An Energy-Efficient Node Address Naming Scheme for Wireless Sensor Networks

Muneeb Ali and Zartash Afzal Uzmi
Computer Science Department, Lahore University of Management Sciences
Lahore, Pakistan
{muneeb,zartash}@lums.edu.pk

Abstract—**In wireless sensor networks the small data rate, generally 16 bits per packet, makes the overhead of globally unique network and MAC addresses, which is typically as much as the payload itself, undesirable [12]. We present a node address naming scheme that assigns locally unique addresses, which could be spatially reused, to nodes in an energy efficient manner and reduces the address size by a factor of 3.6. The focus of our work is solely on clustering routing approaches [8]. Further, we question the need of separate MAC and network addresses and show how our spatially reused locally unique node address could be used in both contexts, leading to greater energy efficiency.**

I. INTRODUCTION

Advances in wireless communications, IC fabrication, and MEMS-based technology have enabled the integration of DSP and sensing in a single chip with low development cost [1], [2]. These tiny chips or sensors observe physical phenomena and report data about the phenomena to the interested observer. Such sensors generally consist of multi-functional sensing hardware, limited memory, battery power, embedded processor, and short-range radio communications [15]. A network of these sensors, called a sensor network, bridges the gap between the physical and the computational world by providing reliable, scalable, fault tolerant, and accurate monitoring of physical phenomena. There are many applications of sensor networks including reliable location tracking, battlefield surveillance, military command and control, habitat monitoring, machinery prognosis, and inventory management [5], [13].

Sensor network environments inherently different from the Internet, pose some unique challenges to systems researchers. Systematic deployment of sensor networks (e.g., in a linear or grid arrangement) is not common [3]. The ad-hoc deployment implies that sensors should themselves be able to cope with the distribution and form communication paths. Once the sensors are deployed they remain unattended, hence all operations e.g. topology management, data management etc. should be automatic and should not require any manual or remote assistance [3]. Further, the environments in which sensor networks are deployed are dynamic, possibly hostile, in nature. Thus, a sensor network should be adaptive and should be able to cope with node or communication failures. Sensors are energy constrained and are regarded as dead once the battery power is insufficient to carry out computation and communication [4]. Thus, in order to increase the network lifetime, the communication protocols need to be optimized for energy consumption. Energy efficiency has been considered as the single most important design challenge in sensor networks [9].

Unlike traditional distributed systems, the packet size and data rate in typical sensor networks is very small, generally 16 bits per packet, as sensor nodes process data locally and forward only the current state or aggregated information [6]. Energy constraints and small data rates of sensor networks make the overhead of globally unique addresses undesirable. We use the term 'address' to denote the name of a sensor node regardless of the context in which the name is used i.e. MAC address or network address. A globally unique address would require 16 to 32 bits, or around as much as the payload, depending on the network size. Internet's large data payload and freedom from energy constraints makes global addressing feasible. Further, every node in the Internet could potentially communicate with every other node and this requirement could only be satisfied with global addressing. However in sensor networks, nodes which are mutually disconnected, in the network topology, can have the same address at the same time without effecting the correctness of the communication protocol. Such spatially reused locally unique addresses consume far less number of bits than global addresses. In sensor networks, where every bit transmitted reduces the lifetime of the network [4], savings on address size translate directly into increase in network lifetime.

In this paper, we question the need of having separate network and MAC addresses and propose a node address naming scheme that assigns locally unique addresses to nodes in an energy efficient manner and greatly reduces the address size. We show how these addresses are multipurpose; serving the purpose of both MAC and network address. The routing protocols for sensor networks fall under two broad categories: multi-hop routing [9] and clustering [8]. We focus only on clustering. Local clustering of sensor nodes, with one node as the head, performs better than multi-hop approaches as it makes local coordination among nodes more efficient [7]. In sensor networks, individual sensors lack global knowledge and they collaborate with each other to achieve a common task [3]. With clustering, the sensors participating in a particular cluster would communicate solely with the members of that cluster and all communications with the rest of the network would be made through the cluster head node. In other words, cluster member nodes of any cluster are exclusive from that of other clusters. We make use of this property in the spatial reuse of

0-7803-8325-7/04/$20.00 ©2004 IEEE

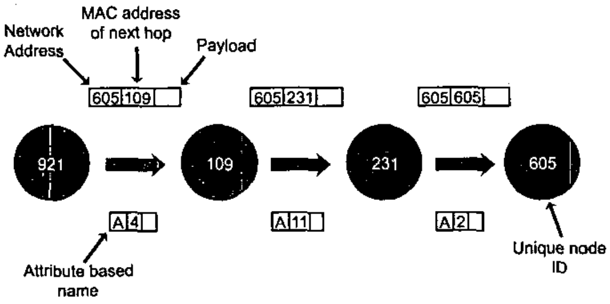

Fig. 1. An example of address usage in sensor networks

the locally unique addresses.

The rest of the paper is organized as follows. Section II describes the role of addresses in sensor networks. We discuss related work in section III and build problem motivation in section IV. Section V presents the node address naming scheme. Section VI presents simulation and testing results. We outline future work and summarize conclusions in section VII.

II. ADDRESSES IN SENSOR NETWORKS

In this section we describe the traditional role of addresses in sensor networks. Each node, in sensor networks, is typically assigned a network wide unique global network address that is used for administrative tasks like configuration of the network, monitoring of individual sensors, and downloading binary code or data aggregation descriptions to specific nodes [21]. However, it is widely suggested by researchers that the global network address need not be used for routing or identifying the final network destination [7] because, in general, the queries in sensor networks are not directed towards specific sensors. Instead of the network address, attributes such as node location or sensor reading identify the final network destination and these attributes are directly used for routing as in [14].

The MAC address is used to identify the next-hop sensor node during packet routing, as shown in figure 1. Each node after receiving the packet determines the next-hop MAC address, by checking the local routing table, and updates the next-hop address of the packet. This process continues till the packet is delivered to the destination node specified by the destination address of the packet.

III. RELATED WORK

In traditional distributed systems, the name or address of a node is independent of it's geographical location and is based on the network topology. However, in sensor networks, it has been widely proposed to use attributes external to the network topology and relevant to the application for low-level naming [16]. Following this design philosophy, many efficient routing protocols have been build [14], [13]. However, this attribute-based naming is unable to remove the need of a global network address for each node [21], which is still needed to carry out various administrative tasks. To reduce the overhead of using a relatively large address size of global addresses, J. Elson and D. Estrin propose using Random, Ephemeral TRansaction Identifiers (RETRI) [12]. These probabilistically unique addresses are randomly selected, by the nodes, for each new communication. RETRI results in smaller address size when compared to statically assigned globally unique addresses, but they do not guarantee the absence of collisions. Our node address naming scheme guarantees the absence of collisions while reducing the address size.

Many energy-efficient MAC layer protocols have been proposed for sensor networks [17], which require unique MAC addresses resulting in MAC header overhead. C. Schurgers et al. propose a comprehensive distributed address assignment mechanism to reduce MAC addresses in [11]. The assigned addresses are reused spatially and further reduction in address size is achieved by encoding the address. In [11] the network wide unique MAC address, of each node, is translated into a locally unique MAC address and this locally unique MAC address is used with the attribute based name [16] identifying the final destination of packets. For example in figure 1, network wide unique MAC address of 109 translates to locally unique MAC address of 4, 231 translates to 11, and 605 translates to 2 respectively. These locally unique addresses require less bits for representation and lead to energy efficiency. The use of locally unique MAC addresses instead of globally unique MAC addresses does not require any changes to the multi-hop routing protocol. The focus of their work is on multi-hop routing whereas we focus on clustering based routing.

A. Dunkels et al. propose constructing the node address of each node, which they call *'Spatial IP'*, from the location information known to it. Each sensor constructs it's spatial IP address by taking the (x,y) coordinates of the node location as the two least significant octets in the Internet style IP address. Spatial IP depends on localization which is a well studied problem in sensor networks and many elegant localization techniques are well known [23], [26], [24], [28], [27], [25]. The idea of spatial IP gains importance as it could support geographic routing as well as routing based on network topology independent of geographic location. However, the address size of such spatial IP would still be relatively large, leading to communication overhead.

IV. PROBLEM MOTIVATION

The clustering division of communication protocols provides a natural, mutually exclusive, grouping of sensor nodes. Same node addresses could be reused amongst members of different clusters leading to reduction in address size without much broadcast overhead. These locally unique addresses could serve the dual purpose of MAC and network address and thus the overhead of sending both MAC and network address in a packet could be reduced.

Some DHT-based communication protocols for sensor networks, e.g. CSN [18], require unique node addresses for their proper functioning. These communication protocols give bounded times for data lookup, provide guarantees to the applications running atop, and open the doors to distributed data-storage research in sensor networks. The benefits of these

DHT-based protocols could not be realized without energy efficient locally unique node addresses.

Further, reduction in TCP/IP protocol stack memory requirements [20] has triggered research into connecting sensor networks with TCP/IP networks like the Internet [22]. TCP/IP protocol requires unique address names for its proper functioning in sensor networks, but the energy constraints of sensor networks make global addresses unfeasible. This problem could also be addressed using energy efficient locally unique addresses.

V. NODE ADDRESS NAMING SCHEME

In this section, we present our node address naming scheme.

A. Assumptions

We consider an environment in which sensors are deployed in an ad-hoc manner, the base-station is located far away from the sensors, data delivery model is observer-initiated [15], and the sensors are static. We assume a clustering routing approach like CSN [18] or Pegasis [19] in which the cluster formation process is completed at network boot time and those clusters are retained, with changes due to node join and parts, throughout the lifetime of the network and it is guaranteed that the network topological neighbors of sensor nodes within the cluster are nodes geographically closest to them. The clustering approach is hierarchical, with layer i cluster node heads participating as member nodes in layer $i+1$. The number of cluster heads in all layers is set 6% and maximum number of cluster member nodes is set to 16.

B. Design Goals

We identify the following design goals for the node address naming scheme:

- *Efficiency:* The node address naming scheme would be efficient if it minimizes the header overhead associated with each data packet.
- *Accuracy*: The addressing scheme should not only guarantee absence of collisions at allocation time but should also maintain the collision free state of the network.
- *Distributed*: To reduce the overhead associated with the address allocation scheme itself, it should be distributed and not centralized in nature.
- *Multipurpose*: The addressing scheme should be assign addresses generic enough to be used both as MAC and network addresses.
- *Scalability*: The addressing scheme should scale well with increase in network size. This implies that widespread use of periodic broadcasts is not desirable.

C. Basic Idea

The basic idea of the node addressing scheme is that as the cluster member nodes of any cluster are exclusive from that of other clusters, the addresses assigned to the members of one cluster could be spatially reused in other clusters. The node addressing scheme makes use of the observation that, as the optimum number of cluster heads in the sensor network should be 6% [8], the optimum number of cluster members in each cluster would be 16 and these cluster members could be assigned locally unique addresses using a 4-bit address space.

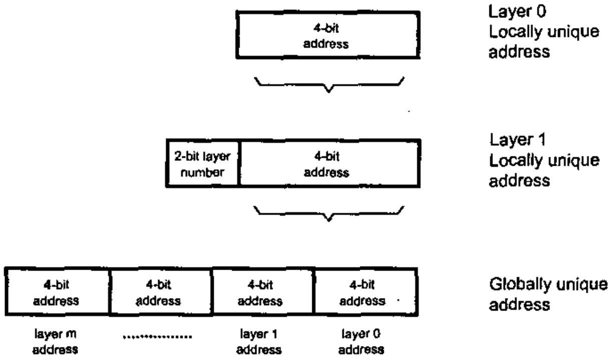

Fig. 2. Constructing a network-wide unique address on-demand basis

D. Naming Scheme

We define collision to occur when two or more sensor nodes, within the communication range of a sensor node s_i, have the same locally unique address assigned to them. We define three kinds of communications in a clustering environment:

1) *Communication within a cluster:* The cluster members nodes collaborate and communicate amongst each other to together achieve a higher task. The clustering network layer protocols [19], [18] generally require cluster member nodes to communicate only with other cluster member nodes and the cluster head node.
2) *Communication amongst clusters:* The cluster head of any cluster i routes all messages going out from the cluster i to all other clusters and also all messages going into the cluster. The cluster member nodes of a cluster i cannot directly communicate with the cluster member nodes of another cluster j.
3) *Overhearing communication:* At the physical level unintentional communication among member nodes of different clusters could take place provided the member nodes have the same address in different clusters and are within the communication range of the sender.

With 16 members per cluster and a 4-bit address space, collisions could be ruled out for communications within a cluster if we ignore all other clusters at hierarchy layer 0. The communication among clusters for layer 0 could be viewed as communication among members for hierarchical layer 1. However, now the 4-bit address space would not be sufficient as we need to have means to distinguish a layer 0 address from a layer 1 address. We propose to attach a 2-bit layer number to the 4-bit node address to construct a higher layer address, as shown in figure 2. Hence, the sensor network is allowed to have 5 hierarchical layers which is seldom the case as typically sensor networks do not have more than 3 layers [7]. Overhearing communication is avoided if all address assignments satisfy the following conditions:

Condition 1: *All member nodes of a cluster C have distinct addresses with a locally unique address, say* a_i*, assigned to exactly one member node of cluster C, say member node* m_i

Condition 2: *All non-member one-hop and two-hop neighbors of all members of cluster C have distinct addresses.*

It is necessary to include two-hop neighbors in condition 2 because of the hidden terminal problem. Consider a sensor node s_1 which is the member of a cluster A with sensor nodes s_2 and s_3 members of another cluster B respectively. s_2 is a one-hop neighbor of s_1 and s_3 is a one-hop neighbor of s_2 whereas s_1 and s_3 are hidden from each other as their radios cannot send signals far enough for them to be aware of the presence of each other. Now if condition 2 considers only one-hop neighbors and s_1 and s_3 have the same locally unique address, then collision could occur when s_2 tries to send out data to s_3. Such collisions are avoided by including two-hop neighbors in condition 2.

Conditions 1 and 2 avoid collision and guarantee a valid assignment of addresses at setup time. However, as nodes fail and join the network with time the address assignment might become invalid leading to possible collisions. In order to maintain the collision free state of the address assignment our scheme requires that each new node, say s_{new}, entering any cluster C must satisfy condition 1 and 2 for the address assignment of s_{new}.

E. Names as Globally Unique Addresses

Our node address naming scheme is flexible enough to support network wide unique network addresses, with an associated increased header overhead. Network wide unique addresses may be required for administrative tasks such as node maintenance etc. Our node address naming scheme constructs a network wide unique, also called global, address dynamically upon application level request. Figure 2 shows how to construct a network-wide unique address on-demand i.e. by dynamically putting together the address of all the hierarchical layers head nodes. The 4-bit address at layer 0 becomes the the least significant 4-bits of the globally unique address. We append the 6-bit address of the cluster head at level 1 towards the more significant side of the already set bits. This process continues until the address of the highest layer cluster head is appended. Thus, the globally unique address of our naming scheme is of dynamic length and this length varies with the network size. The number of layers in the network increase with the number of nodes participating in the sensor network and the dynamic global address size increases by 6-bits with the addition of each new layer.

F. Names as Network Addresses

The main purpose of the network address to identify the end receiver node of a packet. For communications within a cluster, at any layer, 4-bit network addresses would be used. For communication within a layer, at any layer, 6-bit addresses would be used. For communications involving multiple layers the dynamic globally unique address would be used i.e. for packets passing down the hierarchy each layer would extract 6-bits from the dynamic global address and for packets passing up the layer each layer would add 6-bits to the address respectively. Thus, during all types of communications the naming scheme dynamically uses the least amount of bits for the network address.

G. Names as MAC Addresses

The main purpose of a MAC address is to identify the next-hop node during message routing. The addresses assigned by our naming scheme could easily be used as MAC addresses as they guarantee the absence of collisions in the cluster-based sensor network. At layer 0, the 4-bit address of each node is locally unique for each node and hidden terminal collision is avoided because of condition 2. Thus, the 4-bit address could be used as a MAC address at layer 0. In the higher layers the 6-bit address of each node is locally unique and could similarly be used to identify the next-hop destination during message routing. It is important to note that when messages need to pass down or up the hierarchical layers, the first two bits of the 6-bit node address of higher layer nodes help in identifying the next-hop. When the next-hop MAC address is changed from 6-bit to 4-bit that shows that message is passing down to layer 0 and vice versa.

VI. SIMULATION AND EXPERIMENTAL RESULTS

The simulation was done using the simulator developed for CSN [18]. The simulator uses a simple first order radio model [8] for wireless communications. Let $E_{electric}$ be the energy dissipated by the transmitter-receiver and $E_{amplifier}$ be the energy dissipated by the transmit amplifier. Then,

$$E_{Transmit}(k,d) = E_{electric} \times k + E_{amplifier} \times k \times d^2 \quad (1)$$

$$E_{Receive}(k) = E_{electric} \times k \quad (2)$$

Where $E_{electric}$ and $E_{amplifier}$ have values $50nJ/bit$ and $100pJ/bit/m^2$ respectively, k is the data rate in bits per packet and d is the distance. The base station is located far away from the test bed and thus communicating with the base station is a high energy operation. The sensors are randomly deployed on a test bed of $L \times L$ meters, where $L = 200$. The number of cluster heads are set to be 6% of the total sensors participating in the layer, which is a reasonable value [8].

An important performance metric we use to evaluate the relative overheads of global and locally unique addressing is efficiency which is defined in [12] to be:

$$Efficiency, E = \frac{D}{D+H} \quad (3)$$

where D is number of data bits with an H bit header. In figure 3, the values on the X-axis are D and that on the Y-axis are (D + H). The black portion of the bar represents our locally unique address, the black plus grey portion represents the global address, and the grey portion represents their difference

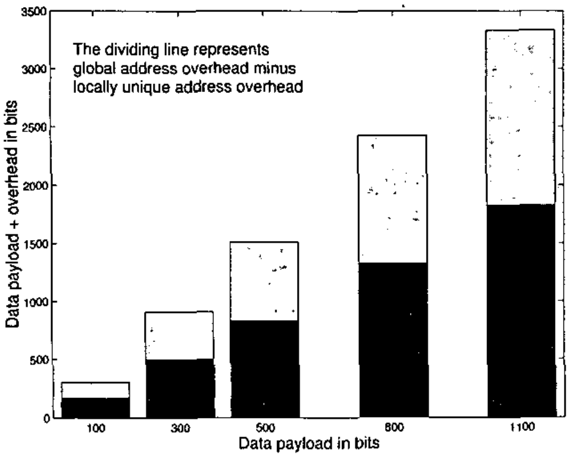

Fig. 3. Overhead of global and locally unique system addressing

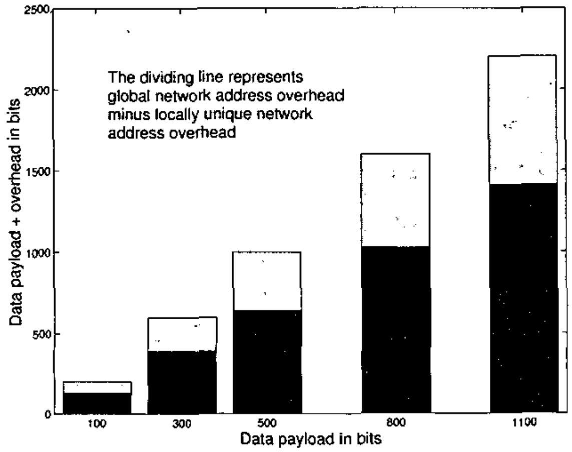

Fig. 4. Overhead of global and locally unique network addressing

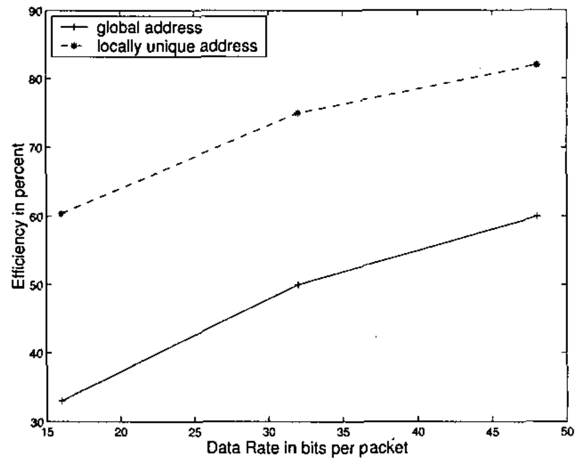

Fig. 5. Efficiency of global and locally unique system addressing

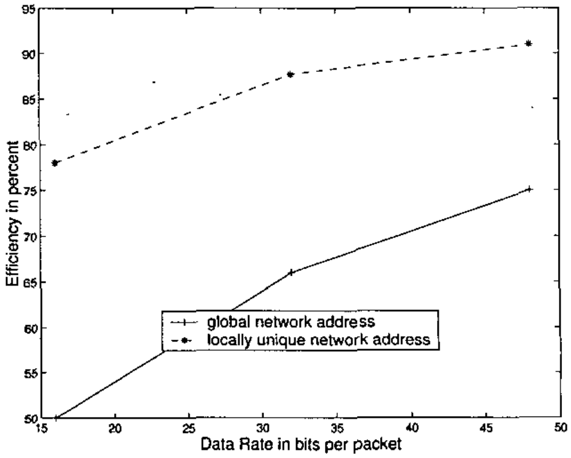

Fig. 6. Efficiency of global and locally unique network addressing

respectively. It is easy to see that locally unique addresses perform much better than global addresses as they have lower header overhead. Figure 4, is similar to figure 3 only this test was performed by not including the effect of MAC addresses whereas figure 3 includes the effect of both MAC and network addresses. Figure 3 and 4 together lead to the finding that the increase in efficiency is not only because of reduction in network address but the reduction in MAC address also plays a significant role in it.

Figure 5 and 6 show the effect on efficiency if we increase the data rate. In this test, we gradually increased the data sent per packet from 16 to 48 bits and found out that the efficiency of both global and locally unique addresses increase. Figure 5 includes the effect of both network and MAC address whereas figure 6 shows the effect of only the network address. The increase in efficiency upon increase in data-rate is justified as more useful bits are transmitted per packet while the number of header overhead bits remains constant. It is important here to note that data rates of more than 27 bits are not typical for sensor networks as the radio medium control divides the packets into frames and sends a maximum of 27 frames at a time [4].

Figure 7 presents a comparison of the scalability of global and locally unique addresses. In the test we set the global address at 16 bits and increase the network size gradually. The global address remains constant and hence scales well till the point where the address space exhausts. After that it can no longer support all nodes in the network. In the test we assigned a new global address of 32 bits after the 16 bit address exhausted. On the other hand the efficiency of our locally unique address deteriorates slowly and gracefully with the increase in network size. Such gradually degrading performance is considered much better than sudden collapse of the system as in the case of global addresses.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a naming scheme, giving locally unique spatially reusable addresses, for cluster-based sensor

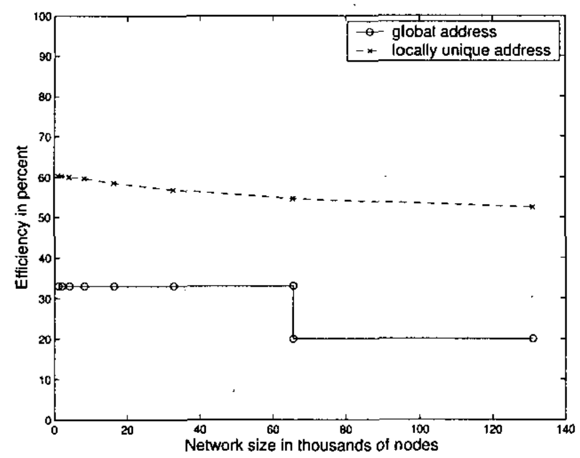

Fig. 7. Scalability comparison of global and locally unique system addressing

network nodes and showed how such addresses result in less header overhead and greater payload efficiency (60.37%) when compared to globally unique addresses (33.5% efficiency). Our main goal was to reduce the extra overhead number of bits from each packet transmission. This ultimately leads to greater energy efficiency and increases the lifetime of the network. We separated the characteristics of a node address from the context in which it is used and showed how we do not need separate addresses for MAC and network address. Finally, our node addressing scheme scales well to very large sensor networks.

We plan to carry out experimentation of our node addressing mechanism in more realistic scenarios using Berkeley MOTES [2]. Also, our naming scheme assumes that cluster formation process is completed at network boot time and those clusters are retained, with changes due to node join and parts, throughout the lifetime of the network and it is guaranteed that the network topological neighbors of sensor nodes within the cluster are nodes geographically closest to them. These assumptions, in our naming scheme, are satisfied by some specific network layer protocols, like CSN [18] and Pegasis [19]. We are exploring ways to relax these assumptions in order to make our naming scheme suitable for other clustering network layer protocols e.g. LEACH [8].

REFERENCES

[1] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava. Energy aware wireless microsensor networks. *IEEE Signal Processing Magazine*, vol. 19, iss. 2, pp. 40–50, March 2002.

[2] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister. System architecture directions for networked sensors. *Architectural Support for Programming Languages and Operating Systems*, pp.93–104, 2000.

[3] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. A Survey on Sensor Networks. *IEEE Communications Magazine*, Vol. 40, No. 8, pp. 102-116, August 2002.

[4] G. Pottie, and W. Kaiser. Wireless Integrated network sensors. *Communications of the ACM*, 43(5):51-58, May 2000.

[5] Albrecht Schmidt and Kristof Van Laerhoven, How to build smart appliances? IEEE *Personal Communications*, pp. 66-71, August 2001.

[6] K. Sohrabi, J. Gao, V. Ailawadhi, and G. Pottie. Protocols for self-organization of a wireless sensor network. IEEE *Personal Communications* Mag., Vol.7, No.5, pp. 16-27, Oct 2000.

[7] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar. Next century challenges: Scalable coordination in sensor networks. Proc. *MOBICOM 1999*, Seattle, 263-270.

[8] W. Heinzelman. Application-Specific Protocol Architectures for Wireless Networks. *Ph.D. thesis, Massachusetts Institute of Technology*, 2000.

[9] W.R. Heinzelman, J. W. Kulik, H. Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. *ACM MOBICOM*, 1999, Seattle, 174-185.

[10] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. Proc. *Sixth Annual International Conference on Mobile Computing and Networking*, pages 56-67, Boston, MA, Aug. 2000. ACM Press.

[11] C. Schurgers, G. Kulkarni, and Mani B. Srivastava. Distributed Assignment of Encoded MAC Addresses in Sensor Networks. *MobiHoc'01*, October 4-5, 2001, Long Beach, CA.

[12] J. Elson, and D. Estrin. Random, Ephemeral Transaction Identifiers in Dynamic Sensor Networks. *ICDCS'01*, Phoenix, AZ, 2001.

[13] D. Estrin, L. Girod, G. Pottie, and M. Srivastava. Instrumenting the world with wireless sensor networks. In *International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2001)*, Salt Lake City, Utah, May 2001.

[14] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In Proceedings of the *Sixth MOBICOM*, pages 56–67, Boston, MA, Aug. 2000. ACM Press.

[15] S. Tilak, Nael B. Abu-Ghazaleh, and W. Heinzelman. A Taxonomy of Wireless Micro-Sensor Network Models. *Mobile Computing and Communication Review*, April 2002, Volume6, Number2.

[16] J. Heidemann, F. Silva, C. Intanagonwiwat, R. Govindan, D. Estrin, and D. Ganesan. Building Efficient Wireless Sensor Networks with Low-Level Naming. In Proceedings of the *Symposium on Operating Systems Principles*, pp. 146-159. Chateau Lake Louise, Banff, Alberta, Canada, ACM. October, 2001.

[17] W. Ye, J. Heidemann, and D. Estrin. An energy-efficient MAC protocol for wireless sensor networks. In *INFOCOM 2002*

[18] M. Ali, and Z. A. Uzmi. CSN: A Network Protocol for Serving Dynamic Queries in Large-Scale Wireless Sensor Networks. 2nd Annual Conference on *Communication Networks and Services Research* (CNSR 2004), Fredericton, N.B., Canada, May 2004

[19] S. Lindsey, and C. S. Raghavendra. PEGASIS: Power-Efficient Gathering in Sensor Information Systems. *International Conference on Communications*, 2001.

[20] A. Dunkels. Full TCP/IP for 8-bit architectures. In *MobiSys'03*, San Francisco, California, May 2003.

[21] A. Dunkels, J. Alonso, and T. Voigt. Making TCP/IP Viable for Wireless Sensor Networks. *First European Workshop on Wireless Sensor Networks* (EWSN 2004), work-inprogress session.

[22] A. Dunkels, T. Voigt, J. Alonso, H. Ritter, and J. Schiller. Connecting Wireless Sensornets with TCP/IP Networks. In Proceedings of the *Second International Conference on Wired/Wireless Internet Communications* (WWIC2004), Frankfurt (Oder), Germany, February 2004.

[23] A. Savvides, C. Han, and M. B. Strivastava. Dynamic fine-grained localization in ad-hoc networks of sensors. In *MobiCom'01*, pages 166-179. ACM Press, 2001.

[24] N. Bulusu, J. Heidemann and D. Estrin. GPS-less Low Cost Outdoor Localization For Very Small Devices. *IEEE Personal Communications*, Special Issue on "Smart Spaces and Environments", Vol. 7, No. 5, pp. 28-34, October 2000.

[25] N. Bulusu, J. Heidemann, D. Estrin and T. Tran. Self-configuring Localization Systems: Design and Experimental Evaluation. *ACM Transactions on Embedded Computing Systems* (ACM TECS), Special issue on networked embedded systems, 2003.

[26] J. Chen, L. Yip, J. Elson, H. Wang, D. Maniezzo, R. Hudson, K. Yao, and D. Estrin. Coherent Acoustic Array Processing and Localization on Wireless Sensor Network. in *Proceedings of the IEEE*, Vol. 91, No. 8, August 2003.

[27] N. Bulusu, V. Bychkovskiy, D. Estrin and J. Heidemann. Scalable, Ad Hoc Deployable, RF-based Localization. In Proceedings of the *Grace Hopper Conference on Celebration of Women in Computing*, Vancouver, Canada. October 9-12 2002.

[28] H. Wang, J. Elson, L. Girod, D. Estrin, and K. Yao. Target Classification and Localization in Habitat Monitoring. In Proceedings of *IEEE ICASSP 2003*, Hong Kong, China. April 2003.