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# A STUDY ON ENERGY EFFICIENT MULTI-TIER MULTI-HOP WIRELESS SENSOR NETWORKS FOR FREIGHT-TRAIN MONITORING

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*Abstract*—**The North American freight railroad industry is trying to leverage wireless sensor networks (WSN) onboard railcars for advanced monitoring and alerting. In railroad environments, freight train WSNs exhibit a linear chain-like topology of significant length. Thus, existing wireless technologies such as the IEEE 802.15.4 communication protocol, based on a star topology, are unable to provide reliable service. The end-to-end communication between nodes generally relies on individual nodes communicating with their respective neighbors to carry the information over multiple hops and deliver it to the preferred destination. The routing performance and reliability significantly degrades with increasing number of hops. We proposed a multi-tier multi-hop network which is designed to overcome these issues in large-scale multi-hop WSNs in railroad environments. This approach has significant advantages, such as more data bandwidth, higher reliability, and lower energy consumption. Our analytical results show that the proposed multi-tier communication approach spends energy more efficiently and utilizes less resource than the traditional chain topology onboard freight trains.**

*Keywords-IEEE 802.15.4; large-scale multi-hop network; wireless sensor networks; wireless personal area networks; energy*

## I. INTRODUCTION

In North America's freight railroad industry, a number of efforts are underway to improve the safety and security of freight transportation, such as Positive Train Control (PTC) and efforts for real-time train consist health monitoring. The freight railroad companies see Wireless Sensor Networks (WSNs) as a potential technology for real-time status monitoring of each individual railcar and reporting changes in status to the train operator and dispatch center for alerting purposes. Such a system could monitor a wide variety of conditions, such as wheel imbalances, problems with the brake system in a railcar, the failure of a refrigeration unit when transporting perishable goods, etc. Freight trains can consist of a very large number of railcars. In each onboard railcar, individual WSN nodes are tasked with data collection and reporting.

The standard IEEE 802.15.4 [1] specifies low-rate wireless

personal area networks (LR-WPAN) supporting small, low-cost, but power-efficient devices operating on battery power. The IEEE 802.15.4 protocol is widely adopted in a variety of embedded applications, such as home automation [2], industrial sensing and control, environment monitoring and sensing, and wireless peripheral equipments. The IEEE 802.15.4, also known as ZigBee, is envisioned by the railroads to provide the interconnectivity for these railcar sensor nodes. However, even though the IEEE 802.15.4 protocol supports multi-hop communications, it was originally designed for star topologies and is therefore not optimized when used in large-scale multi-hop chain-topology networks.

Research related to the performance of IEEE 802.15.4 in a star topology has been reported in [3]. The authors of [4] identified the performance bottlenecks in the MAC layer of 802.15.4. In many applications that utilize a chain topology the performance problems are intensified due to IEEE 802.15.4's limited communication range. Unlike IEEE 802.11, an RTS/CTS handshake is not included in the IEEE 802.15.4 protocol. Therefore, IEEE 802.15.4 does not handle the hidden terminal problem appropriately in multi-hop environments. From these problems associated with IEEE 802.15.4 it becomes obvious that improvements are required in order to develop a reliable and robust solution for chain-topology multi-hop wireless sensor networks. Furthermore, the route discovery becomes significantly more difficult and takes longer time to complete as the number of hops increases. In [5], the authors reported the maximum IEEE 802.15.4 multi-hop throughput. According to their findings, the maximum throughput is decreased from 250 kbps to 40 kbps as the number of hops increases from 1 hop to 5 hops.

In this paper, we focus on the energy efficiency of large-scale multi-hop WSNs onboard freight trains. A typical size in our consideration is around 100 railcars. If there is one sensor deployed per freight car, the end-to-end network length is 99 hops. This hop count far exceeds the original design capabilities of IEEE 802.15.4. We therefore propose a multi-tier multi-hop network approach as an effective solution to the problems associated with IEEE 802.15.4 in such an environment. Detailed performance evaluations and analyses provide a guideline for practical implementations of WSNs onboard freight trains.
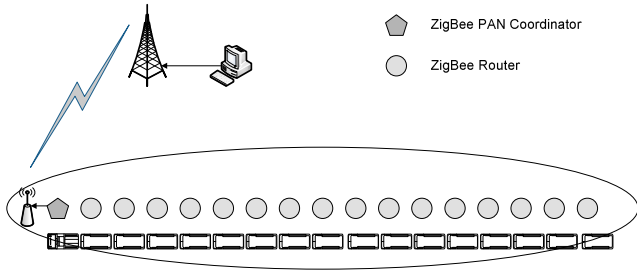
Fig. 1. A large-scale multi-hop sensor network in railroad application with one ZigBee device on each freight car

The paper is organized as follows. Section II provides an overview of the IEEE 802.15.4 standard and multi-hop problems. Section III presents our proposed solution for large-scale multi-hop sensor networks. Our simulation results are given in Section IV. Finally, Section V concludes this paper.

## II. BACKGROUND

### A. IEEE 802.15.4 Standard

The IEEE 802.15.4 [1] standard specifies the physical layer and the MAC sub-layer for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE 802.15.4 offers three operational frequency bands: 2.4 GHz, 915 MHz, and 868 MHz. There is a single channel allocated between 868 and 868.6 MHz, 10 channels between 902 and 928 MHz, and 16 channels between 2.4 and 2.4835 GHz. The maximum data transfer rates are 250 kbps at 2.4 GHz, 40 kbps at 915 MHz and 20 kbps at 868 MHz. In this paper, we consider the physical layer operating in the 2.4 GHz frequency band, which is supported by the MICAz motes [6] from Crossbow Technology.

In the IEEE 802.15.4 standard, there are two types of devices: Full Function Devices (FFDs) and Reduced Function Devices (RFDs). The FFD has full 802.15.4 functionality, including network routing functionality, whereas the RFD provides limited functionality supporting only simple applications such as a remote-controlled switch or data collection sensor to reduce cost and complexity. An IEEE 802.15.4 network consists of at least one FFD operating as the PAN coordinator. Both device types can be interconnected to form either a simple star or a self-configuring peer-to-peer topology. Peer-to-peer topologies are suitable for industrial and commercial applications, where efficient self-configurability and large coverage are important, but its disadvantage is the increased network latency due to message relaying.

### B. Multi-hop Network

Multi-hop wireless networks are an ideal technology to establish an instant communication infrastructure for railroad applications. However, as the size of a multi-hop network grows, the performance tends to decrease. Key causes of such degradation include the resulting excessive control traffic overhead required to build and maintain accurate routing tables. Thus, it is difficult to guarantee performance on a path with many wireless hops, which is particularly critical for the support of real time applications.
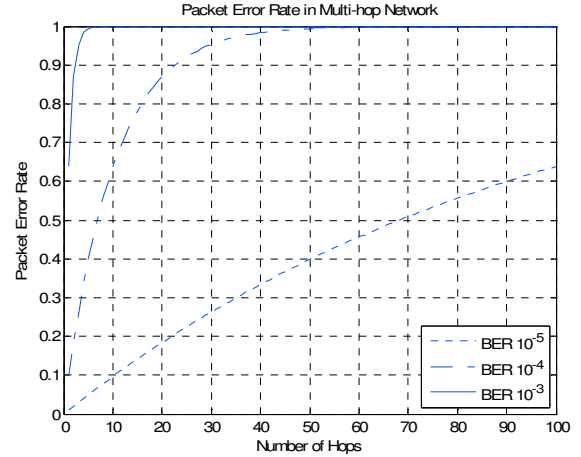


Fig. 2. Packet error rate at specific number of hops in the chain multi-hop scenario when the packet size is 127 bytes.

In addition to the routing issue, the possibility of successful packet delivery is lower as the number of hops increases. This is due to received bit/packet error in wireless communication which can be expressed as follow:

$$PER = 1 - \left(1 - BER\right)^{number\_bits}, \qquad (1)$$

$$PER_{Multihop} = 1 - \left(1 - PER\right)^{number\_hops}. \qquad (2)$$

The *BER* is the bit error rate, which is the number of bit errors divided by the total number of transferred bits during a studied time interval. The packet error rate (*PER*) is the number of incorrectly transferred data packets divided by the number of transferred packets. Fig. 2 shows the packet error rate at specific number of hops in the chain multi-hop scenario when the packet size is 127 bytes. If the link quality is good for entire network, let say BER of $10^{-5}$, the successful packet delivery is still less than 40%. It is certain that retransmission plays a big part in large-scale multi-hop network. In the railroad environment which is considered as a harsh environment, it is very difficult to achieve that good link quality.

## III. MULTI-TIER MULTI-HOP NETWORK

Due to the poor performance of wireless sensor networks where a large number of hops are involved, a multi-tier multi-hop network approach was proposed to significantly reduce the routing overhead, which is identified as the primary problem associated with traditional multi-hop approaches in freight train WSNs. The idea behind the multi-tier multi-hop network is to divide a very long chain-topology network into several short segments and each segment is connected to its neighboring segments using a longer-distance communication protocol, such as Wi-Fi, to greatly reduce the number of required hops for route discovery and data forwarding. Fig. 3 illustrates the multi-tier multi-hop approach. In the upper-tier interconnect, Wi-Fi technology is our preferred choice because it provides
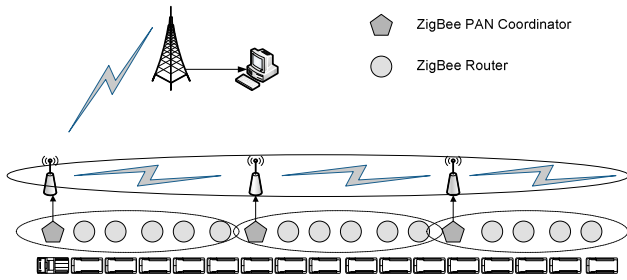
Fig. 3. A multi-tier multi-hop network with one ZigBee device on each freight car

longer range, higher bandwidth, and faster data transfer rates than ZigBee. Moreover, at the current-state-of-art, the cost of ultra-low powered Wi-Fi chipset has moved close to the cost of ZigBee chipsets. The Wi-Fi interface of each node forms an upper-tier multi-hop WLAN network. On the lower tier multi-hop networks, a very long chain multi-hop WPAN network can now be divided into several short-chain multi-hop WPAN networks. Each WPAN has its own PAN coordinator and works independently of the other WPANs. Each ZigBee device now needs only a few hops to reach its local PAN coordinator, which is the node designated to also act as the gateway to the WLAN network. If there is a sensor node failure, this will be of significance only to the WPAN containing the node, not the entire network and thus isolating failure points and increasing the network robustness.

In this paper, we consistently use 100 as the typical number of railcars. If there is one sensor deployed per freight car, the maximum end-to-end network length is 99 hops. In the multi-tier multi-hop network, a 100-node WPAN network using the traditional single-tier approach can be subdivided into 10 individual WPANs using our approach. With this approach, we can reduce the maximum hop count from 99 hops to less than 20 hops (9 WPAN hops and 9 Wi-Fi hops). This number is far more attractive and reasonable, particularly when considering real world implementations.

The advantages of this approach, in addition to the significant reduction in the number of hops, are the higher bandwidth on the upper tier, the increased flexibility, and the greater reliability. Consequently, the overall system throughput is increased as we reported in [7].

## IV. ANALYTICAL RESULTS

For the performance evaluation of our proposed approach, we setup a scenario with 100 freight cars, each car with one ZigBee router. In multi-tier multi-hop analysis, we divide this large WPAN into ten individual WPANs interconnected by one higher-tier Wi-Fi WLAN. One WPAN therefore consists of one PAN coordinator and nine ZigBee routers. Each PAN coordinator has co-located ZigBee and Wi-Fi chipsets. With this approach the maximum number of hops in a WPAN decreases from 99 to 9. In addition, the Wi-Fi higher-tier interconnect encompasses at most 9 hops. In the past, we have setup and tested a similar Wi-Fi chain topology of 8 Wi-Fi hops in our 3.5-mile test bed without any difficulties. This test bed was established on track operated by Burlington Northern
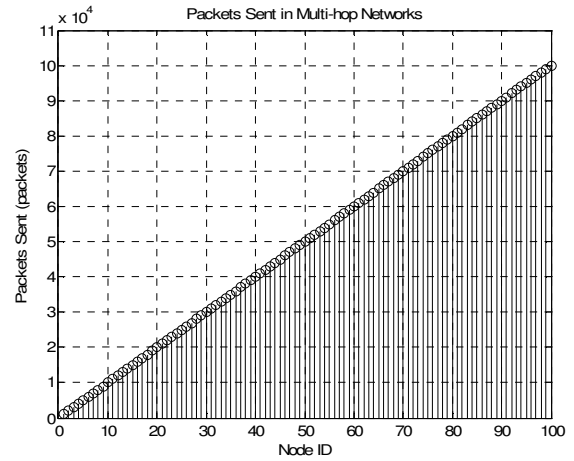


Fig. 4. Expected number of data packets sent at each hop in the multi-hop scenario when the duration is 1,000 seconds and the CBR traffic rate of each node is one packet per second.
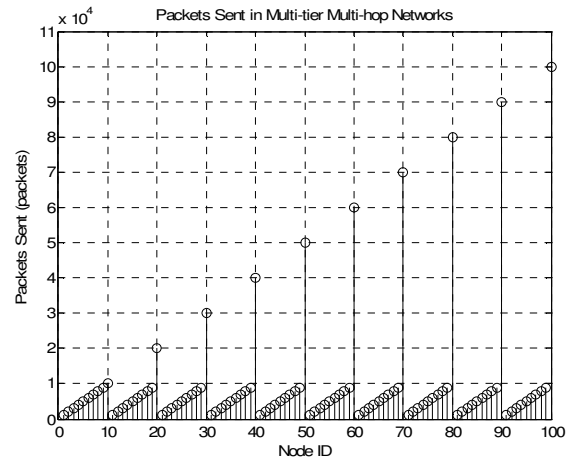


Fig. 5. Expected number of data packets sent at each hop in the multi-tier multi-hop scenario when the duration is 1,000 seconds and the CBR traffic rate of each node is one packet per second.

Santa Fe (BNSF) in Crete, Nebraska to investigate the impact of mobility on end-to-end Wi-Fi performance. A detailed report on this test bed is provided in [8].

After all nodes successfully completed synchronization, every sensor transmits as many data packets as possible to the sink node, which is designated as node 100. Each node has a constant bit rate (CBR) traffic source generating at a rate of one packet per second. The packet size is set to 70 bytes. The intermediate nodes are also responsible for forwarding packets to their neighbors. Similarly, the Wi-Fi higher-tier interconnect effectively aggregates more and more data packets the closer it is to the sink node. In the multi-hop scenario, nodes 1, 2, …, 99 are the FFD devices, which are capable of forwarding packets, while node 100 is the PAN coordinator, which generates beacon frames for its own WPAN network. In the multi-tier multi-hop scenario, nodes 10, 20, …, 100 are the PAN coordinators and the rest are the FFD devices.
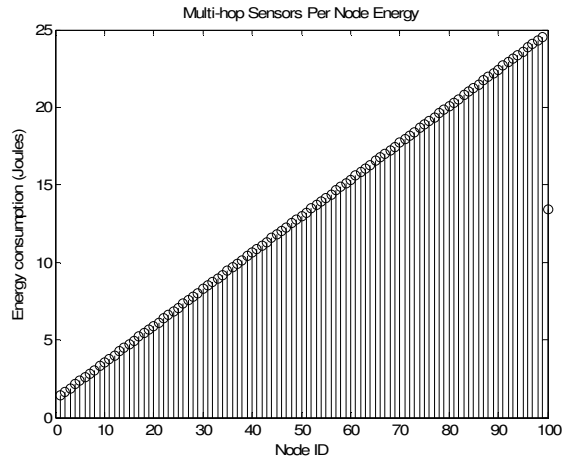
Fig. 6. Energy consumption of each node in the multi-hop scenario when the duration is 1,000 seconds and the CBR traffic rate of each node is one packet per second.
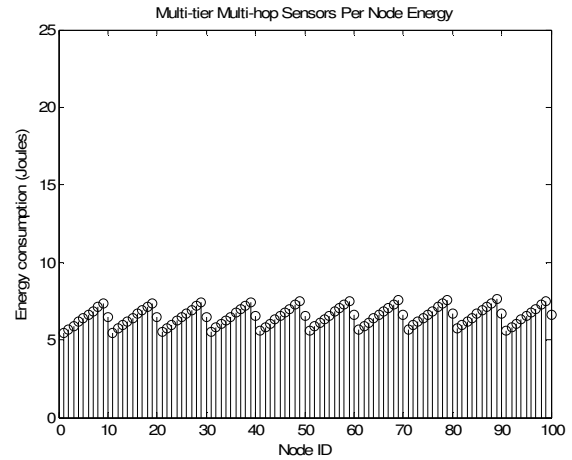


Fig. 8. Energy consumption of each node in the multi-tier multi-hop scenario when the duration is 1,000 seconds and the CBR traffic rate of each node is one packet per second.
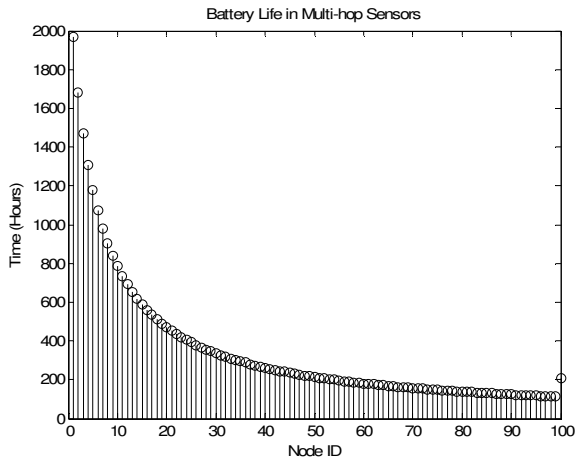


Fig. 7. Lifetime of each node in the multi-hop scenario when the CBR traffic rate of each node is one packet per second.
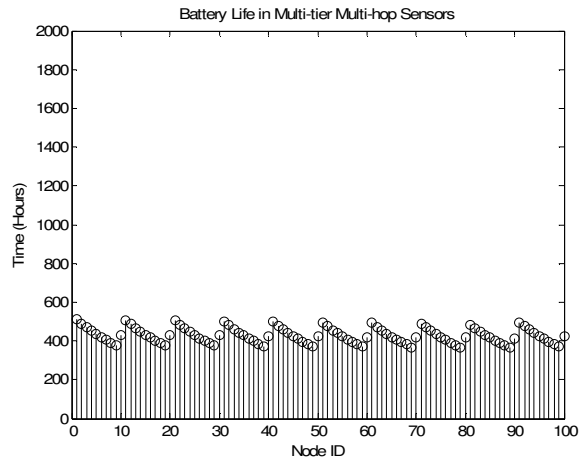


Fig. 9. Lifetime of each node in the multi-tier multi-hop scenario when the CBR traffic rate of each node is one packet per second.

For the regular multi-hop network, the maximum number of packets per hop is limited by the 2-hop shared-channel saturation throughput of 125 kbps, since each node has two neighbors in its communication range. Thus, the maximum number of packets at the destination is 223,214 packets during the 1000-second observation, with the destination node theoretically receiving 2,232 packets from each sensor node. In the multi-tier multi-hop network, the maximum number of packets per hop in each WPAN segment is also limited to 223,214 packets. However, each PAN coordinator is able to handle a significantly larger number of packets due to its integrated Wi-Fi network access. In this environment, the total number of packets at the destination can be increased to 6,696,428 packets, which is approximately 30 times larger compared to the regular multi-hop network and scales favorably with the number of segmented WPANs.

Fig. 4 and Fig. 5 illustrate the number of packets sent in the regular multi-hop scenario and the multi-tier multi-hop scenario, respectively. Both of them represent the amount of packets each node generates and forwards during 1,000 seconds. As can be seen from these graphs, the number of packets that need to be exchanged between nodes in multi-hop is much higher than the corresponding number in its multi-tier counterpart. The worst case is when the node 1 sends a packet to the node 100. It has to be sent through node 2. The packet is then forwarded 98 more times (by node 2, 3, …, and 99) in the multi-hop scenario, whereas in the proposed multi-tier multi-hop scenario it is forwarded only more 8 times using nodes 2, 3, …, and 9 in the sensor lower-tier and another 9 times by node 10, 20, …, and 90 in the Wi-Fi upper-tier. Therefore, the maximum possible number of hops is obviously reduced from 99 hops in the multi-hop network to 18 hops in the multi-tier multi-hop network.

From the results, we can see that the nodes which are closer to the destination spend most of the time forwarding packets. This makes the multi-hop network less efficient with longer the topology chain becomes longer. In addition, the energy stored in those sensor nodes depletes rapidly because they have to be

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TABLE I.    WIRELESS SENSOR NODE POWER CONSUMPTION

| Sensor | Power Consumption |
|---|---|
| RxPower | 56 mW |
| TxPower | 52 mW |
| IdlePower | 1.3 mW |
| SleepPower | 48 uW |

TABLE II.    LOW-POWER WI-FI NODE POWER CONSUMPTION

| Wi-Fi | Power Consumption |
|---|---|
| RxPower | 40 mW |
| TxPower | 360 mW |
| IdlePower | 40 mW |
| SleepPower | 36 uW |

TABLE III.    NODE LIFETIME

| Network Type | Node Lifetime (hours) | |
|---|---|---|
| | *Min* | *Max* |
| Multi-hop Network | 113.1 | 1,965.1 |
| Multi-tier Multi-hop Network | 364.92 | 510.03 |

grows. We have also shown that the proposed multi-tier multi-hop network approach for freight-train WSNs can improve scalability by reducing the number of transmission hops required to reach the destination with the help of a multi-tier network architecture. Compared with the traditional single-tier communication, our analytical study indicates that the use of the proposed multi-tier counterpart can clearly achieve lower energy consumption and less network resource utilization, which is an attractive solution in large-scale multi-hop networks. As a result, the node lifetime of each individual sensor also approaches a more uniform distribution, which increases the overall network lifetime.

awake all the time to keep forwarding packets and do not get a chance to go to sleep mode for energy saving. In an energy constrained system like WSN, this energy concern is very critical. Therefore, we have analyzed energy usage of each node in both traditional multi-hop and proposed multi-tier multi-hop scenarios. We adopted wireless sensor parameters from Texas Instrument's CC2420 chipset specification [9] as shown in Table I. Fig. 6 demonstrates the energy consumption of each node in the multi-hop scenario during a 1000-second simulation where the CBR traffic rate of each node is one packet per second. The energy usage in this scenario can be up to 25 Joules and the range of the nodes' energy usage is considerably large. This signifies an unfair energy usage in this scenario. Typical size AA NiMH batteries have a capacity of about 10,000 Joules. For our analysis, we used this number to determine how long the battery of each sensor node can last. Fig. 7 demonstrates the battery life of each node in the multi-hop scenario.

Table II shows the power consumption of ultra-low-power WiFly RN-111B module from Roving Networks [10]. We utilized these numbers for the Wi-Fi interfaces. Fig. 8 demonstrates energy consumption of each node in the multi-tier multi-hop scenario during a 1000-second simulation for the same CBR traffic rate of one packet per second. The energy consumption is only ranging from 5 to 8 Joules in this scenario. Fig. 9 illustrates the battery life of each node in the multi-tier multi-hop scenario. Table III summarizes the node lifetime in both scenarios. The most important number is the minimum node lifetime because it also reflects the network lifetime. According to our simulation configuration, the proposed multi-tier multi-hop network can significantly improve the network lifetime from 113.1 hours to 364.92 hours.

## V.    CONCLUSION

This paper provides an analysis of multi-hop WSN communication onboard freight trains using traditional single-tier IEEE 802.15.4 communication and assuming a chain-like topology. We have shown the performance degradation when the size of this multi-hop network, and thus the chain length,

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