Chapter 1

Introduction
Recent technological improvements have made the deployment of small, inexpensive, low-power, distributed devices, which are capable of local processing and wireless communication, a reality. A wireless sensor network is a collection of nodes organized into a cooperative network [1]. Each node consists of processing capability (one or more microcontrollers, CPUs or DSP chips), may contain multiple types of memory (program, data and flash memories), have a RF transceiver (usually with a single omni-directional antenna), have a power source (e.g., batteries and solar cells), and accommodate various sensors and actuators. The nodes communicate wirelessly and often self-organize after being deployed in an ad hoc fashion. Systems of 1000s or even 10,000 nodes are anticipated. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes. Recent technological improvements have made the deployment of small, inexpensive, low-power, distributed devices, which are capable of local processing and wireless communication, a reality. A wireless sensor network is a collection of nodes organized into a cooperative network [1]. Each node consists of processing capability (one or more microcontrollers, CPUs or DSP chips), may contain multiple types of memory (program, data and flash memories), have a RF transceiver (usually with a single omni-directional antenna), have a power source (e.g., batteries and solar cells), and accommodate various sensors and actuators. The nodes communicate wirelessly and often self-organize after being deployed in an ad hoc fashion. Systems of 1000s or even 10,000 nodes are anticipated. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes.

1.1 INTRODUCTION TO WIRELESS SENSOR NETWORKS

A wireless sensor network (WSN) is a computer network consisting of many, spatially distributed devices using sensors to monitor conditions at different locations, such as temperature, sound, vibration, pressure, motion or pollutants[1][2][5]. The
development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks are now used in many civilian application areas, including environment and habitat monitoring, healthcare applications, home automation, and traffic control[1][3][5]. Usually, these devices are small and inexpensive, so that they can be produced and deployed in large numbers. The size and price requirements imply that the devices' resources in terms of energy, memory, computational speed and bandwidth are severely constrained. Each device is equipped with a radio receiver, a small microcontroller, and an energy source, usually a battery. Each device relays information from other devices to transport data to a monitoring computer.

Wireless Sensor Networks involve three areas: sensing, communications, and computation (hardware, software, algorithms). Very useful technologies are wireless database technology, such as queries used in a wireless sensor network, and network technology to communicate with other sensors, especially multihop routing protocols. The emerging field of wireless sensor networks combines sensing, computation, and communication into a single tiny device. Through advanced mesh networking protocols, these devices form a sea of connectivity that extends the reach of cyberspace out into the physical world. The mesh networking connectivity will seek out and exploit any possible communication path by hopping data from node to node in search of its destination. While the capabilities of any single device are minimal, the composition of hundreds of devices offers radical new technological possibilities. The power of wireless sensor networks lies in the ability to deploy large numbers of tiny nodes that assemble and configure themselves. Usage scenarios for these devices range from real-time tracking, to monitoring of environmental conditions, to ubiquitous computing environments, to monitoring of the health of structures or equipment. While often referred to as wireless sensor networks, they can also control actuators that extend control from cyberspace into the physical world. The most straightforward application of wireless sensor network technology is to monitor remote environments for low frequency data trends. For example, an office could be easily monitored for fire in any of its rooms by hundreds of sensors that automatically form a wireless interconnection network and immediately report the detection of any
fire. Unlike traditional wired systems, deployment costs would be minimal. Instead of having to deploy thousands of feet of wire routed through protective installers, you simply have to place quarter-sized device at each sensing point. The network could be incrementally extended by simply adding more devices-no rework or complex configuration. In addition to drastically reducing the installation costs, wireless sensor networks have the ability to dynamically adapt to changing environments. Adaptation mechanisms can respond to changes in network topologies or can cause the network to shift between drastically different modes of operation. For example, the same embedded network performing leak monitoring in a chemical factory might be reconfigured into a network designed to localize the source of a leak and track the diffusion of poisonous gases. The network could then direct workers to the safest path for emergency evacuation. Current wireless systems only scratch the surface of possibilities emerging from the integration of low-power communication, sensing, energy storage, and computation. Unlike traditional wireless devices, wireless sensor nodes do not need to communicate directly with the nearest high-power control tower or base station, but only with their local peers. Instead, of relying on a pre-deployed infrastructure, each individual sensor or actuator becomes part of the overall infrastructure. Peer-to-peer networking protocols provide a mesh-like interconnect to shuttle data between the thousands of tiny embedded devices in a multi-hop fashion. The flexible mesh architectures envisioned dynamically adapt to support introduction of new nodes or expand to cover a larger geographic region. Additionally, the system can automatically adapt to compensate for node failures. The vision of mesh networking is based on strength in numbers.

1.2 DIFFERENCE BETWEEN AD HOC NETWORKS AND WIRELESS SENSOR NETWORKS

Following are the differences between ad hoc networks and wireless sensor networks:

- The number of sensor nodes in a sensor network can be several orders of magnitude higher than the nodes in an ad hoc network.
- Sensor nodes are densely deployed.
Sensor nodes are prone to failures.
The topology of a sensor network changes very frequently.
Sensor nodes mainly use broadcast communication paradigm whereas most ad
hoc networks are based on point-to-point communications.
Sensor nodes are limited in power, computational capacities, and memory.
Sensor nodes may not have global identification (ID) because of the large
amount of overhead and large number of sensors.

1.3 APPLICATIONS OF WIRELESS SENSOR NETWORKS

The applications for WSNs are many and varied. They could be used in industry to
monitor dangerous/hermetically-sealed environments. They could be deployed in
wilderness areas, where they would remain for many years (monitoring some
environmental variable) without the need to recharge/replace their power supplies.
They could form a perimeter about a property and monitor the progression of
intruders (passing information from one node to the next). There are many uses for
WSNs. Typical applications of WSNs include monitoring, tracking, and controlling.
Some of the specific applications are habitat monitoring, object tracking, nuclear
reactor controlling, fire detection, traffic monitoring, etc. In a typical application, a
WSN is scattered in a region where it is meant to collect data through its sensor
nodes. Thus, the applications of WSNs can be summarized as follows;

- Environmental monitoring
- Habitat monitoring
- Acoustic detection
- Seismic detection
- Military surveillance
- Inventory tracking
- Medical monitoring
- Smart spaces
1.4 CHARACTERISTICS OF WIRELESS SENSOR NETWORKS

Unique characteristics of a WSN are:

- Small-scale sensor nodes
- Limited power they can harvest or store
- Harsh environmental conditions
- Node failures
- Mobility of nodes
- Dynamic network topology
- Communication failures
- Heterogeneity of nodes
- Large scale of deployment

1.5 CHALLENGES OF WIRELESS SENSOR NETWORKS

In spite of the diverse applications, sensor networks pose a number of unique technical challenges due to the following factors:

- Ad hoc deployment: Most sensor nodes are deployed in regions which have no infrastructure at all. A typical way of deployment in a forest would be tossing the sensor nodes from an airplane. In such a situation, it is up to the nodes to identify its connectivity and distribution.

- Unattended operation: In most cases, once deployed, sensor networks have no human intervention. Hence, the nodes themselves are responsible for reconfiguration in case of any changes.

- Untethered: The sensor nodes are not connected to any energy source. There is only a finite source of energy, which must be optimally used for processing and communication. An interesting fact is that communication dominates processing in energy consumption. Thus, in order to make optimal use of energy, communication should be minimized as much as possible.

- Dynamic changes: It is required that a sensor network system be adaptable to changing connectivity (for e.g., due to addition of more nodes, failure of nodes...
etc.) as well as changing environmental stimuli. Thus, unlike traditional networks, where the focus is on maximizing channel throughput or minimizing node deployment, the major consideration in a sensor network is to extend the system lifetime as well as the system robustness [7].

- **Real-time Constraints:** Since sensor networks deal with the real world processes, it is often necessary for communication to meet real-time constraints. In battle surveillance systems, for example, communication delays within sensing and actuating loops directly affect the quality of enemy tracking.

### 1.6 KEY DEFINITION OF WIRELESS SENSOR NETWORKS

Sensor networking is a challenging research area that draws on contributions from signal processing, networking and protocols, databases and information management, distributed algorithms, embedded systems, and architecture and QoS. A number of key terms and concepts have been used throughout this thesis:

- **Sensor:** A transducer that converts a physical event into electrical or other signals that can be read by an observer or by a device.

- **Sensor node:** Also known as a mote, this is the basic unit in a sensor network and is capable of performing some processing, gathering sensory information, and communicating with other connected nodes in the network.

- **Sink:** Also known as a gateway, this is a special device with more power and memory than a node.

- **Network topology:** The study of the arrangement or mapping of the network elements, such as links, nodes, etc. It can also be a connection graph, in which nodes are sensor nodes and edges are communication links.

- **Routing:** The process of determining a network path from a packet source node to its destination.

- **Task:** High-level system assignments, which include sensing, communication, processing, and resource allocation, or application tasks which may include detection, classification, localization, or tracking.
Detection: The process of discovering the existence of a physical phenomenon.

Classification: The assignment of class labels to a set of physical phenomena being observed.

Resource: Elements including sensors, communication links, processors, onboard memory, and node energy reserves.

Node service: Services, such as time synchronization and node localization that enable applications to discover properties of a node and organize themselves into a useful network.

1.7 PROPOSAL STATEMENT AND CONTRIBUTIONS

In this thesis work, we propose a new network architecture, which has a set of indispensable layers specially tailored to the characteristics of sensor networks. The proposed architecture will be an integrated solution and efficiently address following important issues:

- Real-time communication.
- Energy conservation in the communication and surveillance for a long network lifetime.
- Robustness and self-stabilization to the node failure, mobility and power-down
- Power conservation.
- Application Independent data aggregation.

Briefly, our proposal statement is as following:

*Building a scalable, reliable, robust and time-energy aware network architecture for sensor networks.*

Contributions: In this research work our main focus would on two areas which are further explored for detailed research.
Introduction

- Real time communication
- Robustness and self-stabilization to the node failure and mobility

Prime contribution is proposal of new architecture with new features (Chapter 2). In real time communication, we worked on both hard as well as soft real time guarantee in a single solution (Chapter 3). Congestion control and avoidance to meet real time reliability is explained in details (Chapter 4). Real time scheduling which uses virtual paths for robustness and self-stabilization is covered in Chapter 5. Real time communication capacity limits for data forwarding to meet real time deadlines are defined in Chapter 6. Lifetime maximizing tree construction algorithms for enhancing network life time are derived in Chapter 7. Various techniques for application independent data aggregation are proposed in Chapter 8. Power conservation mechanism in physical layer is described in Chapter 9. Chapter 10 concludes and summarizes the research.

1.8 KEY RESEARCH PROBLEMS OF THE RESEARCH WORK

As mentioned in the previous sections, the unique features of sensor networks necessitate a new set of novel solutions tailored for this type of system. In this section, we specifically identify four essential research topics for the overarching research plan. On the one hand, these topics are orthogonal because they reside in the different layers of the network architecture we are proposing and the solutions of those topics can work independently with each other. On the other hand, these topics are associated in the sense that they are complementary to each other in order to provide an integrated solution for sensor networks.

1.8.1 Soft Real-time Communication for Timely Response

To date, few results exist for sensor networks that adequately address real-time requirements for time-critical applications, such as battlefields and earthquake response systems. The correctness of such systems not only depends on the logical correctness of the results, but also the time when such results are produced. Without real time guarantee, actions taken by these systems would not be as effective as they should be. For example, in a target tracking system, an intruder’s location should be
reported to pursuers within 10 seconds bound so that pursuers can take effective actions. Since sensor networks deal with the real world and communication delays within sensing and actuating loops directly affect the response time of the applications, it is often necessary for communication to meet real-time constraints. We identify our first research problem as providing a real-time communication service that can support soft real-time end-to-end delivery as well as hard real-time guarantee under unpredictable network environments. Specially, following research issues should be addressed:

- A novel mechanism to provide probabilistic soft real-time end-to-end delay guarantee, while underlying MAC only supports the contention-based best effort packet forwarding.
- A mechanism to provide hard real-time guarantee for proper network utilization.
- A mechanism to estimate accurately the transient and long-term utilizations of wireless networks for the purpose of packet admission, scheduling and forwarding.
- Integrated solutions to reduce delay, minimize energy consumption, maximize throughput and guarantee data delivery.
- An enhanced differentiated scheme to meet real-time constraints for packets with different priorities.
- A routing scheme that is pure decentralized in order to cope with scalability issues, while at the same time avoiding system wide race condition and instability.

So, we consider real time communication as the first step in our research work. To achieve real time communication we divide our work in four parts.

First, we propose Robust and Real Time Data Delivery (RRTD) mechanism in Wireless Sensor Networks which provides both hard real time as well as soft real time guarantee. The proposed mechanism uses centralized control plane incorporating the timed token protocol in the MAC layer for wireless token ring architectures for
providing hard real time guarantee and in advance bandwidth reservation method to provide soft real time guarantee.

Secondly, we focused on congestion avoidance to maintain real time reliability for which we proposed a real-time and reliable transport (RRRT) protocol.

Real Time Scheduling (RTS) was kept as third issue with real time communication. RTS provides real-time data dissemination in sensor networks that addresses many of the shortcomings of the existing solutions. RTS delays packets at intermediate hops (not just prioritizes them) for a duration that is a function of their deadline. Delaying packets allows the network to avoid hot spotting while maintaining deadline-faithfulness.

Fourth, we derived real-time communication capacity limits for the wireless sensor networks. These limits define the information carrying ability of the network for given real time deadlines.

1.8.2 Application Independent Data Aggregation for Energy Conservation and Enhancement in Network Lifetime

Data aggregation techniques are proposed to address multiple issues. Data aggregation performed among a group of nodes can effectively reduce total amount of application data shipped out, thus reducing network congestion and energy consumption. To the best of our knowledge, all recent research focuses on application dependent data aggregation techniques (ADDA), in which aggregation heavily depends on the application layer information. By placing a naming (semantic) restriction on the aggregated data, those techniques impose that blower layer protocols must have knowledge of these naming semantics and limit the types of data that can be aggregated. For example, the aggregation module must have the knowledge that the temperature readings from the northeast corner of a network should not be combined with the temperature from the southwest corner just because they share a common type and make sure aggregation is not performed between the messages containing temperature readings and messages containing acoustic readings.
In view of those limitations, our research will focus on three types of application independent data aggregation (AIDA) approach. This approach isolates aggregation decisions from application specifics by performing adaptive aggregation in an intermediate layer that resides between the traditional data-link and network layer. In order to reduce network congestion and achieve a high degree of energy conservation, we should address following research issues sufficiently:

- A modular architecture to isolate aggregation decisions effectively from application specifics.
- An approximate model for the MAC contention for the purpose of control.
- Adaptive aggregations to enhance the network lifetime.
- A novel mechanism to increase the degree of aggregation without jeopardizing the end-to-end delay.
- An enhance scheme to incorporate real-time guarantees and differentiated QoS supports into this aggregation framework.

Our solution is expected to improve the efficiency in bandwidth utilization, a resource that is most precious in sensor networks. The auxiliary benefit of our solution is the energy-conservation by constructing lifetime maximizing tree. These trees minimize end to end delay as well as prolong node lifetime which indirectly enhances the network lifetime.

1.8.3 Robust Data Delivery under Failure and Mobility

Sensor networks are faulty networks where failures should be treated as normal phenomena. Unreliable nodes, constrained energy, high channel bit error ratio, interference and jamming, multi-path-fading, asymmetric channel and weak security make the communication highly unreliable. At the same time, sensor networks are highly dynamic networks where network topologies are constantly changing due to a high rate of node failure, changes of power modes, and nodes’ mobility. It is a challenging research problem to provide a robust data delivery under such a situation. Previous protocols proposed need to update and maintain routing tables or at least neighborhood tables for the purpose of routing, and they suffer delay to establish and
maintain these tables if the network is highly dynamic. With constant node failures and frequent message loss, the state-sensitive routing protocols such as AODV, DSR and DSDV take a huge amount of time and energy to stabilize. Acknowledging that state-based solutions are inefficient to cope with highly dynamical sensor networks; we proposed a solution that is altogether state-free for robust data delivery. In this solution, we aim at providing not only a reliable communication scheme, but also a fast response and recovery from the failures with a much less control overhead. Specifically, following issues will be addressed in our scheme:

- A swift & self-stabilizing approach to deal with instability caused by fast flow dynamics inside networks such as nodes’ failure and mobility
- An efficient approach to reduce the inconsistency between outdated routing information a node keeps and the volatile network situations with minimal overhead
- A reliable scheme which prevents the performance degradations in packet delivery, end-to-end delay and control overhead, while allowing nodes going to a dormant state in order to conserve energy effectively

For robust data delivery support, we proposed a fault tolerant optimal path (FTOP) for data delivery. And self-stabilization is achieved by the virtual paths where a backup node is provided with every node. If there is a node failure, backup node automatically comes in action. On the one hand, applications can deliver data more reliable and fast in face of high node failure rate and mobility. On the other, less bandwidth and energy will be consumed by the solution proposed by us.

1.8.4 Power management

Wireless Sensor networks are non-infrastructure networks which consist of mobile sensor nodes. Since the sensor nodes have limited battery power, it is very important to use energy efficiently in sensor networks. Thus, it is widely accepted that conventional routing protocols are not appropriate for sensor networks and consequently, the design of routing protocols for such networks is a challenging issue taking power factor into consideration. To reduce the energy consumption in mobile
devices, there have been efforts in physical and data link layers as well as in the network layer related to the routing protocol. The physical layer can save energy by adapting transmission power according to the distance between nodes. To minimize the power consumption, we propose an on demand power aware routing protocol. The purpose of on demand power-aware routing protocols is to maximize the network lifetime and minimize energy consumption by only transmitting message when there is demand of that message (Sleep and Wake technology). Our proposed routing algorithm works out in the following ways:

- It balances between minimum transmission energy consumption and fair node energy consumption in a distributed manner.

- This goal is achieved by controlling the rebroadcast time of RTREQ packets.

- In addition, we design a mechanism of estimating the average energy level of the entire network without additional control packets. The estimated average energy is useful to adaptively control the rebroadcast time.

1.9 OVERVIEW OF THE REMAINDER OF THE THESIS

The broad outline of the thesis is as follows: Research began with studying the existing sensor network architecture and proposing new network architecture with different layers supporting various features to overcome the problems with the existing architecture. Chapter 2 describes the existing architecture with open research issues associated with each layer in details. The need of the new architecture is elaborated in the same chapter as well as the proposed architecture is presented in chapter 2. Work has been carried on the 5 layers following the bottom up approach. Protocols for each of these layers are proposed in different chapters of our research. Our research has been divided in two main areas where first area cover’s real time communication, robust and self-stabilization for node failure and node mobility. Second area deals with issues such as enhancement in network lifetime, application independent data aggregation and power minimization. Area dealing with real time communication consists of four chapters. Chapter 3 proposes a Robust and Real Time Data Delivery (RRTD) mechanism in wireless sensor networks which uses centralized
control plane incorporating the timed token protocol in the MAC layer for wireless
token ring architectures for providing hard real time guarantee and in advance
bandwidth reservation method to provide soft real time guarantee. This mechanism is
supporting real time routing layer. Incorporating this mechanism with the proposed
layer minimizes the energy consumption and delay. None of the previous work has
provided a solution for both hard real time and soft real time guarantee in a single
delivery mechanism.

A reliable, robust and real-time (RRRT) protocol is presented in Chapter 4 to address
the need for robust, real-time and reliable event data delivery with minimum energy
consumption and with congestion avoidance in WSNs. The proposed protocol uses a
fault tolerant optimal path (FTOP) for data delivery. FTOP selects a path for each
source node to deliver event packets to the sink node. The selected paths are node-
disjoint and FTOP is thus fault-tolerant in the sense that event packets can be received
by the sink node even if node failures make some paths broken. The RRRT protocol
works on robust and self-stabilized MAC layer of the proposed architecture. The
RRRT protocol operation is determined by the current network state based on the
delay constrained event reliability and congestion condition in the network. If the
delay constrained event reliability is lower than required, RRRT adjusts the reporting
frequency of source nodes aggressively to reach the desired reliability level as soon as
possible. If the reliability is higher than required, then RRRT reduces the reporting
frequency conservatively to conserve energy while still maintaining reliability. This
self-configuring nature of RRRT makes it robust to random, dynamic topology in
WSNs. Furthermore, RRRT proposed by us is the first work that addresses the
reliability at both sensor/sub-sink and sub-sink/sub-sink level.

Real-time data dissemination is a service of great interest to many sensor network
applications. The primary contribution of Chapter 5 is a new approach Real Time
Scheduling (RTS) which uses virtual nodes for self-stabilization approach for real-
time data dissemination in sensor networks that addresses many of the shortcomings
of the existing solutions. RTS delays packets at intermediate hops (not just prioritizes
them) for a duration that is a function of their deadline. Delaying packets allows the
network to avoid hot spotting while maintaining deadline-faithfulness. To the best of
our knowledge, none of the previous work has considered delay as a parameter for real-time dissemination. Secondly, RTS we are proposing uses virtual nodes for self-stabilization that is if any of the nodes runs out of power instead of waiting and increasing the delay, an alternate route is selected for the transmission. The third contribution of this chapter is to explore the role of the routing protocol in the success of real-time scheduling in sensor networks. The basic RTS algorithm distributes the slack time (available time before the deadline expires) uniformly across all the hops. However, in a gathering data collection pattern, the amount of contention is typically higher the closer to the sink. We demonstrate the performance of RTS in comparison to state-of-the-art models in this area (the RAP and SPEED models [34] [35]) using simulation. Real-time dissemination is the scheduling mechanism of differentiated packet scheduling layer.

Real-time capacity of a network is defined to be its information carrying ability for given deadlines. If a packet does not reach its destination by the given deadline, then its contribution to the real-time capacity is 0. In Chapter 6, we derive expressions of real-time capacity that characterize the ability of a WSN to deliver data on time as well as develop network protocols that achieve this capacity. This chapter obtains closed-form analytic expressions for real-time transport capacity of multi-hop wireless sensor networks. The analytic expressions for real-time capacity facilitate the process of designing a network that is guaranteed to meet specified real-time requirements. The feasibility region defined by the capacity expressions can be used for optimization of the operation of the network in the event of dynamically changing network, which is expected with WSN. By achieving the deadlines, we are able to prolong the network lifetime as well as save energy. Real-time limits are defined in the differentiated packet scheduling layer. With this chapter, our part I is concluded where with real-time communication, we are able to meet reliability, node failure, mobility and real-time communication capacity limits. As well as ours is first approach that deals with real-time data dissemination.

Part II of the thesis begins with chapter 7. In this chapter, we construct lifetime maximizing tree for minimizing energy consumption and enhancement in network lifetime. Tree construction is done by three approaches as follows 1) CLMT
Centralized Lifetime maximizing tree construction algorithm which arranges all nodes in a way that each parent will have the maximal-available energy resources to receive data from all of its children. And the minimum energy node is used to collect data for data aggregation. 2) DLMT algorithm explores the highest-energy branch from each source to a root, by first assuming that every source node is a root, using a method similar to Reverse-Path Forwarding (RPF) [56]. This generates a total of $N$ unique trees with each being rooted at a distinct source node. We continue by comparing the energy of these trees and only employ the one with the highest tree energy for data collection/aggregation. 3) DLMTC is construction of decentralized life time maximizing tree based on clustering. This scheme consists of three parts, namely, the clustering of nodes by using the Expectation-maximization (EM) [58] algorithm, construction of decentralized life maximizing tree within the cluster [61], and aggregating the data collected from the WSN nodes by applying a cluster scheduling approach to transfer it, which uses HyMac [57] mechanism. Further, these three approaches are simulated and compared with existing tree E-Span. LMT is constructed as an extended feature of AIDA proposed in next chapter.

Application independent data aggregation techniques are implemented in the application independent data aggregation layer of the proposed architecture for data gathering are proposed in chapter 8. AIDA is able to perform such aggregation without incurring the costs of rewriting components to upper or lower layer protocols. AIDA techniques proposed are as follows: SSB-AIDA scheme attempts to identify the sensor which has the most useful information and the highest signal strength and assigns that sensor as the data aggregator to send packets to the end point. FX–AIDA scheme has the notion of predefined data aggregators in fixed regions of the sensor network region. Sensors surrounding the event send information to the aggregator which eventually sends only the most useful information to the end point. The mobility of events affects the performance of SSB-AIDA and FX-AIDA. We come up with the FLY-AIDA scheme which tries to combine the salient features from both the SSB-AIDA& FX-AIDA when we consider the mobility of the event. Simulation results prove their importance and validity.
Chapter 9 deals with the physical layer with power management of the proposed architecture. In this chapter, an on demand power aware routing algorithm (QDPRA) is proposed. The purpose of on demand power-aware routing protocols is to maximize the network lifetime and minimize energy consumption by only transmitting message when there is demand of that message (Sleep and Wake technology). Our proposed routing algorithm balances between minimum transmission energy consumption and fair node energy consumption in a distributed manner. This goal is achieved by controlling the rebroadcast time of RTREQ packets. In addition, we design a mechanism of estimating the average energy level of the entire network without additional control packets. The estimated average energy is useful to adaptively control the rebroadcast time. None of the previous work has achieved all these objectives simultaneously.

Chapter 10 concludes by summarizing the contributions and evaluating their relevance to real-time communication, robust & self-stabilization in node failure, application independent data aggregation and power conservation in wireless sensor networks. The direction of future research based on this thesis is also discussed.

1.10 NETWORK SIMULATIONS

Simulation modeling is becoming an increasingly popular method for network performance analysis. Generally, there are two forms of network simulation: analytical modeling and computer simulation. Analytical modeling is conducted by a mathematical analysis that characterizes a network as a set of equations. The main disadvantage is its overly simplistic view of the network and inability to simulate the dynamic nature of a network. Thus, the study of a complex system always requires a discrete-event simulation package, which can compute the time that would be associated with real events in a real-life situation. A software simulator is a valuable tool, especially for today’s network with complex architectures and topologies. Designers can test their new ideas and carry out performance-related studies, thus freeing themselves from the burden of "trial and error" hardware implementations. A typical network simulator can provide the programmer with the abstraction of multiple threads of control and inter-thread communication. Functions and protocols are described either by finite-state machine, native programming code, or a
combination of the two. A simulator typically comes with a set of predefined modules and a user-friendly GUI. Some network simulators even provide extensive support for visualization and animation. There are also emulators such as the NIST Network Emulation Tool (NIST Net) [70] [91] [92]. By operating at the IP level, it can emulate the critical end-to-end performance characteristics imposed by various wide-area network situations or underlying sub network technologies in a lab test-bed environment (NIST NET Homepage). The academic simulator used in this thesis is J-sim [70].

1.10.1 J-sim simulator features

J-sim is a free-license simulator. It has advantages and disadvantages like any other simulator, but J-sim was chosen for these main reasons:

- J-sim has been known as Java Sim and is an open-source, component based, compositional network simulation environment.

- J-sim is written purely in Java. At the moment, Java is one of the most widespread and well-known programming languages. Its runtime environments and compilers are available free of charge for most widely used platforms. Java is easy to learn and easy to use.

- Java pre-compiled code is interpreted in the target environment; therefore, both source texts and pre-compiled code are portable. In case of any problems, the source texts provided with J-Sim can be used to generate new code compiled in the target environment and, therefore, completely compatible with JVM (Java Virtual Machine).

- Java provides a class called Thread, whose instances run parallel with other such instances. Thread support is built directly into the language. Therefore, no additional library is necessary, unlike with the C programming language. Moreover, an efficient method of thread synchronization is provided directly in the language. Every object has its own lock, which can temporarily suspend a currently running thread and reactivate it when a wake-up signal is received from another thread.
Java is a fully object-oriented language, providing the concepts of classes, instances, encapsulation, inheritance, and polymorphism. Unlike in C++, the use of object principles is strictly mandatory in Java.

The Java framework is built upon the Autonomous Component Architecture (ACA); the basic entity in J-Sim is components. Ports are the only interfaces of a component to send and receive data. When data arrives at a port, an execution context (a Java thread) is created for the component to process the data.

Components are asynchronous, in the sense that two components may process different data at the same time without synchronizing between each other. These components can be hierarchically structured. A component may be a container mechanism and consist of subcomponents. This facilitates the hierarchical modeling of complex systems [91] [92].

J-Sim provides basic classes for simulation, process, and queue. These classes can be either directly used or extended according to a specific user’s requirements.

There are no special actions required in order to passivate or temporarily passivate a process. Two methods are provided in the process class, whose use is intuitive and easy. The user need not know any implementation details concerning suspension and reactivation.

J-Sim provides two possibilities of running a simulation that can be dynamically switched. The first is the batch mode, sending output to the console. The second is the interactive mode, using a graphics window to control the simulation and to display simulation output. Both modes use only standard Java services, thus rendering them fully portable. However, the possibilities of the target environment may limit their uses.

1.11 CONCLUSIONS

In this section we conclude with the entire features that will be incorporated in the proposed architecture:
The first real-time routing for sensor networks, that will provide both hard real
time as well as soft real time guarantee for delivery of packets.

The first data aggregation scheme that effectively isolates aggregation
decisions from application specifics and eliminates aggregation constrains
imposed by application semantics.

The only time-energy sensitive aggregation scheme that increases the degree
of aggregation without jeopardizing the end-to-end delay.

The first reliable, real time and robust delivery protocol that uses virtual nodes
for self-stabilization.

First real time scheduling algorithm that considers delay.

Lifetime maximizing trees with highest energy branch as data aggregator to
enhance network lifetime.

First On-demand power aware routing protocol to support on demand services
without any extra control packets.

Real time capacity limits for monitoring deadlines.