International Journal of Networked and Distributed Computing, Vol. 2, No. 3 (August 2014), 189-197

Comparative Study of Various Wireless Sensor Network (WSN) Topology Construction Protocols

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Abstract

As the cost for wireless sensors and wireless sensor networks (WSNs) have decreased, they have become more ubiquitous; they are increasingly being used in many applications such as security, structural monitoring and environmental monitoring. Many WSN applications employ a random sensor deployment to provide sensor coverage. The choice of the Topology Construction (TC) and Topology Maintenance (TM) protocols will affect WSN lifetime. In this paper, two new load balancing TC protocols, SWST (Simple Weighted Spanning Tree), EAST (Energy Aware Spanning Tree) as well as three well known TC protocols, Simple Tree, Random Nearest Neighbor Tree (Random NNT) and Euclidean Minimum Spanning Tree (Euclidian MST), are studied using MATLAB and TC protocols such as A3 (A tree), A3 Coverage, Connected Dominating Set under Rule K (CDS Rule K), Energy Efficient Connected Dominating Set (EECDS), Simple Tree and K Neighbor (KNeigh) Tree, are simulated using Atarraya. Comparisons are performed between many of the TC protocols.

Keywords: Wireless Sensor Networks (WSNs), Topology Control, Topology Construction, Topology Maintenance, Energy Optimization, Energy Minimization, SWST, EAST, Connected Dominating Set, Atarraya

1. Introduction

Wireless sensor networks (WSNs) are commonly used for monitoring applications such as environmental, structural health and surveillance.[1-2] Sensor nodes are usually stand-alone devices that contain a sensor, limited power source, processing capability and a transceiver.[3-4] Wireless sensor network implementations need to exhibit maximum lifetime and sensor coverage while using little energy.[5] With more applications depending on WSNs for long-term monitoring, the development and study of Topology Construction (TC) protocols that exhibit maximum coverage or more efficient utilization of energy resources to increase network lifetime continue to be a research topic of great interest.[3-19] In a WSN implementation one first deploys the sensors, builds the topology and then updates and maintains the topology as needed.[3-4] Various simulation tools are available for studying WSNs. A few examples of simulators include a WSN simulator Atarraya,[3-4, 6-7], a network simulator ns-2[20], Prowler: Probabilistic Wireless Network Simulator[21-22] and other user developed WSN simulations coded[10-12] in MATLAB.[23] The network simulator ns-2 was utilized in Refs 24-25. Many examples in the literature study energy efficiency. Li, Huang and Xiao studied variant rate mobile sensor networks.[18] Shiu *et al* developed a distributed topology that would exhibit increased energy efficiency.[19] Other research covered other impacts of TC, such as on network capacity.[26] Nayebi and Sarbazi-Azad studied the effects of node mobility on the effective network's connectivity.[27] Xing, Lu and Pless use a configurable topology control. In their simulations, they used realistic models for the sensors.[28] In this paper, a comparison of various Topology Construction (TC) protocols including the following is performed: SWST (Simple Weighted Spanning Tree) and EAST (Energy Aware Spanning Tree), Random Nearest Neighbor Tree (Random NNT), Euclidean Minimum Spanning Tree (Euclidian MST), A3 (A tree), A3 Coverage, Connected Dominating Set under Rule K (CDS Rule K), Energy Efficient Connected Dominating Set (EECDS), Simple Tree and K Neighbor (KNeigh) Tree. The sections in the remainder of the paper are as follows: Section 2 discusses the various TC protocols utilized in this study, especially the SWST and EAST protocols, Section 3 includes simulations and Section 4 is the conclusions.

2. Topology Construction Protocols

The TC Protocols SWST (Simple Weighted Spanning Tree) and EAST (Energy Aware Spanning Tree), Simple Tree, Random Nearest Neighbor Tree (Random NNT), Euclidean Minimum Spanning Tree (Euclidian MST), A3 (A tree), A3 Coverage, Connected Dominating Set under Rule K (CDS Rule K), Energy Efficient Connected Dominating Set (EECDS), Simple Tree and K Neighbor (KNeigh) Tree are discussed in this section.

2.1 *Random Nearest Neighbor Tree (Random NNT)*[10-11, 29-30]

"The Random NNT is an effective method to create a low cost spanning tree. In this algorithm, nodes pick a random rank between 0 and 1 and connect to the closest node of higher rank." [11] Fig. 1 is an overview of the Random NNT algorithm. More detailed information can be found in Refs. 10-11 and 29-30.

2.2 *Euclidian Minimum Spanning Tree (Euclidean MST)*[10-11, 30]

The Euclidean MST reduces overall power consumption by attempting to reduce the transmission distance for a message. [10-11, 30] Fig. 2 shows the flow of the Euclidean MST protocol. More detailed information can be found in Refs. 10-11 and 30.

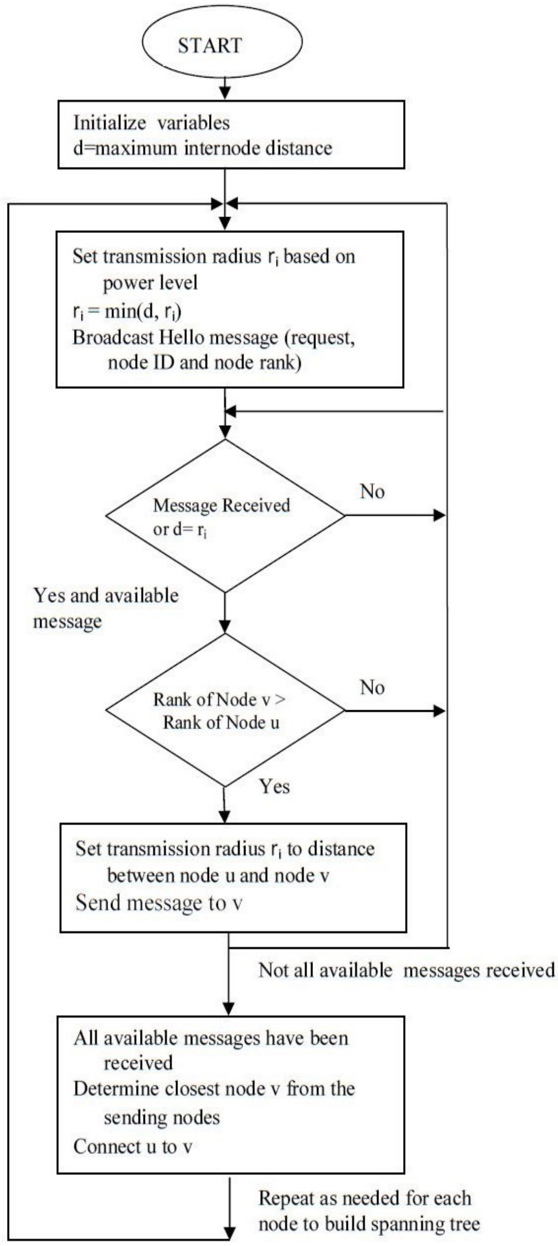

Fig. 1. Random Nearest Neighbor Tree.

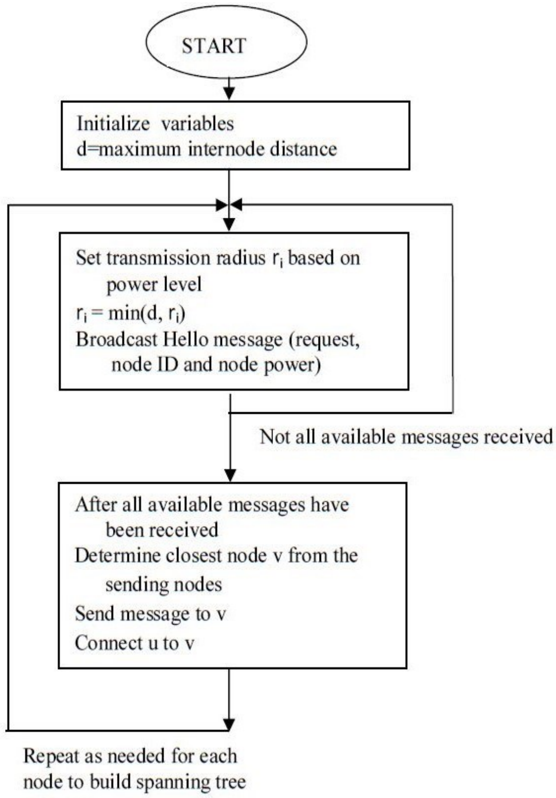

Fig. 2. Euclidean Minimum Spanning Tree.

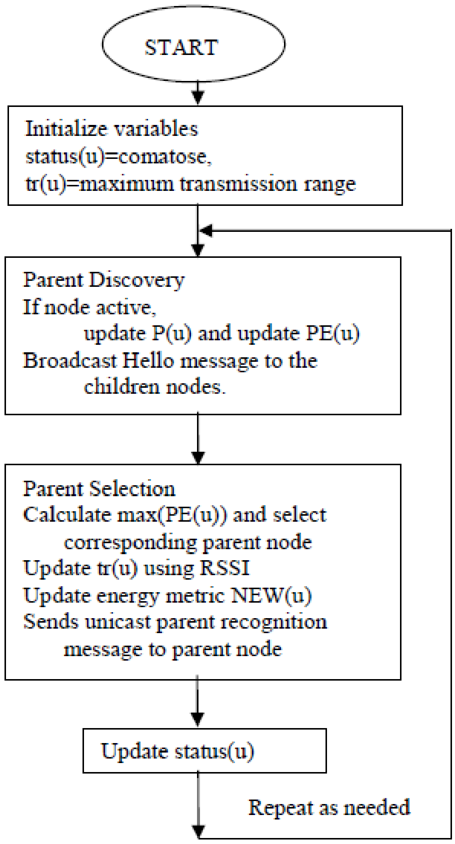

Fig. 3. EAST topology control algorithm.[31]

2.3 *Energy Aware Spanning Tree (EAST)* [10, 12 and 31]

The EAST protocol and the EAST protocol with neighborhood discovery are shown in Figs. 3 and 4. A more detailed description for each can be found in Refs. 10, 12 and 31. The following variables are utilized in Figs. 3 and 4. [10, 12 and 31]

EAST
- E(u)=remaining energy,
- status(u)=either active, sleeping or comatose,
- hop(u)=hop number,
- OEM(u)=old energy metric,
- NEW(u)=new energy metric,
- NE(u)=set of NEWs of neighbor nodes,
- PE(u)=set of NEWs of parent nodes,
- P(u)=set of parent node IDs,
- FP(u)=final parent node ID,
- N(u)=set of neighbor node IDs,
- tr(u)=transmission range.

2.4 *Simple Weighted Spanning Tree (SWST)* [10, 11 and 31]

The SWST protocol is shown in Fig. 5. A more detailed description for the SWST protocol can be found in Refs. 10, 11 and 31. The following variables are utilized in Fig. 5. [10, 11 and 31]

SWST
- E(u)=remaining energy,
- status(u)=either active, sleeping or comatose,
- D(u)=set of distances between the current node and the sender nodes,
- PE(u)=set of energy levels of the parent nodes,
- P(u)=set of parent node IDs,
- FP(u)=final parent node ID,
- tr(u)=transmission range,
- TEL=Threshold Energy Level.

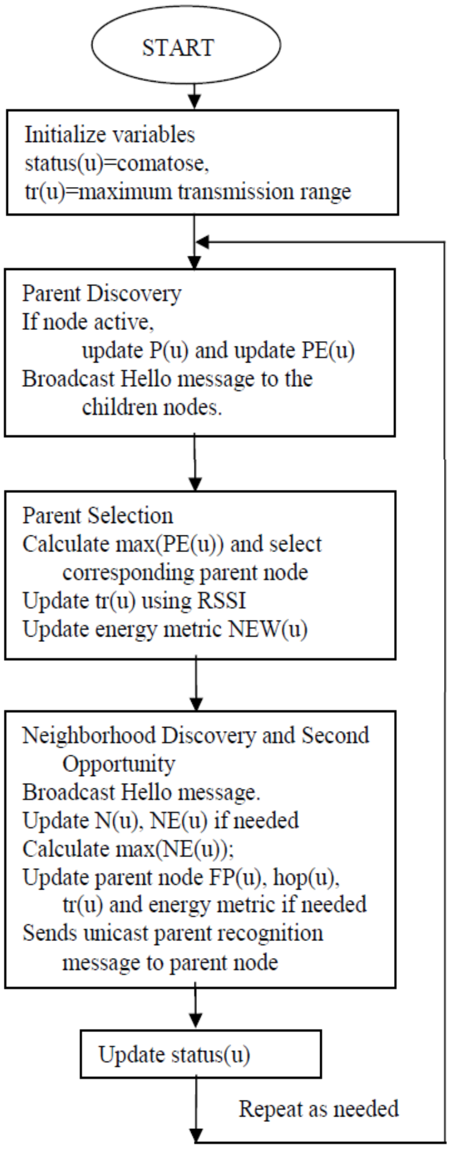

Fig. 4. EAST with neighborhood discovery topology control algorithm.[31]

2.5 Other TC Protocols[4,6]

The Atarraya WSN simulator[4,6] includes many more TC protocols. These include the following: A3 (A tree), A3 Coverage (A3Cov), Connected Dominating Set under Rule K (CDS Rule K), Energy Efficient Connected Dominating Set (EECDS), Simple Tree and K Neighbor (KNeigh) Tree. The K-Neigh protocol determines and connects the K closest neighbors.[4,6] For Connected Dominating Set under Rule K (CDS Rule-K), the protocol removes all the redundant nodes.[4,6] Energy

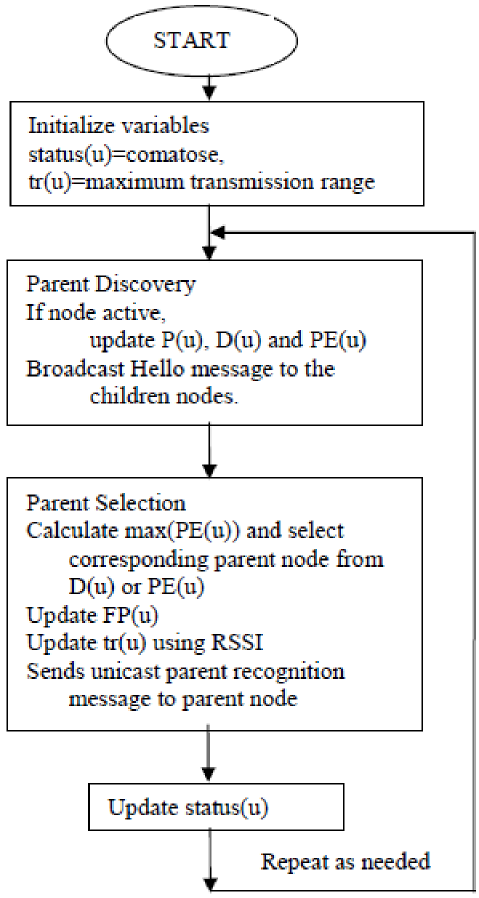

Fig. 5. SWST topology control algorithm.[31]

Efficient Connected Dominating Set (EECDS) determines "a maximal independent set in the first phase, and then selects gateway nodes to connect the independent sets.[4]" The A3 protocol creates "a non-optimal connected dominating set over an originally connected graph considering the remaining energy in the nodes and the distance between them.[4]" "A3Cov, based on the A3 protocol, … increases the coverage ratio considerably compared to the original version.[7]" More detailed information for these protocols can be found in Refs. 3-4 and 6-7.

3. Simulations

The Atarraya WSN simulator was utilized to evaluate the following TC protocols: A3 (A tree), A3 Coverage (A3Cov), Connected Dominating Set under Rule K (CDS Rule K), Energy Efficient Connected Dominating Set (EECDS), Simple Tree and K Neighbor (KNeigh) Tree. The Simple Weighted Spanning Tree (SWST), Energy Aware Spanning Tree (EAST), Simple Tree, Random Nearest Neighbor Tree (Random NNT), and Euclidean Minimum Spanning Tree (Euclidian MST) are simulated in MATLAB. The simulations for the various topology construction protocols utilize the node energy model found in Refs. 13 and 32. Dynamic Global Topology Recreation (DGTRec) was the topology maintenance protocol utilized in both sets of simulations.

Node Energy Model:[13, 32] "Energy used during transmission and reception is:

$$E_t(k,r) = kE_{elec} + k\varepsilon r^2 \quad (1)$$
$$E_r(k) = kE_{elec} \quad (2)$$

where, $E_t(k,r)$ and $E_r(k)$ is the transmitting and receiving energy required for k bit of data, E_{elec} is the energy needed to operate the transmitter radio, ε is the energy consumption of the radio amplifier per unit area and r is the variable transmission range.[12]" The input parameters shown in Table 1 were used to obtain the Atarraya simulation results shown in Table 2.[8]

TABLE 1.[8]
SIMULATION PARAMETERS

Parameters	Value
Sensor and Data Protocol	Simple
Routing/Forwarding Protocol	Forwarding
Deployment area	600m x 600m
Nodes	50
Node Distribution	Normal
Max. Energy of Node	0.050 Joule
Maximum Communication Range	100 m
Sensing Radius	20 m
Linear combination of matrices:	
W1, W2	0.5, 0.5
Inter query period	15 cycles
Inter-reset period	1000 Joules
Energy Threshold Limit	0.9

The ratio of energy spent is a measure of how much the protocol has consumed. Higher values indicate more energy utilized. "The average neighboring nodes around a given node will help determining the connectivity and coverage for a given sensor network. Node density indicates how well the network is connected and greater the value, more effective is the topology connected and vice versa.[8]" The Simple Tree and A3Cov exhibit the highest Average Number of Neighboring Nodes. The lowest ratio of energy spent values are for A3 and A3Cov. Simple Tree which has a higher degree of connectivity based on the Average Number of Neighboring Nodes has one of the highest energy spent ratios 0.97 for the tested cases. A more detailed and thorough analysis of a set of tested cases with varying Topology Maintenance (TM) protocols is found in Ref. 8. Thus the higher values of neighboring nodes imply a higher node degree. The higher energy spent ratio values will imply generally lower node degrees and neighboring nodes as more dead nodes will exist in the network. The network lifetime is increased by having low energy spent ratios and high average number of neighboring nodes; these two conditions though will usually be conflicting leading to tradeoffs in the WSN implementation.

Table 2. Ratio of Energy Spent for Topology Construction and Average Number of Neighbor Nodes[8]

TC	Average Number of Neighbor Nodes	Ratio of Energy Spent
A3	4.1	0.54
A3 Cov	4.6	0.65
CDS Rule K	3.6	0.78
EECDS	4.1	0.71
Simple Tree	4.3	0.97
KNEIGH Tree	4.0	0.97
Average Values	4.1	0.77
Standard Deviation	0.33	0.173

By increasing the maximum transmission range, the node degree will be increased as nodes have more choices for parent nodes.[11] "Changing the network density by deploying more nodes is an alternative way to increase the node degree of each node in the network.[11]" Either way will then raise the average number of neighboring nodes. The simulation parameters for the MATLAB simulations are found in Table 3. Figs. 6-10 were obtained using these parameters. More detailed and thorough analyses of the two algorithms EAST and SWST are found in Refs. 11-12, and 31 From Fig. 6 one can see that the SWST algorithm had more successful events (delivering messages to the sink node) than the Random NNT and Euclidean MST as the transmission range was varied, but in so doing utilized more energy. Fig. 7 demonstrates that as the transmission range is increased the EAST algorithm has more successful events than the

TABLE 3.[11, 12]
SIMULATION PARAMETERS

Parameters	Value
Deployment area	1000m x 1000m
Event number	2000
Time of simulation	2000 seconds
Number of events per unit time	1 event/second
Initial energy of the sink node	1000
Maximum transmission range of the sink	1000m
Topology Maintenance after the amount of time	200 seconds
Energy consumed to transmit message for maximum range	0.1 Joule
Energy consumed for listening in1 second	0.01 Joule

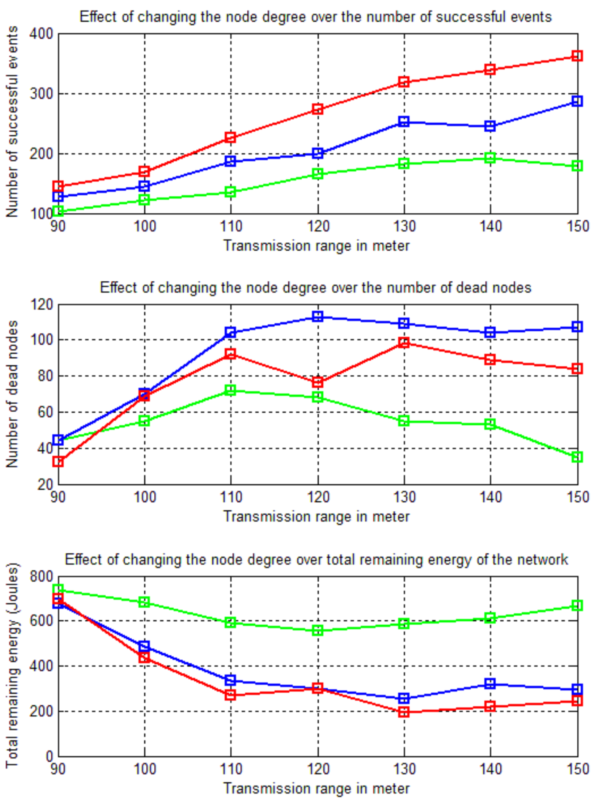

Fig. 6. The transmission range affects the total remaining energy, number of dead nodes and the number of successful events. Green, blue and red lines depict the protocols Random NNT, Euclidian MST and SWST.[11]

Simple Tree, Euclidean MST and Random NNT. Thus the average number of neighboring nodes and node degree should generally be higher for the EAST. This when taken with the data in Table 2 would imply that the EAST should have comparable or better neighboring node values and node degree when compared with the TC protocols found in Table 2 as the Simple Tree has one of the highest numbers of neighboring nodes in Table 2. Fig. 8 on the other hand shows that the energy required by EAST to start will be higher than Simple Tree.

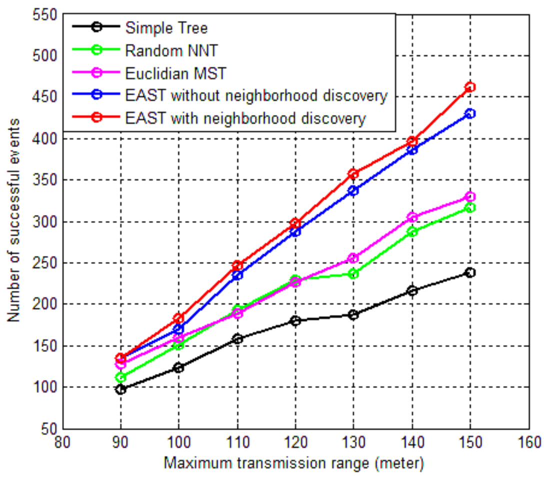

Fig. 7. The number of successful events as a function of the maximum transmission range.[12]

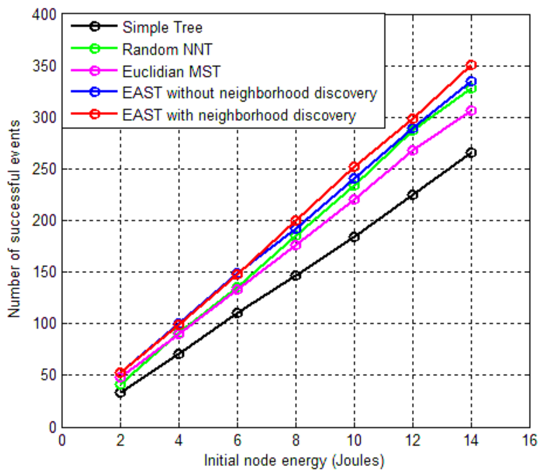

Fig. 8. The number of successful events as a function of the initial node energy.[12]

With data from another set of simulations shown in Fig. 9, one sees that the EAST algorithm has more successful events than the SWST given the same initial node energy. From Fig. 10, the EAST again generally exhibits higher number of successful events for the same transmission range. This again should generally mean a higher number of neighboring nodes and node degree. The EAST algorithm based on the results in Ref. 31 outperforms the SWST algorithm.

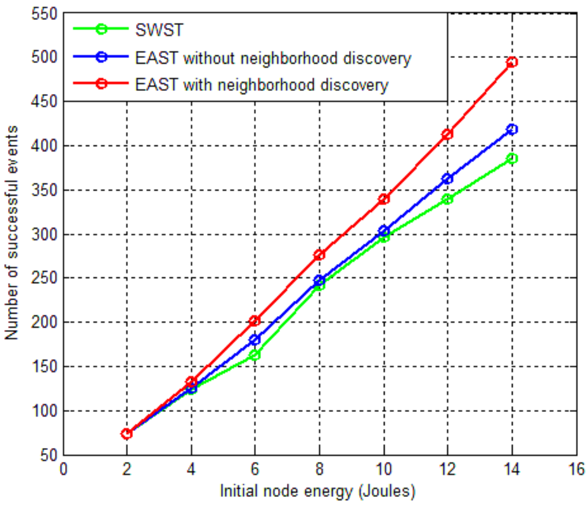

Fig. 9. The number of successful events as a function of the initial node energy for the SWST and EAST algorithms.[31]

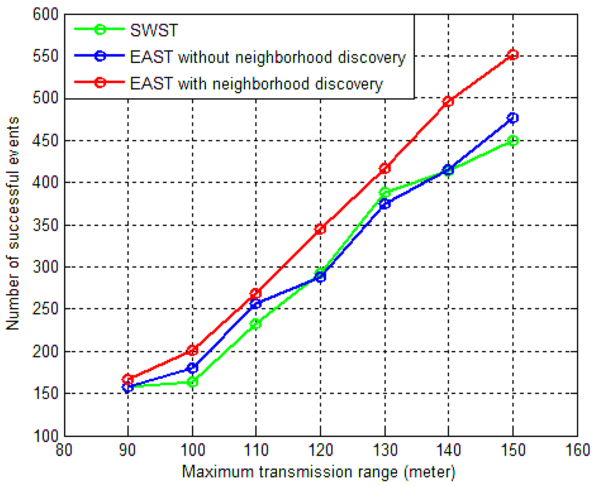

Fig. 10. The number of successful events as a function of the transmission range for the SWST and EAST algorithms.[31]

4. Conclusions

From the simulations, as the transmission range is increased the EAST algorithm has more successful events than the Simple Tree, Euclidean MST and Random NNT. This is expected as the child nodes will have more parent nodes to choose from. Thus the average number of neighboring nodes and node degree will generally be higher for the EAST. One also sees that the EAST algorithm with neighborhood discovery has more successful events than the SWST given the same initial node energy and for the same transmission range. The EAST algorithm should have comparable or better neighboring node values and node degree when compared with the TC protocols found in Table 2 as the Simple Tree has one of the highest numbers of neighboring nodes in Table 2.

Further work involves simulating with direct comparisons between the various topologies to validate the conclusions that were based upon the Simple Tree comparison. In addition, direct comparisons of remaining energy will enable the user to choose a more optimal network protocol from the TC choices.

Acknowledgements

The authors wish to acknowledge and thank Frank H. Dotterweich College of Engineering, the Department of Electrical Engineering and Computer Science and the Office of Research and Sponsored Programs at Texas A&M University-Kingsville for their support of this project.

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