A Dissertation Proposal on

Hermes: A Scalable Sensor Network Architecture for Robustness & Time-Energy Awareness

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1. Introduction

1.1 The Need for New Sensor Network Architecture

Wireless Sensor Networks (WSN) have emerged as a new information-gathering paradigm based on the collaborative efforts of a large number of self-organized sensing nodes. These networks form the basis for many types of smart environments such as smart hospitals, intelligent battlefields, earthquake response systems, and learning environments. A set of applications, such as biomedicine, hazardous environment exploration, environmental monitoring, military tracking and reconnaissance surveillance, are the key motivations for the recent research efforts in this area.

In sensor networks, nodes are deployed into an infrastructure free environment. Without any *a priori* information about the network topology or the global, even local view, sensor nodes must self-configure and gradually establish the network infrastructure from the scratch during the initialization phase. With the support of this infrastructure, nodes are able to accept queries from remote sites, interact with the physical environment, actuate in response to the sensor readings, and relay sensed information through the multi-hop sensor networks.

Different from traditional networks, sensor networks do impose a set of new limitations for the protocols designed for this type of networks. Devices in sensor networks have a much smaller memory, constrained energy supply, less process and communication bandwidth. Topologies of the sensor networks are constantly changing due to a high node failure rate, occasional shutdown and abrupt communication interferences. Due to the nature of the applications supported, sensor networks need to be densely deployed and have anywhere from thousands to millions of sensing devices, which are the orders of magnitude larger than traditional ad hoc mobile networks. In addition, energy conservation becomes the center of focus due to the limited battery capacity and the impossibility of recharge in the hostile environment. With such a vast difference between traditional networks and sensor networks, it is not appropriate and inefficient to port previous solutions for ad hoc networks into sensor networks with only incremental modifications. For instance, the sheer number of sensor nodes makes flooding-based standard routing schemes (e.g. DSR [53]and AODV[80]) for ad hoc networks undesirable.

Although applications for sensor networks remain diverse, one commonality they all share is the need for a network infrastructure tailored for sensor networks. Without a scalable routing service, broadcast storms caused by the route discovery may result in a significant power consumption and possibly a network meltdown. Without a real-time communication service, applications cannot react to the changes of the environment quickly enough to be effective. Without efficient energy-aware design, nodes in the sensor networks could deplete themselves after only several rounds of burst activities. Without fault-tolerance and self-stabilization supports in such a dynamic and faulty system, sensor networks could never converge and are unable to guarantee an effective transport service to the applications. We do not close the eyes to the importance of the killer applications, but we argue that without a new network architecture tailored to the characteristics of sensor networks, the popularity of sensor networks cannot be a reality in the near future.

1.2 Proposal Statement

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:

- Soft real-time communication
- Network congestion reduction and control
- Energy conservation in the communication and surveillance for a long network lifetime
- Robustness and self-stabilization to the node failure, mobility and power-down
- Routing scalability with the localization support

Briefly, our proposal statement is as following:

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

1.3 Proposal Organization

The main purposes of this proposal are to identify the research challenge problems for the PH.D research, propose tentative solutions, and report the status of current PH.D study. We investigate characteristics of large-scale sensor networks and identify related research problems in the section 2. In section 3, we describe the ideas and designs for a novel integrated network architecture covering different aspects of sensor network issues. Corresponding methodologies to materialize and evaluate these designs are discussed in section 4. Current research status, timetable and expected impact are discussed in section 4.3. Section 6 concludes the proposal. A briefing on literature is provided in appendix A.

2. Research Issues in Sensor Networks

2.1 Characteristic of Large-Scale Sensor Networks

The research issues and challenge problems arise along with a set of new constrains and assumptions ingrained in the sensor network paradigm that previous research did not need to address. As a natural step to identify the future direction of the research, we begin with a view on the characteristics of the large-scale sensor networks that distinguishes itself from traditional networks.

- *Large Scale*

Smart hospitals, battlefields and earthquake response systems are applicable sensor network systems. Such systems require a large geographic coverage. At the same time, a high density is required to work against the high failure rate of sensor nodes, the low confidence in individual sensor readings, the limited communication range and low capability of single sensor nodes. Due to these reasons, sensor networks are expected to scale up to thousands and millions nodes, two orders of magnitude larger than traditional ad hoc networks.

- *Constrained Resource*

The low-cost deployment is one acclaimed advantage of sensor networks, which implies the resources available to individual nodes are severely limited. Low processing speed, limited memory, constrained energy supply and bandwidth make the designs that abuse these resources not applicable in sensor networks.

- *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. Due to the nature of the wireless communication and unpredictable traffic pattern, it is infeasible to guarantee hard real-time constrains, however, research that provides probabilistic guarantee for timing constraints is quite achievable and essential.

- *In-network Processing*

The core of the traditional networks such as internet only provides best-effort forwarding. This design decision is suitable for wired networks where the loss due to the bit error and buffer overflow is the orders of magnitude lower than that in wireless networks. With different assumptions, such design philosophy is hard to hold in sensor networks. For example, the throughput of TCP connection shrinks dramatically with interferences between congestion control and a high BER in wireless communication. As a result, the single hop reliability should be supported by the core of the sensor networks. In-network processing imposes additional complexity to the sensor nodes and it is a challenge issue to design in-networking processing protocols with minimum overhead.

- *Data centric Processing*

Data centric processing is an intrinsic characteristic of sensor networks. Sensor data is no longer access by ID by IP in internet and it is more natural to address the data through content, location or constrains. The IDs of the sensor nodes are of no interests to the applications. The naming schemes in sensor networks are often data-oriented. For example, an environmental monitoring system requests the temperature readings through queries such as "collect temperature readings in the region area bound by the rectangle (x1, y1, x2, y2)", instead of queries such as " collect temperature readings from a set of nodes with the sensor net address x, y and z.".

- *High Unpredictability*

Sensor network applications are driven by environmental events, such as the earthquake and fire, anywhere anytime following an unpredictable pattern. Sensor node failures are common due to the sheer number of sensor nodes and the hostile environment. The radio media shared by densely deployed nodes is subject to heavy congestion and jamming. High bit error ratio, low bandwidth and asymmetric channel make the communication highly unpredictable. Such unpredictability usually prevents off-line design of system parameters. Online monitoring and feedback control are required to provide a certain degree of QoS guarantee under such situations.

- *Redundancy*

The highly unpredictable nature of sensor networks necessitates a high redundancy. Nodes are normally deployed with a high degree of connectivity. With such a redundancy, the failure of a single node has a negligible impact on overall capacity of the sensor networks. High confidence in data can also be obtained through the aggregation of multiple sensor readings. Redundancy is one of few positive characteristics that sensor networks have, therefore it should be fully utilized and exploited in the protocol designs.

- *Security-Sensitive*

Sensor network applications, such as biomedicine, hazardous environment exploration and military tracking are typical mission-critical systems that are highly security sensitive. Unfortunately, sensor networks are vulnerable to all kinds of attack, such as eavesdrop, jamming and Trojan horse. With constrained available resource, it is impossible to deal with all possible security issues, however some measures for expected attack must be provided.

2.2 Key Research Problems

As mentioned in 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 proposed 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.

- *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 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 estimate accurately the transient and long-term utilizations of wireless networks for the purpose of packet admission, scheduling and forwarding
- An integrated solution to reduce network congestion through multiple feedback-based adaptations
- 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

The proposed solution will utilize a feedback-based congestion control to guarantee packet delivery speed across the network. With such a support, applications can estimate an end-to-end delay before making admission decisions and dynamically adjust the workload they generate to meet their real-time requirements.

- *Data Aggregation for Congestion Control and Energy Conservation*

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 reduce 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 lower 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 an 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
- An adaptive aggregations scheme based on the feedback on network situations
- 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 reducing packet collisions and control overhead.

- *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 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 challenge 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
- A 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

With robust data delivery support, On the one hand, applications can delivery 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 our novel state-free solution.

- *Localization for Routing Scalability*

When a system scales up to thousands and even millions of nodes, a set of pervious solutions is no longer applicable. For example, DSR [53] and AODV [80] are the standard routing schemes for ad hoc wireless networks with up to hundred nodes. Those protocols depend on a so-called on-demand routing discovery with flooding to find an end-to-end path to a destination. The sheer number of sensor nodes makes such a global flooding undesirable. When thousands of nodes communicate with each other, broadcast storms may result in significant power consumption and possibly a network meltdown.

Location awareness is an essential building block for sensor networks. Besides tagging the sensor data with location context, localization is commonly used for routing scalability. Location-based routings are widely accepted as de fact standard routing technique for sensor networks. This is because that the location-based routing schemes only need to keep neighbor information regardless the scale of the networks. Moreover, the location-address communication precludes the requirement of the route discovery, otherwise needed by ad hoc network protocols. In order to achieve scalability in routing, this research topic addresses the localization problem through which nodes can find out their location and perform location-based routing.

Roughly, localization techniques in sensor networks can be divided into to two major categories: range-based localization and range-free localization. The former is defined by protocols that use absolute point-to-point distance or angle estimates for estimating location. The later make no assumption about the availability or validity of such information. Range-based localizations are widely investigated in recent years. Such technique yells better precision under control environment or by using sophisticated devices. Much less research has be done on range-free localization, which are regard as an cost-effective and sufficient solution for sensor networks without costly hardware requirements. Our range-free localization work will address following research issues.

- A novel cost-effective localization scheme without sophisticated hardware requirements
- A evaluation on the impacts of localization error to the performance of sensor network applications
- A localization algorithm that is robust to both irregular radio pattern and anchor errors.
- A theoretical model to estimate localization error bound and identify optimal system configuration

Our work in this topic will investigate these issues and design a scalable localization algorithm with enhanced performance over pervious solutions. With our scheme, infrastructure for localization can be deployed with much less cost than previous solutions and provide sufficient accuracy for the routing and other location-dependent applications.

3. Proposed Research Plan

3.1 Overview

In this research plan, we are building *a scalable, robust and time-energy aware network architecture* for sensor networks. We address scalability, robustness, real-time and energy conservation issues at different layers of the proposed architecture. Some layers will only deal with one issue, while others engage in multiple issues simultaneously. From the application point of view, this network architecture provides a set of predicable and dependable higher-level service APIs for the programmer. From the system point of view, this network architecture is an integrated solution specifically tailored to the characteristics of sensor networks with a minimum overhead and high throughput.

From bottom up, the proposed network architecture has following essential layers: (Figure 1)

- **Power and Coverage Management Layer:** this *energy-aware* layer is responsible for node duty-cycle scheduling for power conservation and sensing coverage management, which provide full sensing coverage to a geographic area while at the same time minimize energy consumption and extend system lifetime by leveraging the redundant deployment of sensor nodes.

- **Robust and Reliable MAC Layer:** This layer solves the issues related to *robustness* and *self-stabilization*. It can provide per-hop reliability if required by higher layer. Moreover, this layer deals with node failure and mobility issues internally as much as possible before signaling the network layer for further assistances.

- **Application Independent Data Aggregation Layer:** This *time-energy aware* layer provides data aggregation in order to reduce control overhead in MAC layer and energy consumption in radio communication. Adaptive control is provided in order to achieve aggregation without jeopardizing the end-to-end delay.

- **Differentiated Packet Scheduling Layer:** This *QoS-time-aware* layer support differentiated forwarding service among the packets with different priorities. The criterion for the differentiation includes not only the time constraints but also the spatial constraints.

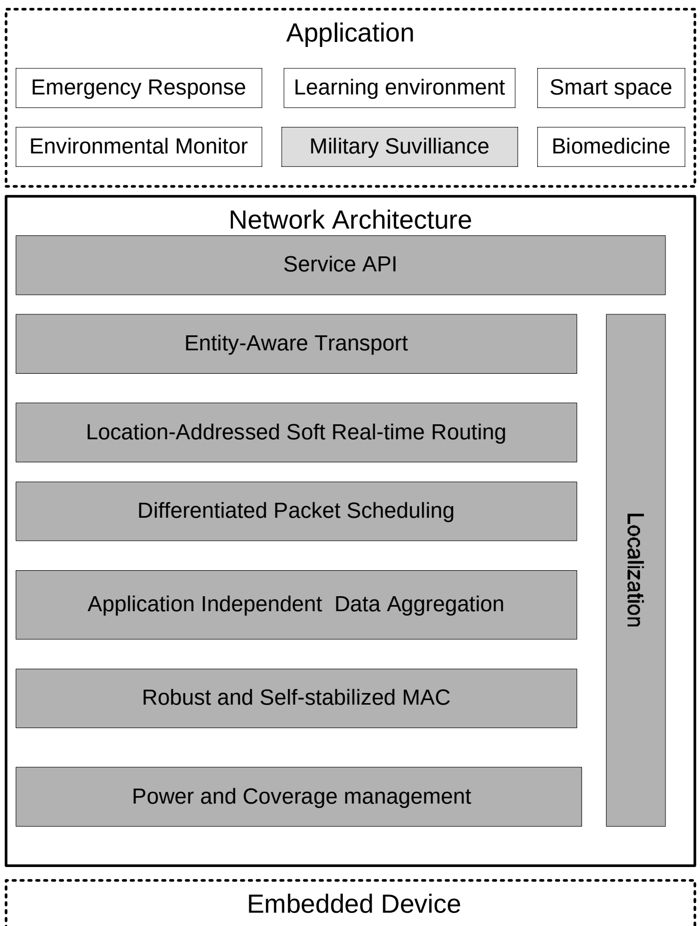

Figure 1 Overarching Plan for the PH.D. Research

- **Location-Address Soft Real-Time Routing Layer:** This *time-aware scalable* routing layer provides soft real-time communication for end-to-end packet delivery. Network congestion control is achieved by localized rerouting and traffic policing to the lower layer. Constant delivery speed is maintained through a combination of non-deterministic forwarding and neighborhood-based feedback control. The scalability issue is solved by the location-based routing and localized control scheme.

- **Entity-Aware Transport layer:** this layer abstracts communication endpoints into entities. This layer maintains *robust* connections between entities while both ends are mobile. Entity abstraction allows aggregation among a group of nodes in order to reduce the communication overhead and *energy* consumption.

- **Localization Service:** Localization is a cross layer service for this network architecture as a whole. It provides location information for 1) the sensing coverage management, 2) the velocity calculation for the differentiated packet scheduling, 3) the location-address soft real-time routing, 4) the entity formation and 5) the location service for sensor network applications such as the enemy tracking and temperature mapping.

Besides new research issues to be addressed inside individual layers, the major challenge is to build an integrated architecture, which takes care of scalability, robustness, real-time and energy conservation issues simultaneously. Since the point solutions we proposed for individual layers are conceived with this integration in mind, we expect this major challenge will be solved in this thesis research.

In following sections, four major components in Figure 1, namely real-time routing layer, data aggregation layer, robust MAC layer and localization service, will be addressed in depth, respectively. Other proposed layers are addressed through cooperation from other group members, thus left as optional work for the dissertation.

3.2 Soft Real-time Communication for Timely Response: SPEED

SPEED design is guided by the key observation that unlike wired networks, where the delay is independent of the physical distance between the source and destination, in multi-hop wireless sensor networks, the end-to-end delay depends on not only single hop delay, but also on the distance a packet travels. In view of this, the design goal of the SPEED algorithm is to support a soft real-time communication service with a desired delivery speed across the sensor network, so that end-to-end delay is proportional to the distance between the source and destination.

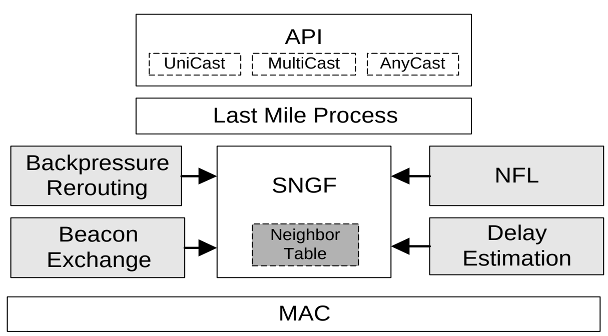

Figure 2 Design of SPEED Protocol

SPEED is an adaptive real-time routing protocol that aims to maintain constant packet delivery speed in sensor networks. Similar to geographic routing [58], each node only maintains the states of one-hop neighbors. The core of SPEED is a feedback-based adaptation algorithm that enforces per-hop delivery speed in face of unpredictable traffic. The first adaptation mechanism is a neighborhood feedback loop on each node that periodically computes the probability of forwarding a packet to every neighbor based on its measured delay and per-hop speed violation in the last sampling period. The feedback loops ensures that more congested neighbors (with longer delays and higher miss ratios) get lower probabilities of receiving packets. When all of its neighbors have deadline misses in the last sampling period, a node regulate its traffic by dropping packets. The packet-drops subsequently cause upstream neighbors to redirect packets away from it, a process called backpressure rerouting. The backpressure can propagate upstream until it reaches outside the congestion region or the sources. The combination of neighborhood feedback loops and backpressure rerouting significantly enforces the per-hop deadline in steady states and reduces the end-to-end deadline miss ratio.

At higher level, SPEED provides two novel real-time communication services, namely, real-time area-multicast and real-time area-anycast, along with a traditional real-time unicast service. Those new communication semantics are fit seamlessly for the purpose of sensor networks where the location of the data instead of sensor ID is more of interest to the applications.

Simulation experiments [40] shows that SPEED can achieve significantly lower deadline miss ratio than geographic routing [58], DSR [53] and AODV [80] in face of sudden congestion. Meanwhile, the control overhead of SPEED is comparable to geographic routing and significantly smaller than DSR and AODV. SPEED demonstrates that localized feedback control is a promising approach for real-time communication in sensor networks. Remaining challenges in this direction includes providing differentiated service for packets with different priorities and establishing stability analysis. With comprehensive knowledge, it is possible to extend this work, however quite challenging, to provide a statistical quantitative guarantee on end-to-end delays.

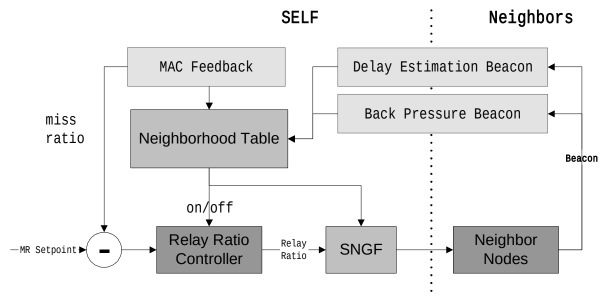

Figure 3 Neighborhood Feedback Loop (NFL)

3.3 Data Aggregation for Congestion Control and Energy Conservation: AIDA

Sensor networks suffer bandwidth, energy and memory constraints that limit the quantity of information transferred from end to end. In order to utilize the available resource efficiently and economically, data aggregation techniques have been extensively investigated in recent literature. Such mechanisms have proven to be effective in reducing application workload, control overhead and network congestion. Pervious work on data centric aggregation [16] [51] [52] utilizes application specific knowledge and provide a means to augmenting throughput, but have limitations due to their reliance on application specific decisions and unable to support cross-application aggregation. We, therefore, propose a novel aggregation scheme that adaptively performs application independent data aggregation in a time sensitive and transparent manner.

Our proposed work, as a novel aggregation approach, distinguishes itself from current state of the art solutions in three respects. First, all prior Application Dependent Data Aggregation (ADDA shown in Figure 4b) relies on application layer information and must have a bi-directional interface, and therefore dependence with, the data centric routing protocol implemented. AIDA isolates aggregation decisions from application specifics by performing adaptive aggregation in an intermediate layer that resides between the traditional data-link and network layer protocols (Figure 4.a). AIDA is transparent to other layers and can be swapped into the network stack without modifying any existing interface. Second, no prior work in data aggregation adapts itself to the traffic situation in a time sensitive manner. AIDA takes the timely delivery of messages as well as protocol overhead into account to adaptively adjust aggregation strategies in accordance with assessed traffic conditions and expected sensor network requirements. AIDA [38] is shown to be adaptive to varying traffic situations and dramatically reduce network congestion and transmission energy consumption. Third, previous data aggregation schemes (e.g., data centric routing [52]) perform in-network processing to reduce the amount of application data transmitted. These in-network processes (e.g. averaging) can achieve higher degrees of aggregation; however, data are less available to the application (e.g. standard deviation of the data set cannot be obtained from the average). In contrast, AIDA performs loss-less aggregation allowing the upper layer to decide whether information compression is appropriate at the time. Very important, our design enables AIDA to remain complementary to other data aggregation strategies (Figure 4.c) while providing significant value-added timesaving benefits in the lower layers of the communication stack.

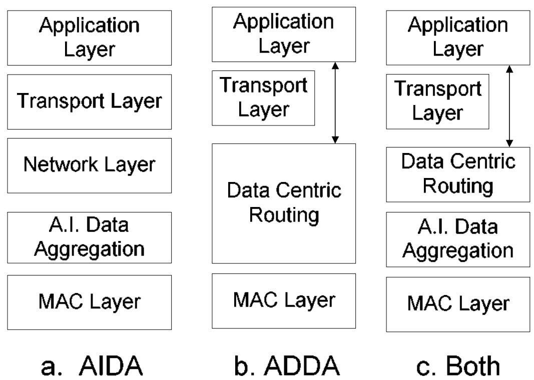

Figure 4: Architectural Design

Our data aggregation work will be a value-added solution that adapts to changing network conditions, improves the efficiency in the use of bandwidth, is simple and fast, has limited overhead, performs aggregation without loss of information, and considers the timeliness of end-to-end traffic. In addition, AIDA is a solution transparent to other components. This will allow AIDA to work with, or exist independently of, other communication protocols so that AIDA can leverage the performance and overcome the limitations inherent to existing data centric aggregation schemes. The future research direction on this topic will focus on differentiated aggregation strategies with different degree of time-awareness and a hybrid solution with both ADDA and AIDA supports. More challenging issue will include a new dynamic model for aggregation control and better adaptation strategies for higher degree of aggregation.

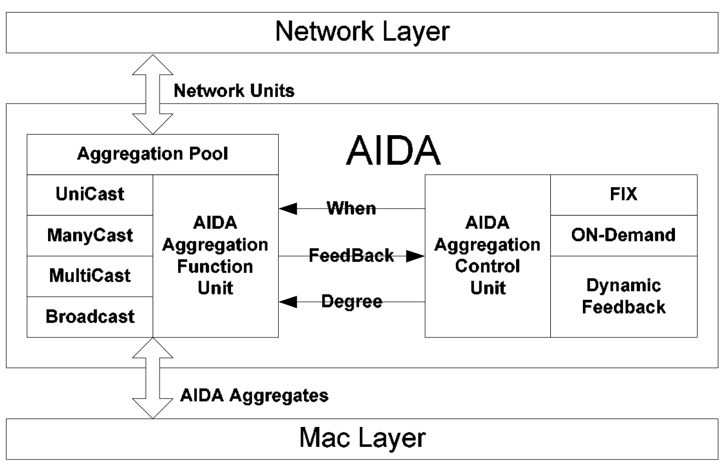

Figure 5 AIDA Architecture Design

3.4 State-Free Robust delivery: IGF

The highly decentralized and dynamic nature of sensor networks prevents nodes from gathering an accurate and clear picture of their surrounding environment. The high node failure rate and possible node mobility make the delay and cost of establishing and updating routing and neighbor tables in a dynamic, ad-hoc environment prohibitive. We note that network protocols which must update and maintain such neighborhood and routing tables suffer delay establishing and maintaining these tables, consume network bandwidth exchanging appropriate routing or neighborhood information, and fail to immediately take advantage of newly deployed or unrecognized neighbors. With constant node failure and frequent message loss, state sensitive routing protocols like DSR [53], AODV [80] and even GF [58] may take an indefinite amount of time and energy to stabilize.

To address the aforementioned problem, state-free robust delivery provides an integrated solution for both routing and media access. The prominent advantage of this solution is robustness and fast response to routing failure and no need for state maintenances. More specifically, we augment the protocol in two major aspects: First routing tables and even neighbor tables are eliminated to provide state-free solution, which is much more robust, than state-based solutions in face of failures. The memory requirement for the routing purpose is reduced to zero, which is suitable solution for the constrained sensor devices. Second, we reduce the number of messages exchanged and prevent the latency of updating state when nodes die or new nodes are added to the system. These added features can help self-stabilize the dynamic system.

Two key ideas of this state-free Robust delivery are: 1) Receiver-based MAC allows the selection of next-hop candidate on the fly, which eliminates the inconsistency between the candidate in forwarding table and the actual candidates that can forward packets. Such inconsistency often happens when a node dies without notifying the neighbors or a node moves out of communication range of the neighbors and 2) Geographic forwarding eliminates the requirement of keeping states for end-to-end routing.

Based on those two ideas, current implementation of state-free robust delivery incorporates the nice features of the geographic forwarding (GF) widely used for sensor network routing and 802.11 Distributed Coordinate Function (DCF). Both network work and MAC solution are seamless integrated in the one protocol, which can bring the intra-layer communication cost and further bring down the memory requirement of the solution.

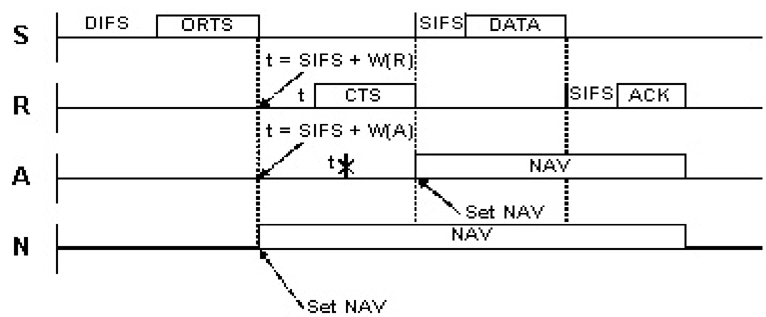

Figure 6 Contention-Based Handshaking

The mechanisms we are adding are incorporated into both the network and data-link layer protocols of the communication stack. IGF works via non-deterministic forwarding, added into the basic routing protocol in one of two ways. The first, as applied to networks where the MAC layer protocol operates based on contention (Figure 6), involves sending a request for some neighbor to help in the forwarding process. Only nodes in an appropriate forwarding area respond to the request. Each of these nodes determines how long to wait before responding based on both how much closer they are to the destination and how much energy remains in the node's battery. In this way, our protocol attempts to choose the shortest route, considering system energy. Once an appropriate node identifies itself, IGF explicitly transmits the data to this node and the transaction is completed by an optional acknowledgment when appropriate.

The second mechanism (Figure 7), targeted for sensor networks without a contention based MAC, is even simpler than the first. In this scheme, a node with a message to send simply broadcasts that message for all neighbors. The nodes within the appropriate forwarding area are eligible to handle the message to ensure that the message travels along a path toward the ultimate destination. Timers are set based on node location and energy, similar to before, however the only difference is that handshaking does not occur. Instead, the node with the lowest timer value receiving the non-deterministic data message simply re-broadcasts the message to an appropriate next-hop node in the direction of the destination. This re-broadcast can act as an acknowledgment

(ACK) to the sender, assuming symmetric channels, and also act as a notification to other neighboring nodes in forwarding area, which consequently cancel re-broadcast of the same message in order to avoid duplications.

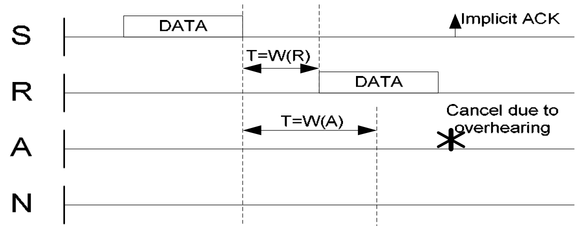

Figure 7 Implicit Handshaking

The future research direction on this topic includes extension for data delivery schemes where location is not available. More advanced schemes that deal with the void can also be investigated.

3.5 Range-Free Localization: APIT

Many localization algorithms have been proposed for sensor networks to date. With regard to the mechanism used for estimating location, we divide localization protocols into two categories: range-free and range-based. The former is defined by protocols that use absolute point-to-point distance or angle estimates for estimating location. The later make no assumption about the availability or validity of such information.

The common range-based protocol, using Global Positioning System (GPS)[47], is deemed unlikely as the push for small cheap energy efficient sensor devices continues. Other localization protocols usually depend on techniques such as timing (TOA/TDOA), directionality (AOA), signal strength (RSSI) and signal pattern matching. For received signal strength and signal pattern matching algorithms, the assumption that a signal propagates in a radial and consistent attenuation pattern make such algorithms suspect in a real implementation. Timing and directionality relies on multiple communication sources (RF and Ultrasound), precise clocks, and derived angles between communicating devices, all of which require sophisticated hardware that are costly and energy consuming on constrained sensing devices. To circumvent aforementioned difficulties experienced in range-based localization algorithm, a set of range-free schemes ([20][72][76]) are proposed for the sensor networks recently. They desire to provide sufficient position estimation without sophisticated ranging hardware supports. In those schemes, proximity and connectivity information are utilized for the purpose of localization. Those schemes are suitable for the purpose of sensor networks in which fine-grained estimation by extensive hardware support is deemed overkill and pre-configuration and fine-tuning is nearly impossible due the sheer number of sensor nodes and hazardous environment.

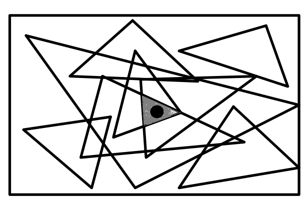

Figure 8 APIT: An Area-based Localization Approach

In this research topic, we propose our novel area-based range-free localization scheme, which we call APIT. APIT requires a heterogeneous network of sensing devices where a small percentage of these devices (percentages vary depending on network and node density) are equipped with high-powered transmitters and location information obtained via GPS or some other mechanism. We refer to these location-equipped devices as anchors. Using beacons from these anchors, APIT employs a novel area-based approach to perform location estimation by isolating the environment into triangular regions between beaconing nodes (Figure 8). A node's presence inside or outside of these triangular regions through APIT test (Figure 9) allows a node to narrow down the area in which it can potentially reside. By utilizing combinations of anchor positions, the diameter of the estimated area in which a node resides can be reduced, to provide a good location estimate.

This work makes three major contributions to the localization problem in WSNs. First, we propose a novel range-free algorithm, called APIT, with enhanced performance under realistic system configurations. Second, though many different protocols [20][72][76] have been proposed to solve the localization problem in a range-free context, no prior work has been done to compare them in realistic settings. This work is the first to provide a realistic and detailed quantitative comparison of existing range-free algorithms to determine the system configurations under which each is optimal. We perform such a study to serve as a guide for future research. Third, no attempt has previously been made to broadly study the impact of location error on various location-dependent applications and protocols. This work provides insight into the effect of localization accuracy on application performance degradation and identifies bounds on the estimation error tolerated by applications. The future research direction on this topic includes establishing a theoretical model to estimate localization error bound and identify optimal system configuration for our range-free localization scheme.

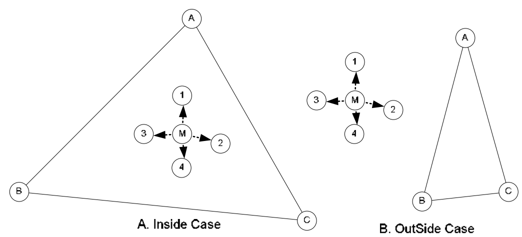

Figure 9 Approximate Point-In-Triangulation Test (APIT)

3.6 Architectural & System Integration: Hermes

As mentioned in 3.1, we expect the ultimate contribution for this thesis work is an integrated system for sensor networks. We divide the integration into two levels: architectural-level and system-level integration. The proposed architectural-level integration is shown in the Table 1.

Layers	***Protocols***
Application	Military Tracking
Entity-Aware Transport layer	EnviroTrack
Location-Address Soft Real-Time Routing Layer	SPEED
Differentiated Packet Scheduling Layer	RAP
Application Independent Data Aggregation Layer	AIDA
Robust and Reliable MAC Layer	IGF
Power and Coverage Management Layer	Differentiated Coverage
Localization Service	APIT

Table 1 Architectural Integration Plan for Hermes

System-level integration focuses on the interface definitions, the redundancy elimination and the integrated tuning. Currently only part of system-level integrations are done on the simulator. For example, due to the layer independency feature of AIDA, it can work with SPEED, IGF and RAP seamlessly. More system-level integrations are yet to be done at both the simulator and testbed to investigate interactions between the protocols and evaluate the performance of the overall solution.

4. Methodologies

4.1 Development Environment

The large-scale simulation is commonly regarded as a viable approach to understand and evaluate the performance of the target systems. After a survey on the wireless simulation platforms available, we adopt GloMoSim, a scalable discrete-event simulator developed at UCLA to support our research. This software provides a high fidelity simulation for wireless communication with detailed propagation, radio, MAC, and network layer components. Moreover, under Parsec (a parallel programming language) support, GloMoSim can support large-scale network simulation up 10,000 nodes, which fits quite well with our research requirement.

We also use motes designed by university of Berkeley as our testbed. However, the large-scale required in sensor networks makes a full evaluation on a physical testbed nearly impossible currently. Therefore, we only use it to provide prove-of-concept evaluations of our designs and support demo requirements for the project.

Items	***Description***
Simulation	GloMoSim
TestBed	MICA Mote [24] with Tinyos [46]
OS	Unix, Linux & Window NT
Language	C++, Java, Perl , nesC
Integral Development Environment	Make, Emacs, UltraEdit, Visual .NET
Statistical tool	Excel, NCSS
Documentation	Word, Visio, Excel, PowerPoint, GnuPlot

Table 2 Development Environment

4.2 Evaluations

Evaluation consists two phases: individual and integrated evaluations. The purposes of the individual evaluations are to identify the performance contributions in each protocol, while an integrated evaluation will further investigate the interactions and complications among the protocols. Table 3 shows the partial plan of individual evaluations

Protocols	***Baselines***	***Metrics***
SPEED	DSR[53],AODV[80],GF[58]	E2E Miss, Delay, Overhead and Energy
AIDA	FIX, ON-DEMAND, DYN	Delay, Overhead, Energy,
IGF	DSR[53],LAR[60],GF[58]	Delivery Ratio, Delay, Overhead
APIT	Centroid[20], Amorphous [72], DVHop [76]	Estimation Error and Overhead

Table 3 Individual Evaluations

To evaluate the performance of the proposed network architecture, the integrated evaluation scenario envisioned will be a military field in which a surveillance service is established through collaborative efforts of a large number of self-organized sensing nodes. This surveillance service allows a command center to track multiple intruders simultaneously. The network architecture proposed in this work should facilitate such tasks by providing following enhance features:

- A longer lifetime of surveillance achieved by a set of energy-aware designs
- a timely response to the movements of intruders through a scalable real-time communication service
- Minimum detection messages loss through a robust data delivery
- Minimum number of intruder misses through a energy-aware full sensing coverage
- Minimum number of false alarms through a group-based detection
- Precise location reports about intruders through node localization

4.3 Current Status and Future Plan

We expect to complete this PH.D research in about one year. A detailed survey on state-of-arts are provide in appendix A. Results from three ongoing topics SPEED[40], AIDA [38] and APIT [39] have be refined for conference and journal publication, and two new topics on robust data delivery (IGF [18]) and differentiated sensing coverage [97] have been submitted for conference publications (appendix B). Code bases for those protocols are also available online. In addition, demos on testbed have been produced for the NEST project.

5. Research Contributions

A Scalable Sensor Network Architecture for Robustness & Time-Energy Awareness with intelligence contributions in the real-time communication, application independent data aggregation, state-free robust data delivery and range-free localization.

- A new set of communication semantics that is fit seamlessly for the purpose of sensor networks where the location of the data instead of sensor ID is more of interest to the applications
- The first real-time routing for sensor networks, maintaining a constant delivery speed for soft real-time communication through a combination of non-deterministic forwarding and neighborhood-based feedback control
- A novel routing scheme with combined adaptation mechanisms of both alterative routing and regulation with small control overhead
- 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 only adaptive aggregation scheme considering the network congestion-level
- The first robust communication scheme that all together state-free
- A receiver-based just-in-time route discovery mechanism that is robust to nodes's failure and mobility
- A novel area-based cost-effective localization scheme without sophisticated hardware requirements

6. Conclusions

Recent advances in the development of the low-cost, power-efficient embedded devices, coupled with the rising need for support of new information processing paradigms such as smart spaces and military surveillance systems, have led to active research in large-scale, highly distributed sensor networks of small, wireless, low-power, unattended sensors and actuators. A set of applications, such as biomedicine, hazardous environment exploration, environmental monitoring, military tracking and reconnaissance surveillance, becomes the key motivations of the recent rise in research efforts in this area. While applications keep diversifying, one common property they share is the need for an efficient network architecture tailored toward sensor networks. Previous solutions designed for traditional networks serve as good references; however, due to the vast differences between previous paradigms and sensor networks, the direct use of these more classical solutions lead to inefficiencies, overkill, or non-functioning systems. This proposal aims at building *a scalable, robust and time-energy aware network architecture for sensor networks*. The topics we address cover every layer of the network architecture, paying special attention to stateless real-time routing, application independent data aggregation, robust data delivery and range-free localization. The integrated network architecture based on these solutions lays a foundation for overall sensor network research and helps bring this new paradigm into reality.

Appendix A: State-of-the-Art

We finished an extensive literature survey on current research for sensor networks. Due to the space limitation, we cannot include all of it. In this appendix, we only focus on those works that are directly related to our research.

A.1 Sensor Network Routing Schemes

Large scale and high-density sensor networks with constraint bandwidth prohibit the used of flat routing with flooding. Pure localized algorithms are those in which any action invoked by a node should not affect the system as a whole. There are a set of routing algorithms proposed in ad hoc networks such as DSR [53] and AODV [80]. Those reactive routing algorithms depend on flooding to discover a path to the destination. They work well in small-scale mobile ad hoc network with at most hundreds of nodes. However, the sensor networks in our vision contain at least thousands of nodes and even up to millions of nodes. In such sensor networks, broadcast storms [74] may result in significant energy consumption and possibly a network meltdown. LAR [60] by Y. Ko enhance on-demand routing algorithms by restricting routing packet flooding in a specified "request zone", which can only partially solve the broadcast storm problem.

The unique characteristics of sensor networks require a different routing paradigm from aforementioned protocols for mobile ad hoc networks (MANET). Data centric communication and location awareness of sensor nodes motivate the location-based routing schemes. In sensor networks, location is of more interest of the applications rather than a specific node's ID. For example, tracking applications only care where an enemy is located, not about the IDs of the reporting nodes. In sensor networks, such location-awareness is necessary to make the sensor data meaningful. Therefore, it is natural to take advantage of the location-aware capability of nodes to perform routing. MFR [94] by Takagi et. al. forwards a packet to the node that makes the most progress toward the destination. Finn [29] proposes a greedy geographic forwarding protocol with limited flooding to circumvent the voids inside the network. Alternatively, GPSR [59] by Karp and Kung uses perimeter forwarding to get around voids. Moreover, Geographic distance routing (GEDIR) [92] guarantees loop-free delivery in a collision-free network. And Basagni, [11] et. al. propose a distance routing algorithm for mobility (DREAM), in which each node periodically updates its location information to other nodes, and an updating rate is set according to a distance effect in order to reduce the number of control packets.

A.2 Real-time Communications

Interactions between sensor networks and the physical world require real-time routing services to play an important role. Several real-time protocols have been proposed for sensor networks and ad hoc networks. SWAN [4] uses feedback information from the MAC layer to regulate the transmission rate of non-real-time TCP traffic in order to sustain real-time UDP traffic. RAP [66] uses velocity monotonic scheduling to prioritize real-time traffic and enforces such prioritization through a differentiated MAC Layer. Moreover, V. Kanodia et. al. [55] propose a service differentiation for delay-sensitive traffic by prioritizing 802.11. Woo and Culler [102] propose an adaptive rate control scheme to achieve fairness among nodes with different distances to a base station. All of these algorithms work well by locally degrading a certain portion of the traffic. However, this kind of local MAC layer adaptation cannot handle long-term congestion where routing assistance is necessary to divert traffic away from any hotspot. To solve this problem, SPEED [38] provides a combination of MAC layer and network layer adaptation that effectively deals with such issues.

A.3 Power-Aware Protocols

Several research efforts have addressed energy issues in sensor networks. Aside from minimizing power consumption at the hardware level [22], MAC layer protocols developed for energy savings mostly take advantage of overhearing and scheduling to allow nodes to sleep while they are not transmitting or receiving messages. Additionally at the network and routing layer, schemes work to minimize power along the transmission path [42] and set routes according to the energy remaining at nodes along that path [53]. Higher layer protocols that often incorporate routing semantics to form groups and rotate leadership responsibilities allowing non-leader nodes to sleep and conserve their energy [9][43]. LEACH [42] partitions a network into clusters and randomly rotates the cluster leader in order to evenly distribute the energy consumption among the sensors. SPAN [12] is another randomized algorithm where nodes make local decisions on whether to sleep or to join a backbone network in order to reduce energy consumption. Deepak Ganesan et. al. [32] proposes a multi-path routing scheme to perform energy efficient recovery form routing failures. SPEED [38] performs load balancing by randomly forwarding packets among multiple concurrent routes to prevent some nodes from dying faster than others die. Some research [96] [106] focuses on how to provide full or partial sensing coverage in the context of energy conservation. In [96], D. Tian allows nodes turn themselves off as long as the neighboring nodes can cover the area for them. In [106], energy conservation for surveillance coverage is done by a probing mechanism. In this solution, after a sleeping node wakes up, it broadcasts a probing message within a certain range and waits for a reply. If no rely is received within a timeout, it will take the responsibility of surveillance until it depletes its energy.

A.4 Data Aggregation

Constrained bandwidth and limited energy supply for sensor networks demand a scheme, which can efficiently utilize the available resources. Data aggregation techniques have been extensively investigated in recent literature. Such mechanisms have been proven effective in reducing application workload, control overhead and network congestion. In general, data aggregation can be divided to two major categories.

Application dependent data aggregation (ADDA) utilizes application specific information to reduce total application data. The merging of data that maintain common properties (semantics) and are destined for the same node has been a common approach to reducing traffic. In this category, networking is tightly bound with application layer. Routing decisions are influenced by the purpose of aggregation. Basic schemes [52] for ADDA include the Center at the Nearest Source (CNS), where data is aggregated at the source nearest to the destination, and Shortest Path Trees (SPT), where data is sent along the shortest path from a source to a sink and is aggregated at common intermediate hops along the way, and Greedy Incremental Trees (GIT), which builds an aggregation tree sequentially to merge paths and provide more aggregation opportunities. An extremely popular ADDA scheme for sensor networks, Directed Diffusion [51], is a data-centric architecture where named (application specific) data is propagated along paths back to the requestor. Effective paths are reinforced as they are used to optimize communication from point to point. Specifically designed for sensor networks, Directed Diffusion aggregates data along these reinforced paths to reduce the quantity of data transmitted across the network. Similarly, Data Placement [16] is designed for applications where multiple sinks coexist and use in-network caching to update and distribute data to leaf nodes at the minimally requested rate. LEACH [42] is a high layer protocol that provides clustering and local processing to aggregate sensor data and reduce global communication. Many other data aggregation schemes provide network, transport, and application level mechanisms that take advantage of application specific knowledge about the data in question. All of these schemes reside either at or above the network layer and are orthogonal and can coexist with our work.

While such mechanisms have proven effective in reducing traffic and easing congestion, several issues that limit the extent to which they are applicable give us an insight into developing an application independent aggregation (AIDA) mechanism. One design principle of AIDA is layer independency. Since AIDA does not bound to specific application semantic, it can aggregation data from different applications and data with different semantics together.

Comparison studies have demonstrated the effect of network parameters and the utility of aggregation mechanisms in a wide variety of applications [52]. These studies discuss potential savings that aggregation can provide and explain the potential for such work to improve network throughput.

A.5 Robust & Reliable Communication

Due the unreliable nature of the wireless communication, robust and reliable communication is another research issue for sensor networks. TCP, XTP [99] and SRM [30] are traditional transport protocols for reliable communication in local LAN and internet. Those protocols perform very well in the wired network where packet loss due to bit error ratio (BER) and buffer overflow is the orders of magnitude lower than the loss in wireless network. However, a higher bit-error rate in networks with wireless links violates many assumptions made by TCP, causing degraded end-to-end performance. Those schemes tend to unnecessarily constrain the throughput a wireless link can achieve. To solve this issue, I-TCP [9] divides one TCP link into two connections: wired network connection and wireless connection and applies difference transportation protocols at two connections. This approach can reduce the performance penalties due to the false congestion indication and smoothly handle the mobility issue inside the network. However, this approach does not maintain the end-to-end semantics for TCP connection. As alterative approach, SNOOP [10] eavesdrops the packet passing to the mobile nodes and performs retransmission when there is a packet loss due to the interference. This approach is transparent to the both ends of TCP connection and end-to-end semantics are maintained.

RMST [91] and PSFQ [107], both proposed as reliable transport layer solutions for sensor network, attempt to provide end-to-end reliability at a minimal cost. RMST acts as a filter in Directed Diffusion, tracking fragments so that receiver initiated requests can be instantiated when individual pieces of an application payload get lost. PSFQ caches packets along the path to the sender, initiating fragment recovery as required, starting with its local neighborhood. While RMST and PSFQ are shown to be effective, their robust and reliable features, designed to tolerate high levels of message loss caused by radio signal reception error (i.e. interference and packet collisions), are not appropriate for dealing with network layer routing problems that result when nodes transition into and out of inactive (i.e. sleep) states. Moreover, those schemes obtain high reliability through redundancy in transmission, which may or may not be a viable solution for bandwidth constrained sensor networks

Finally, to cope with high bit error in wireless links, reliability is commonly supported at the MAC layer. Traditional 802.11 standard [7] provides reliable single-hop communication through a four-way hand shaking. Other MAC protocols MACAW [14], FAMA [31] are also proposed to deal with hidden and exposed terminal problems, which can compromise the reliability of communication.

A.6 Localization for Sensor Networks

Many current systems and protocols attempt to solve the localization problem. These approaches differ in the assumptions that they make about the sensor networks which include assumptions about device hardware, signal propagation models, timing and energy requirements, network makeup (homogeneous vs. heterogeneous), environment of deployment (indoor vs. outdoor), node or beacon density, infrastructure, time synchronization of devices, communication costs, error requirements, and device mobility. In this section, we discuss this prior work with regard to these network characteristics, device restrictions, and application requirements.

The traditional localization systems, currently used in many forms today, are based on GPS or other pre-deployed and pre-configured technology. Such GPS systems as well as some GPS alternatives for indoor use (Cricket [82], Active BAT [36] and RADAR [8]) all rely on extensive infrastructure, pre-configuration and significant per-node processing capabilities to achieve localization. Such systems are extensively analyzed and compared in [43]. In sensor networks and other distributed systems, errors in location information can often be masked through fault tolerance, redundancy, aggregation, or by other means. Depending on the behavior and requirements of protocols using location information, varying granularities of error may be appropriate from systems to systems. Acknowledging that these localization systems are not adequate for senor networks that require deployment with minimal to no infrastructure or pre-tuning, researchers have sought various alternate solutions to the localization problem.

The Time Difference of Arrival (TDOA) technique for ranging (estimating the distance between two communicating nodes) has been widely proposed as an ingredient in localization solutions in wireless sensor networks. While many infrastructures based systems have been proposed that use TDOA [8][36][82], additional work, such as AHLos system in [86][87], has been done to employ such technology in sensor networks where such infrastructure is not available. Time of Arrival (TOA) include GPS technology provides an alternative means of obtaining range information via signal propagation time using precise clock synchronization and has been considered in [22]. To augment and complement TDOA and TOA technologies, an Angle of Arrival (AOA) technique has been used that allows nodes to estimate and map relative angles between neighbors [77].

Despite their adequate performance, techniques based on TDOA, TOA, and AOA technology are not quite applicable to the sensor networks we study, as they require extensive hardware, infrastructure, and pre-deployment fine-tuning. In addition, TDOA techniques using ultrasound require dense deployment (numerous anchors distributed ubiquitously) as ultrasound signals usually only propagate 20-30 feet. TOA such as GPS techniques have the additional limitation of requiring precisely synchronized clocks to differentiate between sending and receiving times.

Receiver Signal Strength Indicator (RSSI) technology such as RADAR [8], SpotOn [44] has been proposed for systems where such hardware is unavailable. In this approach, either theoretical or empirical models are used to translate the signal degradation to the distance estimation. Such RF systems [8][44] run into problems as multi-path fading, background interference, and irregular signal propagation characteristics, shown in empirical study [33], make range estimates inaccurate. Work to mitigate such error such as robust range estimation in [34], Two-phase refinement positioning [85] [87] and parameter calibration in [100], have been proposed that take advantage of averaging, smoothing, and alternate hybrid techniques to reduce error to within some acceptable limit.

Given the inherent constrains of the sensor devices envisioned and suitable ranging technique available for sensor networks, a set of range-free localization schemes are proposed in sensor networks. In [20], a heterogeneous network containing powerful nodes with established location information is considered. In this work, these nodes beacon their position to neighbors that keep an account of all received beacons. Using this proximity information, a simple centroid model is applied to estimate the listening nodes' location. In [76], DV-HOP consists of a heterogeneous network of beaconing nodes. Instead of single hop broadcasts, these nodes flood their location throughout the network maintaining a running hop-count at each intermediate node. Listening nodes calculate their position based on the received beacon locations, the hop-count from the corresponding Beacon, and the avg-distance per hop, a value obtained through anchor communication. Like DV-Hop, an Amorphous Positioning algorithm proposed in [72] uses hop-distance estimations, improving location estimations through neighbor information exchange. Our solution [39] is an area-based approach by isolating the environment into triangular regions between beaconing nodes. A node's presence inside or outside of these triangular regions allows a node to narrow down the area in which it can potentially locate.

A.7 Feedback Control Theory

Due to the high failure rate, event-driven nature and unreliable radio media, the behaviors of individual nodes in sensor networks are inherently unpredictable. On the other hand, the high density and large-scale features of sensor networks give us an opportunity to achieve a predictable overall behavior through the aggregation among nodes. Since the control-based methods are excel in converging the unpredictability into a desired performance, a lot of research [65][66][67][90][111] recently focuses on the approaches to model the target systems from the control perspective and applying standard control methods to regulate and guarantee system performances. In [65], C.Y.Lu etc. al. propose a framework for feedback based scheduling in which a low miss ratio of the tasks and a high utilization of computation nodes are simultaneous achieved under a fluctuating workload. In [18], a control-based QoS differentiated web service is proposed. In addition, Stankovic etc. al. [90] proposed a distributed feedback control scheme to balance the real-time workload among a set of computation nodes. In this scheme, a high-level distributed controller sets a global QoS service level according to the amount of incoming tasks, and the low-level controllers residing in each computation node follow this QoS level dynamically in order to achieve a zero miss ratio. Moreover, Y. Lu [67] applies the control theory to a differentiated caching service in order to increase cache content hit-rate. This scheme eliminates the cost of profiling and configuration by using an adaptive control method in face of unpredictable resource demands.

B. Appendix B

B.1 Publications & under Submission

1. Tian He, Chengdu Huang, B. M. Blum, John A. Stankovic,and Tarek F. Abdelzaher, "Range-Free Localization Schemes in Large Scale Sensor Networks", CS-TR-2003-06. Submit to MobiCom 2003.

2. Tian He, B.M.Blum, John A. Stankovic and Tarek F. Abdelzaher, "AIDA: Adaptive Application Independent Aggregation in Sensor Networks", *Submit to Special issue on dynamically adaptable embedded systems, ACM Transaction on Embedded Computing System* 2003.

3. Ting Yan, Tian He and John A. Stankovic, "Differentiated Surveillance Service for Sensor Networks", *Sumbit to SenSys* 2003.

4. B.M.Blum, Tian He, S.Son and John A. Stankovic, "IGF: A Robust State-Free Communication Protocol for Sensor Networks", *Sumbit to SenSys 2003*.

5. Tian He, John A. Stankovic, Chenyang Lu, and Tarek F. Abdelzaher, "SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks", In *International Conference on Distributed Computing Systems (ICDCS 2003)*, Providence, RI, May 2003. (**Best paper nominee**)

6. T. Abdelzaher, J. Stankovic, S. Son, B. Blum, Tian He, A. Wood and C. Lu, "A Communication Architecture and Programming Abstractions for Real-Time Embedded Sensor Networks",In 1st International Workshop on Data Distribution in Real-Time Systems (DDRTS '03), Providence, RI, May 2003.

7. Chenyang Lu, B. M. Blum, T. F. Abdelzaher, John A. Stankovic, and Tian He, "RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks", In *IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS 2002)*, San Jose, CA, September 2002.

8. John A. Stankovic, Tian He, T. F. Abdelzaher, M. Marley, G. Tao, S. Son, and C. Lu, "Feedback Control Scheduling in Distributed Systems", In *IEEE Real-Time Systems Symposium*, London, UK, December 2001.

B.2 Code Bases Available

All the source codes will be available on online. We adopt Source Forge, a well-known open-source project website, as our project storage. Currently three projects are set up in this website.

Project	Description	URL
TinyOS	Berkeley motes implementations	https://sourceforge.net/projects/vert/
SPEED	Real-time Routing simulation	https://sourceforge.net/projects/speed
AIDA	Application Independent aggregation simulation	https://sourceforge.net/projects/aidas

Table 4 Code Base

Reference

[1] I. Aad and C. Castelluccia, "Differentiation mechanisms for IEEE 802.11", In *Proceedings of IEEE INFOCOM 2001*, Anchorage, Alaska, April 2001.

[2] T. Abdelazaher, B. Blum, et. al. , "EnviroTrack: An Environmental Programming Model for Tracking Applications in Distributed Sensor Networks", Technical Report 2003-02, University of Virginia 2003.

[3] M. Adamou, S. Khanna, I. Lee, I. Shin and S. Zhou, "Fair Real-time Traffic Scheduling over A Wireless LAN", In *Proceedings of the 22nd IEEE RTSS 2001*, London, UK, December 3-6, 2001.

[4] G. S. Ahn, A. T. Campbell, A. Veres and L. H. Sun, "SWAN: Service Differentiation in Stateless Wireless Ad Hoc Networks", In *Proceedings of IEEE INFOCOM'2002*, New York, New York, June 2002.

[5] G. T. Almes, E. D. Lazowska, "The Behavior of Ethernet-Like Computer Communications Networks", In *Proceedings of ACM SIGCOMM* 1979

[6] ANSI/IEEE, "IEEE 802.11 Wireless Local Area Networks," http://grouper.ieee.org/groups/802/11/.

[7] ANSI/IEEE, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", *ANSI/IEEE Std 802.11*, 1999 Edition.

[8] P. Bahl and V. N. Padmanabhan, "RADAR: An In-Building RF-Based User Location and Tracking System", In *Proceedings of the IEEE INFOCOM '00*, March 2000.

[9] A. Bakre, and B.R. Badrinath, "I-TCP: Indirect TCP for Mobile Hosts", In *15th International Conference on Distributed Computing Systems*

[10] H. Balakrishnan, S. Seshan, E. Amir and R. H. Katz, "Improving TCP/IP Performance over Wireless Networks", In *Proceedings of 1st ACM Conf. on Mobile Computing and Networking*, Berkeley, CA, November 1995.

[11] S. Basagni et. al., "A Distance Routing Effect Algorithm for Mobility (DREAM)", In *Proceedings of ACM/IEEE MobiCom '98*, October 1998.

[12] B. Chen, K. Jamieson, H. Balakrishnan and R. Morris, "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks". In *Proceedings of the 6th ACM MOBICOM*, Rome, Italy, July 2001.

[13] J. Beutel, "Geolocation in a PicoRadio Environment", *M.S. Thesis*, ETH Zurich, Electronics Laboratory, December 1999.

[14] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol For Wireless LAN's", In *Proceedings of the SIGCOMM '94 Conference on Communications Architectures, Protocols and Applications*, pages 212-225, August 1994.

[15] S. Bhatnagar, B. Deb, and B. Nath, "Service Differentiation in Sensor Networks," In *Proceedings of Fourth International Symposium on Wireless Personal Multimedia Communications*, September 2001.

[16] S. Bhattacharya, H. Kim, S. Prabh, T. Abdelzaher, "Energy-Conserving Data Placement and Asynchronous Multicast in Wireless Sensor Networks", In *Proceedings of The First International Conference on Mobile Systems, Applications, and Services (MobiSys),* San Francisco, CA, May 2003.

[17] B. Blum, P. Nagaraddi, A. Wood, T. Abdelzaher, S. Son and J. Stankovic, "An Entity Maintenance and Connection Service for Sensor Networks," In *Proceedings of The First International Conference on Mobile Systems, Applications, and Services (MobiSys)*, San Francisco, CA, May 2003

[18] B.M.Blum, T. He, S.Son and J. A. Stankovic, "IGF: A Robust State-Free Communication Protocol for Sensor Networks", Sumbit to *SenSys 2003*.

[19] J. Broch, D. A. Maltz, D. B. Johnson, Y. C. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols", In *Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 1998)*, ACM, Dallas, TX, October 1998.

[20] N. Bulusu, J. Heidemann and D. Estrin, "GPS-less Low Cost Outdoor Localization for Very Small Devices", *IEEE Personal Communications Magazine*, 7(5):28-34, October 2000.

[21] N. Bulusu, J. Heidemann and D. Estrin, "Density Adaptive Algorithms for Beacon Placement in Wireless Sensor Networks", In *Proceedings of IEEE ICDCS '01*, Phoenix, AZ, April 2001.

[22] S. Capkun, M. Hamdi and J.P. Hubaux, "GPS-Free Positioning in Mobile Ad-Hoc Networks", In *Proceedings of the 34th Hawaii International Conference on System Sciences (HICCSS '01)*, Maui, Hawaii, January 2001.

[23] JA Cobb and MG Gouda, "Stabilization of General Loop-Free Routing", In *Journal of Parallel and Distributed Computing*, 62(5):922-944, 2002.

[24] CrossBow Inc, "MICA mote data sheet", http://www.xbow.com/Products/Product_pdf_files/MICA%20data%20sheet.pdf.

[25] L. Doherty, L. E. Ghaoui and K. S. J. Pister, "Convex Position Estimation in Wireless Sensor Networks", In *Proceedings of the IEEE INFOCOM '01*, Anchorage, AK, April 2001.

[26] Shlomi Dolev, "Self-stabilizing routing and related protocols", In *Journal of Parallel and Distributed Computing,* Volume 42 Issue 2, May 1997

[27] D. Estrin, R. Govindan, J. Heidemann and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks", In *Proceedings of the Fifth Annual International Conference on Mobile Computing and Networking (MOBICOM '99)*, Seattle, Washington, 1999.

[28] Deborah Estrin , Ramesh Govindan and John Heidemann, "SCADDS: Scalable Coordination Architectures for Deeply Distributed Systems". http://www.isi.edu/scadds/

[29] G. Finn, "Routing and Addressing Problems in Large Metropolitan-scale Internetworks", *Technical Re-port ISI/RR-87-180*, USC/ISI, March 1987.

[30] S. Floyd, V. Jacobson, C. Liu, S. McCanne, and L. Zhang, "A Reliable Multicast Framework for Light-weight Sessions and Application Level Framing", *IEEE/ACM Transactions on Networking*, December 1997, Volume 5, Number 6, pp. 784-803

[31] C. Fullmer and J.J. Garcia-Luna-Aceves, “Floor Acquisition Multiple Access (FAMA) for packet radio networks”, *Computer Communication Review*, vol. 25, (no. 4), (ACM SIGCOMM ’95, Cambridge, MA, USA, 28 Aug.-1 Sept. 1995.) ACM, Oct. 1995.

[32] D. Ganesan, R. Govindan, S. Shenker and D. Estrin, “Highly Resilient, Energy Efficient Multipath Routing in Wireless Sensor Networks”, In *Mobile Computing and Communications Review* (MC2R) Volume 1, Number 2, 2002.

[33] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin and S. Wicker , “Complex Behavior at Scale: An Experimental Study of Low-Power Wireless Sensor Networks”, In *Technical Report UCLA/CSD-TR* 02-0013, 2002.

[34] L. Girod and D. Estrin, “Robust Range Estimation using Acoustic and Multimodal Sensing”, In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS ‘01)*, Maui, Hawaii, October 2001.

[35] C. Guo, L. C. Zhong and J. M. Rabaey, "Low Power Distributed MAC for Ad Hoc Sensor Radio Networks", In *Proceedings of IEEE GlobeCom 2001*, San Antonio, November 25-29, 2001.

[36] A. Harter, A. Hopper, P. Steggles, A. Ward and P. Webster, “The anatomy of a context-aware application”, In *Proceedings of the Fifth Annual International Conference on Mobile Computing and Networking (MOBICOM ‘99),* Seattle, Washington, 1999.

[37] T. He, L. Gu, B.Blum, Jun Xie Nest Project Source Code, http://sourceforge.net/projects/vert/

[38] T. He, B.M.Blum, J. A. Stankovic, T. F. Abdelzaher, “AIDA: Adaptive Application Independent Aggregation in Sensor Networks”, Submit to *Special issue on dynamically adaptable embedded systems, ACM Transaction on Embedded Computing System*, 2003

[39] T. He, C. Huang, B. M. Blum,J. A. Stankovic,and T. F. Abdelzaher. “Range-Free Localization Schemes in Large Scale Sensor Networks”, *CS-TR-2003-06*. Submit to MobiCom 2003.

[40] T. He, J. A. Stankovic, C. Lu, and T. F. Abdelzaher, “SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks”, In *Proceedings of International Conference on Distributed Computing Systems (ICDCS 2003)*, Providence, RI, May 2003.

[41] J. Heidemann, F. Silva, C. Intanagonwiwat, R. Govindan, D. Estrin, and D. Ganesan, “Building Efficient Wireless Sensor Networks with Low-Level Naming,” In *Proceedings of the Symposium on Operating Systems Principles*, Lake Louise, Banff, Canada, October, 2001.

[42] W. Heinzelman, A. Chandrakasan and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks”, *In HICSS '00*, January 2000.

[43] J. Hightower and G. Boriello, “Location Systems for Ubiquitous Computing”, *IEEE Computer*, 34(8):57-66, August 2001.

[44] J. Hightower, G. Boriello and R. Want, “SpotON: An indoor 3D Location Sensing Technology Based on RF Signal Strength”, *University of Washington CSE Technical Report #2000-02-02*, February 2000.

[45] J. Hill, “A Software Architecture to support network sensors”, Master’s *thesis*, UC Berkeley, 2000.

[46] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler and K. Pister, “ System architecture directions for network sensors,” In *ASPLOS* 2000.

[47] B. Hofmann-Wellenhoff, H. Lichtenegger, J. Collins, “Global Positions System: Theory and Practice”, *Fourth Edition. Springer Verlag*, 1997.

[48] X. Hong, K. Xu, and M. Gerla, “Scalable routing protocols for mobile ad hoc networks”, *IEEE Network magazine*, vol 16, no. 4, 2002.

[49] N. Ickes, F.S. Lee, and P. Phanaphat, “Hardware Architecture for a Power-Aware Microsensor Node”, http://www-mtl.mit.edu/mtlhome/6Res/AR2002/01_ics/006_hapamn.pdf

[50] IETF Working Group on Mobile Ad Hoc Networks, http://www.ietf.org/html.charters/manet-charter.html

[51] C. Intanagonwiwat, R. Govindan and D. Estrin, “Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks”, In *the Sixth Annual International Conference on Mobile Computing and Networks (MobiCOM 2000)*, August 2000, Boston, Massachusetts.

[52] C. Intanagonwiwat, D. Estrin, R. Govindan, and J Heidemann, “Impact of Network Density on Data Aggregation in Wireless Sensor Networks”, In *Proceedings of the 22nd International Conference on Distributed Computing Systems*, Vienna, Austria, IEEE. July, 2002.

[53] David B. Johnson and David A. Maltz, “Dynamic Source Routing in Ad Hoc Wireless Networks”, In *Mobile Computing*, Chapter 5, pages 153-181, Kluwer Academic Publishers, 1996.

[54] D. Kandlur, K. G. Shin, and D. Ferrari, “Real-time Communication in Multi-hop Networks”, *IEEE Trans. on Parallel and Distributed Systems*, pp. 1044-1056, October 1994.

[55] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. W.Knightly, “Distributed Multi-Hop Scheduling and Medium Access with Delay and Throughput Constraints”, In *IEEE MobiCOM 2001*, Rome, Italy, July 2001.

[56] Phil Karn. “MACA – A New Channel Access Method for Packet Radio”. In *ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, pages 134-140, September 1990.

[57] K.D. Kang, S. Son, J. A. Stankovic and T. Abdelzaher, “A QoS-Sensitive Approach for Timeliness and Freshness Guarantees in Real-Time Databases'”, In *Proceedings of Euromicro*, Vienna, Austria, June 2002.

[58] B. Karp, “Geographic Routing for Wireless Networks”, Ph.D. Dissertation, Harvard University, Cambridge, MA, October 2000.

[59] B. Karp and H.T. Kung, “Greedy Perimeter Stateless Routing for Wireless Networks”, In *Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000)*, Boston, MA, August, 2000, pp. 243-254.

[60] Y. Ko and N. H. Vaidya, “Location-Aided Routing (LAR) in Mobile Ad Hoc Networks”, In *the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 1998),* Dallas, TX, October 1998.

[61] B. Krishnamachari, D. Estrin, and S. Wicker, “Impact of data aggregation in wireless sensor networks”, In *International Workshop on Distributed Event-Based Sytems*, Vienna, Austria, July 2002.

[62] James F. Kurose, Keith W. Ross, “Computer Networking A Top-Down Approach Featuring the Internet”, *ISBN 0-201-47711-4 Addison Wesley Longman Inc*.

[63] J. Li, J. Jannotti, D. S. J. De Couto, D. Karger and R. Morris, “A Scalable Location Service for Geographic Ad-Hoc Routing”, In *Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ’00)*, New York, August 2000.

[64] Alvin Lim, “Distributed Services for Information Dissemination in Self-Organizing Sensor Networks”, *the Special Issue on Distributed Sensor Networks for Real-Time Systems with Adaptive Reconfiguration, Journal of Franklin Institute*, 2001.

[65] C. Lu, T. Abdelzaher, J. A. Stankovic, S. Son, “A Feedback Control Approach for Guaranteeing Relative Delays in Web Servers”, In *Proceedings of IEEE Real-Time Technology and Applications Symposium*, TaiPei, Taiwan, June 2001.

[66] C. Lu, B. M. Blum, T. F. Abdelzaher, J. A. Stankovic, and T. He, “RAP: A Real-Time Communication Architecture for Large-Scale Wireless Sensor Networks”, In *IEEE RTAS 2002*, San Jose, CA, September 2002.

[67] Y. Lu, C. Lu, T. Abdelzaher, G. Tao, “An Adaptive Control Framework for QoS Guarantees and its Application to Differentiated Caching Services”, In *Proceedings of IWQoS*, Miami Beach, FL, May 2002.

[68] L.Kleinrock and J.Slivester, “Optimum transmission radii for packet radio networks or why six is a magic number”, In *Proceedings of national Telecomm conference* Pages 4.3.1-4.3.5, 1978.

[69] M. Mauve, J. Widmer, H. Hartenstein, “A Survey on Position Based Routing in Mobile Ad-Hoc Networks”, In *IEEE Network Magazine*, 15(6):30-39, November 2001.

[70] S. Meguerdichian, F. Koushanfar, G. Qu, M. Potkonjak, “Exposure in Wireless Ad Hoc Sensor Networks”, In *Proceedings of 7th Annual International Conference on Mobile Computing and Networking (MobiCom '01),* pp. 139-150, July 2001.

[71] R. Min, M. Bhardwaj, S. H. Cho, A. Sinha, E. Shih, A. Wang, and A. Chandrakasan, “An Architecture for a Power-Aware Distributed Microsensor Node”, *2000 IEEE Workshop on Signal Processing Systems* (SiPS '00), October 2000

[72] R. Nagpal, “Organizing a Global Coordinate System from Local Information on an Amorphous Computer”, *A.I. Memo 1666*, MIT A.I. Laboratory, August 1999.

[73] J. C. Navas, T. Imielinski, “Geographic Addressing and Routing”, In *Proceedings of the Third Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ’97),* Budapest, Hungary, September 26, 1997.

[74] S. Ni , Y. Tseng , Y. Chen , J. Sheu, “The broadcast storm problem in a mobile ad hoc network”, *In IEEE MobiCOM 1999*, Seattle, Washington, August,1999

[75] D. Nicolescu and B. Nath, “Ad-Hoc Positioning Systems (APS)”, In *Proceedings of IEEE GLOBECOM ‘01*, November 2001.

[76] D. Niculescu and B. Nath, “DV Based Positioning in Ad hoc Networks”, In *Journal of Telecommunication Systems*, 2003.

[77] D. Niculescu and B. Nath, “Ad Hoc Positioning System (APS) using AoA”, In *Proceedings of INFOCOM 2003*, San Francisco, CA.

[78] R. Nagpal and D. Coore, “An Algorithm for Group Formation in an Amorphous Computer”, In *Proceedings of the 10th International Conference on Parallel and Distributed Computing Systems (PDCS'98),* Nevada, Oct 1998.

[79] V.D. Park and M.S. Corson, “A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks”, In *Proceedings of IEEE INFOCOM’97*, Kobe, Japan, Apr. 1997, pp. 1405-1413.

[80] C. E. Perkins and E. M. Royer, “Ad-hoc On Demand Distance Vector Routing”, In *Proceedings of WMCSA'99*, New Orleans, LA, February 1999.

[81] C. E. Perkins and P. Bhagwat, “Highly dynamic Destination-Sequenced Distance-Vector routing (DSDV) for Mobile Computers”, in *SIGCOMM Symposium on Communications Architectures and Protocols*, (London, UK), pp. 212-225, Sept. 1994.

[82] N. B. Priyantha, A. Chakraborty, H. Balakrishnan, “The Cricket Location-Support System”, In *ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ‘00)*, Boston, MA, August 2000.

[83] Programming Languages and Operating Systems, November 2000.

[84] R. Ramanathan and R. Rosales-Hain, “Topology control of multihop wireless networks using transmit power adjustment”. In *Proceedings of IEEE lnfocom 2000*, pages 404-413, March 2000.

[85] C. Savarese, J. Rabay, K. Langendoen, “Robust Positioning Algorithms for Distributed Ad-Hoc Wireless Sensor Networks”, In *USENIX Technical Annual Conference*, Monterey, CA, June 2002.

[86] A. Savvides, C. C. Han, M. B. Srivastava, “Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors”, In *Proceedings of the Seventh Annual International Conference on Mobile Computing and Networking (MOBICOM ’01),* 2001, Rome, Italy, July 2001.

[87] A. Savvides, H. Park, M. Srivastava, “The Bits and Flops of the N-Hop Multilateration Primitive for Node Localization Problems”, *In First ACM International Workshop on Wireless Sensor Networks and Application (WSNA ’02),* Atlanta, GA, September 2002.

[88] S. Sebastine, K.D. Kang, T. F. Abdelzaher, S. H. Son, "A Scalable Web-Based Real-Time Information Distribution Service for Industrial Applications", In *Proceedings of 27th Annual Conference of the IEEE Industrial Electronics Society*, Denver, Colorado, December 2001.

[89] R. Sivakumar, P. Sinha, and V. Bharghavan, "CEDAR: a Core Extraction Distributed Ad hoc Routing Algorithm", In *IEEE Journal on Selected Areas in Communication*, vol. 17, no. 8, pp. 1654-65, August 1999.

[90] J. A. Stankovic, T. He, T. F. Abdelzaher, M. Marley, G. Tao, S. Son, and C. Lu, "Feedback Control Scheduling in Distributed Systems", In *IEEE RTSS*, London, UK, December 2001.

[91] Fred Stann and John Heidemann, "RMST: Reliable Data Transport in Sensor Networks", In *Proceedings of the First International Workshop on Sensor Net Protocols and Applications*, Anchorage, Alaska, USA, USC/Information Sciences Institute, IEEE. April 2003.

[92] I. Stojmenovic and X. Lin. "GEDIR: Loop-Free Location Based Routing in Wireless Networks", *In International Conference on Parallel and Distributed Computing and Systems*, Boston, MA, USA, Nov. 3-6, 1999,

[93] M. T. Sun, L. Huang, A. Arora, and T. H. Lai, "Reliable MAC layer multicast in IEEE wireless networks", In *Proceedings of International Conference on Parallel Processing (ICCP)*, Vancouver, 2002.

[94] H.Takagi and L.Kleinrock. "Optimal Transmission Ranges For Randomly Distributed Packet Radio Terminals", *IEEE Trans. on Communication,* 32(3):246-257, March 1984.

[95] D. Tian and N. D. Georganas, "A Coverage-Preserving Node Scheduling Scheme for Large Wireless Sensor Networks," In *Proceedings of ACM Workshop on Wireless Sensor Networks and Applications*, Atlanta, Oct.2002.

[96] D. Tian and N. D. Georganas, "A Node Scheduling Scheme for Energy Conservation in Large Wireless Sensor Networks," *Wireless Communications and Mobile Computing Journal*, May 2003.

[97] T. Yan, T. He, J. A. Stankovic, "Differentiated Surveillance Service for Sensor Networks", In Submission to *SenSys 2003*.

[98] R. Want, A. Hopper, V. Falcao and J. Gibbons, "The Active Badge Location System", *ACM Transactions on Information Systems*, January 1992.

[99] A. Weaver, "Xpress Transport Protocol", *Cluster Computing*, Volume 1, Prentice-Hall, pp. 301-316, 1999.

[100] K. Whitehouse, D. Culler, "Calibration as Parameter Estimation in Sensor Networks", In *First ACM International Workshop on Wireless Sensor Networks and Application (WSNA '02)*, Atlanta GA, September 2002.

[101] R. Williams, "Geometrical Foundation of Natural Structure: A Source Book of Design", *Dover Publications Inc*, New York, pp. 51-52, 1979.

[102] A. Woo and D. Culler, "A Transmission Control Scheme for Media Access in Sensor Networks," In *ACM/IEEE International Conference on Mobile Computing and Networks (MobiCOM 2001)*, Rome, Italy, July 2001.

[103] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed Energy Conservation for Ad Hoc Routing," In *ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2001)*, Rome, Italy, July 2001.

[104] W. Ye, J. Heidemann and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks", In *Proceedings of the 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2002)*, New York, NY, USA, June, 2002.

[105] W. Ye, J. Heidemann and D. Estrin, "A Flexible and Reliable Radio Communication Stack on Motes", *Detailed Documentation of the Radio Communication Stac*k, http://www.isi.edu/scadds/projects/commstack/

[106] F. Ye, G. Zhong, S. Lu, and L. Zhang, "Energy Efficient Robust Sensing Coverage in Large Sensor Networks", *UCLA Technical Report 2002*.

[107] C.Y. Wan and A. T. Campbell, "PSFQ: A Reliable Transport Protocol For Wireless Sensor Networks", In *Proceedings of First ACM International Workshop on Wireless Sensor Networks and Applications (WSNA 2002)*, pp. 1-11, Atlanta, September 28, 2002.

[108] Y. Xu, S. Bien, Y. Mori, J. Heidemann, and D. Estrin, "Topology Control Protocols to Conserve Energy in Wireless Ad Hoc Networks," submitted for review to *IEEE Transactions on Mobile Computing*, January 2003.

[109] Y. Yu, R. Govindan, D. Estrin, "Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks",

[110] X. Zeng, Rajive Bagrodia, and Mario Gerla , "GloMoSim: a Library for Parallel Simulation of Large-scale Wireless Networks". In *Proceedings of the 12th Workshop on Parallel and Distributed Simulations -- PADS '98*, May 26-29, 1998

[111] R. Zhang, C. Lu, T. F. Abdelzaher, J. A. Stankovic, "ControlWare: A Middleware Architecture for Feedback Control of Software Performance", In *International Conference on Distributed Computing Systems*, Vienna, Austria, July 2002.

Hermes: Hermes' main role was as a messenger. As the special servant and courier of Zeus, Hermes had winged sandals and a winged hat and bore a golden caduceus, or magic wand, entwined with snakes and surmounted by wings. He is also a Greek god of commerce, eloquence, invention and travel.

@inproceedings{He2003HermesA, title={Hermes : A Scalable Sensor Network Architecture for Robustness & Time-Energy Awareness}, author={Tian He and John A. Stankovic}, year={2003} }. Tian He, John A. Stankovic. Published 2003. Wireless Sensor Networks (WSN) have emerged as a new information-gathering paradigm based on the collaborative efforts of a large number of self-organized sensing nodes. These networks form the basis for many types of smart environments such as smart hospitals, intelligent battlefields, earthquake response systems, and learning environments. A set of applications, such 1 Hermes: A Scalable Event-Based Middleware Peter Robert Pietzuch Queens College University of Cambridge A dissertation submitted for the degree of Doctor of Philosophy February 2004. 2.Â ubiquitous sensor-rich environment concentrated on a small area, such as the Active Office building shown in Figure 1.2. In this building, sensors that are installed in offices provide information about the environment to interested devices, applications, and users.Â After that, the chapter proposes a design and architecture for the distributed detection of composite events focusing on the composite event language and the composite event detectors. Finally, we deal with issues related to distributed detection and finish with an evaluation and related work. Request PDF on ResearchGate | A Scalable Energy Efficient and Delay Bounded Data Gathering Framework for Large Scale Sensor Network | This work details a new class of energy efficient and delay bounded data gathering framework viz. generalized intra cluster chaining (GICC) framework for large scale wireless sensor network.Â All sensors will exhaust their energy at the same time. Sensors use at most three different transmitting power levels to relay the gathered data. The simulation results show that the network can endure longer.Â LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station.