Data Aggregation Techinques in Sensor Networks

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Abstract

Advancement in computing technology has led to the production of wireless sensors capable of observing and reporting various real world phenomena in a time sensitive manner. However such systems suffer from bandwidth, energy and throughput constraints which limit the amount of information transfered from end-to-end. Data aggregation is a known technique addressed to alleviate these problems but are limited due to their lack of adaptation to dynamic network topologies and unpredictable traffic patterns. In this project, we propose three novel data aggregation schemes; in-network data aggregation, grid-based data aggregation and hybrid data aggregation, which increases throughput, decreases congestion and saves energy. Our simulation results show that the end-to-end transmission delay is reduced by a factor of 2.3, the throughput increases by a factor of 2.4 under heavy load conditions and the energy dissipated is reduced by a factor of 2.2. We conclude our evaluation by proposing an hybrid aggregation scheme through which sensor nodes can dynamically change from one aggregation technique to the other in an unpredictable environment and adapt to dynamic changes in the network.

Keywords: Sensor Networks, AODV, Data Aggregation

1 Introduction

The phenomenal growth in distributed wireless commmunuication technology has led a novel paradigm known as sensor networks. They have been proposed for use in various applications including military and civilian applications. Many dynamically changing scenarios such as battlefield, commercial inventory must be monitored using adaptive methods that utilize critical, real-time information gathered from integrated low-powered sensors. With large number of sensor devices being quickly and flexibly deployed in these networks, each sensor device must be autonomous and capable of organizing itself in the overall community of sensors to perform coordinated activities with global objectives. The sensors are programmed to listen for events. When an event occurs, the sensors inform the end-point by generating wireless traffic. As the number of nodes in the sensor network increases the probability of congestion near events increases. This localized congestion leads to sub-optimal routing performance. Additionally, lot of packets get dropped and the overall response time increases. Further, sensors around the event spend considerable amount of energy to transmit packets which finally do not reach the end point.

Data aggregation is a technique which tries to alleviate the localized congestion problem. It attempts to collect useful information from the sensors surrounding the event. It then transmits only the useful information to the end point thereby reducing congestion and its associated problems. We propose three data aggregation techniques: In-Network, Grid-based and Hybrid schemes to perform data aggregation. The In-Network scheme attempts to identify the sensor which has the most useful information and assigns that sensor as the data aggregator to send packets to the end point. Grid-based scheme has the notion of pre-defined data aggregators in fixed regions of the sensor network region. Sensors surrounding the event send information to the aggregator which eventually sends only the most useful information to the end point. The mobility of events affects the performance of in-network and grid-based schemes. We come up with the Hybrid scheme which tries to combine the salient features from both the In-Network and Grid-based schemes when we consider the mobility of the event. We have carried out a performance analysis of the three schemes with best and worst aggregation scenarios. Our analysis reveals that overall response time increases by a factor of 2.3 for In-Network scheme as compared to the case without any data aggregation. Additionally, the throughput observed increases by a factor of 2.4 in the case of In-Network scheme. Further, the energy dissipated is reduced by a factor of 2.2 in the Grid-based scheme. However, mobility of the events affects the performance of the Grid-based scheme becomes 4 times better than the In-Network scheme.

The remaining part of the paper is organized as follows: In Section 2 we give a brief background of a typical sensor network environment. Section 3 deals with the design of the two aggregation techniques, In-Network data aggregation and Grid-Based data aggregation. The Hybrid scheme which takes advantage of the other two schemes is dealt in section 4. Section 5 describes the experiments performed and results obtained.

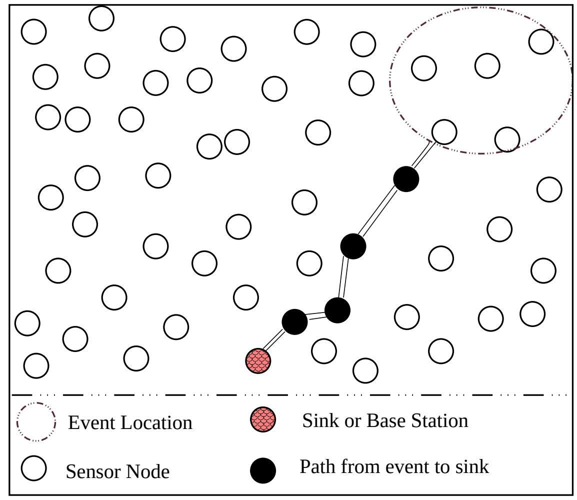

Figure 1. A Typical Sensor Network Environment

2 Background

In this section we briefly describe the relevant background details regarding Sensor Networks.

2.1 Sensor Network Environment

A sensor network consists of large number of sensors deployed in a region for the purpose of event monitoring or detection. The sensors are pre-programmed to listen for specific events. For example, a sensor network deployed in a high security region might be programmed to detect infrared heat signals to indicate an intruder. Figure 1 shows a typical sensor network deployment.

Each node in a sensor network is responsible for observing and reporting various dynamic properties of their surroundings in a time critical manner. These mobile and miniaturized information devices are equipped with embedded processors, wireless communication circuitry, information storage capability, smart sensors and actuators. These sensor nodes networked in an adhoc way, with little or no fixed network support, to provide the surveillance and targeting information for dynamic control. Sensor devices are mobile, subject to failure, deployed spontaneously and repositioned for more accurate surveillance. Despite these dynamic changes in configuration of the sensor network, critical real-time information must still be disseminated dynamically from mobil sensor data sources through the self-organizing network infrastructure to the components that control dynamic re-planning and re-optimization of the theatre of operation based on newly available information.

With large number of sensor devices being quickly and flexibly deployed in most impromptu networks, eacch sensor device must be autonomous and capable of organizing itself in the overall community of sensors to perform coordinated activities with global objectives. When spontaneously placed together in an environment, these sensor nodes should immediately know about the capabilities and functions of other sensor noedes and work together as a community system to perform co-operative tasks and networking functionalities. Sensor networks need to be self-organizing since they are often formed spontaneously from large number of mixed types of nodes and may undergo frequent configuration changes. Some sensor nodes may provide networking and system services and resources to other sensor nodes. Others may detect the presence of these nodes and request services from them.

The characteristics of sensor nodes necessary for creating self-organizing sensor networks are agility, self-awareness, self-configurability and autonomy. Sensor nodes with these features will have capabilities for self-assembling impromptu networks that are incrementally extensible and dynamically adaptable to device failure and degradation, mobility of sensor nodes, and changes in task and network requirements. Nodes are aware of their own capabilities and those of other nodes around them which may provide the networking and system services or resources that they need. Although nodes are autonomous, they may cooperate with one another to disseminate information or assist each other in adapting to changes in the network configuration. An impromptu community of these nodes may cooperate to provide continual coordinated services while some nodes may be newly deployed or removed from the spontaneous community.

Nodes will act in response to environmental events and relay collected and possibly aggregated information through the multi-hop wireless network in accordance with desired system functionality. The inherently dynamic and distributed behavior of these networks, coupled with inherent physical limitations such as small instruction and data memory, constrained energy resources, short communication radii, and a low bandwidth medium in which to communicate, make developing communication protocols difficult. Using these sensors as a basis for development, the software architecture and communication stack residing on these devices are built taking into consideration the prolific research in the areas of ad-hoc networking, data aggregation , cluster formation, distributed services, group formation, channel contention , and power conservation. An event is an abstraction, identifying anything from a set of sensor readings, to the nodes processing capabilities. For the purpose of the simulation studies in this project, events are assumed to be localized phenomenon, occurring in a fixed region of space. This assumption will hold for a wide variety of sensor-net applications, since many external events are localized themselves.

2.2 Mobile Ad-Hoc Routing

The sensors in the sensor network communicate to the end-point or amongst themselves using wireless Ad-Hoc routing protocols. In our implementation of the sensor network as a simulation in NS-2 [1] we used Ad hoc On Demand Distance Vector (AODV) routing algorithm [11], [12], [2]. The Ad hoc On Demand Distance Vector (AODV) routing algorithm is a routing protocol designed for ad hoc mobile networks. AODV is capable of both unicast and multicast routing. It is an on demand algorithm, meaning that it builds routes between nodes only as desired by source nodes. It maintains these routes as long as they are needed by the sources. Additionally, AODV forms trees which connect multicast group members. The trees are composed of the group members and the nodes needed to connect the members. AODV uses sequence numbers to ensure the freshness of routes. It is loop-free, self-starting, and scales to large numbers of mobile nodes.

AODV builds routes using a route request / route reply query cycle. When a source node desires a route to a destination for which it does not already have a route, it broadcasts a route request (RREQ) packet across the network. Nodes receiving this packet update their information for the source node and set up backwards pointers to the source node in the route tables. In addition to the source node's IP address, current sequence number, and broadcast ID, the RREQ also contains the most recent sequence number for the destination of which the source node is aware. A node receiving the RREQ may send a route reply (RREP) if it is either the destination or if it has a route to the destination with corresponding sequence number greater than or equal to that contained in the RREQ. If this is the case, it unicasts a RREP back to the source. Otherwise, it rebroadcasts the RREQ. Nodes keep track of the RREQ's source IP address and broadcast ID. If they receive a RREQ which they have already processed, they discard the RREQ and do not forward it.

As the RREP propagates back to the source, nodes set up forward pointers to the destination. Once the source node receives the RREP, it may begin to forward data packets to the destination. If the source later receives a RREP containing a greater sequence number or contains the same sequence number with a smaller hopcount, it may update its routing information for that destination and begin using the better route.

As long as the route remains active, it will continue to be maintained. A route is considered active as long as there are data packets periodically travelling from the source to the destination along that path. Once the source stops sending data packets, the links will time out and eventually be deleted from the intermediate node routing tables. If a link break occurs while the route is active, the node upstream of the break propagates a route error (RERR) message to the source node to inform it of the now unreachable destination(s). After receiving the RERR, if the source node still desires the route, it can reinitiate route discovery.

3 Detailed Design

In this section the best and worst aggregation scenarios are discussed in detail. Two data aggregation schemes, In-Network and Grid-based scheme are proposed and compared with the existing schemes.

3.1 No Data Aggregation

In *No Data Aggregation* scheme, sensor devices are unaware of other neighbouring nodes. Each sensor upon detecting an event attempts to send the amount of information collected, however small it may be, to the end nodes (sink). Sensor devices do not apply any data aggregation technique and simply forward the data packets toward the sink node. As we can can clearly see, such a scheme suffers from high packet dropping rate and low bandwidth due to congestion in the network. Additionally, it also suffers from energy limitations as each device attempts to send packets received from multiple destinations irrespective of the importance of the data being transmitted. Furthermore, the total amount of information received at the sink nodes would be less due to several packets getting dropped. However such schemes may become useful under scenarios like battlefield or military surveillance where events may move at a very fast rate.

3.2 Perfect Data Aggregation

In this hypothetical scenario, each sensor device is assumed to know the best data aggregator. In other words, the sensor device which would send the most critical information about a particular event is predecided. Such an environment is highly desirable since the sink nodes get the most critical, complete information about the events and such a scheme results in high bandwidth, improved response time and adheres to the energy constraints. However, in an environment which is highly dynamic in nature and with unpredictable traffic patterns achieving such an environment is almost impossible.

3.3 In-Network Data Aggregation

This scheme is highly suitable for environments where events have localized phenomenon, occuring in a fixed region of space. Such environments will hold for a wide variety of sensor network applications, since many external events are localized themselves. In this scheme, the sensor network environment is divided into pre-defined set of grids or regions. Each region or grid is responsible for observing and reporting events that occur inside the region to the sink nodes. Also each sensor device inside the region sends data to other sensor devices only inside the region. Only one sensor, the data aggregator, sends the critical information received either from other sensor devices or by itself to the sink nodes.

A typical in-network data aggregation scheme is shown in Figure 2. As we see in the figure, all sensor devices inside the region detect the event. The corresponding signal strengths detected by each sensors are shown in the figure. Now each sensor transmits its signal strength only to its neighbours. If the neighbour has a strength more than the sender, the sender decides to remain silent and stops transmitting packets. Otherwise, it waits for packets from other sensors and after receiving packets from all its neighbours, if the sender has the highest signal strength, it will then become the data aggregator and all other sensor devices stop detecting the event and helps only in routing the packet to the sink nodes.

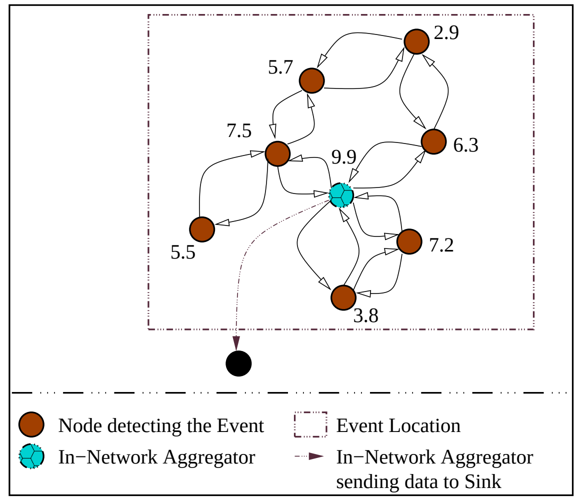

Figure 2. An In-Network Data Aggregation Scheme

3.4 Grid-based Data Aggregation

Grid-based Data Aggregation is highly suitable for mobile environments where the time duration of an event at a particular place is very small. Such scenarios will hold for a variety of sensor network applications like military surveillance, weather forecasting, etc. As seen in the previous scheme, the sensor network environment is divided into pre-defined set of grids or regions. Each region or grid is responsible for observing and reporting events that occur inside the region to the sink nodes. In addition, one sensor device based on geographical position with respect to either the sink or the center of the grid is chosen as data aggregator. All other sensors inside the gird are aware of this information. During event detection, all other sensors are supposed to send the event information to this data aggregator. The data aggregator after collecting data from other sensors sends only the critical information to the sink node.

A typical Grid-based data aggregation scheme is shown in Figure 3. As seen in the figure, during event detection, all sensors send data to the aggregator. After collecting all data from other sensors, the aggregator sends only the critical information to the sink nodes.

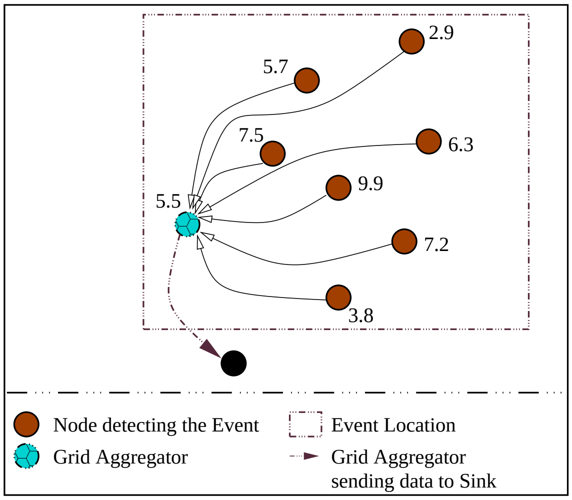

Figure 3. A Grid-based Data Aggregation Scheme

Grid-based data aggregation adapts well to dynamic changes in the network topology and event mobility. If the event is highly mobile in nature, we see that many packets are exchanged between the sensors inside the grid. But, once the packets reach the aggregator, we see that only the most important information is sent to the sink nodes. Thus, Grid-based scheme reduces the traffic in such environments and makes sure the critical information is transmitted to the end nodes interested in the data. It also increases the throughput in such environments. However Grid-based scheme performs worse in environments where events are highly localized and mostly immobile in nature. We see that the data packets exchanged between the aggregator and other sensors inside the grid falls in the critical path. This increases the end-to-end response time. Grid-based scheme also increases congestion due to increased number of packets exchanged in the protocol compared to the in-network scheme.

4 Hybrid Model

Generally, the In-Network data aggregation is preferred over grid-based scheme in environments where events are highly localized. Is it to be noted, however, that in many of sensor network applications either of the schemes could be used. The only concern in this case is the performance provided by each of the schemes.

Due the advantages and disadvantages associated with each of the In-Network and Grid-based schemes, a hybrid approach of choosing schemes on the fly based on event duration and event mobility would be highly beneficial. Such an hybrid scheme would take the best of both the approaches. The basic approach of such a scheme is shown in Figure 4.

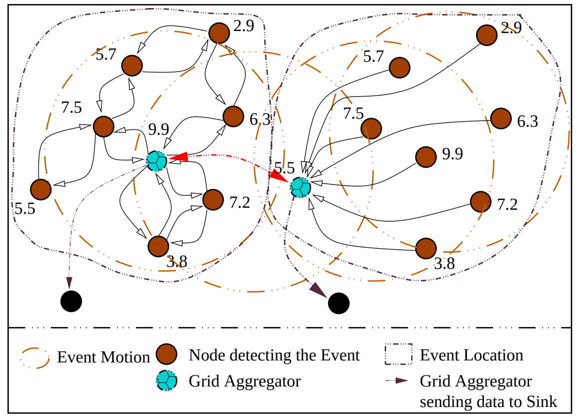

Figure 4. An Hybrid Data Aggregation Scheme

As shown in the figure, every sensor initially is configured based on In-Network scheme. When a sensor detects an event, it first attempts to identify the sensor with the highest signal strength. In other words, the sensor which has the most critical and complete information about the event is identified. This is done the same way as described in the in-network scheme. In addition each sensor also maintains a history of past events and the corresponding signal strengths the sensor detected. During event detection, each sensor checks its table for the previous entry and attempts to identify whether the event is highly mobile in nature or stationary. If it turns out that the event is localized, the in-network scheme is followed and accordingly an aggregator is chosen. On the other hand, if sensor realizes a slow movement in the event, it tries to send the information to the default aggregator (for example, sensor which is close to the center of the grid and the sink node).

5 Experimental Results

In order to compare the different data aggregation schemes discussed in the previous sections, we extended the functionality of the *ns* software package. Using this simulation framework we compared the three data aggregation techniques with the classic flooding (no aggregation) scheme and the ideal (perfect data aggregation) scheme. We found that both In-Network and Grid-based schemes provide higher throughput and improves the overall response time. At the same time both the schemes uses substantially less energy compared the flooding scheme. We also found that the In-Network scheme performs better than the Grid-based scheme in situations where event mobility is a rarity. The analytical model proposed for the hybrid scheme seemed to take the advantages of both the schemes. We found that in all our simulations, the sensors surrounding the event seemed to dissipate more energy than other sensors which creates a weak point in a battery-operated network.

5.1 ns Implementation

ns [1] is an event-driven simulator with extensive support for simulation for TCP, multicast protocols and also routing protocols in sensor networks. *ns* supports different routing protocols; AODV, DSR [6], GPSR [7], Directed Diffusion [5], etc. In this simulation, we fixed the routing protocol as AODV. Also, to implement the In-Network data aggregation scheme, we modified the ns source code to add some features to the *ns* simulator. In particular, we added a *CBR-Broadcast* event for a CBR (Constant Bit Rate) traffic. We made use of this feature while simulating In-Network data aggregation scheme.

5.2 Simulation Testbed

For our experiments, we created a 100-node network shown in Figure. This network, which was randomnly generated was deployed over a 1000 x 1000 grid. The power of the sensor's radio transmitter is such that any node within a 100 meter radius is within the communication range and is called a neighbor of a sensor. The radio speed (2 Mbps) and the power dissipation were set to default values. The processing delay for transmitting a message was chosen to be 5 ms. The size of each data packet was set to 200 bytes and the packet interval was set to 100 ms. Table 1 summarizes these network characteristics.

Using this network configuration, we ran each data aggregation scheme and tracked its progress in terms of rate of data dissemination, energy usage, throughput and average response time to reach the end nodes. The results of these experiments are presented in the following sections.

5.3 Data (Throughput) acquired over time and Loss Rate

Figure 5 shows the throughput achieved by the network over time for each of the data aggregation

Feature	Value
Nodes (Sensors)	100
Grid	1000 x 1000
Radio Speed	2 Mbps
Processing delay	5ms
Data Size	200 bytes
Data interval rate	100ms

Table 1. Characteristics fo the 100 node wireless test network

schemes. As expected, *No Aggregation* scheme achieves very less throughput due to localized congestion. However the other three schemes achieves a considerably higher throughput. Also, it is interesting to note that using the *In-Network* scheme, the system is able to achieve a throughput which is comparable to the *Perfect Aggregation* scheme. This is due to the fact that the *In-Network* scheme has only the startup cost of finding an aggregator and the rest of the protocol remains the same as the *Perfect Aggregation* scheme. Figure 5 also shows that the *Hybrid* scheme performs equally in comparison with the *Perfect Aggregation* scheme.

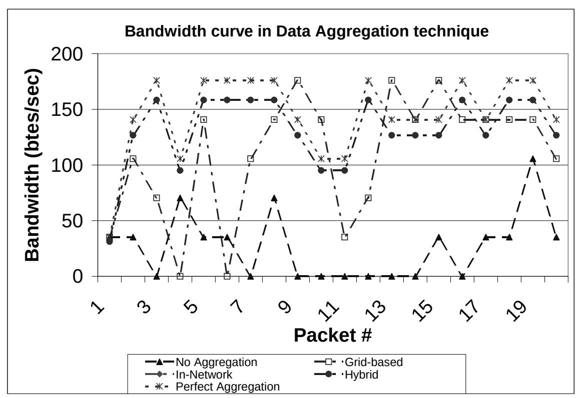

Figure 5. Bandwidth Comparison in Data Aggregation

We also measured the loss rate for each sensor and the results are shown in Figure 6. We see that the loss rate for the *No Aggregation* scheme is very high for some sensors. These are the sensors surrounding the event and the reason for huge packet loss is due to multiple re-transmissions as an effect of collisions in the network. Since there is no data aggregation, all sensors are unaware of its neighbours signal strength and attempt to re-transmit packets in the event of collision. However we see that in the three schemes we proposed, the packet loss is considerably minimal due to data aggregation and reduced congestion.

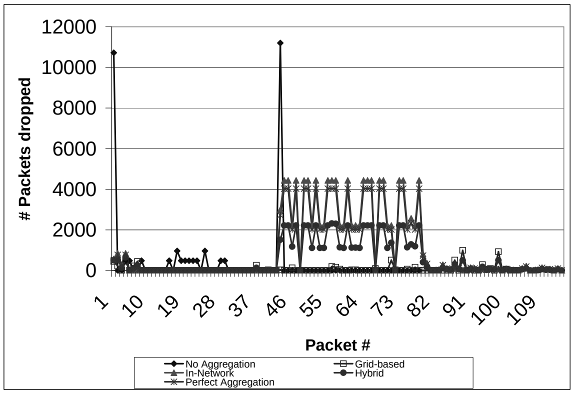

Figure 6. Packet Loss Rate Comparison in Data Aggregation

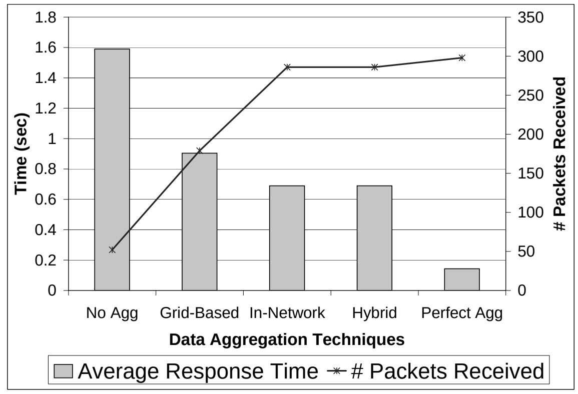

Figure 7. Average Response Time Comparison and Packets Received in Data Aggregation

5.4 Average Response Time at end points

For the previous experiment, we also measured the average latency achieved by each of the data aggregation schemes, as shown in Figure 7. These graphs show that *No Aggregation* scheme performs the worst in terms of average response time seen at the end points. Both *In-Network* and *Grid-based* schemes achieve improved response times under high traffic conditions. Since the *Hybrid* scheme is a variation of these two schemes, we see that the *Hybrid* scheme also achieves good response time.

Another dimension to this figure is the number of packets received at the end points for each of the data aggregation schemes (shown as the secondary axes in the figure). We see that the number of useful packets trasmitted to the end node is very less for the *No Aggregation* scheme. This is due to the collisions that occur in the region surrounding the event and also in the path towards the end point. In *Grid-based* scheme, we see that the number of packets that reach the end node is considerably high compared to *No Aggregation* scheme since there are collisions only in the region surrounding the event. The *In-Network* scheme performs the best transmitting packets which is comparable with the *Perfect Aggregation* scheme.

5.5 Response Time achieved over Time

In order to observe the impact of data aggregation overhead, we measure the individual latencies for all three schemes. The results are reported in Figure 8. In this figure, we see that initially, all three data aggregation schemes perform worse in comparison with *No Aggregation* scheme due to collisions in the network for choosing the data aggregator. However, once the system stabilizes, we see that the latencies observed for the three schemes reduces drastically compared to the *No Aggregation* scheme.

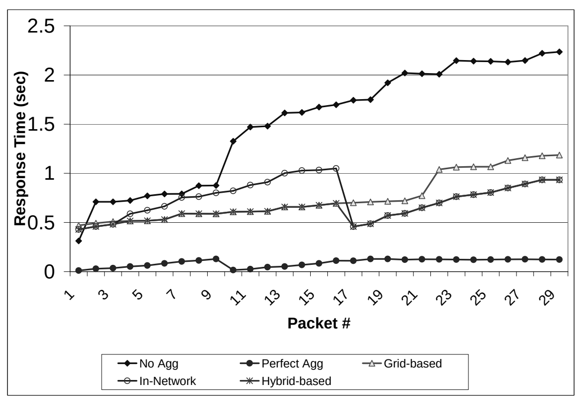

Figure 8. Latency Comparison in Data Aggregation

5.6 Energy Dissipated Over Time

Apart from the throughput and response time, we also measured the energy dissipated by the network as shown in Figure 9. These graphs show that the *No Aggregation* scheme again is the most costly protocol; it requires much more energy than the three data aggregation schemes to accomplish the same task. Figure 9 also show that the *Grid-based* scheme requires a factor of 2.2 less energy compared to the *No Aggregation* scheme. Thus by sacrificing a small, constant overhead in sending data only to the aggregator, *Grid-based* scheme achieves a dramatic reduction in system energy. We see a similar trend in the *In-Network* scheme but the factor of improvement is 2.4, performing better than the *Grid-based* scheme. The *Hybrid* scheme, due to no mobility in the event, is the same as the *In-Network* scheme.

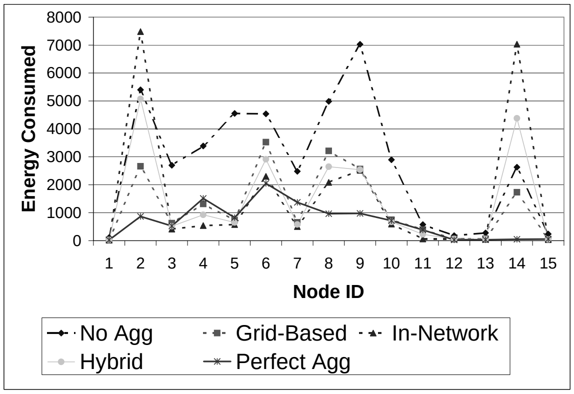

Figure 9. Energy Spent in each of the Data Aggregation techniques

5.7 Performance Estimation for Mobile Events

One of the most important feature of sensor network is tracking mobile events. Since the proposed *Hybrid* scheme chooses the aggregation scheme on the fly, we define a series of terms in order to find the average latency. Let,

Total number of variations in mobility from low to high	$= T$
Average Latency of In-Network	$= l_{In-Network}$
Average Latency of Grid-based	$= l_{Grid}$
Startup overhead of Hybrid switching from one scheme to the other	$= S_{overhead}$
Average Latency of Hybrid scheme	$= l_{Hybrid}$

Since the Hybrid scheme, chooses the aggregation scheme on the fly and adapts to the environment, the overall latency would be the sum of minimum of latencies of both the schemes and the startup overhead associated with switching from one data aggregation scheme to the other. This startup overhead occurs every time the Hybrid scheme changes from one scheme to the other. Hence the overall latency is calculated as given below.

$$l_{Hybrid} = \frac{(min(l_{In-Network}, l_{Grid}) + S_{overhead} * T)}{T}$$

The results of this model are reported in Figure 10. As shown in this figure, we find that *In-Network* scheme performs well when the mobility of the event is low. As mobility increases, the In-Network latency increases exponentially due to more congestion. However, in the *Grid-based* scheme the latency increase is not exponential, thereby scales well with mobility of the event. In case of the *Hybrid* scheme, we see that if the startup overhead of switching from one scheme to the other is less, the *Hybrid* model performs equal in comparison with the *Grid-based* scheme. But if the startup overhead is sufficiently huge, *Hybrid* scheme performs worse compared to all other schemes.

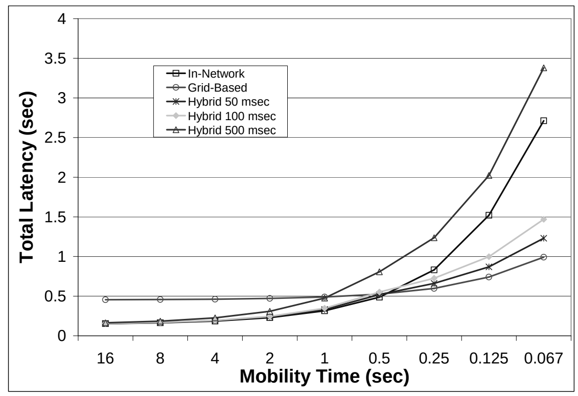

Figure 10. Performance Model for Mobile Events with Data Aggregation

6 Related Work

Event-driven sensor networks has been an active area of research. Various researchers have tried to tackle the challenges arising out of congestion in the event-driven sensor networks. Wan et al, come up with a congestion detection and avoidance model in [13]. Other researchers have tried to address the challenges of Data Aggregation directly. He et al, propose a scheme for application independent data aggregation for sensor networks in [3]. Kulik et al, propose adaptive protocols in sensor networks by negotiation in [9]. Madden et al propose a query based aggregation scheme in [10]. At the same time, various researchers have tried to evaluate the impact of data aggregation. Krishnamachari et al evaluate the impact of data aggregation in low power sensor networks in [8]. Intanagonwiwat et al, investigate the impact of network density on data aggregation in [4].

However, to the best of our knowledge, there hasn't been a direct study of various schemes to design and implement data aggregation as has been done in this work.

7 Concluding Remarks and Future Work

The phenomenal growth in distributed wireless commmunuication technology has led to the production of a wireless sensors which are capable of observing and reporting various real world phenomena in a time sensitive manner. However such systems suffer from bandwidth, energy and throughput constraints which limit the amount of information transfered from end-to-end. Data aggregation is a known technique addressed to alleviate these problems but are limited due to their lack of adaptation to dynamic changes in the network and unpredictable traffic patterns.

In this project, we propose three data aggregation techniques: In-Network (aggregator with high signal strength), Grid-based (pre-defined aggregators) to perform data aggregation. We come up with the Hybrid (adaptive) scheme which tries to combine the features from both these two schemes when we consider the mobility of the event. Our simulation analysis reveals that overall response time increases by a factor of 2.3 for In-Network scheme as compared to the case without any data aggregation. Additionally, the throughput observed increases by a factor of 2.4 in the case of In-Network scheme. Further, the energy dissipated is reduced by a factor of 2.2 in the Grid-based scheme. We conclude our evaluation by proposing an analytical model for hybrid aggregation scheme through which sensor nodes can dynamically change from one aggregation technique to the other in an unpredictable environment and adapt to dynamic changes in the network. In summary, data aggregation hold the promise of achieving high performance at a low cost in terms of complexity, energy, computation and communication.

Although our initial work and results are promising, there is still a great deal of work to be done in this area. Different scenarios for the wireless network with more sparse sensors deployed needs to be tested. The adaptive Hybrid scheme is only proposed but needs to be implemented under various scenarios. We also need to consider the impact of multiple events in data aggregation.

References

[1] The Network Simulator: Ns-2. http://www.isi.edu/nsnam/ns/.

[2] I. D. Chakeres and E. M. Belding-Royer. AODV routing protocol implementation design. In *Proceedings of the International Workshop on Wireless Ad Hoc Networking (WWAN)*, 2004.

[3] T. He, B. M. Blum, J. A. Stankovic, and T. F. Abdelzaher. AIDA: Application independent data aggregation in wireless sensor networks. In *ACM Transactions on Embedded Computing System Special issue on Dynamically Adaptable Embedded Systems*, 2003.

[4] C. Intanagonwiwat, D. Estrin, R. Govindan, and J. Heidemann. Impact of network density on data aggregation in wireless sensor networks. Technical report, University of Southern California, 2001.

[5] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *MobiCom*, 2000.

[6] D. B. Johnson and D. A. Maltz. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*, 1996.

[7] B. Karp and H. T. Kung. GPSR: Greedy perimeter stateless routing for wireless networks. In *MobiCom*, 2000.

[8] B. Krishnamachari, D. Estrin, and S. Wicker. The impact of data aggregation in wireless sensor networks. *IEEE International Workshop on Distributed Event-Based Systems (DEBS)*, pages 575–578, July 2002.

[9] J. Kulik, W. Rabiner, and H. Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *MobiCom*, 1999.

[10] S. R. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong. TAG: a tiny aggregation service for ad-hoc sensor networks. In *OSDI*, 2002.

[11] C. E. Perkins and E. M. Royer. Ad hoc on-demand distance vector routing. In *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, 1999.

[12] E. M. Royer and C. E. Perkins. An implementation study of the AODV routing protocol. In *Proceedings of the IEEE Wireless Communications and Networking Conference*, 2000.

[13] C.-Y. Wan, S. Eisenman, and Andrew Campbell. CODA: Congestion detection and avoidance in sensor networks. In *SenSys 2003*, 2003.