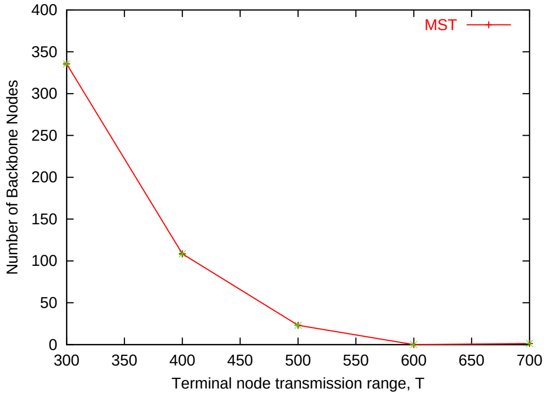

Figure 5: Backbone nodes M vs. Terminal node transmission range δ, N=1000, Δ=2500

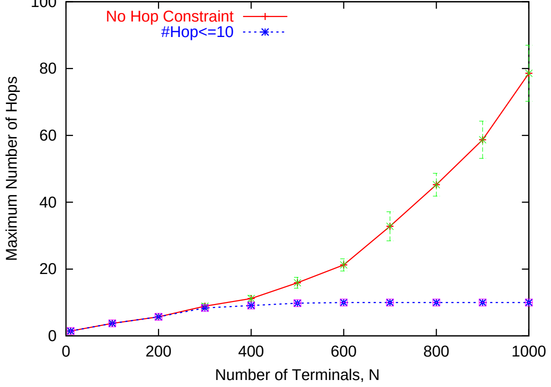

Figure 6: Maximum hops vs. Terminal node N, δ=500, Δ=2500, MST algorithm

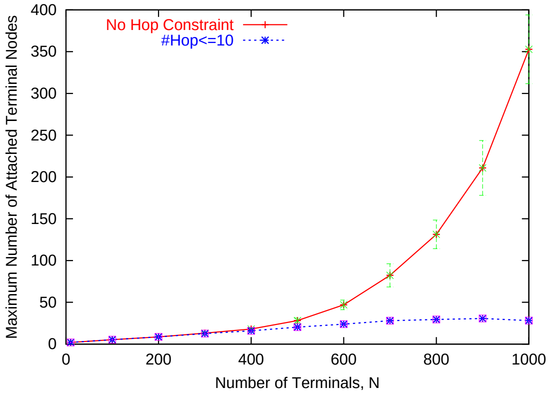

Figure 7: Maximum Number of Terminal Nodes attached to a backbone node vs. Terminal node N, δ=500, Δ=2500, MST algorithm

confidence interval is so tight that is hardly observable. This suggests that the result is not sensitive to the positional distribution of the terminal nodes, which is a very desirable result if the mobility of the terminal nodes is considered.

Figure 3 shows the computation time of the three algorithms. Combining the results from the two figures above, MST turns out to be a better alternative compared to other heuristics as its computational complexity is much lower. Therefore, from now on we will present additional results only using the MST algorithm.[3]

In Figure 4 we examine the number of backbone nodes required when the backbone node transmission range is varied while the number of terminal nodes is fixed to 1000. We observe almost an exponential decrease in the number of required backbone nodes with increasing transmission range. However, after reaching a certain value (2500 in this case), almost no more additional backbone nodes is needed. The rationale behind this is that even though backbones can talk to each other over longer distances, they still need to communicate with the terminal nodes over the shorter transmission range and this limits the decrease in the number of backbone nodes required. This idea is supported by the results presented in Figure 5 where we vary the terminal node transmission range. As we start to increase the terminal node transmission range, number of backbone nodes required decreases sharply. These two results are important in the sense that they can help us deciding on reasonable transmission ranges for both backbone and terminal nodes.

In the following figures we observe three other important topology characteristics from the simulation. Figure 6 shows that there is a quadratic relationship between the number of terminal nodes and the maximum number of hops (H) required for a terminal node to reach its closest backbone node. The same observation holds for the maximum number of terminal nodes attached to a backbone node as shown in Figure 7[4]. This is obviously an unscalable performance. Therefore, we need to put a constraint on H by using the algorithm $Alg-hop(N, A+B, \rho)$ with the additional cost of increased number of backbone nodes. Figure 6 together with Figure 9 allow us to observe this trade-off. Clearly, we can see that when there is no constraint on the maximum number hops for a terminal node to reach a backbone node, the ad-hoc paths can get quite long. In addition, a backbone node may have to serve a large number of terminal nodes. On the other hand, a limit on the the maximum hop count may require more backbone nodes to be added, though the increase is rather moderate.

Figure 8 shows the maximum degree of backbone node in

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[3] We have used the code from [9] to obtain the minimum spanning tree for a given set of points geometrically distributed in a Euclidean plane.

[4] A terminal node t is assumed to be attached to a backbone node b if it is at most ρ hops away from b and there is no other backbone node that is closer to t. If a terminal node is equidistant from more than one backbone node, a tie braking rule is applied.

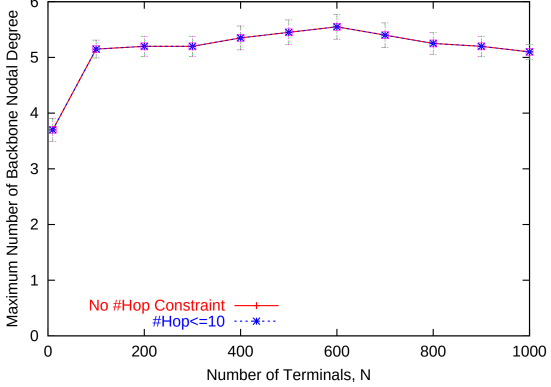

Figure 8: Maximum Backbone Network Nodal Degree vs. Terminal node N, δ=500, Δ=2500, MST algorithm

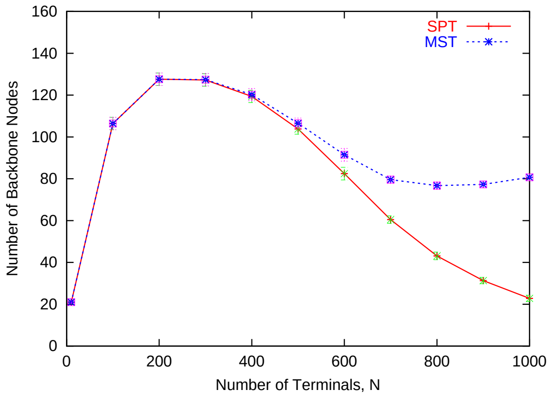

Figure 9: Backbone Nodes vs. Terminal node N, δ=500, Δ=2500, ρ=10, MST algorithm

the network (*i.e.*, one hop neighbors in the topology). Recall that in a regular minimal Steiner tree problem each steiner node should have a degree of 3 [7]. However, in that problem the objective is to minimize the summation of the edge lengths. On the other hand, our primary objective is to minimize the number of backbones needed. In other words, we would like to connect as much terminal node clusters[5] as possible using a backbone node. However, a simple analysis shows that, using a single backbone node, we can at most connect 5 clusters of terminal nodes. This can be easily seen by the fact that each cluster should be away from each other with a distance more than the terminal node transmission range r_{tn} while the distance between the backbone node and each cluster should be smaller than or equal to r_{tr}. Figure 10 illustrates this fact. Indeed, our simulation results confirms this result as the maximal degree is almost constant around 5, verifying that we use minimal number of backbone nodes in order to have a connected topology. Note that the maximal degree is slightly larger than 5. This is because in addition to the overall network, the backbone topology is required to be connected. Hence, every backbone have at least one backbone neighbor causing the maximum backbone node degree to be slightly higher than 5.

This is very desirable for the case where the backbone nodes

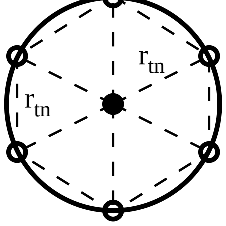

Figure 10: A backbone node located at the center having 6 terminal node neighbors. Terminal nodes are apart from each other as well as from the backbone node with a distance of r_{tn}; the terminal transmission range. Note that, terminal nodes are already connected without the backbone. Hence, a backbone node can connect at most 5 disconnected terminal node clusters.

have directional or FSO antennas since it means that a small number of interfaces is sufficient for the backbone nodes irrespective of the number of terminal nodes existing in the network.

V. CONCLUSION

In this paper, we study the problem of designing the optimal topology for backbone based hybrid wireless ad-hoc networks. The problem is formulated as a generalized optimal geometric Steiner network problem with minimum number of Steiner nodes under the various practical constraints. In this new problem formulation, the backbone (Steiner) nodes have two heterogeneous transmission ranges, one for connecting to the terminal nodes and the other for connecting to other backbone nodes. The overall network and the backbone network are both connected. We also consider the case when the number of hops from a terminal node to its closest backbone node is constrained. As the problem is NP-hard, we propose a multiple-step solution approach and compare several heuristic algorithms by a comprehensive simulation study. In addition to the number of backbone nodes needed to be added, we also obtained results on a few important topological characteristics, such as the maximum number of hops (H) required for a terminal node to reach its closest backbone node, the maximum number of terminal nodes attached to a backbone node, and the nodal degree within the backbone network. The results show that a highly scalable backbone network can be built for a large number of terminal nodes.

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[5] A terminal node cluster is a connected graph of a subset of terminal nodes, which are already connected without use of a backbone node.

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