Broadcast Server Architecture for Wireless Sensor Networks

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Abstract - *In the Wireless Sensor Networks Architecture with the existing routing schemes, the downlink communication from Base station to the Sensors is significantly more expensive than that in the uplink direction. In this paper, we propose a new Wireless Sensor Networks Architecture where the Base Station directly communicates to the Sensor Nodes in the downlink direction over the wireless broadcast channels without involving intermediate routing Sensors. This architecture significantly simplifies the downlink communication and helps centralize many energy draining tasks at the resourceful Base Station and communicate results over the wireless broadcast channels. We also qualitatively compare the advantages of the new schemes implemented in this architecture over the existing schemes. This architecture also helps to address several issues which could not be resolved in earlier architectures due to resource deficient sensors.*

Keywords: Wireless Sensor Networks; Broadcast Channels; Routing Schemes.

1 Introduction

In Wireless Sensor Networks, the sensor nodes not only monitors their environment and also do several other functions such as routing, data aggregation, network topology maintenance, etc. The schemes used in the traditional networks for these functions are not optimal and most of the time they are impractical in the resource crunch wireless sensor networks. Hence, several new schemes which work for specific sensor network architectures and scenarios are proposed. They also have several deficiencies and drawbacks. Most important of all of them is the increased cost of downlink communication.

In Wireless Sensor Networks, the cost of downlink communication (from Sink to Sensor Nodes) is significantly higher than that of uplink communication (from Sensor Nodes to Sink). In the uplink communication, since the destination is the Base Station for all the messages, each sensor node needs to store the id of next hop node towards the Sink and accordingly forward all the incoming packets to it. Whereas, in the downlink direction the routing path vary based on the destination node. Unlike in traditional networks, table based routing in the downlink communication is impractical in Wireless Sensor Networks due to the large number of nodes, resource scarce sensor nodes. Usually, the flooding schemes are used. So, it is safe to assume that in wireless sensor networks, the routing for uplink communication is table based and that for downlink communication is flooding. This holds good even after numerous new routing schemes developed for Wireless Sensor Networks.

In order to compare the costs of Uplink and Downlink communication, let us represent WSN as a graph G with N nodes and E edges, with Nodes representing sensor nodes and the Edges representing the connectivity between two sensor nodes. Let us define a cost metric C as the sum of the costs incurred in receiving and transmission of a message at each sensor node. For example, let us say a message is either received and/or forwarded by three nodes. Then the cost C = 3. Figure 1 represents a WSN with S as the Source Node and T as the Destination Node. For a table based routing scheme, each node along the path receives and transmits a message exactly once. For flooding based routing schemes, each node receives the message from all its neighbors, although it transmits only once. For Table based routing case, the C is O(D), where D is diameter of the graph, which may be anywhere between O(logN) to O(N) based on the network topology. For dense wireless sensor networks, the cost is more like O(logN). For flooding based routing, the cost is O(E). Again, for dense wireless sensor networks, the O(E) = O(N2). As the number of sensor nodes increases, the cost of downlink communication becomes significantly higher to the uplink communication.

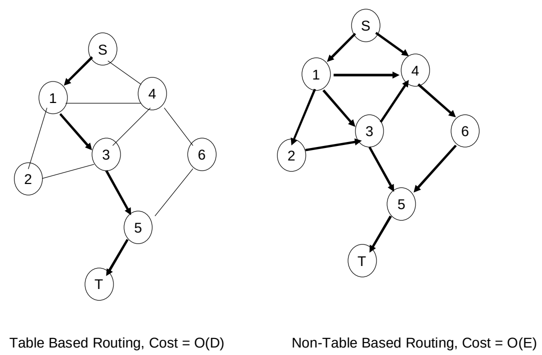

Figure 1 Cost of Table based and Non-Table based Routing

The downlink communication is, although small in the existing wireless sensor networks, not zero. In some of the schemes [10], the base station sends queries to a specific node or a group of nodes, requesting some information. In future, the downlink communication will increase as the Sensor networks become more intelligent and widespread. For example, the sensor nodes must be synchronized with each other and with the Base Station for real-time applications. Similarly, the Base Station communicates to sensor nodes in order to dynamically change their characteristics, for e.g. change the frequency of monitoring.

In this paper we propose an architecture that reduces the cost of downlink communication to O(1). This architecture, called Broadcast Server architecture consists of the Base station directly communicating to all the sensor nodes directly over the broadcast channel. Therefore, cost of the communication is the cost of the accessing the packet by receiving node: O(1). Of course, the uplink communication still uses multi-hop routing by the sensor nodes. More detailed description of the broadcast architecture is given in the next section.

In addition to reducing the cost of downlink communication, this architecture also helps in centralizing many non-monitoring related functions from sensor nodes to the Base Station. This tremendously reduces the energy spent by the sensor nodes for these activities. Some of the advantages are:

- The proposed architecture allows the use of the centralized schemes for various issues in WSN networks. This avoids the implementation of distributed schemes at the Sensor Nodes that drain their resources. In addition, there exist several well studied centralized schemes, which eliminate the need of finding new distributed schemes specific to WSNs.

- Being in their infancy, the deployment issues of the current schemes are not fully understood. In the current architecture, it is difficult to resolve the failures in the field that arise due to software bugs. Patches, which are applied in traditional networks, are difficult to apply here. This proposed architecture efficiently addresses both these issues. First, since the centralized schemes have been well studied, understood and implemented for several decades, they are less prone to software errors. Second, a bulk of the development is done at the Broadcast Server and therefore, it is easy to make corrections and propagate the updates, if any.

- Some network related schemes, such as identification of network partitioning[4], which are known to be very expensive to implement as distributed schemes in WSN, could now be cost effectively implemented in this current architecture.

- Several existing solutions in the current WSN have been developed and implemented independent from each other. This proposed architecture offers a common platform that can be shared by different applications, which makes the development easier.

Along with these advantages, in the proposed architecture, an additional communication overhead is introduced. A Sensor Node continuously or intermittently listens to the Broadcast channels in order to access the relevant data. And, it needs to listen to two wireless channels, one-to-one from neighbors and the broadcast channel from the Broadcast Server. If this overhead is too expensive, some special resourceful nodes are introduced which listen to the Broadcast channels continuously and communicate to the nearby Sensor Nodes through sensor routing nodes as in the current architectures. In order to make the current discussion simple, we assume that the additional communication overhead is tolerable.

2 BASIC ARCHITECTURE

In the Broadcast Server architecture (Figure 2), the Broadcast Server broadcasts any relevant information to all the sensors in the network directly and each sensor is capable of receiving this information from the base station. This architecture has been extensively studied in the context of teletext systems and mobile/wireless systems with either one-way or asymmetric two-way communication channels[5][9]. It was used in the scenarios where a large number of users access the same information. Examples are news, stock quotes, weather reports, etc. The proposed architecture is similar to that with minor variations.

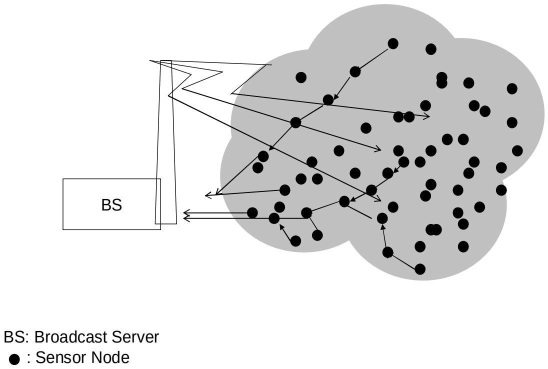

Figure 2 Data Dissemination Architecture

The proposed architecture consists of three main entities: the Broadcast Server, the Broadcast Cycle and the Sensor Nodes. The Broadcast server continuously broadcasts the messages over broadcast channels. The messages are organized in blocks and transmitted in a series of timeslots. Each message block contains the address of the receiving Sensor Node, message sequence number and the message. These messages are broadcast in cycles, each of which is called a Broadcast Cycle. At the beginning of each cycle, the server arranges all the message blocks in the increasing order of the addresses of the destination sensor nodes as shown in Figure 3. Each sensor node continuously or at specific instances listen to the Broadcast cycle and accesses the relevant blocks destined to it.

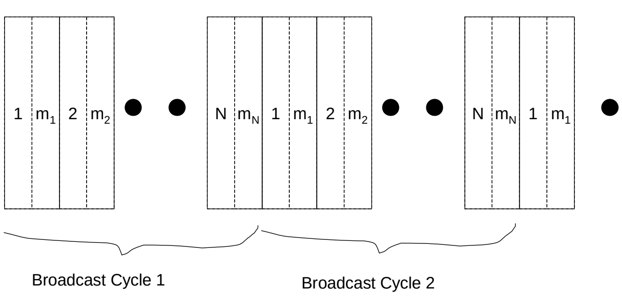

Figure 3 Broadcast Cycle

The cost of downlink communication in the Broadcast Server architecture is the total energy spent by all the sensor nodes while receiving a message. For example, if all N nodes listen to a message, then the cost is N. This metric is same as that used earlier while calculating the cost of Table based and flooding routing schemes. This cost depends on several parameters: the length of the broadcast cycle, the size of each message, whether the sensor nodes continuously tune to the channel or only at specific instances, whether the position of the message for a node is fixed in the broadcast cycle or not, whether clocks of the sensor nodes and the Broadcast server are perfectly synchronized or not, etc.

Let us assume the simplest scenario where the sensor nodes continuously listen to the broadcast cycle. This is equivalent to each message received by all the nodes whether they are intended recipients or not. (Of course, this cost is much smaller than that where a sensor node receives the message, processes it and forwarded to the next node.) Thus, the cost per message is O(L) where L is the length of the Broadcast Cycle in terms of number of messages or blocks. In the worst case, L=N. Therefore, the cost of message transmission is O(N). This is much better than flooding based routing schemes, where the cost is O(N2).

The cost is further reduced if the following conditions are met: the position of message blocks for each sensor node is fixed in the broadcast cycle and the clocks of the Sensor nodes and the Broadcast Server are perfectly synchronized. In such as case, each Sensor Node listens to the broadcast cycle only when its message is transmitted and accesses it. In such a scenario, the cost is O(1).

The Downlink communication costs of various routing schemes are shown in Figure 4. It clearly demonstrates that the Broadcast server architecture is significantly superior over other routing schemes.

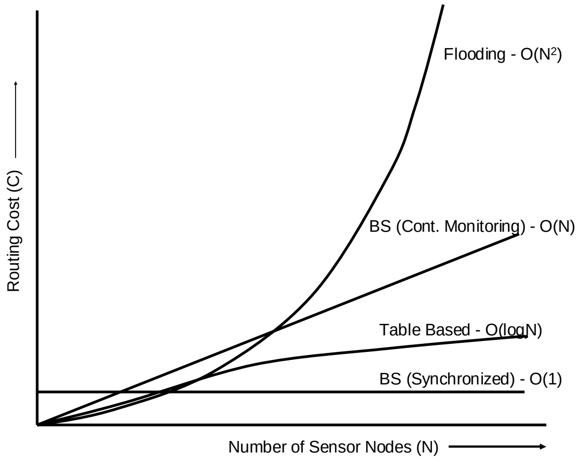

Figure 4 Cost of Downlink Communication

3 MULTIPURPOSE BROADCAST SERVER ARCHITECTURE

The proposed architecture also helps in centralizing many non-monitoring related functions from sensor nodes to the Base Station. This tremendously reduces the energy spent by the sensor nodes for these activities. A more detailed and multipurpose architecture is discussed in this section.

Figure 5 defines the software layer architecture at the Broadcast Server. The bottom layer consists of Broadcast Protocols, which define the physical characteristics of the wireless channels, frame structure, etc. The Broadcast Cycle layer decides the content and format of the broadcast information. The information is repeatedly broadcast in cycles called broadcast cycles (Figure 6), which are a sequence of predefined records or blocks. Each block contains the destination address and data. Based on the application, the destination address may be broadcast, multicast or unicast. The broadcast part contains the information that is accessed by all the sensors. The multicast part contains the information accessed by different groups of sensors. The unicast part contains the information specific to individual sensors.

A broadcast cycle need not contain all three types all the time and it can be of fixed length or variable length. In a fixed length broadcast cycle, the position of each information block or frame is fixed relative to other blocks in the broadcast cycle and broadcast at predetermined regular intervals. If there is no valid information to broadcast, either the earlier version is repeated or a filler block is used. In a varying size broadcast cycle, the positions of the blocks are not fixed, although their relative order is maintained. The advantage of a fixed size broadcast cycle is that a Sensor Node knows when its relevant information is broadcast and can be dormant the remaining time. The disadvantage is, if the broadcast cycle is too large, the time taken to propagate an update also becomes very large.

The broadcast cycles can either be flat or hierarchical. In the flat broadcast cycle, the information in the cycle is scheduled uniformly. That is to say, the frequency with which each block is transmitted remains the same for all the information blocks. The hierarchical broadcast cycle consists of multiple broadcast cycles broadcast with different frequencies. Some of the information is broadcast more often than the others.

The Middleware software acts as the common software platform for various schemes at the Application layer that use the Broadcast Server architecture.

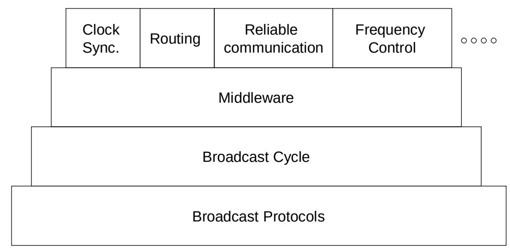

Figure 5 Software Layer Architecture at the Broadcast Server

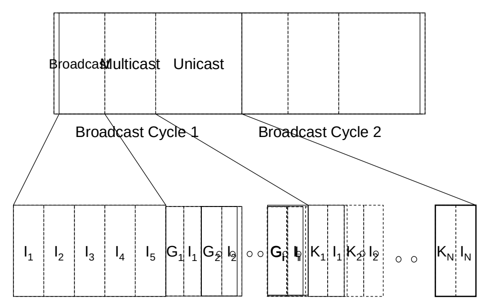

Figure 6 Broadcast Cycle Architecture

4 APPLICATIONS

In this section, we provide examples of simple centralized schemes at a high-level that greatly benefit from this architecture. A more detailed analysis is beyond the scope of this paper and will be addressed in later work.

4.1 Clock Synchronization

Clock synchronization is one of the fundamental requirements for many real-time applications. For example, it is used in order to suppress the redundant messages by the duplicate detection of the same event by different sensor node. The broadcast server architecture significantly improves the accuracy of clock synchronization. The current time at the Broadcast Server is continuously or periodically broadcast by the Broadcast Server so that all the Sensor Nodes synchronize their clocks with the Broadcast Server. This is similar to the scheme proposed to WLAN networks by Mock et. al. [11]. Although, the exact accuracy of the clock synchronization is beyond the scope of this work, the direct broadcast scheme in general introduces the least error in synchronization compared to the multi-hop solutions[2]. In addition, direct communication to each Sensor Node does not have overhead of additional synchronization messages, which requires processing and routing.

4.2 Simple (or Flat) Routing

Even for the uplink communication, each Sensor Node needs to know the next hop router towards the Base Station. Obtaining the next hop router does not add significant overhead if the network topology does not change. A simple flooding of a message by the Base Station can be used to create a shortest path spanning tree from Base Station to all the Sensor Nodes. Unfortunately, the topology is not static either due to the failure of nodes or due to the nature of network where sensor nodes themselves move. Several new schemes are proposed that reduce/eliminate topology maintenance requirements and try to optimize the energy consumption[3]. There are several limitations to these schemes. These schemes still involve communication overhead, a trade-off of not maintaining topology. They are significantly different from traditional routing schemes and therefore, have potential implementation risks. These schemes are also not universal and each of them is limited to specific scenarios only.

In the proposed architecture, the Broadcast Server can have the complete knowledge of the network. When one of the nodes along the path fails, the failure is communicated to the Base Station by its parent node (along the path towards the server). The server recalculates affected routing paths and communicates to all the affected nodes through the Broadcast cycle. Each record in the broadcast cycle consists of a node and the next hop node (that acts as a router) as shown in Figure 7.

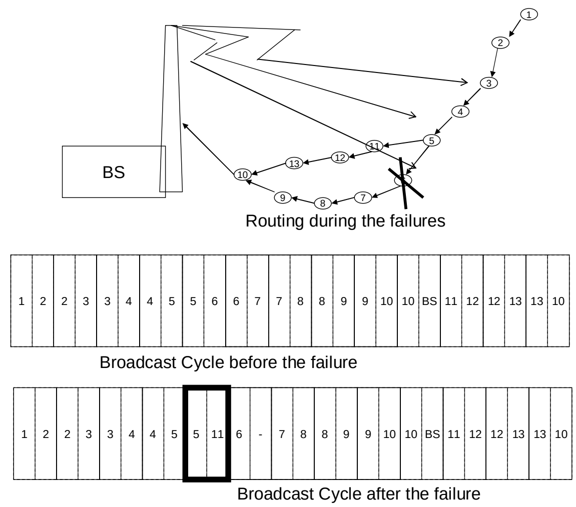

Figure 7 Routing in the Proposed Architecture

4.3 Complex Routing Schemes

A routing scheme also needs to address several other issues than just finding the next hop. For example, when a node fails, the packets at the uplink router must be buffered until the alternate next hop router is broadcast. Or, if a small packet loss is tolerated, it could drop these packets. Another option is to have two disjoint paths, primary and secondary, to the Base Station from each Sensor Node. When a node in the primary path fails, the packets are routed through the secondary path. In a WSN, a significantly large number of nodes are involved and there is a very high probability that two disjoint paths exist to the Base Station from each node. Finding disjoint paths in the existing WSN architecture is additional overhead. Where as, in this proposed architecture, the Broadcast Server calculates the two disjoint paths from each Sensor Node and broadcast two, primary and secondary, next-hop Sensor Nodes. This fault tolerant routing scheme does not have any additional overhead at the Sensor Nodes.

The lack of scalability is one of the main drawbacks of the flat routing schemes discussed above. As the number of Sensors and the geographical area increases, most of the energy is drained in routing. Therefore, hierarchical, such as cluster based routing schemes have been proposed [2]. In the cluster based schemes, the network is logically divided into multiple clusters with each cluster having a special node cluster head. The cluster head performs more functionality than the normal Sensor Node. For example, all the nodes in a cluster send their data to the cluster head and the cluster head aggregates the data and instead of routing through the adjacent nodes, directly routes the data to the other cluster head from the adjacent cluster. Therefore, the cluster head expends more energy than the normal nodes. In homogeneous networks, the cluster head is chosen dynamically in order to increase the life expectancy of the whole network. Several schemes are developed regarding choosing a cluster head and communicating that information to other cluster heads. This scheme involve three steps: identification the cluster heads, each sensor making a decision on which cluster it belongs to and each cluster head identifying all other (or adjacent) cluster heads.

In the proposed architecture, the hierarchical schemes are easily implemented. The Broadcast Server identifies the Cluster Heads, their respective Sensor Nodes and broadcasts to all the nodes.

4.4 Dynamically changing the characteristics of the sensors (or Increase/Decrease Frequency of Monitoring)

The frequency with which a sensor monitors its surrounding has significant impact not only on its own power consumption but also other routing sensors. The frequency must be just enough to gather the necessary and sufficient information and is decided by several factors, such as type of application, environmental conditions, number of neighboring sensors, criticality of the information, etc. Sometimes, this frequency needs to be changed dynamically. For example, it is more important and with high frequency, to monitor the environment during disaster conditions than during the normal conditions. In the proposed architecture, the Broadcast Server continuously broadcasts the frequency with which each sensor needs to monitor its surroundings.

4.5 Identification of Network Partitions (or Islands)

It is expected that different sensors in the WSN will have different life expectancies depending on their roles and how their energy is spent. For example, sensors which route more packets die faster than those which route fewer or no packets. Because, it is possible that network partitions could occur where a subset of sensors can not communicate to base station, it is very important for sensors to identify the network partitioning. During the network partitioning, it is no use for the sensors to monitor and send the information as it can not reach the Base Station. Worse, this useless information is unnecessarily routed thereby draining the energy of routing Sensor Nodes. It would be useful for these sensors to sleep during the network partitioning and awaken once the dead sensors are replaced. In the current architectures, identification of network partitioning by Sensor Nodes involves resource draining distributed schemes [4]. Where as, in the proposed architecture, it is easy to identify the network partitioning and communicate to relevant sensors. The Broadcast Server identifies the network partitioning due to the failure of a node, as it has the knowledge of the complete network and requests all the non-reachable sensors not to monitor. When the new nodes are deployed and routing paths established, the Broadcast Server then activates the sensors.

4.6 End2End Reliable Communication

The importance of reliable communication in WSN is recognized and a few reliable transport schemes already exist[6][7][8]. [6] and [8] propose hop by hop reliable transmission, where as [7] proposes event based reliable transmission. The main disadvantage with these schemes is the sender does not know whether the data it's sent is received at the Base Station correctly or not. In order to achieve this, the acknowledgements must flow from the Base Station to the Sensors. In the current architecture, the routing of these acknowledgements significantly affects the routing nodes closer to the Base Station as mentioned earlier. With the Broadcast Server architecture, acknowledgements are broadcast over the broadcast channels and therefore, they do not consume the energy or power of the routing sensors.

5 SUMMARY AND FUTURE WORK

In this paper we proposed a new architecture that simplifies the function of a Sensor Node, thereby considerably reducing its power consumption. Several examples of simple schemes are provided in order to demonstrate the significant benefit of using this architecture. This has been the focus of this paper. A detailed implementation of these and more complex schemes and their quantitative performance analysis is work in progress.

4 References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless Sensor Networks: A Survey," Computer Networks, vol. 38, Issue 4, March 2002, pp. 393-422.

[2] Qun Li, Daniela Rus, "Global Clock Synchronization in Sensor Networks", IEEE INFOCOM, 2004.

[3] J. N. Al-Karaki, Ahmad E. Kamal, "Routing Techniques in Wireless Sensor Networks: A Survey", IEEE Wireless Communications, Volume 11, Issue 6, Dec. 2004 Page(s):6 – 28.

[4] Deepak Ganesan, Alberto Cerpa, Wei Ye, Yan Yu, Jerry Zhao, Deborah Estrin, "Networking issues in wireless sensor networks," Journal of Parallel and Distributed Computing, Volume 64 , Issue 7, July 2004, Pages:799-814

[5] Swarup Acharya, Rafael Alonso, Michael J. Franklin, Stanley Zdonik, "Broadcast disks: Data management for asymmetric communication environment," SIGMOD Conference, 1995, Pages: 199-210

[6] Chieh-Yih Wan, Andrew T. Campbell, Lakshman Krishnamurthy, " Pump-Slowly, Fetch-Quickly (PSFQ): A Reliable Transport Protocol for Sensor Networks," IEEE Journal on Selected Areas in Communications, Volume 23, No. 4, April 2005, Pages: 862-872

[7] Sukun Kim; Fonseca, R.; Culler, D., “Reliable transfer on wireless sensor networks,” 2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 4-7 Oct. 2004 Pages: 449 - 459

[8] F. Stann and J. Heidemann. “RMST: Reliable Data Transport in Sensor Networks,” In Proceedings of the First International Workshop on Sensor Net Protocols and Applications, Pages 102--112, Anchorage, Alaska,USA,April 2003.

[9] M. H. Ammar and J. W. Wong, “The design of Teletext Broadcast Cycle, Performance Evalution, Vol. 5, No,. 4, December 1985, Pages: 235-242.

[10] C. Intanagonwiwat, R. Govindan, and D. Estrin, “Directed diffsuion; a scalabel and roubust communication pradigmfor sensor networks, “ Proceedings of ACM MobiCom ’00, Boston, MA, 2000, pp. 56-67.

[11] Mock, M.; Frings, R.; Nett, E.; Trikaliotis, S., “Continuous clock synchronization in wireless real-time applications”, Reliable Distributed Systems, 2000. SRDS-2000. Proceedings The 19th IEEE Symposium on 16-18 Oct. 2000 Page(s):125 - 132