Minimum-Hop Load-Balancing Graph Routing Algorithm for Wireless HART

Abdul Aziz Memon and Seung Ho Hong

***Abstract*—In this paper load-balancing routing algorithm for WirelessHART standard is proposed. WirelessHART is open standard for Industrial automation to fulfill specific requirements of industrial environments, WirelessHART is secure, time synchronized mesh network with frequency hopping and graph routing. Graph routing is used in WirelessHART to provide path redundancy. Whereas in proposed algorithm; not only path redundancy is considered but also minimum hop end to end communication to fulfill stringent real time requirements as well as device load balancing is considered to increase overall network life. Results show that network life with proposed algorithm is dramatically increased in comparison with minimum hop graph routing.**

***Index Terms*—Graph routing, load balancing, minimum hop, wirelessHART**

I. Introduction

WSN is a collection of hundreds or even thousands of devices called wireless sensors that are densely deployed, consist of sensing, data processing, and communicating components being able to organize themselves into a network created in an ad hoc manner to measure the ambient conditions in the environment surrounding them and then transform these measurements into electrical signals that can be processed to reveal some characteristics about the phenomena located around these sensors [1, 2]. The potential features of wireless sensor networks over the conventional approach can be summarized as self-powered, self-healing, self-organizing, small in size, consume less power, greater coverage, easy deployment, accuracy and reliability at possibly lower cost [3]. Some of the early works on WSNs [4-6] motivate and discuss these benefits in detail. Due to such features, WSNs are realized in numerous applications such as Military, Environmental, Health, Home and Commercial but not limited to. Although designing, manufacturing and networking wireless sensor devices to support such a wide variety of applications is a complex and challenging endeavor [3]; yet recent advancements in micro-electro-mechanical systems (MEMS) and low power highly integrated digital electronics have expedited the development of such small sized, inexpensive, low-power and multifunctional sensing devices [2,7-10].

Traditionally industrial automation systems are realized through wired communications for industrial applications such as safety, control and monitoring. However the wired automation systems require expensive communication cables to be installed and maintained regularly. With the recent unprecedented success of WSN in the home and the office has led to the emergence of WSN in the industrial setting as well [11]. However, due to the special constraints in industrial applications, e.g., hard real-time, limited energy, path redundancy, security etc it is probably not the best solution to simply use existing WSN protocols, which often are designed for different application areas. Some of Industrial organizations, such as WirelessHART [12], ZigBee [13] and ISA [14] have been actively pushing the application of wireless technologies in industrial automation.

Routing plays very important role for any network and our research work is also focused on routing specifically; routing in WirelessHART industrial automation networks.

Manuscript received August 15, 2012; revised October 19, 2012

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II. Related Work

Industrial wireless sensor networks have specific routing requirements such as:

- *Security*: Industrial applications such as safety, monitoring and control are usually considered as sensitive applications and small intruder attack may cause severe damages to industry and workers. So security is always considered important for industrial environments.
- *Path redundancy*: Wireless industrial sensor networks are huge in span, deployed densely and real time networks, so it is not desirable for routing to be performed from source to destination again and again; in case if data is corrupted, or some intermediate node or link is failed. So there should be alternative paths available from source to destination for each node involved in routing.
- *Scalability*: In industrial environments new nodes may be added depending on the requirements, so established routing protocol should support new nodes.
- *Fault tolerance:* Routing Protocol should work well even if some node is dead or link is failed.
- *Minimum Communication Delay*: Industrial networks have *stringent* real time requirements, so minimum possible paths should always be preferred.
- *Energy Awareness*: Usually wireless sensors are left *unattended* for years after their deployment. So routing should be performed in a balanced way such that each node has routing responsibility in a fair way.

Many of the algorithms presented in [15] that are based on flat, hierarchical and location based routing don't fulfill all requirements for Industrial WSNs.

ZigBee, WirelessHART and ISA100.11a are the standards

DOI: 10.7763/IJIEE.2013.V3.303

used for industrial automation. WirelessHART and ISA100.11a are specifically designed for industrial automation and both standards use Graph routing, whereas ZigBee yet proving its success for industrial automation networks and it uses Ad hoc On-demand Distance Dector (AODV) routing [16].

In WirelessHART™ two types of routing protocols are used namely source routing and graph routing [17]. Whereas most of the data flow is between field devices and network manager through gateway. In source routing complete path from source to destination device is statically specified in the packet and each intermediate field devices forward packet to next specified device. In source routing current network conditions may break the packet's specified path causing packet loss. As a result source routing is not redundant and reliable, and it is usually used for troubleshooting the network paths. On the other hand; unlike source routing a graph ID is carried inside the packet for graph routing, consequently the specific paths associated with each graph must be explicitly configured by the network manager in the individual field devices prior to its use and route is taken based on the current network conditions. As a result graph routing is highly redundant and reliable used for normal and routine communications both upstream and downstream and it is best suitable for process automation applications but yet there is need for how graphs should be generated to achieve redundancy, minimum end to end communication delay to fulfill real time requirements and generated graphs should be energy efficient.

WirelessHART and ISA 100.11a are designed to be very robust communications technologies in the presence of interference and fading. That is why graph routing specifically in WirelessHART is studied and Minimum-hop Load-balancing algorithm is proposed which not only provides path redundancy like WirelessHART, but also minimum hop graphs are generated to fulfill real time requirements and moreover load balancing is performed to balance the routing responsibility of network devices for prolonging the overall network life.

III. Minimum Hop Load Balancing Graph Routing Algorithm

Suggested algorithm is mainly consisting of two phases with the goals of achieving minimum hop end to end communication along with path redundancy to fulfill stringent real time and mesh networking requirements for industrial networks, and load balancing for individual devices to increase overall network lifetime. So in the first phase of algorithm, minimum hop graphs are generated with maximum possible path redundancy and in the second phase of algorithm; device load balancing is performed to prolong network lifetime.

A. *Minimum Hop Graph Generation*

In WirelessHART network; network manager is responsible for generating graphs after "WirelessHART network initialization procedure" [17] and "Network join procedure" [18] are successfully finished; which is considered as step 1 in Fig. 1. In step 02 Breadth First Search (BFS) algorithm [19] is run over topology graph started at gateway to divide all devices into levels as shown in Fig. 2. In step 03; by utilizing the level information, neighbors of each field device are divided into three categories i-e; upstream neighbors, downstream neighbors, same level neighbors. Upstream neighbors are neighbors towards gateway, downstream neighbors are neighbors towards end devices and remaining neighbors are same level neighbors. In step 04 minimum hop graphs for each device towards gateway are generated. Initially all possible minimum hop redundant paths are considered and devices are restricted not to communicate with their same level neighbors to achieve minimum hop end to end communication; as same levels links are crossed and shown in Fig. 2.

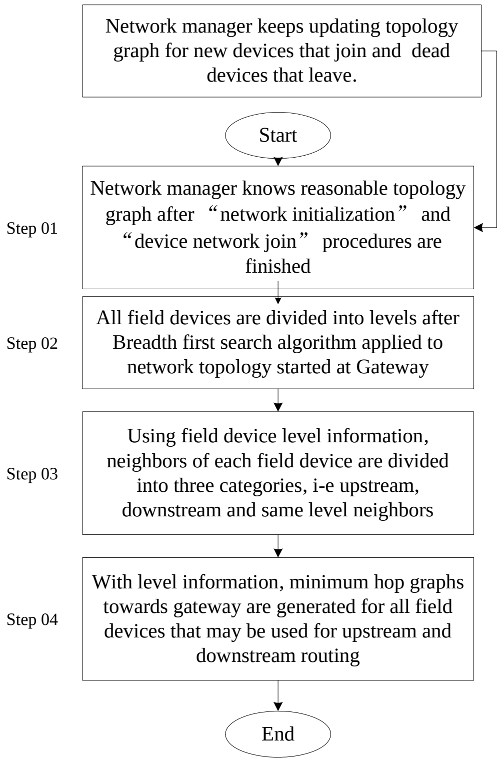

Fig. 1. Graph generation procedure

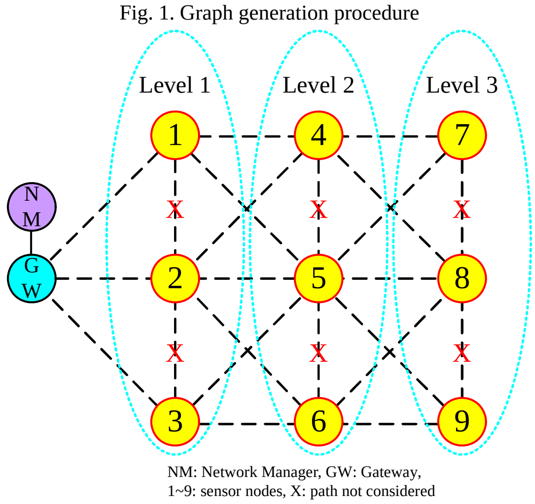

Fig. 2. Minimum hop network topology

B. *Device Load Balancing*

Device load balancing is performed to lower the routing responsibility of devices having higher routing responsibility. For this reason initially routing responsibility of each device is found using equation *(i)*, where it is considered that for any node/device *D*; its next hop neighbors have equally likely probability to route the data of device *D*.

$$RR\ of\ device\ D = \left[\frac{SR\ of\ device\ D}{\sum_{z=1}^{n}(SR\ of\ device\ z \times lz)} + \sum_{x}\frac{RR\ of\ DSN\ x\ of\ device\ D}{100 \times Ux}\right] \times 100\% \qquad (1)$$

where

- *RR*: Routing Responsibility
- *SR*: Data scan rate of device in Hertz
- *n*: Total number of network devices
- *lz*: Level number of device z
- *DSN*: Downstream neighbor
- *x*: One of *DSN* of device D
- *Ux*: Total number of *USNs* of *x*
- *USN*: Upstream neighbor

After routing responsibility of devices is known then device load balancing procedure is initiated as shown in Fig. 3. For device load balancing procedure, step 1 is the loop from level 1 to level *L* to perform load balancing per level and if this loop is finished it means load balancing is performed for whole network and devices will be notified about graphs and related upstream and downstream neighbors in step 2.1, else in step 2.2 it is checked whether all devices in level *L* have same routing responsibility? Usually devices don't have same routing responsibility; so in step 3 devices having *routing responsibility > average* are listed according to decreasing value of their routing responsibility. The reason why devices are listed according to decreasing value of their routing responsibility; is because if load balancing is performed for devices having lower routing responsibility then it may be possible that routing responsibility of devices having already higher routing responsibility will be increased and it is not desirable. Other advantage of listing devices according to their decreasing value of routing responsibility is that when load balancing algorithm is running for devices having higher to lower routing responsibility, then there will be some saturation point after which load balancing algorithm may not produce further load balancing, so when that saturation point is reached; graph reshaping will automatically be stopped for further devices at step 6 and control will be shifted to step 1 for next level. '*Average*' is the average of routing responsibilities of devices in level *L*. Step 4 is the loop for listed devices to perform graph routing for each individual device *D*. In step 5 device *D* and other devices with higher routing responsibility in level less than *L* are considered as dead/not present to find if down streams neighbors of device *D* can still find paths with required redundancy as shown in step 6. If it is true and downstream neighbors of device *D* can find required number of redundant paths with minimum hop and without device *D*, then device *D* will be no more responsible to route data for such downstream neighbors. Yet in step 7 it is checked if load balancing for device *D* is not increasing load of any other device; then this load balancing for device *D* is confirmed in step 8. Device load balancing algorithm produces routing graphs as shown in Fig.4 with minimum path redundancy of two paths.

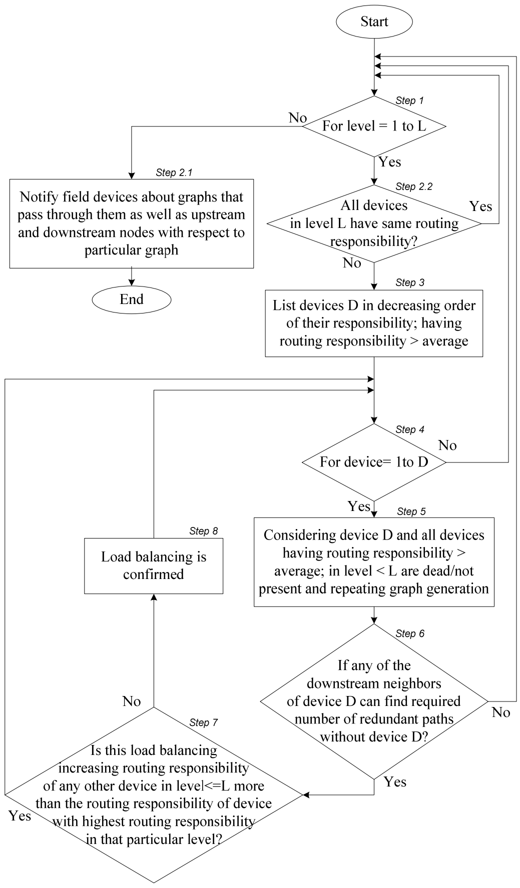

Fig. 3. Device load balancing procedure

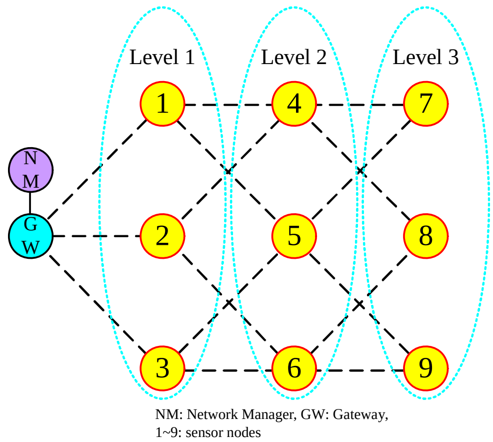

Fig. 4. Device load-balanced routing graph with path redundancy

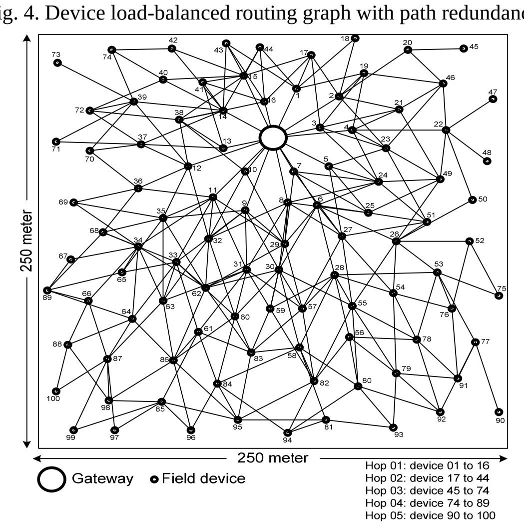

Fig. 5. Simulation scenario

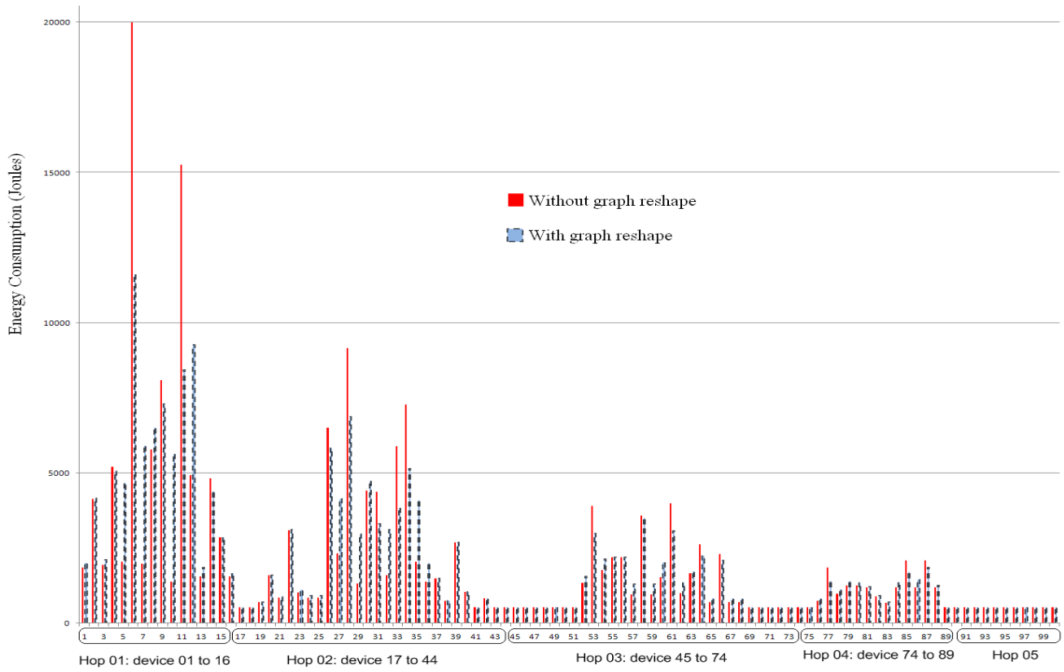

Fig. 6. Energy consumption with and without device load balancing

IV. Simulation Scenario and Analysis

In this paper, description for generation of minimum hop graph is skipped, because BFS algorithm is used to categorize nodes into levels and it is obvious from the properties of BFS that minimum hop paths will be generated. So minimum hop mesh network is simulated before and after device load balancing algorithm is adopted to know the efficiency of device load balancing algorithm in terms of energy balancing.

TABLE I: Simulation Parameters

Parameters	Value
Number of nodes	100
Area	250x250 m square
Transmission range of each node	50 m
Scan rate of each node	1 Hz
Node distribution	Uniform
Battery of each node	2 AA (20,000 Joules) [20]
Transmit energy consumption per message	1 mJ
Receive energy consumption per message	0.7 mJ
Simulation running time	till 1st network device is dead

For this reason following network scenario is considered as shown in Fig. 5. The simulation parameters for this experiment are shown in Table I. After this network is simulated till first network device is dead, following results are obtained as shown in Fig. 6.

From Fig. 6 It is clear that lower level nodes have higher routing responsibility as compared higher level nodes and it is also clear that before device load balancing some nodes having higher routing responsibility which may die earlier and network will be disturbed but with device load balancing; routing load of nodes having higher routing responsibility before device load balancing is shared with their same level neighbor nodes after device load balancing such that 25% of network lifetime is increased without any device is dead earlier. It is also observed that total energy consumption per hop before and after device load balancing remains same.

V. Conclusion and Related Work

In this paper load-balancing routing algorithm for WirelessHART is proposed. With this algorithm minimum hop graphs along with path redundancy were generated to fulfill stringent real time, data and path redundancy requirements for Industrial networks. Moreover device load balancing was performed to balance the routing responsibilities of devices having higher routing responsibilities such that overall network life should be increased without some devices are dead earlier.

So results show that not only path redundancy and minimum hop end to end communication is important for industrial WirelessHART networks, but also device load balancing techniques dramatically increases overall network lifetime to avoid any device dead earlier.

In this paper we have simulated the network scenario till first network device is dead and results are not compared with other routing algorithms. So for the future works; different network scenarios with different node distributions will be considered and results will be compared with some other routing protocols with real world simulation parameters.

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