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On the Design and Analysis of Transport Protocols over Wireless Sensor Networks

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1. Introduction

Sensor networks are typically data driven where the whole network cooperates in communicating data from source sensors to sinks (typical repository/server). One of the main characteristics of a typical sensor node is the limited power supply it has (Kahn et al., 1999). Usually, it is battery operated which might last for some months to a year (depending on the type of application and other application specifications). Sensing nodes typically exhibit limited capabilities in terms of processing, communication, and especially, power (Pottie et al., 2000). Different application would have different constraints and priorities on how their sensor network must behave. Thus, energy conservation is of prime consideration in sensor network protocols in order to maximize the network's operational lifetime. Rather than sending individual data items from sensors to sinks, it is more energy efficient to send aggregated data. The net effect of this aggregation is, by transmitting less data units, considerable energy savings can be achieved which is the main idea behind in-network (Madden et al., 2002) aggregation and further distributed processing of the data.

Since enabling communication between sensors and sinks is the major role of sensor networks, many research works [Gopalsamy et al., 2002] have investigated energy-aware data delivery. However, sensor networks experience wireless errors and congestion more severely than other wireless networks because of the low capability to recover from losses and the high node-density. Therefore, robustness is also important to energy conservation since unreliable data delivery, which increases the probability of data retransmission under high loss rates, results in the consumption of a large amount of energy. Although the problem has been addressed by previous works [Heinzelman et al., 1999 & Ye et al., 2003] in the context of wireless ad-hoc networks, such approaches cannot be directly applied to the sensor environment. Because of the distinctive characteristics of multipoint-to-point communication vs. point-to-multipoint communication, the data delivery problem in sensor networks can be seen as consisting of two problems: downstream and upstream data delivery. Therefore, we address these problems as two separate ones. Firstly, a sink-to-sensors energy-aware data delivery scheme is proposed to solve the downstream problem while considering robustness simultaneously. Secondly, a sensors-to-sink energy-aware data delivery scheme is proposed to address the upstream problem.

Therefore, in this chapter, first we construct a probability model for existence of such redundancy among closely related sensor nodes. In the model, we assume sensor nodes are generated with two associated bi-variate Poisson distribution in a plane. We then propose a scalable framework for reliable data delivery. The proposed framework addresses and leverages the characteristics of the wireless sensor networks while achieving the reliability in an efficient manner. First, for downstream data delivery, we formulated the reliable data delivery problem theoretically using the minimum set cover problem and transformed it to the minimum dominating set (MDS) problem. For upstream data delivery, we formulate the perfectly correlated data aggregation problem using the Steiner minimum tree (SMT). We propose a decentralized aggregation method by integrating the shortest path tree and the minimum dominating set to approximate the optimal solution, the SMT. We evaluate the performance of the proposed approach with other previous schemes and we show that the proposed scheme performs substantially. With the help of proposed probability model for redundancy condition, we comment on the design of such schemes.

2. Condition for Data Redundancy between Sensing Nodes

In this section, we introduce a heuristic model for data redundancy in spatially distributed sensor network to characterize the amount of redundancy existing among near neighbour nodes. For the general scenario, although in our analysis we introduce two different kind of sensor nodes (further referred as A and B), it does not affect the general analysis for uniform sensor node scenario. However, it may lead to useful result considering that there are at least two kinds of sensor nodes that differ in some sense1 and still lead to a simplified analysis. We consider that whatever differences sensors have, they are distributed with the same master Poisson process. We recognise that the near neighbour distribution is the main factor contributing to the overlap of sensing regions among nodes that introduces data redundancy among sensor nodes. We give a probabilistic expression giving near node distribution and argue that for a given sensing range how many sensors can deliver partially redundant data.

2.1 System Model
Continuing our two node scenario and assuming data is uniformly distributed throughout the spatial region, the data collected by some node n_i in its sensing region A_i is proportional to the sensing area. Hence, data sensed in area $A_i = \gamma A_i$ Where, γ is some proportionality constant that depends on sensing ability of sensors. Hence, for sensing nodes A and B, the correlation factor is given by,

$$\frac{A \cap B}{A \cup B} \tag{1}$$

Assuming uniform node configuration of all the nodes, the sensing radius is r_s and transmission range is r_t. the sensing area is given as $A = \pi r_s^2$.
For a particular node say s, all the other nodes in area $4r_s^2$, shares some degree of redundant information with s. In figure 1, two nodes A and B has position vectors r and r' respectively and r_s is their sensing range, the condition that these two nodes share redundant information is given by,

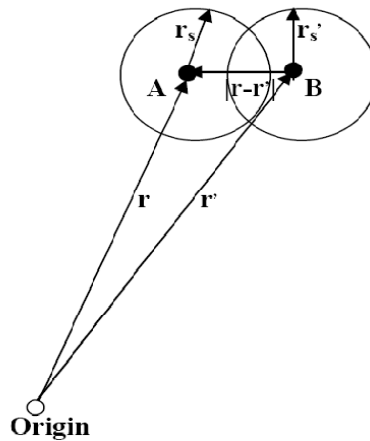$$|r - r'| < 2r_s \qquad (2)$$

Fig. 1. Condition for Data Redundancy between two nodes A & B

Hence, to quantify the redundancy for all the neighbours around a sensor node we have to find out its near neighbour distribution in its own sensing range. Next section presents an analysis, assuming sensor nodes follows a spatial bi-variate distribution for sensor nodes, A and B. Here, we consider nodes A and B which are different in terms of sensing rate or some other figure of merit, say, sensing capability factor or can be totally different sensors.

2.2 Nearest Neighbour Distribution

Maritz (Maritz, 1952) obtained the probability generating function for the bivariate poison assuming that, in any interval of length dt, the combinations $(A\bar{B}, \bar{A}B, AB \text{ and } \overline{AB})$ of the two events A and B, occur with probabilities λdt, vdt, μdt and 1 - (λ+v+μ)dt. Since, this analysis involves time bivariate distribution, we write the spatial bivariate distribution by following the same line of analysis by assuming event A represents the sensor type A and B represents sensor type B.

The distribution of the distance between two adjacent points, the nearest neighbour distribution considering marginal distributions are Poisson, we get the following relationship,

$$\text{prob}(X_{BB}(\text{distance from a point B to next nearest point B}) < r) = 1 - e^{-(\mu+v)\pi r^2} \qquad (3)$$

and similarly for A. The distribution of the distance from a point A to a nearest point B may be derived as follows:

prob (X_{AB}(distance from a point A to nearest point B) > r)

= prob (A single) prob (distance from A to nearest B > r | A single) + prob (A double) prob (distance from A to nearest B > r | A double)

$$= \frac{\lambda}{\lambda+v} e^{-(\mu+v)\pi r^2} (1 + \int_{|x|>r} h(x,0)dx \qquad (4)$$

Hence, prob ($X_{AB} < r$)=

$$1 - e^{-(\mu+v)\pi r^2}(\lambda + v\frac{\int_{|x|>r} h(x,0)dx}{\lambda+v}) \tag{5}$$

When A and B are independent, i.e. when $v = 0$, 5 reduces to the distribution of the distance from a random point to the nearest point B which is the same distribution as given in equation 3. For the sensing range $2r_s$ equation 4 gives the condition for two sensors sharing redundant data as below:

$$1 - e^{-(\mu+v)\pi r_s^2}(\lambda + v\frac{\int_{|x|>2r_s} h(x,0)dx}{\lambda+v}) \tag{6}$$

3. Down Stream Reliable Data Delivery over Sensor Network

In this section, we consider the problem of reliable downstream point-to-multipoint data delivery, from the sink to the sensors, in wireless sensor networks (WSNs). The need (or lack thereof) for reliability in a sensor network is clearly dependent upon the specific application the sensor network is used for. Consider a security application where image sensors are required to detect and identify the presence of critical targets. Given the critical nature of the application, it can be argued that any message from the sink has to reach the sensors reliably. The problem of reliable data delivery in multi-hop wireless networks is by itself not new, and has been addressed by several existing works in the context of wireless ad-hoc networks (Tang & Gerla, 2001). However, such approaches do not directly apply to a sensor environment because of three unique challenges imposed by the following considerations:
The issue of reliability is addressed in following context:
Downstream Reliability: We restrict the scope of this work to downstream reliability.
Communication and Node failures: A scheme that addresses reliability in a sensor network environment, has to deal with communication failures and node failures. The proposed algorithm will handle both communication and node failures.
Message size: We assume that the message size to be sent by the sink consists of one or more packets.
Metrics: We consider latency and energy consumption as the metrics of interest for comparison with other existing approaches. The goals is to minimize these metrics.
Network Model: We assume that both the sink and the sensors in the network remain static. We also assume that there is exactly one sink coordinating the sensors in the field. Further, since sensor networks have a large number of sensor nodes, the proposed approach must be scalable to the number of nodes in the network.

3.1 Design Choices and Challenges
We have following basic design choices:
1. A NACK based loss recovery scheme is preferable to an ACK based scheme as the latter suffers from the ACK implosion problem.
2. Local and dynamically assigned designated servers are essential to minimize the retransmission data overhead.
3. Out-of-sequence forwarding should be preferred to maximize the spatial reuse in the network.

We outline following challenges that need to be addressed to provide effective downstream data delivery:

1. Environment Constraints: It is evident that sensor network have two main constraints. First, Bandwidth and energy constraint and second frequent node failure problem.

2. ACK/NACK Paradox: This challenge stems out from the constraints imposed by typical message types that can be expected to use the downstream reliability. While the query-data and control code can be expected to be of non-trivial message size, queries pose a unique problem because of their short message sizes. While an ACK based recovery scheme would address the problems, its other deficiencies (in terms of ACK implosion) however clearly prohibit it from being used. Whereas, NACKs cannot handle the unique case of all packets in a message being lost at a particular node in the network. Since the node is not aware that a message is expected, it cannot possibly advertise a NACK to request retransmissions. NACK based scheme require in-sequence forwarding of data by nodes in the network to prevent a NACK implosion (Wan et al., 2002). This will clearly limit the spatial re-use achieved in the network.

3.2 Ideal Solution: Minimum Set Cover Problem

To solve the reliability problem at wireless sensor networks, it is necessary to formulate the problem into an optimization problem which has been known as a common and typical problem and investigated for optimal solutions. Assuming that the lost packet can be retransmitted and recovered by one of neighbours which received the lost packet before, a solution tries to designate a set of nodes, called recovery servers, which retransmit the lost packet in an optimal fashion. We will call this problem as loss recovery server designation problem. By the nature of local broadcasting of wireless communication, one recovery server can recover the lost packet of all neighbours around it. Therefore, it is optimal to minimize a size of the set of recovery servers covering all nodes which did not receive the packet. And it is necessary to find the optimal recovery sets for different loss patterns of each packet. The above loss recovery server designation problem can be defined as a set cover problem in the graph theory, the problem of covering a base set (nodes which did received a packet successfully) with as few elements of a given subset system (a set of recovery servers) as possible. However, Karp (Karp, 1972) showed that the decision version of the minimum set cover (MSC) is NP-complete. A common approach of coping with NP-hard problems is approximation algorithms that run in polynomial time and deliver solutions that are close to the optimal solution.

Therefore, we address the loss recovery server designation problem with an alternative which has similar complexity and advantages to solve the problem in decentralized fashion.

In a graph, a dominating set is a subset of nodes such that for every node v in a graph, either a) v is in the dominating set or b) a direct neighbour of v is in the dominating set. The minimum dominating set problem asks for a dominating set of minimum size. The reason to choose MDS is considering the fact that MSC is equivalent to the MDS problem under L-reduction closely related to each other and have been shown to be NP-hard (Garey & Johnson, 1979). Although the MDS problem has different instances reduced from different instances of MSC problem, an instance for MDS problem can include a whole network by covering a set of nodes and edges which are not adjacent to a given set S. Therefore, we can handle the MDS problem without concerning the loss pattern S although there are trade-offs: the advantage of MDS is that we can solve MDS problem without considering different

instances for different loss patterns; and the disadvantage of MDS is that the cost of optimal solution for an instance of MDS is larger than that of optimal solution for an instance of MSC for given loss pattern S. we can use the approximated solution of MDS to solve the MSC which is the optimal solution of the loss recovery server designation problem

3.3 A Framework for Down Stream Data Delivery Scheme

The centerpiece of proposed design is an instantaneously constructible loss recovery infrastructure called the core. The core is approximation of the minimum dominating set (MDS) of the network sub-graph to which reliable message delivery is desired. While using the notion of a MDS to solve networking problems is not new (Sivakumar et al., 1999), the contributions of this work lie in establishing the following for the specific target environment: the relative optimality of the core for the loss recovery process, how the core is constructed, how the core is used for the loss recovery, and how the core is made to scalably support multiple reliable semantics.

3.3.1 Core Construction

We assume that the first packet is reliably delivered for the initial discussions. The core forms the set of local designated loss recovery servers that help in the loss recovery process. The core is constructed using the first packet delivery. The reliable delivery of the first packet determines the hop count of the node in the network, which is the distance of the node from the sink. A node, which has a hop count that is a multiple of three, elects itself as a core if it has not heard from any other core node. In this fashion, the core selection procedure approximates the MDS structure in a distributed fashion (Figure 3). The uniqueness of the core design in this approach lies in the following characteristics: (i) the core is constructed using a single packet flood, more specifically during the flood of the first packet; and (ii) the structure of the sensor network topology (with sensors placed at fixed distances from the sink) is leveraged for more efficient, and fair core construction.
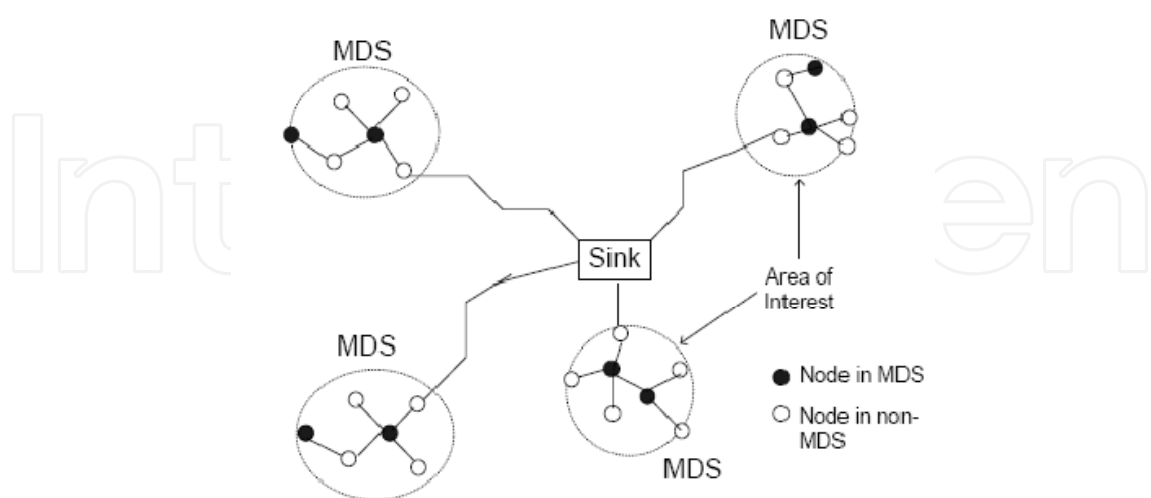

Fig. 3. Core Construction as an approximation of MDS

The core construction uses following algorithm:
Sink: When the sink sends the first packet, it stamps the packet with a "band-id" (bId) of 0.

When a sensor receives the first packet successfully, it increments its bId by one, and sets the resulting value as its own band-id. The band-id is representative of the approximate number of hops from the sink to the sensor.

Nodes in 3i bands: Only sensors with band-ids of the form 3i, where i is a positive integer, are allowed to elect themselves as core nodes. When a sensor S_0 with a band-id of the form 3i forwards the packet (after a random waiting delay from the time it received the packet), it chooses itself as a core node if it had not heard from any other core node in the same band. Once a node chooses itself as a core node, all packet transmissions (including the first) carry information indicating the same. If any node in the core band that has not selected itself to be a core receives a core solicitation message explicitly, it chooses itself as a core node at that stage. Every core node S_3 in the 3(i+1) band should also know of at least one core in the 3i band. If it receives the first packet through a core in the 3i band, it can determine this information implicitly as every packet carries the previously visited core node's identifier, bId, and Amap. However, to tackle a condition where this does not happen, S_3 maintains information about the node (S_2) it received the first packet from, and the S_2 node maintains information from the node (S_1) it received the first packet from. After a duration equal to the core election timer, S_3 sends an explicit upstream core solicitation message to S_2, which in turn forwards the message to S_1. Note that by this time, S_1 will already have chosen a core node, and hence it responds with the relevant information.

Nodes in 3i+1 bands: When a sensor S_1 with a band-id of the form 3i+1 receives the rst packet, it checks to see if the packet arrived from a core node or from a non-core node. If the source S_0 was a core node, S_1 sets its core node as S_0. Otherwise, it sets S_0 as a candidate core node, and starts a core election timer. If S_1 hears from a core node S_0 before the core election timer expires, it sets its core node to S_0 . However, if the core election timer expires before hearing from any other core node, it sets S_0 as its core node, and sends a unicast message to S_0 informing it of the decision.

Nodes in 3i+2 bands: When a sensor S_2 with a band-id of the form 3i+2 receives the first packet, it cannot (at that point) know of any 3(i+1) sensor. Hence, it forwards the packet without choosing its core node, but starts its core election timer. If it hears from a core node in the 3(i+1) band before the timer expires, it chooses the node as its core node. Otherwise, it arbitrarily picks any of the sensors that it heard from in the 3(i+1) band as its core node and informs the node of its decision through a unicast message. If it so happens that S2 does not hear from any of the nodes in the 3(i+1) band (possible, but unlikely), it sends an anycast core solicitation message with only the target band-id set to 3(i+1). Any node in the 3(i+1) band that receives the anycast message is allowed to respond after a random waiting delay. The delay is set to a smaller value for core nodes to facilitate re-use of an already elected core node. A boundary condition that arises when a sensor with a band-id of 3i+2 is right at the edge of the network, is handled by making the band act just as a candidate core band (3i). Such a condition can be detected when nodes in that band do not receive any response for the anycast core solicitation message. Thus, at the end of the first packet delivery phase, each node knows its bId, whether it is a core node or not, and in the latter case its core node information. In addition, every core node in the 3(i+1) band knows of at least one core node in the 3i band.
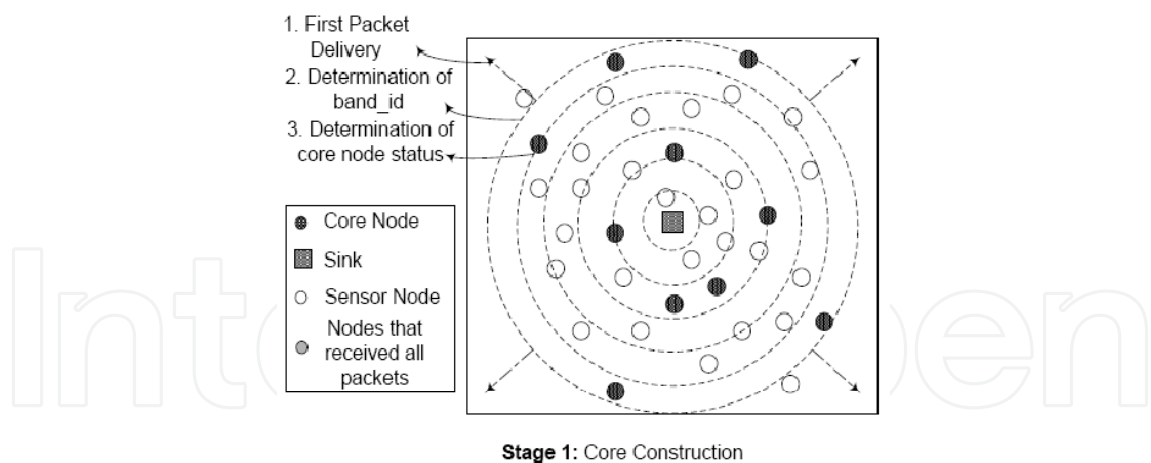
Stage 1: Core Construction

Fig. 4. Core Construction

3.3.2 Loss Recovery Process

Once the core is constructed, the framework employs a two-stage recovery process that first involves the core nodes recovering from all lost packets, and then the recovery of lost packets at the non-core nodes. The reasons for using two-stage recovery are threefold: (i) the number of non-core nodes will be a substantial portion of the total number of nodes in the network, and hence precluding any contention from them is desirable; (ii) when the core nodes perform retransmissions for other core nodes, holes corresponding to a single packet among a core node's neighbours would also be filled with a single retransmission; and (iii) when only the core nodes are performing retransmissions during the second phase, due to the nature of the core (ideally, no two core nodes are within two hops of each other), the chances for collisions between retransmissions from different core nodes are minimized. The recovery process for the core nodes is performed in parallel with the underlying default message-forwarding (Figure 5). This parallel recovery process for the core nodes does not increase the contention in the network significantly because the fraction of core nodes is very small compared to the total number of nodes in the network, and all requests and retransmissions are performed as unicast transmissions to the nearest upstream core that has a copy of the lost packet.

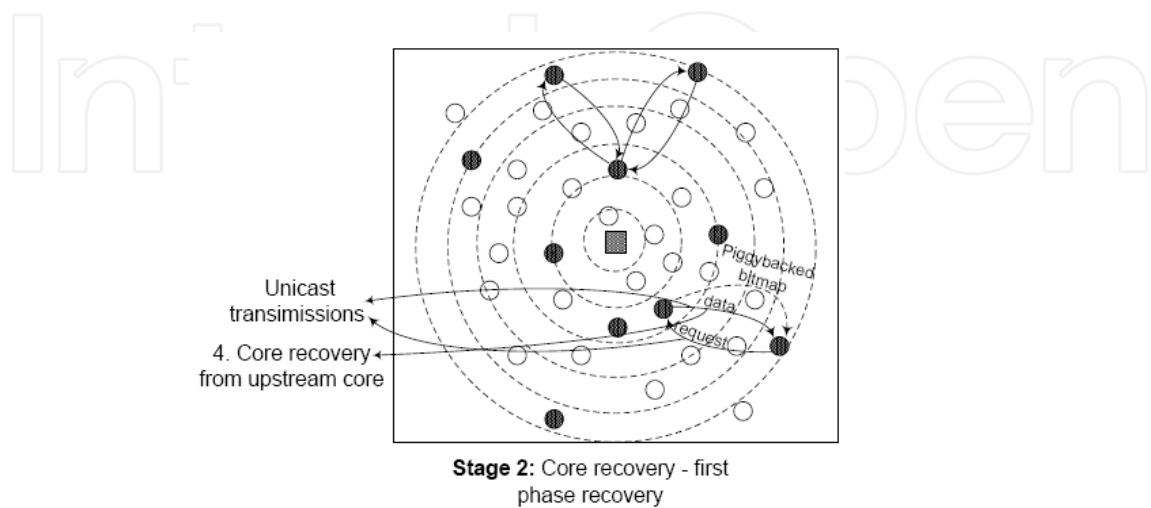**Stage 2:** Core recovery - first phase recovery

Fig. 5. Loss recovery for Core Nodes

The second phase of the loss recovery starts only when a non-core node overhears an A-map from the core node indicating that the core node has received all the packets in a message. Hence, the second phase of the loss recovery does not overlap with that of the first phase in each local area, preventing any contention with the basic flooding mechanism, and with the first phase recovery. To inhibit unnecessary retransmission requests, proposed scheme uses a scalable A-map (Availability Map) exchange between core nodes that conveys meta-level information representing availability of packets with bits set. Any downstream core node initiates a request for a missing packet only if it receives an A-map from an upstream core node with the corresponding bit set. The core recovery phase is highly efficient as the core nodes initiate requests only when they are sure of an upstream core node having a particular packet.

3.3.3 Role of WFP Pulse Transmission

Reliable single packet delivery is leveraged for the instantaneous core construction. To achieve that, we use WFP pulse transmission. WFP Pulse can be regarded as a short period signal which does not include any information, the transmission period of the WFP pulse is significantly smaller when compared to the transmission time T_D required for a regular data packet. Also, twice the regular transmission power is used to transmit the pulses to achieve relative amplitude of 3dB at the receiver. To increase the robustness of the pulse detection, every set of pulse transmission includes p pulses transmitted consecutively within a period T_P ($T_P \ll T_D$). Figure 6 shows the transmission scheme for the WFP pulse. Hence, receivers infer an incoming WFP signal only after detecting p pulses. As shown in figure, the WFP pulse is forced in this design.
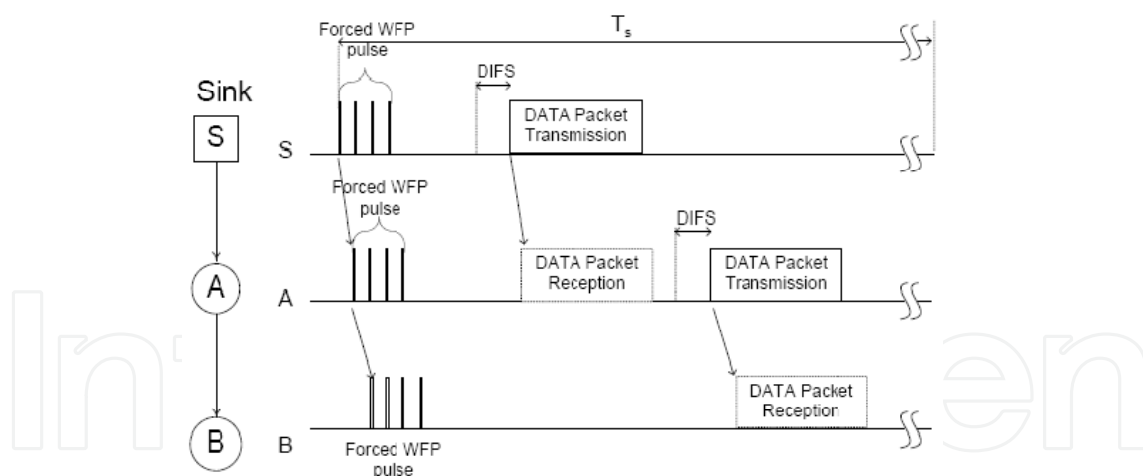

Fig. 6. Example for Single or First Packet Delivery

Figure 6 shows the basic procedure of the single or the first packet delivery with a simple topology. When a sink wants to initiate a reliable single first packet delivery, it sends a set of forced WFP pulses without sensing the wireless channel. When neighbouring sensors hear WFP pulses, they send a set of forced WFP pulses immediately. After a deterministic period that is set based on the diameter of the network, the sink transmits the single first data packet subject to the medium access scheme, e.g., CSMA. If the node A receives the single/first packet, it changes its operation from the advertisement mode to the delivery

mode by halting the WFP pulses, and by sending the single/first data packet after carrier-sensing. However, if the single/first packet is lost, nodes will continue to transmit the WFP pulses, which in turn trigger retransmissions. Figure 7 shows the case of retransmission. Since the forced WFP pulses sent every Ts period play the role of a NACK signal, node B will wait for a duration of at least Ts to send next set of forced WFP pulses. Therefore, the latency for the single/first packet delivery is directly dependent upon T_s.

Fig. 7. Loss Recovery using WFP Pulse Transmission

To reduce the latency, it uses another kind of WFP pulse which a node sends after a regular carrier sensing operation. Node B sends p number of WFP pulses after carrier-sensing (WFP$_{cs}$) opportunistically (unless it has received the single/first packet) with a period T_c which is smaller than T_s. The period T_c should be proportional to the hop distance of the node B from the sink because a node should wait until the upstream nodes between the node and the sink receives the single/first packet. Since a node senses the state of channel before transmitting WFP$_{cs}$ pulses, the WFP$_{cs}$ pulses have a lesser probability of colliding with data packets than WFP pulses. When a node gets to transmit WFP$_{cs}$ pulses, it resets the timer corresponding to the Ts time period for forced WFP pulses.

4. A Framework for Energy Efficient Upstream Data Delivery

In Section 2, probability condition (Equation 6) is derived based on near neighbour distribution for spatial correlation among data between neighbouring nodes. In this Section, we consider the problem of data aggregation in environments where the data from the different sensors are spatially correlated to each other. To do that, we present a simple, scalable, and distributed approach for approximating the Steiner minimum tree, and thereby achieve the potential cost benefits introduced earlier. Moreover, we can solve the upstream data delivery problem without any overhead because the proposed approach uses the same minimum dominating set structure, the core, which already has been constructed through the query delivery. To aggregate perfectly correlated data in an energy-efficient way, we use two structures that have been constructed during downstream data delivery: (i) the minimum dominating set (MDS) which is same to the core structure proposed in Section 4.6 and (ii) the shortest path tree which is constructed through a basic flooding. The purpose of the MDS structure is to aggregate correlated data from neighbouring sources; that of SPT is to gather aggregated data among core nodes in the MDS. The correlation factor depends on the degree of correlation i.e., the probability of finding a near neighbour node to a particular node. The probabilistic model is helping to design such an Up-stream data

delivery mechanism however, it is not limited to any particular case of distribution and hence provides a generalized approach.

Although there have been many previous works in (Hwang et al., 1992) on the approximation of the SMT, those schemes still require computational and communication overheads that WSNs cannot support. In this section, we design an aggregation structure that approximate the optimal solution in a distributed fashion with less amount of overhead than distributed approximation of the SMT. From the definition of the Steiner minimum tree (SMT), we need to find an additional set of nodes that are not sources and inserted into the SMT in order to achieve the shortest connectivity. In graph theory, this set is called "Steiner points. Therefore, one of the above heuristics also tries to find these Steiner points. However, since these Steiner points depend on the locations of sources, we need to find the optimal set of Steiner points after we know the exact locations of sources. Instead of solving the SMT problem of which optimal solutions are different to each other based on given set of sources, we address it with the minimum dominating set (MDS) problem of which optimal solution is not changed irrespective of given set of sources. Assuming perfect correlation among all data, it is well known that the early aggregation around sources is to reduce redundant data in tree structures. And, we can utilize the above heuristic using the MDS approach. Each node in MDS can work as a Steiner point if it has any neighbouring sources around it.

After a query flooding constructs the core structure, data aggregation can use the core to find the set of Steiner points which aggregate data from neighboring sources. Then the data at some core nodes can be forwarded to its upstream core locating at inside core band since the core structure has the shortest path information toward a sink. Eventually, all data from core nodes will reach a sink through the shortest path that was constructed while a query was flooded. Although there is a gap between the optimal solution of the Steiner minimum tree and the approximated solution using the minimum dominating set, the proposed MDS approach can obtain a promising result compared to other approximations that assume centralized coordination and high computational complexity.

The following are the key goals that the design of proposed data aggregation strategy is based on following:

Perfect Correlation: Since our focus is on the aggregation problem, assuming all data from sensors are perfectly correlated, the amount of aggregated data is equal to the amount of original data before aggregation.

Efficiency: Since the energy conservation is the critical issue in WSNs, the goal of design is to minimize the energy consumption at data aggregation. To minimize the energy consumption, it is better to reduce redundancy among data while data are delivered. Therefore, the proposed scheme will aggregate correlated data as soon as and as much as possible to reduce redundancy.

Scalability: In general, WSNs might have more than tens of thousands sensors. The proposed scheme should be operated efficiently with reasonable amount of overhead linearly increasing to the scale of WSNs.

Decentralization: Since using global information in a distributed environment such as a sensor network can incur high overheads, the proposed scheme should use purely local information in its approach. Then it will be operated in a decentralized fashion over large scale of WSNs.

Loose Synchronization: To minimize the cost of aggregation, most of theoretical solutions use tree structures, e.g., the shortest path tree, the minimum spanning tree and the Steiner

minimum tree. Although these tree structures reduce the redundancy among data, they also requires synchronization among nodes that transmit, aggregate or forward data. However, since the synchronization is also one of hard problems in WSNs, the proposed scheme will relax the degree of synchronization so that it can be operated without assumption of other synchronization algorithms.

Mobility and Node Failures: The dynamic change of network topology due to mobility and node failures makes aggregation schemes in WSNs inefficient and even more out of service. Therefore, the proposed scheme will address this problem by constructing an aggregation structure, dynamically and instantaneously.

4.1 Core Construction

Same core construction mechanism is used as presented in section 3. Based on this core structure, a node in a network should be one of core nodes, non-core nodes, or leaf nodes.

A core node is a node at a core band of which band-id2is 3i. Two core nodes in the same core band should have at least two-hop distance between each other to reduce the total number of core nodes. A core node also keeps the information of a precedent in the shortest path tree root at a sink, so that the core at 3i band can transmit the data to another core node at inner core 3(i-1) band, eventually.
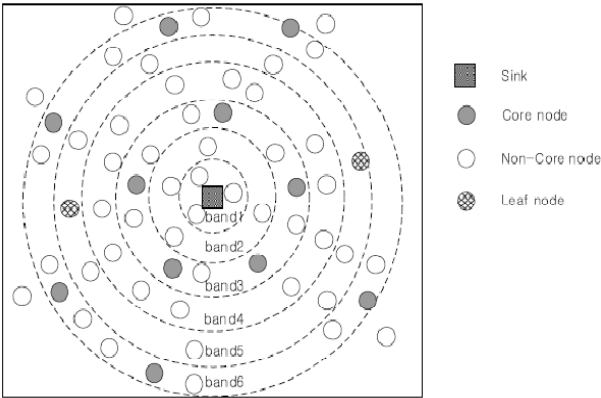

Fig. 8. Instantaneous Core Construction in Up-Stream Data Delivery Scheme

All nodes at non-core bands 3i+1 or 3i-1 should be a non-core node. And some nodes at core band 3i might become a non-core node based on the core construction procedure. All non-core nodes should access two nodes: its core node at 3i band and its precedent in the SPT, of which band-id is less than its band-id. Some non-core nodes at 3i+1 or 3i-1 band cannot have a neighboring core node at 3i band. In this case, they can still access a core node at 3i band through its neighboring non-core node at 3i band indirectly. For exceptional cases, some non-core nodes of which band-id is 3i+2 cannot have any neighboring nodes located at core band 3i+3. These non-core nodes declare themselves as a leaf node. Then they always transmit data to a precedent that is a non-core node at inner band 3i+1. Figure 8 shows the instant result for core construction by disseminating a query through a network.

4.2. Two Stages of Data Aggregation

Stage 1: Original Data Transmission
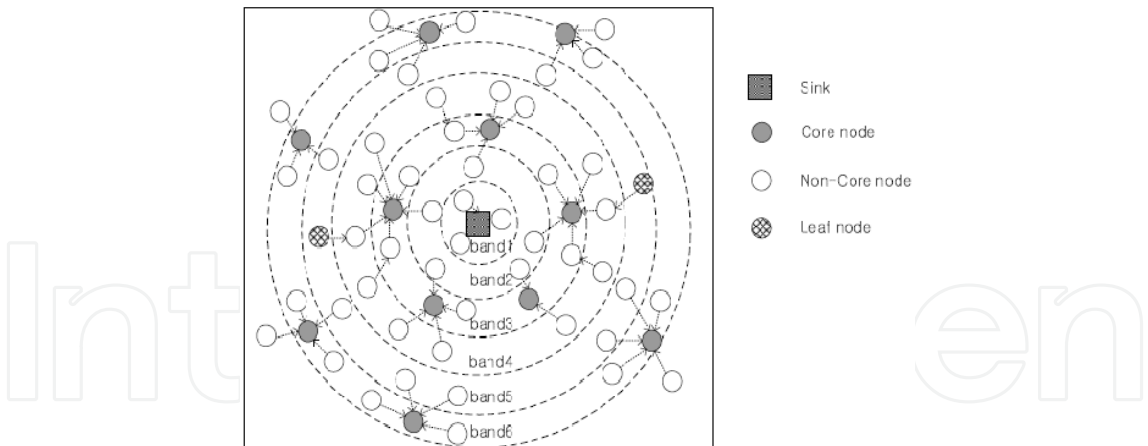We assume that all nodes know the start time of data transmission for each query.

Fig. 9. Stage 1: Original Data Transmission

If a non-core node at 3i-1 or 3i+1 band is a source node, it will transmit data to its core at core bands after some delay. If the receiving node at core band 3i does not declare itself as a core node, it will forward the data to its core node at the same core band 3i. We use a contention-free medium access control scheme to coordinate all non-core sources around a core node based on the number of non-core nodes around the core node. In Figure 9, all non-core nodes, white circles, send data to core nodes, gray circles. Between different groups around each core node, we don't need to consider scheduling because they are separated with each other at least two-hop distance.

If a leaf node at 3i+2 band is a source node, it will transmit data immediately to its neighbouring non-core node at 3i+1 bands so that the neighbouring non-core node can receive the data successfully before it sends its own data. In Figure 9, leaf nodes at band 5, checked circles, send data to transmit data successfully to a non-core node within that delay.
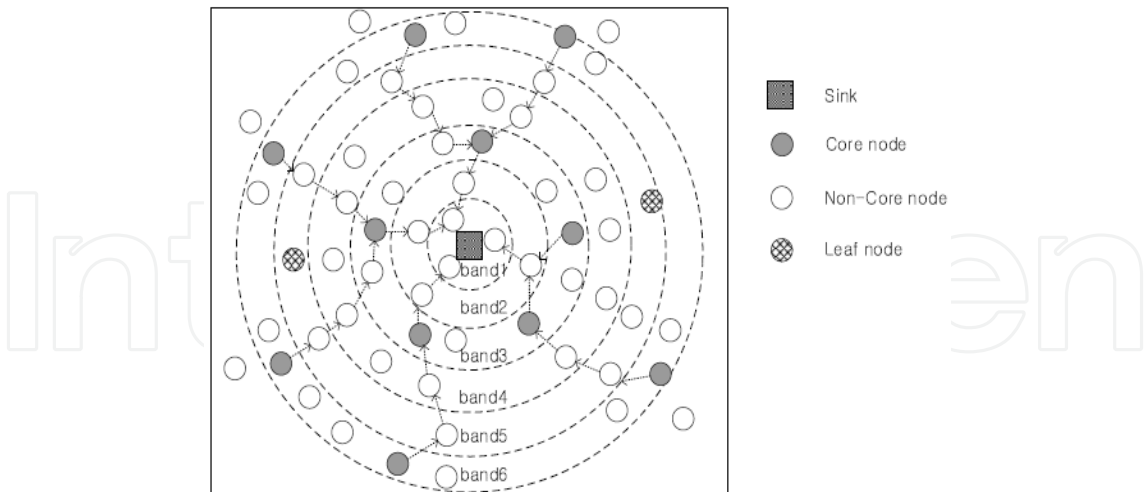

Fig. 10. Stage 2: Aggregated Data Transmission

If a core node at core bands is not a source node, it does not need to transmit data unless it receives any data from its non-core nodes or core nodes at outer core band. Although the core node has data to send, it will wait for some time. so that it can wait and aggregate its own data with incoming data from other core nodes that are located at outer bands.

Stage 2: Aggregated Data Transmission

After stage 1, we assume that all data from non-core nodes are received by core nodes and aggregated with other data. The remaining procedure is to deliver the aggregated data to a sink. To deliver these aggregated data, this scheme uses the shortest path tree that was constructed during the corresponding query flooding. Figure 10 shows delivery paths between core nodes at different core bands. Compared to the original shortest path tree, the paths have some differences. Instead of reaching a sink directly using the SPT, it is better to reach another core node at inner band since it can reduce redundancy among other aggregated data. Whenever a non-core node at core bands receives aggregated data from other core nodes at outer bands, it will forward them to its core node at the same core band.

5. Peformance Analysis and Discussion

This section is focussed on a formal analysis and performance evaluation of the protocol design proposed in this chapter.

5.1. Downstream Data Delivery

For easy reference we call our downstream data delivery scheme GARUDA. The NS2 simulator is used for all evaluations. For all experiments: (a) the rst 100 nodes are placed in a grid fashion within a 650m x 650m square area to ensure connectivity, while the remaining nodes are randomly deployed within that area, and the sink node is located at the centre of one of the edges of the square; (b) transmission range of each node is 65m ; (c) channel capacity is 1 Mbps; and (d) each message consists of 100 packets (except for the single packet delivery part); and the size of packet is 1 KB. CSMA/CA is used as the MAC protocol. We use basic flooding as the routing protocol. All the simulation results are shown after averaging the metrics over 20 randomly generated topologies and calculating 95% confidence intervals. We choose a fixed packet loss rate of 5% for wireless channel error, and vary the number of nodes in the network, which in turn increases the degree of contention in the network.

5.1.1 Latency

The latency involved in receiving a single packet reliably and multiple packet delivery with increasing number of sensors is presented in Figure 11(a) and (b) respectively for both the proposed framework and the ACK based scheme. The latency of the proposed scheme was significantly smaller because of the two radio approach, which used an implicit NACK scheme. This means that there was no explicit NACK sent to the sender of a packet if a packet was not received, thus not increasing the load in the network. Although, our core construction scheme used out-of-sequence delivery, we piggybacked the A-map of the core node along with the transmission of each packet which allows the non-core nodes to wait for the core to recover from all loses prior to any retransmission requests thus eliminating the NACK implosion problem.
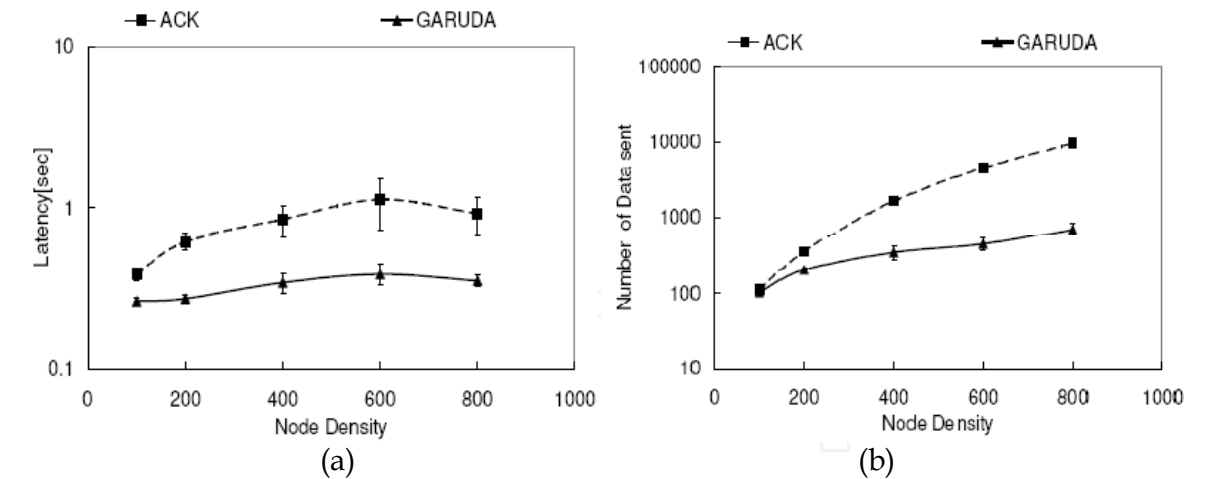
Fig. 11. Latency Comparison between proposed Down Stream Data Delivery Scheme and Basic ACK Scheme for (a) First/Single Packet Delivery and (b) Multiple Packets Delivery
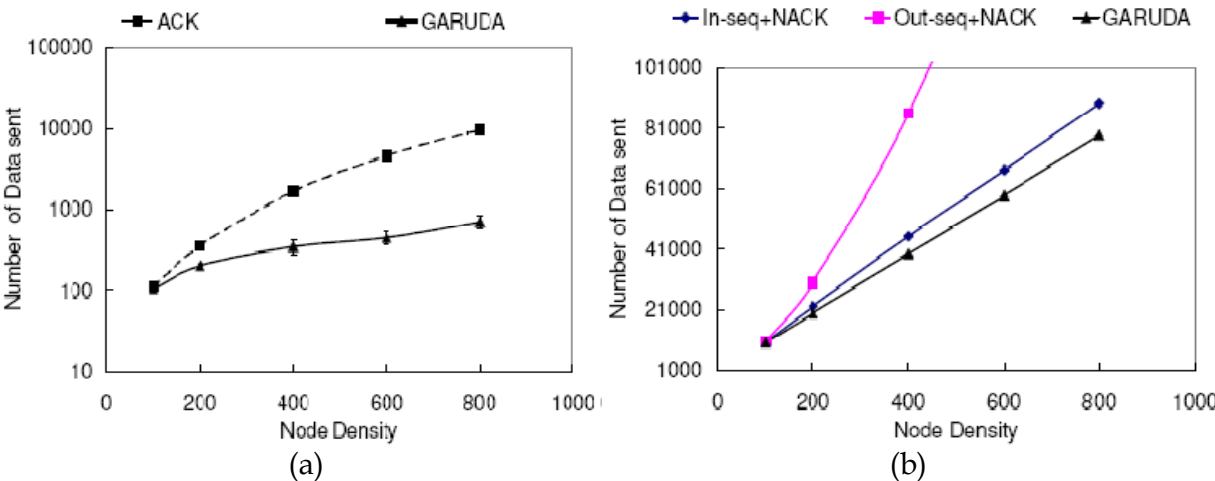
5.1.2 Number of Data Packet Sent

Fig. 12. Number of Data Packets Sent among among the proposed approach and (a) Basic ACK Scheme for First/Single Packet Delivery (b) Alternatives for Multiple Packets Delivery

Figure 12(a) shows the number of data sent by the proposed framework and the ACK based scheme. It is interesting to note that in our proposed framework, the number of data sent increased more or less linearly (with a slope of 1 approximately) as the number of nodes increased. The implicit NACK scheme coupled with the inherent redundancy involved in the flooding process itself is the main reason for this trend. The implicit NACK scheme alleviates congestion related losses, while the inherent redundancy and the broadcast nature of the flooding process ensures that the packet is received successfully without any need for retransmission even in the presence of losses. For the ACK based scheme, the number of data packets sent was appreciably higher and showed a nonlinear increasing trend with increasing number of nodes in the network. This is again because of the increased load in the network due to the presence of ACK transmissions thus increasing the losses in the network. We observe in the case of multiple packet delivery (Figure 12(b)), that the proposed scheme outperforms alternative schemes.

5.1.3 Energy Efficiency

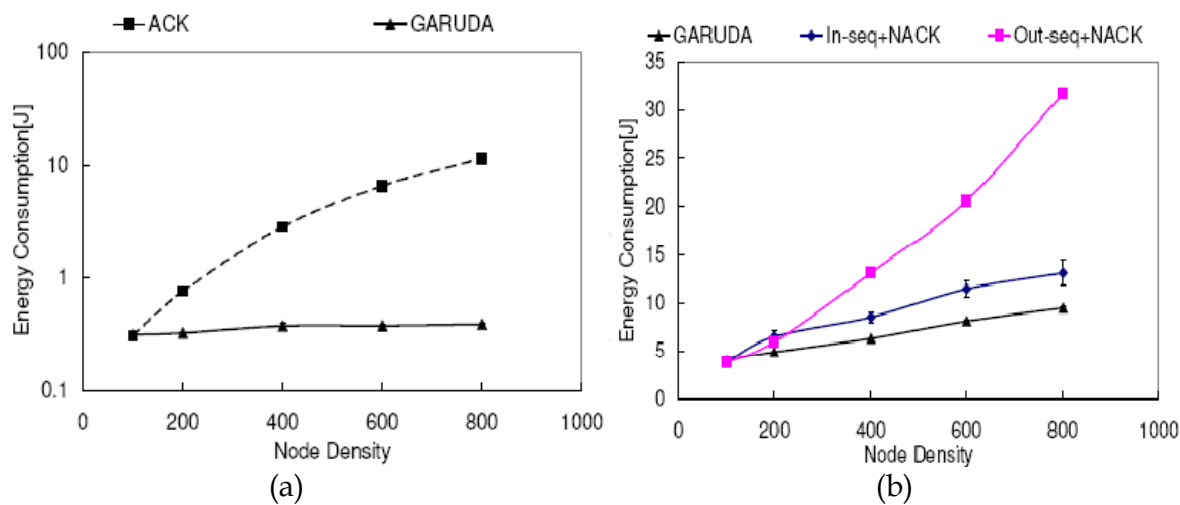(a)   (b)

Fig. 13. Energy Consumption per node Comparison between proposed Down Stream Data Delivery Scheme and Basic ACK Scheme for (a) First/Single Packet Delivery and (b) Multiple Packets Delivery

Figure 13 shows energy consumption per node comparison between proposed scheme and other alternative schemes. The average energy consumed per node is significantly smaller for the our case when compared to the other two cases (Figure 13(b)). The average energy consumed for all three cases was directly proportional to the number of transmissions, which was the sum of the number of requests sent and the number of data sent per node. Hence, the reduction in energy consumption follows.

5.2 Up Stream Energy Efficient Data Delivery
Likewise, we refer GARUDA-UP in the graphs for easy reference in this section for upstream data delivery scheme proposed in this chapter. We assume a typical one-shot query-response model in sensor networks. In this model, a sink broadcasts a query to the entire network and sensors that have corresponding information will reply with one message.

In terms of message size, we assume that every source sends one message of the same size, but the specific length of the message does not matter. We use a discrete event simulator for all evaluations. The simulation topologies are largely similar to that used in general sensor networks: 2000 to 8000 nodes uniformly distributed within a circular field of radius 400m. The number of sources that generate messages for one specific query varies from 1/10 to 1/4 of the total number of nodes in the network. We compare GARUDA-UP with SPT since most of the current routing protocols in the context of WSNs such as Directed Diffusion and GPSR try to approximate the message complexity of SPT. We are interested in how GARUDA-UP performs better compared to the centralized algorithm. We also compare it with MST, which represents the optimal solution in the target environment. Ideally, we should have compared it with the Steiner minimum tree. But as we mentioned before, the computation overhead is very high, especially since we are considering thousands of nodes, and the time it takes to generate even one sample is prohibitive. For this reason, we use MST to approximate Steiner Tree performance which has the same message complexity order,

that of Steiner minimum tree, but a much less computation cost. We generate SPT with Dijkstra's algorithm and MST with Prim's algorithm. We evaluate the GARUDA-UP approach using message complexity that is equal to the total cost of data aggregation. For message complexity, we measure the total number of transmissions required for all responses to reach the sink. To focus on the comparison of aggregation efficiency of different structures, we assume a perfect MAC layer that avoids collisions for all approaches. All the simulation results are derived after averaging results over 10 random seeds and are presented within 95% confidence intervals.

5.2.1 Node Densities

From Figure 14(a) and (b), we observe that proposed scheme outperforms the SPT scheme under all situations. Therefore, from the simulation results, we can say that GARUDA-UP is a good decentralized approximation to the MST. We can also see that the cost of the SPT increases faster than that of the proposed approach as the number of nodes increases. This is expected since more number of nodes reduces the efficiency of aggregation in the SPT as the paths chosen by different sources are less likely to overlap.
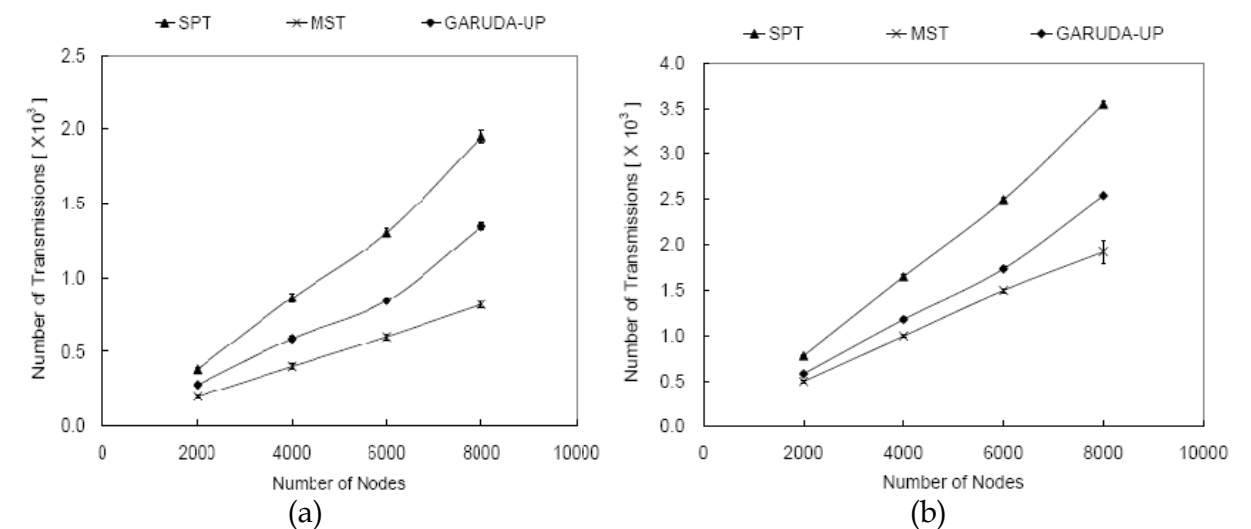

Fig. 14. Performance Comparison among SPT, MST, and Proposed Upstream scheme for Varying Number of Nodes and Fixing the Ratio of Number of Nodes to that of Sources to (a) 10 and (b) 4

Therefore, the proposed approach can be considered as a more scalable decentralized approach as the number of nodes increases. Furthermore, it is observed that the difference between two schemes increases as the ratio of the number of sources to the number of nodes, decreases because more number of sources increase the probability of aggregation for the SPT.

5.2.2. Role of Redundancy

We outline that upstream design is very much dependent on spatial distribution of sensor nodes in a plane. It is interesting to know with what probability we can find sensor nodes in the neighbourhood that support this kind of scheme. To illustrate this, we take an isotropic

Gaussian case and show how probability of detection of redundancy varies with distance. We integrate equation 6 over the region of the area $4\pi r_s^2$. We get the following equation:

$$p(X_{AB} < 2r_s) = 1 - e^{-(\mu+v)\pi r_s^2}\left(\lambda + v\frac{\frac{1}{4}\sqrt{\frac{\pi}{a}} - \sqrt{\frac{1}{4a}}\mathrm{erf}(2ar_s)}{\lambda+v}\right) \tag{7}$$

where,

$$a = \frac{1}{2(\sigma_1{}^2 + \sigma_2{}^2)}$$

and erf(x) is error function for each element of x.

Event type AB is related to the event that A and B both occur i.e., the event type AB. Hence, we are interested in the variation of $\mathrm{pr}(X_{AB} < r)$ with radial distance r. In figure 4, we show the probability variation for three values. As we can see, when it is very low (0.001), the $\mathrm{pr}(X_{AB} < r)$ is low and as we increase the value of the probability, its value increases. Those values play an important role in nearest neighbour probability. For a densely distributed sensor network, value is large and hence results into more redundant data collected by neighbourhood nodes.
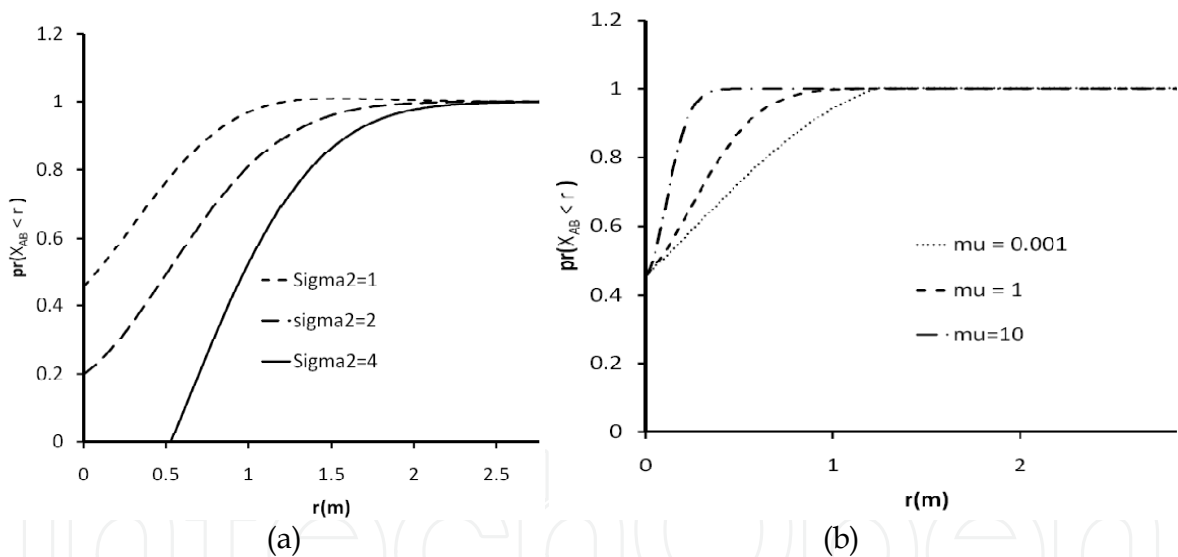

Fig. 15. Near Neighbour probability Variation with relative distance r for (a) different σ_2(Sigma2) values for $\lambda = 0{:}1$, $\mu v = 0{:}1$, $v= 0.1$ and $= \sigma_1$ and (b) different v (mu) values for σ_2 =1 values for $\lambda = 0.1$, $\mu = 0.1$, $v= 0.1$ and $\sigma_1= 1$

Figure 15(b) shows the variation of $\mathrm{pr}(X_{AB} < r)$ with distance r for different variance values. As the value of variance increases, we expect less redundancy in the data values as shown in the figure. The figure demonstrates that variance is one critical design parameter. In both figures (15(a) and (b)), we see as distance increases, probability to find a nearest neighbour point increases and converge to 1. However, not necessarily they all satisfy the condition of redundancy. Only those sensors first the condition of redundancy that are separated by not more than sum of their sensing ranges. There are different sensing ranges for different sensor networks and under the given distribution, we can easily calculate the probability of

two sensors overlapping each other's sensing ranges. We show the figures for only 3m range as after that the probability converge to 1 (however it may not be true for all the distributions) and remain constant for larger values of radial distance. Hence, the upstream protocol gives better results if nodes are closely located and can exploit the redundancy.

6. Conclusion

Dense deployment of sensor network results in better operation using collaborative nature of wireless sensor networks. This collaboration results in redundant data which proved as a unique characteristic of a typical sensor network. In this chapter, we introduced a redundancy model. In this model, we observed that redundant data occurs when the nearby sensor devices are separated by not more than twice their sensing radius. It is seen that when condition of redundancy meets near neighbour distribution, which is a very important factor which gives the degree of overlap among sensors in the near neighbour distribution. We proposed the reliable downstream data delivery. Reliable data delivery problem is formulated theoretically using the minimum set cover problem and transformed it to the minimum dominating set (MDS) problem for a practical and feasible standpoint. Proposed framework consist of (i) the core to approximate the MDS; (ii) WFP pulses to tackle a new challenge, lost-all-packet problem; (iii) two-stage recovery to reduce possibility of collision as well as utilize the broadcast nature of wireless networks; and (iv) A-map to prevent error propagation. Performance of this scheme is evaluated with other previous schemes; and showed that it outperforms other schemes in terms of latency and the number of retransmissions and per node energy efficiency.

Upstream energy efficient framework is formulated for the perfectly correlated data aggregation problem by using the Steiner minimum tree (SMT) and showed the upper bound for message complexity. We also compare the performance of this approach with the SPT and the minimum spanning tree (MST) through simulations and showed that it outperforms the SPT and closely approaches the SMT with less computational complexity and without global coordination. We believe in addition to the shortest path tree and the minimum dominating set, one can also exploit the characteristics of the minimum spanning tree or minimum set cover with small amount of overhead and distributed coordination.

The other way is to find an optimal solution for the upstream data aggregation problem assuming a correlation factor between 0 and 1; and then design an approximation solution for the general aggregation problem in a decentralized fashion so that one can implement it over wireless sensor networks. We also discuss the role of near neighbour distribution in design of such schemes.

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