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Improving Lifetime of Wireless Sensor Networks

Michael Segal

Communication Systems Engineering Department

Ben-Gurion University of the Negev, Beer-Sheva, Israel

Tel: +972-8-6472210 E-mail: segal@cse.bgu.ac.il

Abstract

A wireless sensor network consists from a collection of transceivers positioned in the plane. Each transceiver is equipped with a limited battery charge. The battery charge is reduced after each transmission, depending on the transmission distance. One of the major problems in wireless ad hoc network is designing a route network traffic algorithm that will maximize the lifetime of the network i.e., the number of successful transmissions. Our objective is to construct a broadcast routing tree rooted at the source node with the longest possible lifetime. We perform a simulative study of the problem and show an improvement to currently existing BIP algorithm [18].

Keywords: sensor networks, energy-efficient algorithms, lifetime problem; low power algorithms and protocols.

1. Introduction

A wireless ad hoc network is a collection of transceivers positioned in the plane. Our study concentrates on wireless sensor networks. Such a network is made up of a large number of sensors deployed randomly in an ad hoc manner in the area/target to be monitored.

The technology of sensor networks has the potential to change the way we interact with physical environments. For example, inexpensive tiny sensors can be embedded or scattered onto target environments in order to monitor useful information in civil or military situations.

In our study we are interested in *broadcast* transmissions. In a broadcast transmission, a message originated from a source node needs to be forwarded to all the other nodes in the network. Each node is equipped with omni-directional antenna. This means that the transmission of some node is received by all the nodes within the transmission range. In the cases where the communicating sensors are out of reach, they need to rely on intermediate sensor nodes to relay the data back and forth between sensors.

Every node v has a limited, non-replenishable initial power charge (battery) $b(v)$. The battery charge is reduced after each transmission, depending on the transmission distance. Hence, energy efficiency becomes a crucial factor in wireless network design.

In our work, we are interested in maximizing the *network lifetime*, i.e., maximizing the number of successful transmissions, by routing the network traffic efficiently, until the first node failure due to battery depletion. The definition of the network lifetime as the time of the first node failure is a meaningful measure in the sense that a single node failure can make the network become partitioned and further services to be interrupted.

In a wireless network, there is always a tradeoff between reliability and network lifetime. Let us observe two topologies. One is flooding (uncontrolled topology) where the network is most reliable at the cost of minimal network lifetime. The other is a spanning tree. Since spanning tree is the minimal graph structure supporting the network connectivity, it is clear that a connected topology which maximizes the network lifetime under transmissions should be a tree.

There are 2 different formulations of the maximum network lifetime problem (MLB). In the discrete version node v can transmit at most $\lfloor b(v)/d^{\alpha} \rfloor$ times, where α is a distance power gradient. In the fractional version, transmission from node v to distance d is valid for $b(v)/d^{\alpha}$ time units. In this paper we will consider the discrete version. We also will focus omni-directional type of antenna: a single message transmission to the most distant node in a set of nodes is sufficient that all the nodes in the set will receive the message.

In a **general broadcast lifetime problem**, we are given a source node and wish to maximize the number of successful broadcast message propagations, while satisfying the battery constraint. Our objective is to construct a broadcast routing tree rooted at the source node with the longest possible lifetime. Figure 1 shows different variations of the problem and the resulting solution for them. In fact Figure 1 shows that the careful choice of broadcast tree may lead to an increase in the network lifetime (1(b) and 1(c)). Moreover, it can be seen that if we allow to use many broadcast trees (in our case 2) instead of one single broadcast tree, we also can obtain an increase in the network lifetime (1(d)).

We are interested in the following relaxation of the above-mentioned problem. We are given a complete undirected graph, initial battery charges, and a sequence of *m* sources nodes. Each of the sources nodes has one message to broadcast to all other nodes. We aim to maximize the number of successful broadcast transmissions, i.e. maximize the number of broadcast trees rooted at the nodes of given sequence until the first node runs out of energy. The problem is very important in wireless sensor networks when the nodes periodically broadcast information to other nodes in the network, thus, consuming energy at each transmission.

1.1 Previous work

The authors in [1] show that for broadcast, the problem is NP-Hard in the case of single source and has a polynomial solution for fractional version when allowing multiple topologies for single source. They also show that it is NP-Hard in both of these cases for multicast. Segal [2] improved the running time of the solution for the broadcast protocol and also showed an optimal polynomial time algorithm for the integral version of convergecast (the reverse of broadcast). For multiple topology convergecast fractional version Kalpakis et al. [3] does have a polynomial solution in $O(n^{15} \log n)$ time. To counter the slowness of the algorithm, Stanford and Tongngam [4] proposed a (1-*e*)-approximation in $O(n^3 \frac{1}{e} \log_{1+e} n)$ time based on the algorithm of Garg and Konemann \cite [5] for packing linear programs. Elkin et al. [6] gave an $\Omega\left(\left\lfloor \frac{1}{\log n} \right\rfloor\right)$-approximation for the discrete version of multiple topology convergecast problem. Additional theoretic results can be found in [7-14].

The problem has been received also an extensive attention in experimental evaluations of the suggested methods. In [18], the authors propose a global knowledge scheme called broadcast incremental power (BIP) algorithm. A simple improvement to the BIP algorithm called broadcast average incremental power (BAIP) was proposed in [12]. In this method, the metric considered when adding a new node to the tree is the average incremental cost, which is defined as the ratio of the minimum additional power increased by some node in the current tree to reach some new nodes to the number of these new nodes. Chiganmi et al. [15] presents a novel approach, called INOP, for network wide broadcast. INOP is a variable power broadcast approach that uses local (two-hop neighborhood) information. Cartigny et al. [16] gives localized protocol where each node requires only the knowledge of its distance to all neighboring nodes and distances between its neighboring nodes (or, alternatively, geographic position of itself and its neighboring nodes). Hua and Yum addressed the problem of jointly optimizing data aggregation and routing so that the network lifetime can be maximized using the recursive smoothing method. Other results can be found in [19-21].

1.2 Our contributions

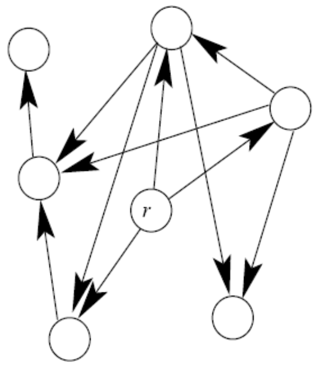
We will analyze BIP - broadcast incremental power algorithm (and its improvement) for receiving spanning trees from the point of view of the lifetime performance. Analysis and comparison will be done using the simulator OMNET. Each node will have its initial battery energy level. This initial battery energy level will be drawn according to specified probability distribution, e.g, uniform distribution with unit ranging from any minimum value to some maximum value. We also show that our modified algorithm performs better in simulation than BIP. We built our simulations using the OMNET tool.

2. Improved BIP algorithm

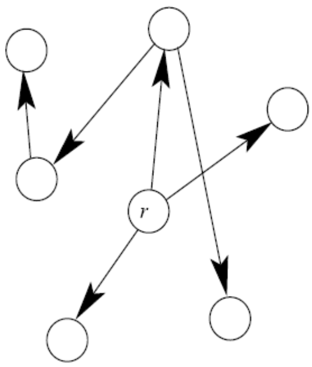
We base our new solution on a popular broadcast incremental power (BIP) algorithm [11] which builds a spanning tree with total minimum energy to spend for future use. The total energy of the spanning tree is calculated as the sum of all nodes' transmissions. We start with the explanations about BIP solution. The algorithm starts at some node called the source node. In each step it adds a new node, the cheapest one, to the tree. Cheapest refers to the node that requires the least energy to be reached. BIP is based on the Prim algorithm for constructing a minimum spanning tree, having one fundamental difference. Whereas the inputs to Prim's algorithm are the link costs (which remain unchanged throughout the execution of the algorithm), BIP must dynamically update the costs at each step. This is because the fact that the cost of adding new nodes to the transmitting node's list is the update of the incremental cost.

BIP has designed for constructing one tree, one broadcast message. It did not fit exactly to our objective, since we are given a sequence of sources. Each source has a broadcast message to transmit to all other nodes. Thus, we need to implement a heuristic algorithm which maximizes the number of successful broadcast message propagation while satisfying the battery constraints. In our improvement solution we have assumed that the initial energy is identical to all the nodes in the network.

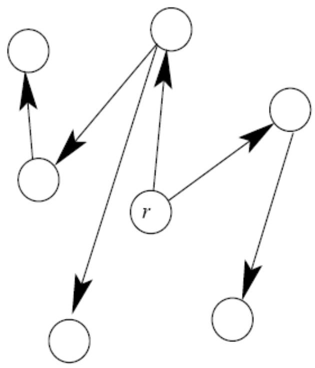
For each newly arriving broadcast session request, we first construct a minimum energy tree using BIP algorithm. In addition to the battery charge of each node, we determine a threshold value which a node cannot pass. Node that its battery charge reaches this threshold value, will not serve as a relay in the next spanning tree construction. If all the remaining nodes reached the threshold value, this value will be decreased in 10%. This allows us controlling the energy consumption, in order to avoid situation of wasting unnecessary battery charge. In addition we apply the following strategy previously described at [12]. At node u, our strategy finds the nodes that lie within u's transmission range, but are currently not child nodes of u. Assigning such nodes (except those being upstream nodes of u) to be child nodes of u may result in power saving at the current parents of these nodes. We refer to our method as an *improved BIP sweep strategy*.



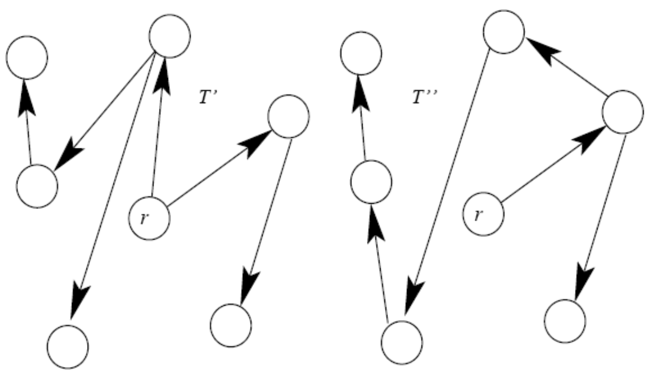
a) G=(V,E), b(v) = 6, w(e) =1.



b) Single Topology Broadcast Tree. Lifetime=2, since r can be activated only twice.



c) Single Topology Optimal Broadcast Tree. Lifetime=3.



d) Multiple Topology Optimal Broadast Trees: T' and T''
Lifetime=4, by running twice T' and twice T''.

Figure 1: Different types of broadcast lifetime problem.

Algorithm sweep goes through all nodes in vertex set according to some order (e.g., the natural order 1,2, . . .,N). Applying sweep more than once may lead to further improvement. Typically, however, the improvement obtained from additional rounds of sweep is very small [18]. Moreover, algorithm sweep has a quadratic time complexity [22] since for each node we have to check what nodes lie in its transmission range. We can reduce time complexity by using the following observation. Our problem is the range searching problem where every range is a disk of certain radius. It is well known that range searching with balls in the plane can be formulated as an instance of halfspace range searching in 3-dimensional space. The technique is called *linearization*, see [23]. The halfspace range searching problem in d-dimensional space is defined as follows. Given a set of n points in d-dimensional space, build a data structure that allows us to determine efficiently how many points lie in a query halfspace. We will use a data structure, called *partition tree*, being proposed by Matoušek [24] that is based on simplicial partition for a set of points, can be build in $O(n\log n)$ time and $O(n)$ space and answers queries with updates in $O(n^{1-1/d+\varepsilon}+k)$ time. In our planar case, it becomes $O(n^{1/2+\varepsilon})$. Overall, by utilizing this data structure we obtain the total running time for sweep procedure to be $O(n^{3/2+\varepsilon})$ which is better than previously known bound by almost $O(\sqrt{n})$ factor.

3. OMNET

OMNET++ is a public-source, component-based, modular and open-architecture simulation environment with strong GUI support and an embeddable simulation kernel. Its primary application area is the simulation of communication networks and because of its generic and flexible architecture, it has been successfully used in other areas like the simulation of IT systems, queuing networks, hardware architectures and business processes as well.

OMNET++ provides component architecture for models. Components *(modules)* are programmed in C++, and then assembled into larger components and models using a high-level language *(NED)*. Reusability of models comes for free. OMNET++ has extensive GUI support, and due to its modular architecture, the simulation kernel (and models) can be embedded easily into the applications.

The parameters we observed over the simulations are: the total energy of the constructed trees, the number of messages sent over the simulation and the most important parameter that influences the whole simulation is the number of successful broadcast sessions through the simulation.

4. Simulation and results

In this section we investigate the efficiency of our improved algorithm. In order to provide explicate results, we ran a lot of simulations with different varying parameters such as the initial battery power of the node, the maximum distance between nodes, and the highest value of threshold that can be used in the specific simulation. Moreover, we checked how the change of those parameters reflects on a dense or long- range network. The topologies we explored are: random graphs and mesh graphs.

Each specific set of parameters have been tested over 100 different random topologies.

<u>Simulation characteristics:</u>

- Number of nodes in a network 100.
- All the nodes have identical initial battery charge in the range [70-150].
- MAX = Maximum distance between nodes in range [10-50].
- Path loss alpha 2.
- 2 kinds of topologies: Random and Mesh.

5.1 Random topology

In this section we present the results we received by testing a random topology. The topology is considered random because the distances between the nodes were drawn uniformly between 0 and the maximal distance between the nodes (MAX). As was mentioned before, the maximal distance between the nodes is one of the varying parameters tested in our simulation. The total energy sum is referred as the sum of all nodes' transmissions.

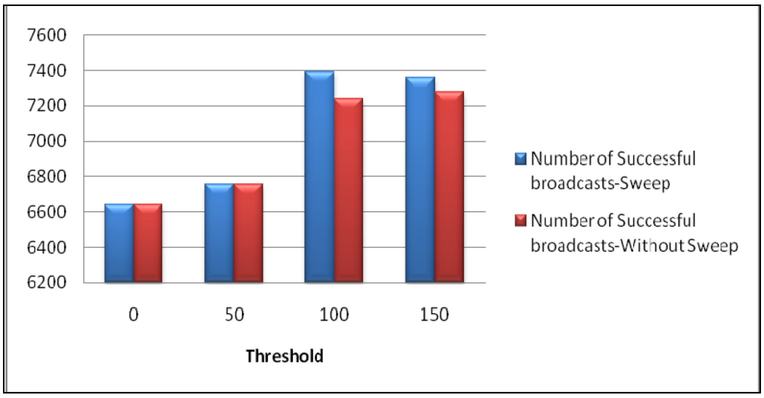


Figure 2. Sweep method improves BIP performance for random networks.

The hop-diameter distance (the number of edges in the longest path of the connected graph) in our experiments varied in the range from 3 to 15, averaging at 8, while the degree of each node in most cases guaranteed to be at least 7, following the well-known fact from [25] that in order to guarantee the connectivity in a network with n nodes with high probability, the degree of every nodes should be at least $\lceil \log n \rceil = 7$. In our setting the nodes initiated broadcasts randomly (up to fixed number of times, varied between 1 and 5), until every node served as the source. Then, this procedure repeated over the time.

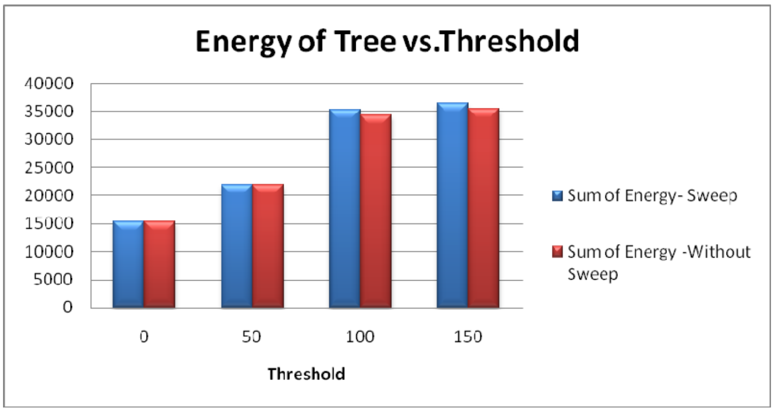


Figure 3. Sweep method produces better lifetime trees.

It can be seen from both Figure 2 (number of successful broadcasts) and Figure 3 (number of successful nodes' transmissions), that at each threshold value the number of successful broadcasts and the total number of node's transmissions with the usage of the improved BIP sweep strategy is more than the number without the usage of the sweep procedure. We also observe that we have a good percentage of nodes that succeeded to transmit according to Figure 4. This happens since we are controlling the energy consumption in order to avoid situation of wasting unnecessary battery charge as it happen in standard BIP scheme.

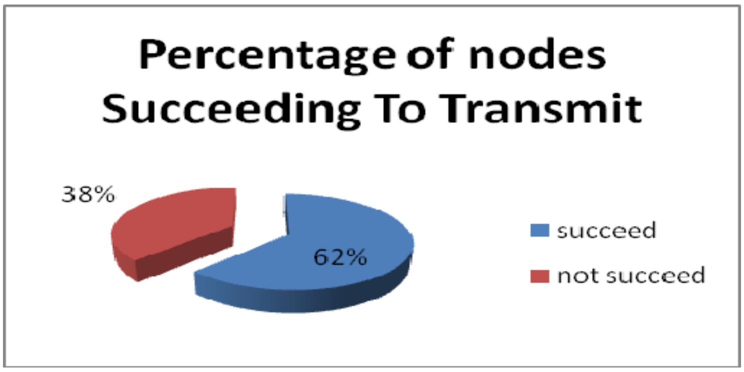


Figure 4: Percentage of successful and unsuccessful nodes' transmissions for random graphs

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In addition we have checked whether the number of successful transmissions changes depending on the threshold change in the random network with relatively large (more than 10) hop-diameter (maximal number of hops between any two nodes). As we can see from the Figure 5 below we did not found any improvement in terms of the number of broadcasts in this case.

5.2 Mesh topology

We have obtained slightly different results (still inclined towards the improved sweep BIP version) while considering mesh topology.

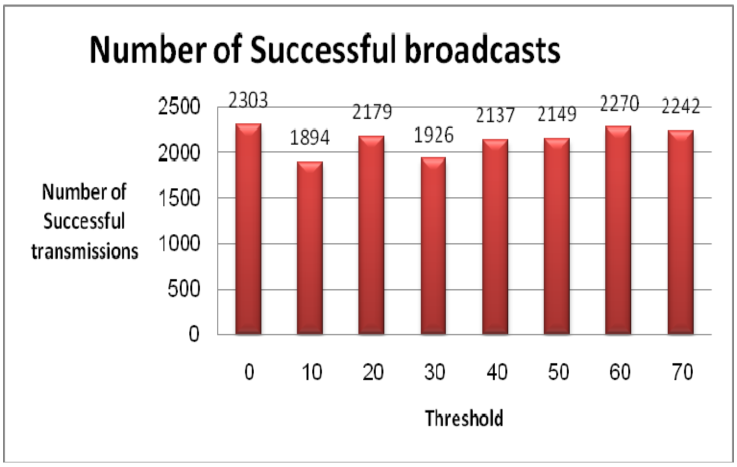

Figure 5. Number of successful broadcasts for different threshold values in random graphs.

We can learn from the Figure 6 below that the number of transmissions is almost the same while comparing the two methods. This can be explained by the fact that the sweep strategy does not improve the energy performance of the broadcast protocol for random networks [12], even of improved time complexity that can produce better solution in terms of energy waste.

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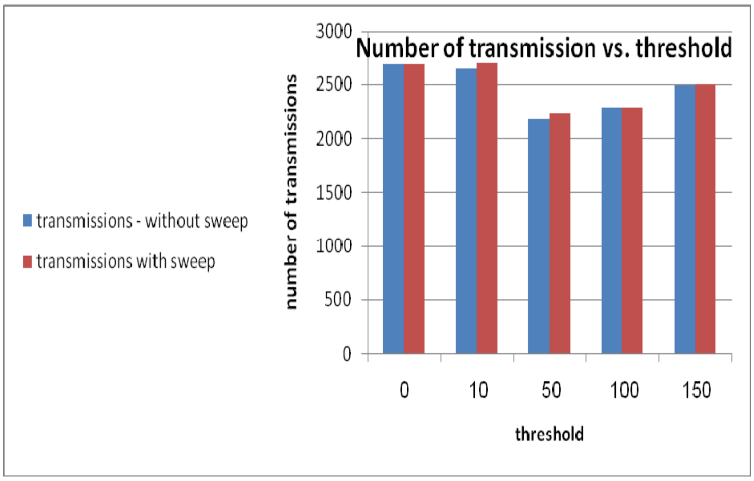

Figure 6. Dependence between the number of transmissions on threshold value in mesh network.

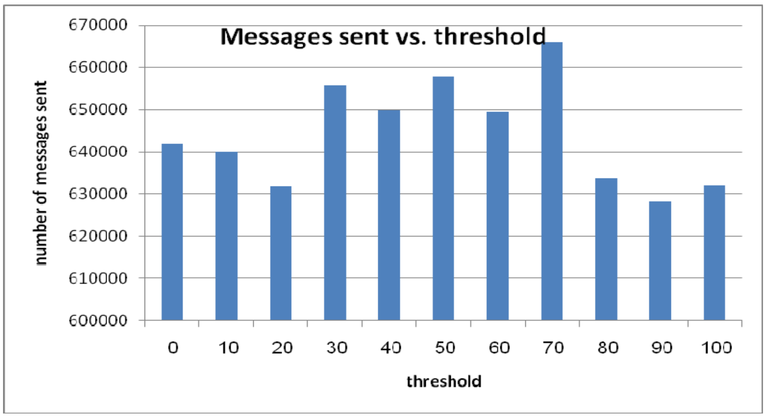

Figure 7: Number of messages sent depending on threshold value (initial battery charge is 100)

Figure 7 shows us that the best value of threshold that leads to an increase in the number of message transmissions has been achieved while being in the range of 1/3 to 2/3 of the initial battery nodes' charge (i.e. between 30 to 70, while the initial battery charge is 100).

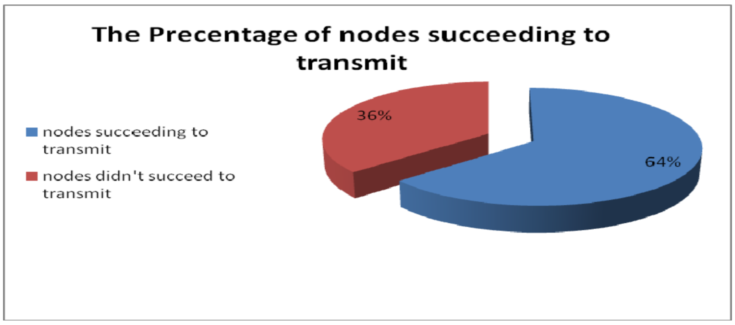

Figure 8: Percentage of successful and unsuccessful nodes' transmissions for mesh graphs

Similarly to the case of random graphs, we observe that we have a good percentage of nodes that succeeded to transmit according to Figure 8. Moreover, according to Figure 9, the best value for the threshold in this case is to be between 30%-70% of initial maximal battery charge.

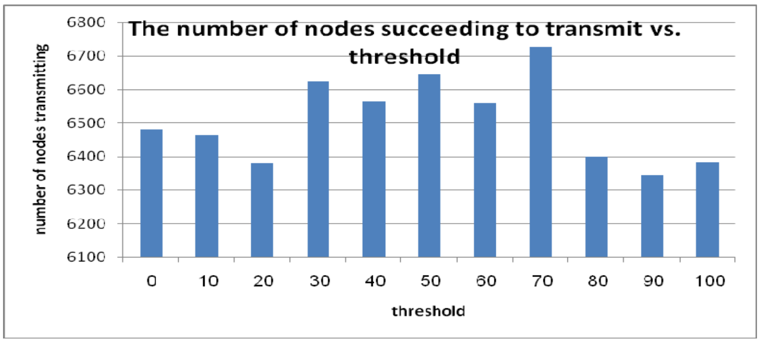

Figure 9. Number of successful transmissions for different threshold values in mesh graphs.

We can conclude from the above results that our suggested improved BIP sweep strategy method improves the performance of BIP algorithm. The simulations also indicate that it performs slightly better for random topologies than for mesh networks.

5. Conclusions

In this paper we analyzed by means of simulations the network lifetime problem for broadcast transmissions in sensor networks. We presented an improvement for well-known BIP algorithm while augmenting it with a threshold value decision function and modified sweep method. Our simulations have shown an improvement over the existing BIP solutions for random and mesh networks while the improvement has been more significant for the random networks.

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