Study on Energy Consumption and Reliability Issues in Multi-hop Wireless Sensor Networks

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Micro Electro Mechanical Systems (MEMS), which is a technology of the low power micro sensors, integrated circuits, and wireless technologies, has led to the expansion of Wireless Sensor Networks (WSNs). WSNs has shown tremendous progress in the last decade due to its significant contribution in a variety of promising solutions in the diverse application scenarios. The scale of WSNs deployments for real life applications has rapidly increased in last few years and it is expected to rise significantly in the near future.

The deployment of WSNs is believed to be very useful in critical situations like emergency response and the disaster area management, where deployment of sensor nodes is random. In disaster areas, sometimes it may be impossible to enter in the affected zones due to the severe circumstances. In such a case, WSNs will be an alternative technology to be utilized in the scenarios, such as monitoring an area, which is polluted with the nuclear radiation, where human intervention can lead to serious health issues. In the course of such real life implementation, all sensor nodes cannot communicate directly with a centralized sink node. Due to the short communication range of an individual sensor node, the information has to be routed through the intermediate nodes to be delivered to the sink node. It has been observed during the experiments that a WSNs that operates in an error-prone multi-hop network environment and where deployment of sensor nodes is random, suffers from serious reliability issues, which result in the decrease of the energy resources of a node. The network environment becomes error-prone due to the noisy wireless channel and due to the failure probability of the sensor nodes, which lead to the data loss.

With the involvement of WSNs in the energy-hungry applications and the error-prone network environments, the energy conservation, efficient utilization of the resources and the reliable communication, are becoming the critical research issues. Therefore, it is important to design a communication model, which can estimate the overall energy consumption for a specific duration and at the same time estimate the accurate lifetime of the whole network. In addition, to reduce the latency and energy consumption in the error-prone environment, it is necessary to use a good channel quality estimation technique for selecting the best link to route data.

In Chapter 1, introduction about WSNs, various applications, and challenges that are being faced in real deployment of sensor nodes, are explained in detail. It has been found that energy estimation and reliability are the two important research issues in real deployment of WSNs recently. In order to address both the energy estimation and reliability issues, the thesis is logically divided into two parts; the energy consumption/estimation and the lifetime modeling of the whole network, are discussed in Chapter 2, 3, while the reliability issues in multi-hop WSNs are introduced in Chapter 4.

In Chapter 2, in order to estimate the energy consumption of an individual sensor node and ultimately the lifetime of the whole WSNs, a Distributed Communication Model (DCM) is introduced that can accurately determine the energy consumption through data communication from a source to a destination node in the error-prone multi-hop network. The energy consumption is affected with the quality of link, which is affected by interference, wave reflection, wave diffraction, and the multipath effects. Link quality is characterized by symmetry, directivity, instability, and irregularity of the communication range of a sensor node. Due to the weak communication links, significant data loss occurs that affects the overall energy consumption of a node and ultimately the lifetime of the whole network. While other proposed energy models are unable to determine energy consumption due to lossy links in the error-prone network environments, DCM can be used to accurately estimate the energy consumption in such environments. The analysis performed using DCM, is validated through rigorous simulations and practical implementation. Both simulations and experimental results show that DCM outperforms all the other energy models designed for data communications in WSNs, in terms of accuracy and diversity of the environments.

In Chapter 3, by using the idea of DCM, a detailed analysis of the power dissipation through various factors involved in WSNs communications using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), based on IEEE 802.15.4 Medium Access Control (MAC) protocol is performed. It is observed that most of the MAC protocols designed in WSNs are based on the CSMA access mechanism. However, energy estimation models designed for WSNs, mostly consider Time Division
Multiple Access (TDMA) protocols for energy analysis. A major drawback with TDMA based protocols is that such protocols need a good centralized synchronization scheme. For distributed WSNs, CSMA based protocols are the ultimate solution. In the power dissipation analysis using IEEE 802.15.4 CSMA/CA MAC protocol, the loss rate of frames, neighbor nodes density in the communication range of a sensor node, number of hops, distance of source to the sink, and the density of the network, are taken into account. To assess the true nature of the MAC protocol predictability, the random nature of the parameters of CSMA/CA protocol is used in both analyses and simulations. A comprehensive analysis of the affects of these factors on the energy consumption along with the overheads caused by message routing through multi-hop distributed networks is performed. The accuracy of the analysis is then verified through Monte Carlo simulations. Results from both analysis and simulations show that the power dissipation analysis is more realistic compared to other proposed models in terms of accuracy and complexity of the network environment.

In Chapter 4, channel quality estimation in error-prone multi-hop WSNs is addressed. To route data on the lossy links in the error-prone networks, the selection of a good quality channel is very important. To tackle this issue, a channel estimation technique, called Hybrid Adaptive Parameter Tuning based Estimation (HAPTE) is introduced. HAPTE estimates the current channel conditions using cross-layered approach, and then utilizes this information to change the MAC protocol parameters adaptively. The HAPTE, designed for IEEE 802.15.4 MAC protocol utilizes the four bits concept of 4-Bits (4B) hybrid channel quality estimation, by adaptively tuning MAC protocol parameters for required level of reliability, while maintaining layered networking abstractions. Comparison of HAPTE in the IEEE 802.15.4 multi-hop networks in error-prone environments is drawn with the physical, logical, and hybrid channel quality estimators. Simulation results show that the HAPTE outperforms all the physical, logical, and hybrid channel quality estimators in terms of energy consumption, delay, and end to end packets delivery rate, using the same surrounding conditions.

Finally, in Chapter 5, conclusions of all the research findings, which have been introduced in this thesis, are drawn. On the basis of the research findings, some directions toward the future works and the research collaboration plans have been proposed at the end of the chapter.