Design and Optimization of Wireless Sensor Network with Mobile Gateway

Mukesh Shakya, Jianhua Zhang, Ping Zhang
School of Telecommunication Engineering,
Beijing University of Posts and Telecommunications, Beijing, China
Email: shakyamsh@hotmail.com

Mattias Lampe
Siemens Ltd., Beijing, China
Corporate Technology
Radio Access Technology and Solutions

***Abstract*—Conventional wireless sensor networks (WSN) convey information from a set of sensors to the desired destination by mutual collaboration in a multi-hop fashion. This paper presents an IEEE 802.15.4 standard based low power WSN with mobile gateway (MG) which for some applications has advantages over conventional WSN. The MG centric data communication network minimizes the conventional WSN's *premature network partition problem* i.e. separation of sink due to exhaustion of certain nodes at the stationary sink's one hop distance. Moreover a tree reconfiguration algorithm and two optimization schemes, multiple associations and hybrid tree mesh topology, are proposed in this paper. The presented approach is analyzed and validated in network simulator (NS-2).**

***Keywords*—Wireless Sensor Network, IEEE 802.15.4 Standard, Mobile Gateway, Topology Optimization**

I. Introduction

The WSN is composed of sensing, computation and communication capable randomly distributed tiny sensors interconnected in an ad-hoc fashion. Usage scenarios of this interconnected network range from real-time tracking, to monitoring of environmental conditions, to *in situ* monitoring of the health of structures or equipments.

The WSN gathers and relays remote information to the fixed destination called sink or gateway (GW). The sink relays information to/from tree or mesh configured WSN to the external network e.g. Internet, WLAN. These types of WSN are termed as conventional WSN (CWSN). The CWSN has limited numbers of nodes at one hop neighborhood of the stationary GW (SG). These nodes at one hop neighborhood or nodes at level one (considering the sink as level 0) are termed as “forwarders”.

In the CWSN, nodes at lower level have to bear higher data traffic load as compared to the nodes at higher level. In other words, batteries of the lower level nodes exhaust quicker than the higher level nodes. Since the forwarders are the lowest level nodes, there is a high probability of death of forwarders due to energy exhaustion. The death of all forwarders segregates the whole network from the sink. It leads to premature death of the network although most of the sensor nodes still have sufficient energy. The MG approach proposed in this paper distributes the role of forwarders among all nodes. Different from the CWSN, any node can become a forwarder depending on the MG’s trajectory. Thus our approach increases network lifetime by load sharing and avoids premature network partitioning as in the CWSN. Moreover, in CWSN there is a high probability of packet collisions close to the SG because of data traffic convergence towards the SG. In our proposed network, nodes will transfer their stored data as requested by the MG. Data traffic will at any instant be restricted to the vicinity of the MG (e.g. to its *N*-hop neighborhood), while nodes outside the neighborhood of the MG just collect information and store it.

Our proposed design is suitable for several applications as compared to the SG. Such as,

(a) Military application: Consider a battle field scattered with sensors. During battle, a soldier carrying a MG can collect information from those sensors in his vicinity and collect information about the enemies. Each soldier may collect information from its vicinity (e.g. *N*-hop neighborhood) by selecting appropriate value of N. It will give some information about the enemy e.g. location of the land mines around that soldier. It will help to protect as well as give some idea about the safest route towards destination. Furthermore, the collected information can be passed to the external network with or without processing, depending on application requirements. The external network may alert other soldiers. The soldier can decide the information range by selecting an appropriate value of the maximum hop-distance *N,* for example.

(b) Intelligent traffic management: A MG equipped driver can collect traffic information in the vicinity from the sensors deployed in its N-hop neighborhood. Beside that, it can get traffic information from other parts of the road through the external network. In these classes of applications, the MG will be more beneficial than the SG.

(c) Work safety: In dangerous working areas such as coal mines, for example, stationary sensor nodes can monitor the environmental conditions (e.g. gas concentration etc.). Workers carrying a MG device can query the sensor data in their respective environment independently of other (centralized) communications infrastructures.

The proposed network inherits the low power operation features of the 802.15.4 standard [1] that describes the physical (PHY) and Medium Access Control (MAC) layers for low-cost short range communications. For battery-powered operation over an extended period of time, low-duty-cycle operation based on synchronized sleep-wakeup timing is required. For this purpose, 802.15.4 defines a beacon enabled mode of operation that allows hierarchical synchronization of nodes in a tree-like WSN.

The rest of the paper is organized as follows: section II summarizes related works in this area; section III presents a brief overview of energy efficient and low data rate WSN with MG support and consequent challenges due to MG support; section IV describes the system setup and reconfiguration algorithm of the proposed design; section V proposes two optimization schemes; section VI presents the system simulation with numerical results. We conclude this paper in section VII.

This project was completed as a part of internship in Siemens Ltd., China, Corporate Technology.

21st International Conference on
Advanced Information Networking and Applications Workshops (AINAW'07)
0-7695-2847-3/07 $20.00 © 2007 IEEE

IEEE COMPUTER SOCIETY

II. Related Works

Although several publications have addressed the issue of CWSN, only few papers have focused on WSN with MG support. Among them, [2] proposed a location based approach to reduce frequent rerouting and topology management overhead using forwarders and call forwarders. Rerouting is performed only when the current route setup becomes fairly inefficient to provide the desired network operation. Similarly, the Minimum Cost Forwarding (MCF) approach finds shortest paths from all the sensor nodes to the base station without explicit routing tables. This shortest path approach might potentially drain all the energy from upstream nodes, thus losing coverage in some regions of the network. Our proposed system mitigates this possibility by limiting data communication to the N-hop neighborhood of the MG.

Several data dissemination protocols such as directed diffusion [3], declarative routing protocol and gradient broadcasting [4] suggests frequent location updates by each MG. Thus, every node will get the location information of the MG which will be used to forward data. But this frequent location updates of every sensor node both increases collisions in wireless transmission and energy consumption of each individual node. In [2] a protocol named two tier data dissemination (TTDD) also considered MG but restricts the location update to some grid nodes. The TTDD can work well with event-driven systems where sources are queried on demand, but it will not be suitable for those applications where sources generate burst data. The scalable energy efficient asynchronous dissemination protocol is another mechanism based on minimum Steiner tree for routing the sensors' data to mobile sinks [5].

Moreover, MAC protocols defining different sleep/wake-up mechanisms are described in [6][7][8]. It is important to mention that the MG based Low-duty-cycle synchronized WSN without location information is not covered by any of the above literatures.

III. Framework

A. System Overview

The proposed WSN is synchronized by a dedicated node called PAN coordinator [1] as shown in figure 1. The PAN coordinator manages the system setup and decides appropriate channel, sleep wake-up timing etc as described in the 802.15.4 standard. After the specific setup duration, an interconnected tree network synchronized by beacon transmissions with the GW as the master timing reference is constructed. The MG moves freely in the deployed region and collects information from its *N*-hop neighborhood and relay it to the external network. It can select suitable value of *N* on its trajectory.

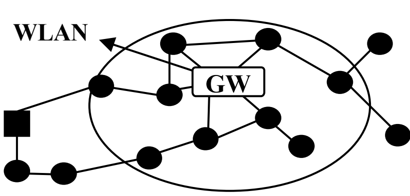

Figure 1: System overview (*N*-hop neighborhood = 2)

B. IEEE 802.15.4 Sleep Wake-up Mechanism

The 802.15.4 beacon-enabled sleep/wake-up mechanism is implemented to prolong the life time of energy constrained sensor nodes. The periodic transmission of a beacon frame by the PAN coordinator and relaying of the beacon by the forwarding nodes synchronizes the whole network. Each node takes the beacon of its parent as a timing reference and will synchronize with its parent. The energy consumption of the network depends on the beacon interval and duty cycle which can be varied over a wide range by appropriate choice of MAC parameters. The super-frame structure for the sleep/wake-up mechanism shown in figure 2 is well described in [1].

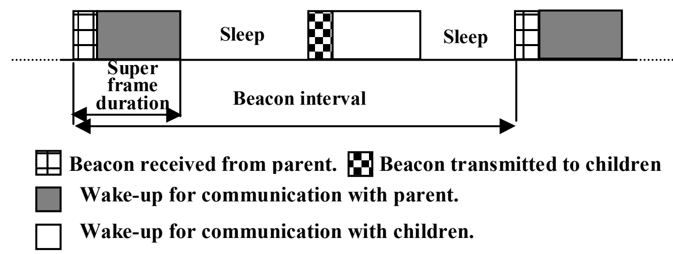

Figure 2: Beacon and sleep wake-up timing of 802.15.4

Coordinator nodes do not only have to wake up when their respective parent wakes up but also transmit their own beacons providing the timing reference for communication with their children. Only the PAN coordinator and end devices don't have to wake-up for communication with the parent and children respectively, so they have only a single wake-up period per beacon interval duration. A coordinator node will be awake twice per beacon interval and may sleep during the rest of the time as shown in figure 2. The timing of a coordinator's beacon transmission relative to the beacon received from its parent can be chosen by a relatively simple beacon scheduling scheme as described in [5].

IV. System Setup And Reconfiguration

The system setup starts after the deployment of sensor nodes in the sensor field. During the setup phase, the PAN coordinator initiates the construction of the tree topology by transmitting periodic beacons. It is followed by random power-on of other nodes. Upon power-on, each node scans for the beacons and possibly evaluates the signal quality for the received beacons. The signal quality is determined by an LQI (link quality indicator) value. The RSSI (receiver signal strength indication) is taken as the basis for LQI [10]. On scanning, if the received beacon has LQI greater than the threshold (LQI_{th}), then it selects that beacon transmitter as a suitable parent node and schedules its own beacon transmission. If the node could not synchronize to any parent within the *expiration time* (maximum allowable beacon scanning time), it stops beacon scanning and considers itself as an orphan node. The expiration time prevents nodes from indefinite beacon scanning and draining of its battery. Thus, each node will get synchronized with the first beacon that satisfies above criteria. This scheme is named as a *First Beacon Reception scheme* (FBR). It is obvious that the tree structure

IEEE COMPUTER SOCIETY

resulting from such a simple scheme depends strongly on the sequence in which the nodes are powered on.

Especially in dense deployment scenarios, this kind of scheme is likely to yield trees of large depth with inefficient routes and poor match between geographical and hop distance which is reflected in a relatively low number of nodes within the *N*-hop neighborhood of the MG. Thus, the initially constructed synchronized tree is reconfigured by using a distributed algorithm which outperforms global algorithms in terms of communication cost (overhead), corresponding energy consumption and latency [11] [12]. The tree depth is minimized using one hop local information of hop count and LQI. Each node will update its association in order to achieve the *Minimum number of Hops towards the PAN coordinator* (MHP). This scheme is termed as a *MHP reconfiguration algorithm* described in chart 1.

```
Set record time (t) = 0 and maximum allowable record time =T_max.
Set Z = size of the neighbor table of the local node (LNT).
Set N_p = number of node(s) towards the PAN coordinator.
Read "received beacons from neighbors of the local node" (NT).
While the number of beacons already read <=Z || t <= T_max Do
        Write N_p from received beacons & LQI entry to LNT.
        Count+1; number of beacons already read +1; t +1
End While
If count >1 Then
        N_p-min = minimum N_p in the LNT with LQI > LQI_th.
        N_p-local = Previous N_p value of the local node.
        If N_p-min < N_p-local Then
          Set new parent = beacon with N_p-min
          Set update yes
        Else If N_p-min = N_p-local && LQI of N_p-min > LQI of N_p-local
          Set new parent = beacon with N_p-min
          Set update yes
End If
If Update = yes Then
          Synchronize with the new parent
          Delete other records of LNT.
          Reconfigure path i.e. selecting the new parent link.
End If
```

Chart 1: MHP reconfiguration flow chart

In this algorithm, nodes have to include their respective MHP count in their beacon transmission. They can either use mutual information exchange or use the depth attribute of the neighbor table as in [9] to derive the MHP count. All the other nodes except for the PAN coordinator listen to the received beacon(s), extract the MHP count information, and evaluate the LQI from those beacon(s). Each node (local node) tabulates the MHP count and respective LQI value in a local neighbor table (LNT). The tabulation terminates either when the time duration exceeds a certain time threshold (T_{max}) or when the number of exclusive beacons exceeds the size of the LNT. The local node selects the minimum "MHP count entry" from its LNT having LQI value over $LQI_{th.}$. If this new entry of MHP count is greater than its old entry of MHP count, then the local node selects the node having that new entry as its new parent. After selection of the new parent, it abandons its previous beacon schedule and synchronizes with the beacon schedule of the new parent. If the new entry is equal to its old entry and the old LQI value is lower than the new one (both of the LQI values should be greater than $LQI_{th.}$), it selects the new entry and synchronizes itself. Otherwise, it will maintain its old beacon schedule, i.e. no reconfiguration.

All nodes deployed in the sensor field must participate in this reconfiguration procedure. The resulting MHP tree not only gives a better match between the geographical and hop neighborhood but also balances the load within the tree. To measure how well the load is balanced across different branches of the tree, the Chebyshev sum inequality [13] is selected as the load balancing metric. The load balance factor derived from the Chebyshev sum inequality is defined as

	Number of nodes	Random	
$\theta = \dfrac{\left(\sum_{i=1}^{n} W_i\right)^2}{n\sum_{i=1}^{n} W_i^2} \le 1$		16m	22m
	49	$\theta = 0.81$	$\theta = 0.78$
	196	$\theta = 0.79$	$\theta = 0.77$

Table 1: Load balance factor for different scenarios

Where, W_i represents the number of children of the parent node i. According to this inequality, the tree gets well balanced when all the nodes (except end nodes) have equal number of children. Under this ideal situation, the result of the inequality will be maximum i.e. 1 as in perfectly balanced binary tree. The simulation result shows that the load balance factor is greater than 0.75 for different scenarios (table 1).

V. SYSTEM OPTIMIZATION

The system optimization of MHP reconfigured tree is done in terms of "average number of nodes within the *N*-hop neighborhood of MG" (*X*). Thus, the optimization of our proposed network is quite different from the CWSN because data communication is restricted within the *N*-hop neighborhood of the MG. Hence, increment of *X* due to optimization improves the information collected by the GW.

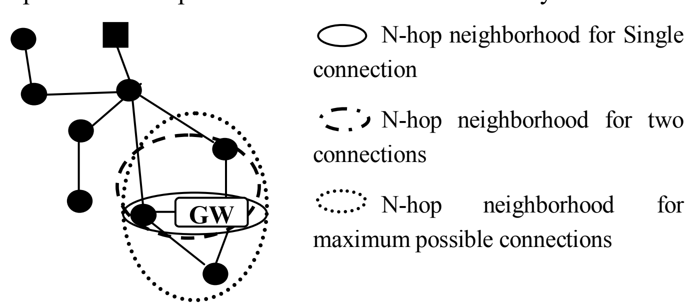

Figure 3: Multiple associations of the MG

21st International Conference on
Advanced Information Networking and Applications Workshops (AINAW'07)
0-7695-2847-3/07 $20.00 © 2007 IEEE

As will be shown in the simulation results, the MHP based tree optimization can increase X significantly as compared to the FPR tree construction. Even larger values of X and hence a better match between the N-Hop neighborhood and the geographic neighborhood of the gateway can be achieved if the gateway has the capability to trigger a local reconfiguration of the network topology in its vicinity. One possible way for such local topology reconfiguration would be to allow the gateway to act as a coordinator and to implement a mechanism that allows the gateway to "adopt" children from other coordinator nodes. A simpler, yet more powerful approach is to allow multiple associations of the gateway and the nodes within its neighborhood.

A. *Mutiple Associations of the Mobile Gateway*

It is possible to allow the MG to connect with more than one parent which is termed as "multiple associations" as shown in figure 3. In other words, the MG can select one or more parent(s) as per its requirement. The multiple associations increase the number of neighbors within a given hop distance in expense of some energy. This extra energy is due to the increase in duty cycle of the MG after multiple associations i.e. the MG has to listen to beacons and active periods of every connected parent. Thus, energy consumption depends on the number of multiple connections selected by the MG. However, it is not a big issue in case of the MG because there is a possibility to recharge the MG after certain interval of time. Compared to the potentially very large number of sensor nodes that cannot easily be serviced frequently, for the generally small number of MGs an increased maintenance effort for recharging batteries is acceptable. Furthermore, it may be assumed that in many cases the MGs have less restricted power supplies, e.g. they may operate on a car's battery or be powered be connected to some other device as a laptop, which can provide comparatively large amounts of power. Figure 3 illustrates the effect of multiple simultaneous associations, and the impact on X in a realistic system will be demonstrated in section VI.

B. *Hybrid Tree Mesh Topology (HTMT)*

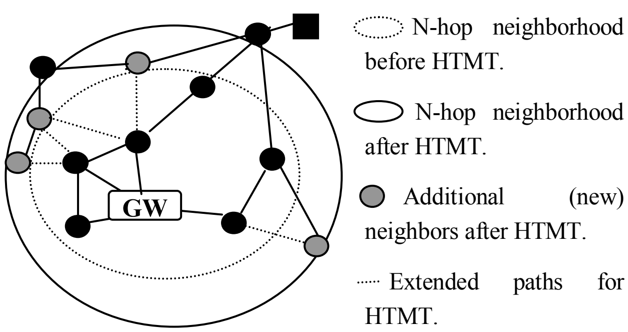

Figure 4: HTMT around the MG

In this scheme, above described topology is more optimized by introducing a local mesh reconfiguration in existing tree. During this optimization, the MG issues a request to its entire *N*-hop neighborhood to construct a Mesh network. On reception of this request, each and every node up to level of *N*-1 (N = neighborhood hop count) connects to all possible nodes around its range. The existence of a temporary mesh network around the MG greatly depends on the speed, direction, range of the MG etc. Thus a node that would not normally be in the *N*-hop neighborhood of the MG according to the tree topology can become a member of the *N*-hop neighborhood temporarily. As the MG moves on, the membership expires, each node returns to its original tree configuration. The HTMT scheme trades off the advantages of mesh networking for limited complexity in the vicinity of the MG. It improves *X* with better resilience towards node failure and decreases end to end latency by uprooting long paths but consumes more energy for multiple listening.

VI. SYSTEM SIMULATION

A. *System Simulation Setup And Parameters*

The concepts outlined above are validated under NS-2 [1]. During simulation, 196 nodes are randomly distributed in a square field of 130 meters. Location of each node in the square field is chosen randomly with the constraint that each node must have at least one neighbor within its communication range. This ensures that a coherent tree can be constructed. The node distribution in a terrain also determines the total energy consumption and hence, the network lifetime [14].

Simulation results have been averaged over a large number of experiments. For each experiment, the placement of the PAN coordinator and the tree construction are performed independently. Furthermore, during each experiment random movement of the MG is simulated. During its trajectory, we evaluated 'X' in periodic intervals of time.

The channel model is kept very simple and considers only path-loss effects. For the following simulation results, the influence of channel path loss will be represented by a maximal communication range. It is assumed that all nodes use the same fixed transmit power.

Primarily, the tree is constructed by using the FBR scheme. It is subsequently optimized by adopting several optimization schemes as described above. Simulation results unveil the prior and subsequent effect of optimization.

B. *Numerical Results*

Figure 5 illustrates the impact of MHP on *X* for multiple MG connection(s). It depicts results for a random distribution of nodes within the sensor field for increasing MG associations. It can be observed that the reconfigured tree leads to a significantly larger *X* than the more or less random tree structure resulting from the FBR scheme. This effect is particularly large in case of dense and random deployment with gradual improvement until the saturation hop count is attained. The saturation observed in all cases reflects the fact that nearly all nodes are contained within a certain hop neighborhood of the MG. It also depends on the selection of *N* by the MG.

Moreover, the effect of MHP before saturation seems to be more prominent for higher hop counts as compared to lower hop counts. Thus, the hop count should be selected sufficiently high to get benefit from MHP. Otherwise, it will just increase delay and energy consumption without any benefit.

21st International Conference on
Advanced Information Networking and Applications Workshops (AINAW'07)
0-7695-2847-3/07 $20.00 © 2007 IEEE

The MHP gives a better performance than increasing the range of the node as shown in figure 6 for dense and random deployment of nodes. In figure 6, imp-196 (1conn) and imp-196 (8conn) represent improvement achieved by the MHP optimization versus increase in range without optimization at 196 nodes with single connection and 196 nodes with eight connections, respectively. It depicts that under dense and random distribution, the MHP is more advantageous than the range increment, although the latter consumes much more energy. But this result is specific to our particular assumption of range and number of connections.

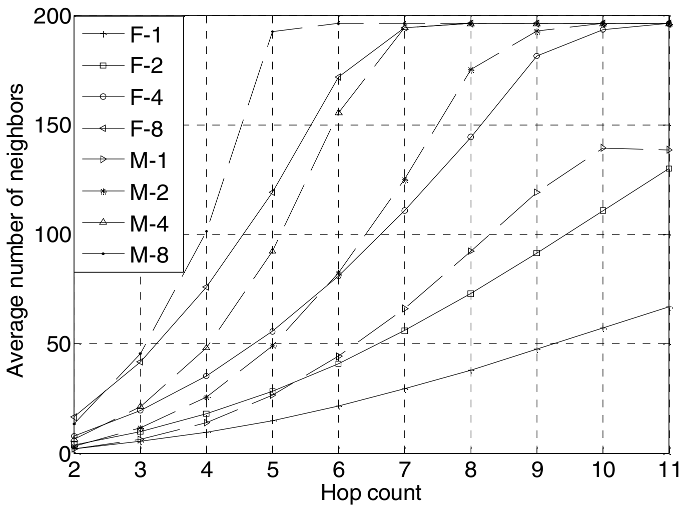

Figure 5: Average number of N-hop neighbors for non-optimized and optimized tree structures; random node placement and 16m communication range*

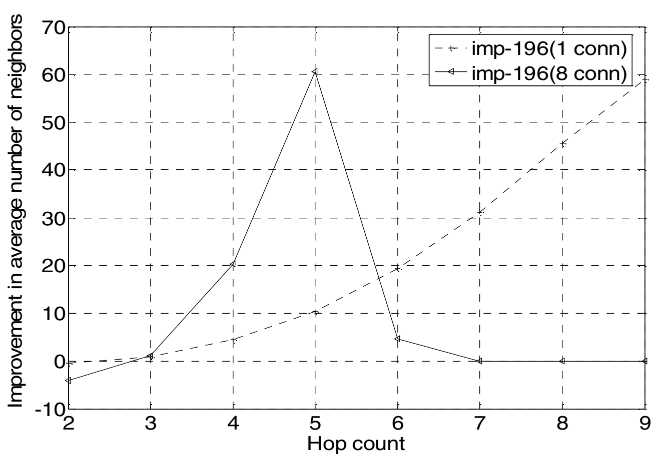

Figure 6: Increase in average number of nodes by increasing range of the node without optimization versus constant range with optimization for single and multiple connections

In figure 6, the increase in range dominates the effect of the MHP below hop count 3 because the MHP has no significant effect when the hop count is low. Hence, sufficient hop count should be taken to get benefit from the MHP. The negative slope after hop count 5 is the post effect of saturation. Above simulation reveals the influence of multiple associations on X. Thus, the benefits from above approaches, the MHP and multiple associations, combine in a nearly additive way. In the dense scenarios, the beneficial effect of the MHP even increases significantly when the possible number of simultaneous associations is increased. Hence, it is useful to combine both approaches in a system.

The impacts of HTMT on randomly distributed WSN are shown in figure 7. In figure 7, I-16 and I-22 represent the increase in average number of nodes after implementing HTMT at 16 and 22m. It reveals that under constant node density, HTMT is more beneficial for MG having a smaller number of parents. In other words, the increase in number of multiple associations dominates the effect of the mesh configuration. The negative slope seen in the graph is due to the saturation of the number of nodes. It is obvious that a network with larger operating range of nodes saturates in less hop counts.

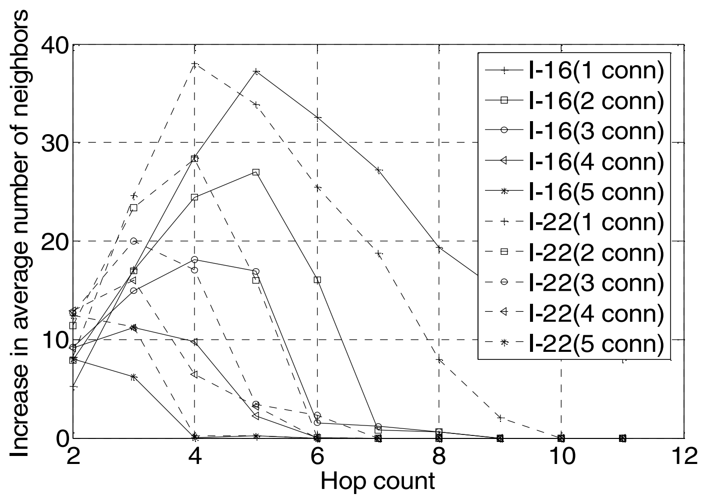

Figure 7: Increase in average number of nodes after implementing HTMT for 16 and 22m; random node placement

VII. CONCLUSIONS

The WSN with MG support provides an energy efficient alternative suitable for aforementioned applications. It reduces the premature network partition problem of the CWSN and improves the system performance. This approach reduces energy consumption by restricting data communication within the *N*-hop neighborhood of the MG and allowing low-duty-cycle operation by synchronized sleep and wake-up. Besides that, this beacon enabled network doesn't require any localization technique, hence it is attractive from a resource constraint point of view. Furthermore, the proposed topology reconstruction algorithm will minimize routing complexity as it implements a simple network topology i.e. shortest path tree. The simulation results show that the proposed algorithm and successive optimization significantly increase *X*. Along with other parameters, *X* also has significant influence on information collection and performance of the overall network. Thus, the above analysis and simulation results indicate that the proposed network may be a good alternative for the current trend of WSN.

**F-1 represents FBR with single connection and M-1 represents MHP with single connection*

This paper has considered single PAN coordinator and single MG. But in reality, there may be multiple numbers of PAN coordinators and multiple MGs that may bring additional complexity. There are several factors still to be investigated such as resilience towards node failure, protocol overhead, energy analysis etc. On the other hand, this proposed system is only designed for low speed of MG. Thus, it may have to cope with frequent handover or switching for moderate speed of MG.

REFERENCES

[1] IEEE 802.15.4 standard, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), Oct. 2003. http://www.ieee802.org/15/pub/TG4.html

[2] Kemal Akkaya and Mohamed Younis. "Energy-aware Routing to a Mobile GW in Wireless Sensor Networks"

[3] C. Intanagonwiwat, R. Govindan, and D. Estrin. "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks." ACM International Conference on Mobile Computing and Networking (MOBICOM'00), 2000.

[4] F. Ye, S. Lu, and L. Zhang. "GRAdient Broadcast: A Robust, Long-lived Large Sensor Network". http: //irl.cs.ucla.edu/papers/grab-tech-report.ps,2001

[5] H. Kim, T. Abdelzaher, and W. Kwon, "Minimum-energy Asynchronous Dissemination to Mobile Sinks in Wireless Sensor Networks", Proceedings of the 1st international conference on Embedded networked sensor systems, 2003.

[6] W. Ye, J. Heidemann, and D. Estrin. Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks. In IEEE Transactions on Networking, Apr. 2004.

[7] Frazer Bennett, David Clarke, Joseph B. Evans, Andy Hopper, Alan Jones, and David Leask, "Piconet Embedded Mobile Networking", IEEE Personal Communications, 4(5):8-15, October 1997.

[8] Joseph Polastre, Jason Hill, David Culler. "Versatile Low Power Media Access for Wireless Sensor Networks". in Proceedings of the 2nd international conference on Embedded networked sensor systems. Nov. 2004.

[9] Zigbee specification, http://www.caba.org/standard/zigbee.html

[10] Jin-Shyan Lee, "An Experiment on Performance Study of IEEE 802.15.4 Wireless Networks.pdf", To be published in Proc. IEEE International Conference on Emerging Technologies and Factory Automation, 2005

[11] Fan bai, Ahmed helmy, "Comparative Analysis of Algorithms for Tree Structure Restoration in Sensor Networks" , 2004 IEEE.

[12] D. Estrin. R. Govindan, J. Heidemann, and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," in Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking, 1999.

[13] Hui Dai, Richard Han, "A Node-centric Load Balancing Algorithm for Wireless Sensor Networks", IEEE, Globecom Dec 2003

[14] Frank Y.S. Lin and P.L. Chiu, "A Simulated Annealing Algorithm for Energy-Efficient Sensor Network Design"

21st International Conference on
Advanced Information Networking and Applications Workshops (AINAW'07)
0-7695-2847-3/07 $20.00 © 2007 IEEE