Distributed Sensor Networks Based on Hybrid Communication Model

Mohammed Ketel
School of Information Technology
University of Baltimore
1420 North Charles Street
Baltimore, MD 21201
mketel@ubalt.edu

Abstract— Distributed sensor networks (DSNs) are being developed for a wide range of applications. A sensor network consists of a large number of nodes performing distributed sensing/event detection. Sensor nodes are energy-constrained, efficient routing is essential for increasing the lifetime of a sensor network. A DSN requires interoperability, low latency, and low power consumption in order to operate for long periods of time. To reduce the energy cost and to maximize the lifetime of the DSN, a hybrid paradigm combining the advantages of both the client-server and mobile agent paradigms is used.

Keywords- Distributed sensor networks, client-server, mobile-agents, traffic model, cluster

I. INTRODUCTION

The development of low-cost, low-power, multi-functional sensor network is due to advancement in wireless communications and VLSI [1, 10]. Individual sensor nodes are tiny low-power devices that integrate sensing, computing, and wireless communication capabilities. They are able to sense the physical environmental information and process this information locally, or send it to one or more collection points (base stations) typically through wireless communications. Processing such information reveals some properties about objects located and/or events happening in the vicinity of the sensor nodes. A fundamental limitation of sensor networks is the constrained energy source at each node. Communication between sensors/base station is energy-intensive, since transmission goes as d^a (a is typically 2-4). The limited sensor's power and signal transmission impose fundamental constraints on performance issues such as the capacity of data transmissions (bandwidth) and the operational lifetime of the sensor network. Each sensor node is powered by limited battery-supplied energy.

As sensor nodes can be deployed in large numbers at remote locations/harsh environments, it is typically not feasible to recharge their batteries. Once a node depletes its energy, it is considered dead (i.e. unable to sense, transmit or receive any messages). In this case, the initial energy levels in the sensor nodes and ongoing energy consumption rates directly affect the operational lifetime and the data transmission capacity of the sensor network. It is therefore evident that efficient routing schemes and effective power management mechanisms are important in sensor network design.

In this paper, we focus on the application of mobile agents in network routing. The mobile agent paradigm promises to open up computing possibilities especially with the popularity of wireless networks. Agent mobility addresses some limitations faced by classic client-server paradigm, namely, in minimizing bandwidth consumption, and in solving problems caused by intermittent or unreliable network connections encountered in wireless environments. Consequently, mobile agents create a new way for data exchange and resource sharing in the field of computer networks. Some of the emerging applications of mobile agents are in the field of sensor networks can be found in references [4, 5, 7]. A mobile agent is a software agent that can migrate autonomously among nodes in a heterogeneous network environment and can interact with other mobile agents. Unlike the traditional client-server model, where non-executable messages propagate across the network, a mobile agent can carry a code, data and state with itself when it migrates. Because they access sensor nodes locally, transferring multiple requests and responses across congested network links is not necessary, thus making the overall performance more efficient. Some merits of mobile-agent paradigm are described in [3, 4], including network load and latency reduction, adaptation, heterogeneity, robustness and fault-tolerance.

II. COMPUTING PARADIGMS FOR DISTRIBUTED SENSOR NETWORKS

Sensor network forms a typical distributed environment and the client-server paradigm has been one of the most popular models adopted in distributed computing [5, 10]. In this paradigm, a server offers a set of services, resources, and know-how (execution code or processing task provided by a server) needed for service execution. The client requests the execution of a service. As a response, server performs the requested service by executing the corresponding know-how and accessing the involved resources at the server. Although widely used, it has some disadvantages when used for wireless sensor networks [3, 5]. Reference [5, 6] summarizes some of the disadvantages.

- The client may suffer from a slow and unpredictable response time, especially when the number of client is large.

- In some particular applications, such as data processing or data fusing, large amounts of data are moved from the clients to the server. This will require many round trips over the network in order to complete the transaction. Each trip creates network traffic and consumes bandwidth.

- The design of a client-server-based system requires precise consideration of the network traffic, the number of clients and servers, transaction volumes, etc. If the estimates are inaccurate, the performance of the system will suffer.

In the mobile-agent-based paradigm, the service know-how is owned by the server, but most of the resources are located at the clients. The server sends out mobile agents carrying service know-how. The mobile agents complete the service using resources available at the clients. A mobile agent is a software agent that can migrate autonomously among nodes in a heterogeneous network environment. Unlike the traditional client-server model where non-executable messages propagate across the network, a mobile agent can carry a code, data and state with itself when it migrates. Mobile agents can take two forms based on the nature of mobility: strong or weak migration. Strong migration involves the transfer of code, data and agents' states among nodes. This might be expensive and time consuming in sensor networks where sensor energy is limited. Weak migration involves the transfer of code and data but not all the states. For wireless distributed networks, agents that support weak migration seem to be more suitable since they incur low communication and storage overhead. Further reduction of this overhead can be achieved by caching partial code of the mobile agent on each visited node [8, 9].

Mobile agents provide improved performance in several distributed systems and applications. They offer the following important benefits [5, 6]:

- Network bandwidth requirement is reduced: Instead of passing large amounts of raw data over the network, only the agent with small size is sent.

- Better network scalability: The performance of the network is not affected when the number of sensor is increased.

- Stability: Mobile agents can be sent when the network connection is alive and return results when the connection is re-established. Therefore, the performance is not much affected by the reliability of the network.

Figure 1 illustrates the concept of moving the computations to the data rather than moving the data to the computations [3].

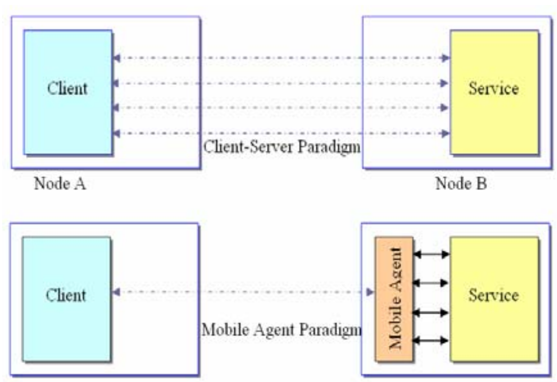

Figure 1: Client-Server vs. Mobile-Agent Paradigm

Table 1 shows the comparison between the client-server and mobile-agent-based paradigms before and after service execution [9]. S_A and S_B represent the sites (hosts machines) where the computational/service A and B are located.

TABLE I: Location of the computational components before and after service execution

Paradigm	**Before**		**After**	
	S_A	S_B	S_A	S_B
Client-Server	A	know-how resource B	A	know-how resource B
Mobile Agent	know-how A	resource	—	know-how resource A

III. NETWORK TRAFFIC EVALUATION

Below are the models for the overall traffic generated by the client–server and mobile-agent paradigms [2].

A. Client-Server:

Let Q be the number of request messages of size I sent by the server (base station or the cluster head is sensor clustering is used) to P clients (sensor nodes). The i^{th} node answers the q^{th} request with a reply (result) whose size is R_{qi}. The overall traffic in bits for the client-server case [2] is then:

$$T_{CS} = \sum_{i=1}^{P} \sum_{j=1}^{Q} (\eta_{CS} I_j + \tilde{\eta}_{CS} R_{ij}) \quad (1)$$

Where η_{CS} ($\tilde{\eta}_{CS}$) is the protocol overhead for request (reply) (η_{CS}, $\tilde{\eta}_{CS} > 1$) for the client-server case. In sensor networks, we assume that $\eta_{CS} = \tilde{\eta}_{CS}$ (similar sensor nodes).

B. Mobile Agent:

The server launches a mobile agent that visits each of the *P* nodes and collects information locally. When modeling such a component, the code and the portion of the state needed for its execution C_{MA} as separate from the portion of the state relevant to the application [2]. The latter grows as long as the mobile agent travels from node to node. Let $S_{MA,i}$ be the size of the state of the mobile agent during the trip towards node i, then

$$S_{MA,i} = \sum_{m=1}^{i-1} \sum_{q=1}^{Q} R_{mq} \ \ if\ \ i > 1 \ \text{ and } \ S_{MA,i} = 0 \ \ if\ \ i = 1 \quad (2)$$

The overall traffic in bits for the mobile agent case is:

$$T_{MA} = \sum_{i=1}^{P} \eta_{MA} (C_{MA} + S_{MA,i}) + \tilde{\eta}_{MA} \sum_{i=1}^{P} \sum_{j=1}^{Q} R_{ij} \quad (3)$$

η_{MA} ($\tilde{\eta}_{MA}$) are the protocol overhead for the mobile agent case. They are defined in a similar way as in the client-server case.

C. Averages and Normalization:

Instead of differentiating the contribution of each request I_j and reply R_{ij} in (1) and (3), we consider $\bar{I}$ and $\bar{R}$ to be the averages request message and average reply respectively. By normalizing $\eta_{CS} = \tilde{\eta}_{CS} = 1$ ($\eta_{MA} = \tilde{\eta}_{MA} = 1$) and after some mathematical manipulations equations (1) and (3) can be rewritten as:

$$T_{CS} = PQ(\bar{I} + \bar{R}) \quad (4)$$

$$T_{MA} = PC_{MA} + \frac{P(P+1)Q\overline{R}}{2} \quad (5)$$

It can be seen from the above equations that a mobile agent implementation generates more traffic than the client server one.

D. Traffic Around the Base Station/Cluster Head:

Although the overall traffic is an important parameter to be optimized, it is important to note that the key benefit of mobile agent is that it enables decentralized network management, reducing the load on the base station. With the client server paradigm, the expression for the traffic around the base station coincides with the expression for the overall traffic. Instead, a mobile agent design involves the base station only when the mobile component is injected into the network and when it comes back to the station, giving the expression:

$$T_{MA}^{'} = 2\eta_{MA}C_{MA} + \tilde{\eta}_{MA}\sum_{i=1}^{P}\sum_{j=1}^{Q}R_{ij}$$

Or in term of average after normalization:

$$T_{MA}^{'} = 2C_{MA} + PQ\overline{R} \quad (6)$$

We can see that the traffic around the base station is diminished, when $T_{CS} > T_{MA}^{'}$, or

$$\frac{C_{MA}}{PQ} < \frac{\overline{I}}{2} \quad (7)$$

If $PQ >> 1$ the left hand side of (7) is always less than the right hand side. This provides quantitative evidence for the fact that improvement of traffic increases with the number of nodes (P) visited by the mobile agent and with the number of replies (Q) that can be packed into the component code.

IV. ENERGY MODEL

The energy consumption at each node is expressed as:

$$E = E_S + E_D + E_C \quad (8)$$

Where E_S, E_D, and E_C, are the energies required for sensing, data processing, and communication, respectively. The amount of energy spent in each operation would depend on the network and event model. Usually the communication energy (transmission/reception) per bit of data is much higher than the sensing and processing energy per bit.

In the paper, we use the communication energy model introduced in [11]. Specifically, the energy consumptions considered are described as follows: If a data agent carries k-bit data travels from node N_i to node N_j,

- For node N_i, the energy consumed is

$$E_{N_i}(k,d) = A.k + B.k.d^2 \quad (9)$$

where A is the dissipated energy in the transmitter or receiver circuitry for 1 bit, B is the dissipated energy in the transmit amplifier, and d is the distance from node N_i to N_j.

- For node N_j, the energy consumed is:

$$E_{N_j}(k) = A.k \quad (10)$$

Hence, for each intermediate node N_i to receive and forward data agent, it consumes the energy:

$$E_{N_i}(k) = 2.A.k + B.k.d^2 \quad (11)$$

Using a communication from the source (data originator node) to the destination base station, the energy consumption for communication for each model is derived below.

- Client Server paradigm:

The base station sends $PQ\overline{I}$ requests and receives $PQ\overline{R}$ replies, thus, the energy consumption is:

$$E_{CS-BS} = A_{BS}(PQ\overline{I} + QP\overline{R}) + B_{BS}PQ\overline{I}d^2 \quad (12)$$

Here we assume d is the average distance between the base station and the nodes.

Each node sends $Q\overline{R}$ replies and receives $Q\overline{I}$ requests, thus, the energy consumption per node is

$$E_{CS-Node} = A_{Node}(Q\overline{I} + Q\overline{R}) + B_{Node}Q\overline{R}d^2 \quad (13)$$

- Moving Agent paradigm:

The base station sends and receives back the mobile agent code C_{MA} and $PQ\overline{R}$ replies from the nodes, thus, the energy consumption is:

$$E_{MA-BS} = A_{BS}(2C_{MA} + QP\overline{R}) + B_{BS}C_{MA}d^2 \quad (14)$$

In the mobile agent case, the i^{th} node receives $C_{MA} + (i-1)Q\overline{R}$ from node $(i-1)$ and sends $C_{MA} + iQ\overline{R}$ to node $(i+1)$, thus, the energy consumption at node i is:

$$E_{MA-Node_i} = A_{Node}[2C_{MA} + (2i-1)Q\overline{R}] + B_{Node}(C_{MA} + iQ\overline{R})d^2 \quad (15)$$

The energy consumption is a function of the order in which the mobile agent visits the nodes.

From the above analysis, we can draw a conclusion that the client server paradigm performs well when the number of nodes is large (large networks) in terms of the overall traffic. On the other hand, the base station represents a bottleneck for the client server paradigm. The mobile agent paradigm has advantages for small networks.

V. HYBRID COMMUNICATION MODEL

Based on the previous conclusion, a hybrid communication paradigm that combines the advantages of the client server and mobile agent paradigms will be considered. The idea is to use clustering.

A. Clustering:

We cluster the sensor nodes into groups, so that sensors communicate information only to cluster heads and then the cluster heads communicate the information to the processing center. We divide our distributed sensor network into l clusters $\boldsymbol{C}_1$, $\boldsymbol{C}_2$, …., $\boldsymbol{C}_l$ such that:

$C_1 \cup C_2 \cdots \cup C_l =$ Set that contains the total number of nodes (P).

$\boldsymbol{C}_i \cap \boldsymbol{C}_j = \varnothing$ ($\boldsymbol{i} \neq \boldsymbol{j}$, i.e., a node belongs to only one cluster)

B. Cluster Model:

- The network consists of P sensors, uniformly distributed over the physical space.

- The sensors are organized into disjoint clusters. Each cluster is managed by a distinct cluster head.

- All cluster-heads have globally unique ids. The ids of the sensors in a cluster are unique only within the cluster they belong to.

- Communication within a cluster is single hop.

- The cluster heads communicate among themselves in a single hop or using multiple hops depending on the range.

- The size of the cluster is an important model parameter. It determines the ratio of the number of cluster heads to sensors in the network. The size of the cluster imposes constraints on the memory and bandwidth of the cluster head.

C. Cluster Size:

For large clusters ($\frac{P}{l}$ small), we propose to use the client server paradigm within the cluster (because it generates less traffic) and the mobile agent paradigm is used between the cluster heads (only few of them for large clusters). In this scheme, the nodes within each cluster send their results to their respective cluster head. A mobile agent is then launched from the base station to collect these results from the cluster heads.

For small clusters ($\frac{P}{l}$ large), we propose to use the mobile agent paradigm within the cluster and the client server paradigm is used between the cluster heads. In this scheme, a mobile agent is launched by the cluster head to collect results from the nodes within each cluster. After collecting results from the mobile agents, the cluster heads send their results to the base station.

By using the hybrid paradigm, energy is saved and the lifetime of the sensor network is maximized.

VI. CONCLUSION

In this paper, the performance of the mobile agent and client-server models from the traffic and energy perspectives was examined. To reduce the energy cost and to maximize the lifetime of the DSN, a hybrid paradigm combining the advantages of both the client server and mobile agent paradigms was used.

VII. REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A survey," Computer Networks, vol. 38, no. 4, pp. 393–422, 2002.

[2] M. Baldi and G.P. Picco, **"**Evaluating the Tradeoffs of Mobile Code Design Paradigms in Network Management Applications," Proceedings of the twentieth IEEE International Conference on Software Engineering, April 1998, pp.146-155.

[3] D. Lange and M. Osima, "Seven Good Reasons for Mobile Agents," Communications of the ACM, Vol. 42, pp. 88-89, 1999.

[4] N. Minar, M. Gray, O. Roup, R. Krikorian, and Pattie, "Distributed Agents for Networking Things," IEEE Concurrency, April-June 2000 (Vol. 8, No. 2), pp. 24-33.

[5] Qishi Wu et al, "On Computing Mobile Agents Routes for Data Fusion in Distributed Sensor Networks" IEEE Transactions on Knowledge and Data Engineering, 2004, pp. 740-753.

[6] H. Qi , S Iyengar, and K. Chakrabarty, "Distributed Multi-Resolution Data Integration Using Mobile Agents," IEEE, 2001, pp.1133-1141.

[7] L. Tang and B. Pagurek, "A Comparative Evaluation of Mobile Agent Performance for Network Management,".Proceedings of the Ninth Annual IEEE International Conference and Workshop on the Engineering of Computer-Based Systems (ECBS'02), 2002.

[8] M. K. Denko, "The Use of Mobile Agents for Clustering in Mobile Ad Hoc Networks," Proceedings of the ACM, SAICSIT 2003, pp. 241-247.

[9] A. Fuggetta, G. P. Picco, and G. Vigna, "Understanding Code Mobility," IEEE Transactions on Software Engineering,Vol.24, Issue 5, May 1998 pp. 342 – 361.

[10] R. Min et al., "Energy-Centric Enabling Technologies for Wireless Sensor Networks," IEEE Wireless Communications, pp. 28-39, Aug. 2002.

[11] W. Heinzelman, A.P. Chandrakasan, and H. Balakrishnan "Energy-Efficient Communication Protocols for Wireless Microsensor Networks." In Proc. of Hawaiian Intl. Conference on Systems Science, 2000.