Maximizing the System Lifetime of Query Based Wireless Sensor Network: QOS Control Algorithm

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Abstract

Wireless Sensor Networks (WSNs) present several unique characteristics such as resource-constrained sensors, random deployment, and data-centric communication protocols. These characteristics pose unprecedented challenges in the area of query processing in WSNs. This dissertation presents the design and validation of adaptive fault tolerant QoS control algorithms with the objective to achieve the desired Quality Of Service (QoS) requirements and maximize the system lifetime in query-based WSNs.

Data sensing and retrieval in WSNs have a great applicability in military, environmental, medical, home and commercial applications. In query-based WSNs, a user would issue a query with QoS requirements in terms of reliability and timeliness, and expect a correct response to be returned within the deadline. Satisfying these QoS requirements requires that fault tolerance mechanisms through redundancy be used, which may cause the energy of the system to deplete quickly. We analyze the effect of redundancy on the mean time to failure (MTTF) of query based cluster-structured WSNs, defined as the mean number of queries that a WSN is able to answer correctly until it fails due to channel faults, sensor faults, or sensor energy depletion. We show that a tradeoff exists between redundancy and MTTF. Furthermore, an optimal redundancy level exists such that the MTTF of the system is maximized.

In this paper, we develop adaptive fault tolerant quality of service (QoS) control algorithms based on hop-by-hop data delivery utilizing “source” and “path” redundancy, with the goal to satisfy application QoS requirements while prolonging the lifetime of the sensor system. We develop a mathematical model for the lifetime of the sensor system as a function of system parameters including the “source” and “path” redundancy levels utilized. We discover that there exists optimal “source” and “path” redundancy under which the lifetime of the system is maximized while satisfying application QoS requirements. Numerical data are presented and validated through extensive simulation, with physical interpretations given, to demonstrate the feasibility of our algorithm design.

Keywords
Timelines, Redundancy, Reliability, Query Processing, Energy Conservation, QoS, Mean Time to Failure, Wireless Sensor Networks

I. Introduction

A. Wireless Sensor Network Applications

WSNs can be used in many applications for continuous sensing, event detection, location sensing, and local control of actuators. The applications in WSNs can be categorized into military, environmental, medical, home, and commercial applications. Military applications: WSNs can be an integral part of military command and control, communications, computing, intelligence, surveillance, reconnaissance and targeting systems. The rapid deployment, self-organization and fault tolerance characteristics of WSNs make them a very promising sensing technique for military. Some of the military applications of WSNs are monitoring forces, equipment and ammunition; battlefield surveillance; reconnaissance of opposing forces and terrain; targeting; battle damage assessment; and nuclear, biological and chemical attack detection and reconnaissance [1-2]. For example, A Patrol, Search and Rescue vehicle (PSAR) uses information provided by a WSN to patrol the border, detecting illegal border crossings, drug trafficking, and other criminal activities. Also, a rescue mission in this inhospitable terrain may involve PSAR(s) navigating the terrain, interacting continuously with the WSN, tapping into the stored information to chart safe paths. The WSN informs the PSAR in real-time of sources of imminent danger, the presence of trapped or wounded people, etc. The nature of these interactions requires the WSN to provide timely, high-quality information.

Over the last few years, we have seen a rapid increase in the number of applications for WSNs [1-2]. WSNs are used in battlefield applications, and a variety of vehicle health management and condition-based maintenance applications on industrial, military, and space platforms. For military users, a primary focus has been area monitoring (security and surveillance applications). For industrial platform, WSNs are targeted for health monitoring of equipment for complex machinery and processes inside factories or on board ships. For air and space platforms, a main focus is on the overall integrate vehicle health management system for use on aircraft, rotorcraft, and spacecraft. WSNs are also used for habitat and environmental monitoring for wildlife and seabird habitat management.

WSNs inherit most of the QoS challenges from general wireless networks. Moreover, their particular characteristics pose unique challenges as follows [3-4].

Extreme resource constraints: Sensor nodes (SNs) are small-scale devices with their sizes approaching a cubic millimeter in the near future [5]. Such small devices are very limited in the energy they can store or collect from the environment. Furthermore, SNs are subject to failures due to depleted batteries or, more generally, due to environmental influences. Limited size and energy also typically means restricted resources (CPU performance, memory, wireless communication bandwidth and range). As a result, these constraints impose an essential requirement on any QoS support mechanisms in WSNs, that is, simplicity. Computation intensive algorithms, expensive signaling protocols, or overwhelming network states maintained at SNs are not feasible.

1. Unbalanced Traffic

In most applications of WSNs, traffic mainly flows from a large number of SNs to a small subset of sink nodes. QoS mechanisms should be designed for an unbalanced QoS-constrained traffic.

2. High Data Redundancy

WSNs are characterized by high redundancy in the sensor data. However, while data redundancy helps satisfy the reliability/robustness requirement of data delivery, it may unnecessarily...
spend too much precious energy. Data fusion or data aggregation is a solution to maintain robustness while decreasing redundancy in the data, but this mechanism also introduces latency and complicates QoS design in WSNs.

3. Network Dynamics
Node mobility, node failures, environmental obstructions, and node state transitions due to the use of power management or energy efficient scheme cause a high degree of dynamics in WSNs. This includes frequent network topology changes and network partitions. Communication failures are also a typical problem of WSNs [6]. Such a highly dynamic network greatly increases the complexity of QoS support.

4. Balancing Energy Consumption
In order to achieve a long-lived network, energy load must be evenly distributed among all SNs so that the energy at a single SN or a small set of SNs will not be drained out very soon. QoS support should take this factor into account.

5. Scalability
A generic wireless sensor network is envisioned as consisting of hundreds or thousands of SNs densely distributed in a terrain. Therefore, QoS support designed for WSNs should be able to scale up to a large number of SNs.

6. Multiple Sink Nodes
Multiple sink nodes may exist in a WSN, which impose different requirements on the network. For instance, one sink may ask SNs located in the northeast of the sensor field to send a temperature report every minute, while another sink node may only be interested in an exceptionally high temperature event in the southwest area. WSNs should be able to support different QoS levels associated with different sink nodes.

7. Multiple QoS Levels
The content of data or high-level description reflects the criticality of the real physical phenomena and is thereby of different priority with respect to the quality of the applications. QoS mechanisms may be required to differentiate data importance and set up a priority structure.

This dissertation research is motivated by the challenges in the WSNs. We develop a Hop-by-Hop Data Delivery (HHDD) protocol that utilizes path and source redundancies to achieve the required QoS requirement in terms of reliability and timelines while maximizing the system lifetime. Our Adaptive Fault Tolerant QoS Control (AFTQC) algorithm, built on top of the HHDD protocol, addresses the issues of resource constraints, unbalanced traffic, high data redundancy, network dynamics, balancing energy consumption, scalability, multiple sink nodes, and multiple QoS levels. We consider a homogeneous WSN with SNs being deployed massively. The AFTQC algorithm supports multiple QoS levels by using different levels of redundancy to answer queries with different QoS requirements. It does not require an initial route setup for data delivery in order to save energy of WSNs. This algorithm is simple enough to be executed on resource constrained WSNs. It supports concurrent queries from multiple sink nodes. It is also scalable to a large WSN and adaptive to network dynamics. The optimal level of redundancy used to answer a query is dynamically adjusted when the sensor density is changed due to channel failures, sensor failures or sensor energy depletion.

B. Quality of Service
From the network QoS perspective, we consider how the underlying communication network can deliver sensor data while efficiently utilizing network resources. A WSN can be source-driven or query-based depending on the data flow. In source-driven WSNs, sensors initiate data transmission for observed events to interested users, including possibly reporting sensor readings periodically. An important research issue in source-driven WSNs is to satisfy QoS requirements of event-to-sink data transport while conserving energy of WSNs. ESRT [11] has been proposed to address this issue with reliability as the QoS metric. The goal of ESRT is to achieve reliable event detection in WSNs with minimum energy expenditure. It includes a congestion control component that serves the dual purpose of achieving reliability and conserving energy. The algorithm of ESRT mainly runs on the sink with minimal functionality required at resource constrained SNs. A sink would estimate the event-to-sink reliability and adjusts the reporting frequency of sensor nodes to achieve the desired reliability.

This dissertation research concentrates on query-based rather than source-driven WSNs. We consider both reliability and timeliness as the QoS requirement. Further, while ESRT aims to provide end-to-end reliable transport between a sink-source pair by means of congestion control exercised by the sink node based on feedback, our hop-by-hop data delivery protocol is designed to propagate data hop by hop to satisfy the QoS requirements without feedback in order to conserve energy and better satisfy a query deadline requirement.

II. Motivation
1. ReInForM:— End to End reliability issues, information awareness/adaptability of network resources
2. Multiple Path MMSPEED—Most related to AFTQC, however, does not take energy consumption into account
3. M. Perillo (paper) – satisfy minimum application QoS reliability while maximizing lifetime of WSNTurn off sensors for periods of time to save energy
   • It’s a multipath, multispeed routing protocol
   • Takes timeliness and reliability into account (we need that)
4. HEED/LEACH—Clustering WSN; HEED rotates CH among SN to achieve better energy efficiency, LEACH autonomously forms small clusters

III. Existing System
Existing research efforts related to applying redundancy to satisfy QoS requirements in query-based WSNs fall into three categories: traditional end-to-end QoS, reliability assurance, and application specific QoS.

Traditional end-to-end QoS solutions are based on the concept of end-to-end QoS requirements. The problem is that it may not be feasible to implement end-to-end QoS in WSNs due to the complexity and high cost of the protocols for resource constrained sensors. This method does not consider the reliability issue.
   • Complexity and high cost of the protocols for resource constrained sensors
   • Does not consider the reliability issue.
   • Does not consider energy issues.
   • Data delivery such as reliability and timelines are not considered.

IV. Proposed System
In this paper, we develop adaptive fault tolerant quality of service (QoS) control algorithms based on hop-by-hop data delivery
utilizing “source” and “path” redundancy, with the goal to satisfy application QoS requirements while prolonging the lifetime of the sensor system. We discover that there exists optimal “source” and “path” redundancy under which the lifetime of the system is maximized while satisfying application QoS requirements.

- To applying redundancy to satisfy application specified reliability and timeliness requirements for query-based WSNs.
- We develop the notion of “path” and “source” level redundancy
- Lifetime of the system is maximized.
- Timeliness, Multiple data delivery speed options.
- Reliability, Multi-path forwarding.

A clustering algorithm that aims to fairly rotate SNs to take the role of CHs has been used to organize sensors into clusters for energy conservation purposes. The function of a CH is to manage the network within the cluster, gather sensor reading data from the SNs within the cluster, and relay data in response to a query. Clustering algorithm is executed during the system lifetime.

- Aggregation of readings
- Each cluster has a CH
- Users issue queries through any CH.
- CH that receives the query is called the Processing Center (PC)
- Each non-CH node selects the CH candidate with the highest residual energy, sends it a cluster join message (includes the non-CH node’s location). The CH will acknowledge this message.
- Randomly rotates role of CH among nodes -> nodes consume their energy evenly

**B. System Model**

Transmission power reduced to minimum level (enough for one-hop radio range, r). It can increase with time dynamically when network becomes less dense.

Routing:
- Based on Geographic routing
- No path information maintained by individual SNs
- Location of neighboring node known to a sending node
- All nodes receive and maintain location of CH (through election process)

**C. Transmission Power**

SNs operate in power saving mode to save energy:
- Active mode
- Sleep mode

Energy to transmit a data packet of length nb bits a distance r (m) =

\[ E_T = n_p (E_{elec} + E_{amp} r^2) \]

Where:
- \( E_{elec} \) = Energy to run the transmitter and receiver circuitry (J/bit)
- \( E_{amp} \) = Energy used by the transmit amplifier to achieve an acceptable signal to noise ratio (J/bit/m²)
- \( r_e \) = energy loss due to channel transmission

Energy to receive a message = \( E_{rx} = n_p E_{elec} \)

**D. Query Reliability**

Sensor Failure some times:
- Hardware- Probability of failure is q
- Software- probability of failure is qs
- Transmission Failure-Probability of failure is ej

**Speed Violation-Not meeting Treq** (time requirement)

Query success probability \( R_s = 1 - Q_f \)

Query failure probability \( Q_f = 1 - (1 - q)^2 (1 - q^s_j) \)

**E. Speed Violation**

Other than speed violation failure, a node may also fail to relay sensor data because of either a sensor failure or a transmission failure, or both. Let \( Q_{r;j} \) be this failure probability of an SN, say, SNj. Then, \( Q_{r;j} \) is given by

\[ Q_{r;j} = 1 - [(1 - q)(1 - e_j)]. \]
F. Query Processing Energy Consumption

We calculate energy consumed per query. For source redundancy, in response to a query, an SN assigned would transmit a data packet to its source CH. Since the average number of hops between an SN and its CH is given by Nh intra, as derived above, and a query requires the use of ms SNs for source redundancy, the total energy required for these ms SNs to forward sensor readings to the CH is given by

\[ E_s = m_s N_{iter}^{m_s} \left[ E_T + \lambda (\pi r^2) E_R \right]. \]

For path redundancy, let Ech be the total energy consumed by the WSN to transmit sensor data from the source CH to the PC with mp paths connecting the CH to the processing center. The source CH would broadcast a copy of the data packet and all first-hop neighbors would receive. Then, among the first-hop neighbors, mp nodes would broadcast again and all 2nd-hop neighbors would receive. In each of the subsequent hops on a path, only one node would broadcast and the neighbors on the next hop would receive. Consequently, Ech is given by

\[ E_{ch} = E_T + \lambda (\pi r^2) E_R + \pi r m_p (N_{iter}^{m_p} - 1) \left[ E_T + \lambda (\pi r^2) E_R \right]. \]

The total amount of energy spent by the system, Eq, to answer a query that demands a source cluster to respond, using ms SNs for source redundancy and mp paths for path redundancy, is given by

\[ E_q = E_{ch} + E_s. \]

Energy Consumption Due to Clustering

For clustering, the system would consume energy for broadcasting the announcement message and for the cluster-join process. Since p is the probability of becoming a CH, there will be pn SNs that would be broadcasting the announcement message. This announcement message will be received and retransmitted by each SN to the next hop until the TTL of the message reaches the value 0, i.e., the number of hops equals Nh intra. Thus, the energy required for broadcasting is. The cluster-join process will require an SN to send a message to the CH informing that it will join the cluster and the CH to send an acknowledgement to the SN. Let Niteration be the number of iterations required to execute the clustering algorithm. Then, the energy required for each execution of the clustering algorithm, Eclustering, is given by

\[ E_{clustering} = pn N_{iteration}^{m_s} \left[ N_{iter}^{m_s} \lambda (\pi r^2) \left( E_T + E_R \right) \right]. \]

IV. Conclusion

Adaptive fault tolerant QoS control (AFTQC) algorithm incorporating path and source redundancy to satisfy QoS requirements while maximizing lifetime of query-based sensor networks. We discussed how these mechanisms can be realized using hop-by-hop packet data delivery and derived the probability of successful data delivery within a real-time constraint (Rq), as well as the amount of energy consumed (Eq) per query. When given a set of parameter values characterizing the operating and workload conditions of the environment, we identified the optimal (mp, ms) setting that would maximize the MTTF while satisfying the application QoS requirements.

References


