SENSOR NETWORKS WITH MOBILE AGENTS

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ABSTRACT

An architecture for large scale low power sensor network is proposed. Referred to as sensor networks with mobile agents (SENMA), SENMA exploit node redundancies by introducing mobile agents that communicate opportunistically with a large field of sensors. The addition of mobile agents shifts computationally intensive tasks away from primitive sensors to more powerful mobile agents, which enables energy efficient operations under severely limited power constraints. An opportunistic ALOHA random access coupled with a direct sequence spread spectrum physical layer is proposed. A comparison of SENMA with a flat ad hoc sensor network shows a substantial gain in energy efficiency.

1. INTRODUCTION

1.1. Sensor Networks with Mobile Agents

We propose SENMA, a new network architecture for low power and large scale sensor networks. SENMA stands for SEnsor Networks with Mobile Agents (SENMA). As illustrated in Fig. 1, SENMA have two types of nodes: sensors and mobile agents. Sensors in SENMA are low power and low cost nodes that have limited processing and communication capability. These battery operated sensors have a finite operational life and low duty cycles. They are deployed in a large quantity, perhaps randomly through aerial drop. There is no need, nor possible, to have a careful network layout.

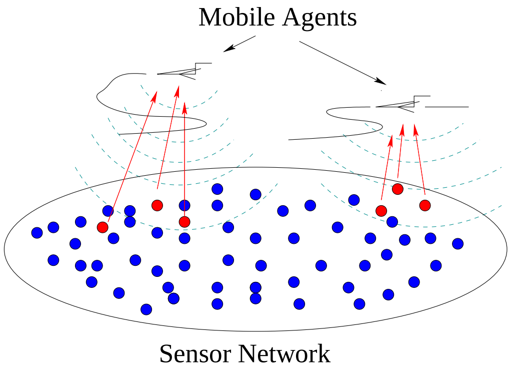

Fig. 1: Sensor Networks with Mobile Agents

The defining feature of SENMA is the addition of mobile agents. By mobile agents we do not mean software programs [1] that migrate from host to host in the network. Mobile agents in SENMA are powerful hardware units, both in their communication and processing capability and in their ability to traverse the sensor network. Examples of mobile agents are manned/unmanned aerial vehicles, ground vehicles equipped with sophisticated terminals and power generators, or specially designed light nodes that can hop around in the network. These mobile agents may have high data rate connections to satellites, allowing reachback to remote command control centers. Mobile agents need not always be present or operational along with sensors in SENMA; they are in actions only when it is necessary to collect data and perform network maintenance.

The proposed SENMA architecture is based on two propositions that are sensor network specific. The first is that, given the scale of the network and the low complexity of each sensor, it is impractical, if not impossible, to rely on sensors to organize the medium access control, to discover and maintain routes, to store and relay packets, to encode and decode. We believe that many critical network operations should be performed by a smaller number of powerful mobile agents, and the burden of sophisticated processing be shifted away from the sensor network.

The second proposition is that the inherent node redundancy in such dense networks must be exploited. Unlike commercial wireless networks where each user demands a certain level of quality of service, dense sensor networks such as SENMA require neither each node be connected to the network all the time nor every packet be delivered to its final destination. We take the view that the information contained in the network can be reconstructed from a *fraction of the packets* generated by a *fraction of the sensors*. The protocol stack for SENMA that incorporates opportunistic transmissions focuses on these two fractions and relies on node redundancy for energy efficient and reliable operations.

1.2. Ramifications of SENMA

We draw specific comparisons between SENMA and the more conventional flat ad hoc network architecture, focusing on energy efficiency and protocol overhead.

Energy Efficiency For sensor networks, a predominant concern is energy efficiency. Indeed, energy efficiency is the chief reason that the multihop ad hoc architecture that relays packets in short distances is considered superior over the one-hop network

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with fixed access points or gateway nodes. The presence of mobile agents, however, changes this underlying premise for several reasons.

First, in SENMA, mobile agents are the only receiving terminals in data collection—the so-called sensor reachback. As a result, sensors spend little energy in receiving signals. With the flat ad hoc architecture, however, a neighbor of one transmitting sensor may have to listen to the transmission in order to determine if it is required to relay the packet. Since the transceiver could consume 2-3 times more power in receiving than in transmitting [2] and a sensor can have a large number of neighbors in densely deployed networks, power consumed by packet reception can dominate the overall energy consumption.

Second, most transmissions in a flat ad hoc sensor networks are between low-lying antennas where signal decays as the 4th power of distance due to partial cancellation by ground-reflected rays [3, 4]. In SENMA, however, we may have a free space between the sensor field and the mobile agents (for example, flying airplanes) where signal only decays as the 2nd power of distance [5].

Finally, SENMA uses mobile agents for complicated signal processing and network maintenance. With sophisticated receivers (for example, multiple antennas for spatial diversity), the required SNR for a given BER can be considerably lower at the mobile agents, leading to lower sensor transmitting power.

The central concern of using direct transmission to mobile agent, however, is whether low power sensors can reach a mobile agent afar. We argue that the distances between sensors and mobile agents do not impose a fundamental limitation to SENMA. Our approach to this problem is to trade the size of the network for power efficiency. Specifically, as described in Section III, we employ opportunistic transmissions to exploit multiuser diversity. The mobility of the mobile agents introduces fading, and a sensor transmits only if its channel is in the most favorable fading condition. The large size of the network ensures that there are always some sensors whose channel enjoy constructive fading conditions.

Protocol Overhead The overhead of a flat ad hoc network can be staggering. Headers are added at each network layer; pilot symbols are inserted in each transmission for synchronization and channel estimation; addresses must be included. Along with framing and error control, the overhead to establish and maintain connections makes up 99% of the network traffic. Furthermore, MAC and routing protocols for sensor networks with a flat ad hoc architecture usually require that sensors know their neighbors' profile: location, energy supply, transmission and reception scheme in terms of timing, frequency, or spreading code, etc.. Unfortunately, the topology of sensor networks change frequently due to node failure, duty cycles, and mobility. As a result, sensors need to periodically send out query packets for neighbor profile update. This can lead to unacceptable overhead in power consumption.

In addition to transmission overhead, there is also substantial but less quantified storage overhead. In the ad hoc architecture, to route packets through the network, buffers of sufficient size must be implemented at sensor nodes. Before reaching the final destination, packets stay in buffers at various locations of the network. The low duty cycle of the network prolongs the time packets stay in buffers, which makes it necessary to equip sensors with large memory cells.

SENMA are examples of "connectionless" network. By connectionless we mean that connections are not required, nor need to be maintained. SENMA focuses instead on the one-hop transmission between sensor nodes and mobile agents. By transmitting directly to mobile agents, the overhead associated with MAC, routing and higher layer functions is sharply reduced.

1.3. Related Work

There is a growing body of literature on sensor networks, most focusing on the flat ad hoc architecture (see [6] for a recent survey on sensor networks). There are several cases where mobile nodes have been involved in the sensor network. For example, mobile sensors are considered in [7] to provide an extension of a stationary sensor network. A specific MAC protocol—the Eavesdrop-And-Register—is introduced that integrates mobile nodes into the sensor network. Different from SENMA considered in our case, the primary network functions in [7] are not handled by these mobile nodes. In [8], the idea of using mobile nodes for message ferry is considered. While the objective of [8] is to use mobile nodes to provide non-random proactive routes, the basic network in [8] bears considerable similarity as SENMA, and the insights obtained in this paper apply to a large degree there.

Protocol design is a vibrant theme of sensor network research. Indeed, developing energy efficient protocols for flat ad hoc sensor networks presents a tremendous challenge to engineers and computer scientists. Numerous protocols have been developed for medium access control [7, 9, 10], multi-hop routing [11–13], topology discovery and route maintenance [14, 15]. In [16], a hierarchical ad hoc architecture where sensors form clusters and only the cluster heads are responsible for relaying packets to a fixed remote base station is proposed. MAC protocols are developed [17] for the transmission from sensors to cluster heads and a variation of this architecture with improved performance is developed in [18]. In [19, 20], MAC protocol design under the architecture of SENMA is addressed.

Analysis on energy consumption in sensor networks has also received considerable interest. In [21], the global energy expenditure of a flat ad hoc sensor network is derived and its relation to non-protocol parameters such as transceiver characteristics, data traffic distribution, node density, and access point location is revealed. The case of a mobile access point is also considered in [21]. To reduce the adverse effect of a large network on the total energy consumption, the author proposed that the network be partitioned into several subnetworks and a mobile access point periodically visit and retrieve data from each subnetwork. Different from SENMA, this architecture still features multi-hop communications between sensors and the mobile access point; it consists of several peer flat ad hoc sensor networks. In [22], upper bounds on the lifetime of a flat ad hoc sensor network with controlled deployment are derived by analyzing the network energy expenditure. A comparison on energy efficiency of the flat ad hoc and hierarchical ad hoc architectures is presented in [23]. A common assumption in [21–23] is that only one sensor node is involved in receiving for the transmission of each hop. This assumption requires that the route of each packet and the transmission schedule of each hop be planned in advance and then stored at each sensor node. In densely deployed network with time-varying topology, neglecting the energy overhead associated with route discovery and transmission scheduling may lead to over-optimistic results. In energy analysis presented in this paper, we assume that all sensors in the neighbor of one transmitting node listen to the transmission in order to know who is responsible for relaying. We reveal that energy consumed in receiving can change the order of total energy expenditure in dense sensor networks.

2. ENERGY EFFICIENCY ANALYSIS

Assume that N sensors are randomly and uniformly deployed on a disk with a radius of R meters. Each sensor has a packet of L bits to be retrieved. For the flat ad hoc architecture, each packet needs to reach the fixed access point located at the center of the disk. Each sensor broadcasts its packets (originally generated or relayed) to its neighbors and the one closest to the access point will relay the packet. The transmitted signal decays as the 4th power of distance, and the transmission range is chosen to minimize total energy consumption. In SENMA, sensors transmit directly to a mobile agent which is an airplane flying H meters above the sensor field. We assume free space transmission from the sensor to the airplane where signal decays as the 2nd power of the distance. We intentionally favor the flat ad hoc architecture by ignoring energy consumed by MAC and routing protocols and assuming the same SNR requirement for reliable packet reception at the mobile agent (SENMA) and at each sensor (flat ad hoc). It is likely in practice that the overhead associate the routing and MAC protocol will dominate the power consumption in the flat ad hoc network.

We use the radio model and typical transceiver power consumption values given in [2], where the radio dissipates, respectively, e_{tx} J/bit and e_{rx} J/bit to run the transmitter and the receiver circuitry. The transmitter outputs e_{out} J/bit to traverse a unit distance and reach the receiver with an acceptable SNR. A minimum amount of energy e_{out} J/bit is radiated for transmission distances smaller than 1 meter. Thus, to transmit and receive an L-bit packet a distance r, the radio consumes[1]

$$\mathcal{E}_{tx}(L,r) = L(e_{tx} + e_{out}\bar{r}^4), \;\; \mathcal{E}_{rx}(L) = Le_{rx},$$

where $\bar{r} \triangleq \max(r, 1)$.

We now calculate the expected total energy expenditure $\mathcal{E}_{\text{AdHoc}}(r)$ of the flat ad hoc architecture for a given transmission range r. A more detailed derivation can be found in [24]. With the independent and identical distribution of sensors on the disk, it suffices to consider the energy $\mathcal{E}^{(1)}_{\text{AdHoc}}(r)$ consumed by transmitting one sensor's packet to the access point. Averaging over all possible distances from the sensor of interest to the access point, we have

$$\mathcal{E}^{(1)}_{\text{AdHoc}}(r) = \frac{2}{R^2}\int_0^R \mathcal{E}_1(r)h(x,r)x\mathrm{d}x, \tag{1}$$

where $\mathcal{E}_1(r)$ and $h(x,r)$ are, respectively, the expected energy consumed by the one-hop transmission of a sensor which is at a distance x away from the access point and the expected number of hops that sensor's packet need to make to reach the access point. With a transmission range of r, a sensor has, on the average, $(\frac{r^2}{R^2}N - 1)$ neighbors who listen to that sensor's transmission. We thus have

$$\mathcal{E}_1(r) = L(e_{tx} + e_{out}\bar{r}^4 + (\frac{r^2}{R^2}N - 1)e_{rx}). \tag{2}$$

Since the distances covered by each hop are independent and identically distributed, we have, from Wald's Identity,

$$h(x,r) = \begin{cases} \frac{x}{D_1(r)} & \text{if } x > r \\ 1 & \text{otherwise} \end{cases} \tag{3}$$

where $D_1(r)$ is the expected distance toward the access point that one hop can cover. A lower bound on $D_1(r)$ is given by

$$D_1(r) \leq r\sum_{n=1}^{N-1} B(N-1, n, \frac{r^2}{2R^2})\frac{2n}{2n+1},$$

where $B(u, U, s)$ denote the probability mass at the value u of a Binomial random variable with total U trials and a success probability s. With an upper bound on $D_1(r)$, we obtain an lower bound on $\mathcal{E}_{\text{AdHoc}}(r)$. Combining (1,2,3), we have

$$\begin{aligned} &\mathcal{E}_{\text{AdHoc}}(r) = N\mathcal{E}^{(1)}_{\text{AdHoc}}(r) \\ &= \frac{2N}{R^2}(\frac{1}{2}\mathcal{E}_1(r)r^2 + \frac{\mathcal{E}_1(r)}{3D_1(r)}(R^3 - r^3)) \sim \mathcal{O}(N^2). \end{aligned} \tag{4}$$

For SENMA, using H as an approximate of the distance from the mobile agent to each sensor, we have

$$\mathcal{E}_{\text{SENMA}} = NL(e_{tx} + e_{out}H^2) \sim \mathcal{O}(N). \tag{5}$$

In Figure 2 we plot the aggregated energy expenditure as a function of node density defined as the ratio of the total number N of sensors to the area πR^2 of the sensor field. For the flat ad hoc architecture (solid line), the optimal transmission range r is chosen to minimize the energy consumption. As indicated by (4,5), energy consumption grew exponentially with sensor density in the flat ad hoc architecture but only linearly in SENMA (dashed line). Orders of magnitude of improvement are expected in dense sensor network.

3. PHY AND RANDOM ACCESS IN SENMA

SENMA is an asymmetrical network where the physical and MAC layers for the sensors must be simple and distributed whereas, at the mobile agents, sophisticated algorithms and protocols may be allowed. In this paper, we focus on the PHY and MAC design for sensor reachback where the goal is to upload information in the sensor network to mobile agents. A key to low power and effective MAC is the joint PHY and MAC layer design that incorporates channel state information (CSI) at each node. A more sophisticated PHY/MAC design can be found in [19, 20].

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[1] A similar radio model is considered in [16]

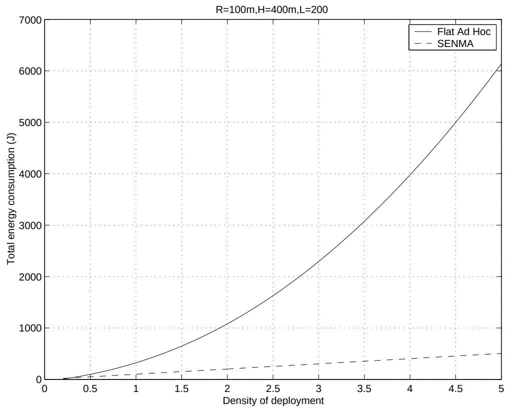

Fig. 2: Energy Efficiency Comparison.

3.1. The Transmission Protocol and the Channel

We assume a slotted time division duplexing (TDD) system. At the beginning of each slot, the mobile agent transmits a beacon, which serves as a synchronization or wake-up signaling. The sensor listens to the beacon decides if it should transmit its packet based on the opportunistic ALOHA described below.

The physical channel between a sensor node and a mobile agent is time varying and subject to fading. Let the channel state of each node be the gain γ between the sensor and the mobile agent, and it fades randomly according to distribution $F(\gamma)$. We assume that the reception power (γ) at the mobile agent has the form [25]

$$P_R = R^2 K_s e^{\xi} K r^{-\alpha} P_T,$$

where P_T is the transmission power, R a Rician or Rayleigh random variable, ξ a Gaussian random variable, r the distance from the mobile agent and α a propagation constant.

We consider a DS-CDMA system where each sensor uses a random spreading sequence of spreading gain G. The mobile agent uses the matched filter or the linear MMSE receiver. In both cases, simultaneous reception from transmitting sensors are possible. In other words, the mobile agent has a multiuser physical layer.

We assume that a packet is successfully demodulated if the signal to interference ratio (SIR) at the output of the linear receiver front-end is greater than a threshold β, which is a function of the modulation and the error control code used. For random signatures, large network size, and high spreading gains, the SIR can be approximated by a simple function of the received powers, according to Tse and Hanly [26]. For the linear MMSE receiver, given that K users transmit and their channel states are given by γ_i, the transmission from user i is successful if

$$\frac{\gamma_i}{\sigma^2 + \frac{1}{G}\sum_{k=1,k\neq i}^{K} \frac{\gamma_i \gamma_k}{\beta\gamma_k + \gamma_i}} > \beta.$$

3.2. Opportunistic ALOHA

Opportunistic ALOHA, first considered in [27, 28], is a scheme that incorporates channel state information in the ALOHA protocol. Each sensor estimates its fading state γ during the period when the mobile agent transmits the beacon. The node then flips a biased coin with the probability $s_n(\gamma)$ of being ”head”, where n is the size of the network. If the outcome is ”head”, the node transmits its packet. Otherwise, the node is silent for the current slot and restarts in the next slot. Note that although all nodes use the same probability mass function, because the fading conditions are different, the probability of transmission for one node is different from that of others.

Opportunistic ALOHA allows each sensor to transmit only when it has a favorable fading state, and the chance of success is high. A by product of such a strategy is that it can operate without a feedback channel from the mobile agent. This is particularly important for sensor network because informing the sensor that its packet has successfully received—a process that implicitly assumed by the standard ALOHA—is nontrivial and may require substantial system resources when the number of sensors is large, which makes it difficult for the sensor to know when it should stop its transmission. The opportunistic ALOHA shuts off the sensor automatically as the mobile agent moves away from the sensor.

A key design parameter is the transmission probability $s_n(\gamma)$. The optimal design of $s_n(\gamma)$ appears to be difficult in general. For large network size, however, we can use asymptotic analysis of the ALOHA throughput as a guide. Along this line, we have found in [28, 29] that the following simple scheme achieves the throughput of G—the spreading gain of the CDMA system:

$$s_n(\gamma) = \min\{\frac{e^{\frac{\gamma}{P_T}}}{\gamma^{\delta+1}}\frac{\mu}{n}, 1\}1_{\gamma\geq\gamma_0} \tag{6}$$

where P_T is the transmitter power, μ a parameter to be optimized and related to average number of packets transmitted in a slot network-wide, δ the parameter used in designing the a posteriori channel distribution, γ_0 an arbitrarily small constant, and $1_{\mathcal{A}}$ the indicator function.

Before we present an analysis of this scheme, we note here the obvious connection between the channel state γ and the probability of transmission. For weak channels with small γ, the probability of transmission is small, and the node is likely to be silent. If the node is in a favorable fading, *i.e.,* when γ is large, the node is almost certain to transmit.

3.3. Analysis and Interpretations

We have performed the analysis of ALOHA with CSI under a general reception model [28]. Outlined below are the major steps of our analysis. We will assume symmetrical arrivals, *i.e.,* the arrival rate at each sensor is the same. It is the asymmetry induced by each user's fading state that we will exploit.

We will first consider the network of n nodes, each transmits with probability $s_n(\gamma)$. The unconditional probability of transmission is given by $p_{s_n} = \int_{-\infty}^{\infty} s_n(\gamma)dF(\gamma)$ where $F(\gamma)$ is the (prior) fading distribution given by nature.

Because a node does not always transmit, the mobile agent will only ”see” certain types of channels. In other words, if the nature gives a prior channel distribution $F(\gamma)$, and the transmission probability at each node is $s_n(\gamma)$, the channel distribution at the receiver is given by the a posteriori distribution

$$\tilde{F}_{s_n}(\gamma) \triangleq \frac{1}{p_{s_n}} \int_{-\infty}^{\gamma} s_n(\gamma) dF(\gamma)$$

It is this a posteriori distribution that will affect the reception probability.

We show in [28] that the maximum achievable throughput of an n-user ALOHA system with CSI is

$$\lambda_n(s_n(\cdot)) \triangleq \sum_{k=1}^{N} \binom{N}{k} (1-p_{s_n})^{N-k} \, p_{s_n}^k C_k(\tilde{F}_{s_n}(\cdot)), \qquad (7)$$

where $C_k(\tilde{F}_{s_n}(\cdot))$ is the average number of received packets when k nodes transmit. Note that the average is based on the a posteriori channel distribution $\tilde{F}_{s_n}(\cdot)$.

The maximum asymptotic stable throughput (AST) is then defined as

$$\lambda_\infty(\{s_n(\cdot)\}) \triangleq \liminf_{n\to\infty} \sum_{k=1}^{n} \binom{n}{k} (1-p_{s_n})^{n-k} p_{s_n}^k C_k(\tilde{F}_{s_n}(\cdot)). \qquad (8)$$

If we consider the class of transmission probabilities $s_n(\gamma) = \min\{\frac{x}{n}\frac{d\tilde{F}}{dF}, 1\}$ of which given in (6) is a special case, we can then show that the maximum asymptotic stable throughput (AST) is given by

$$\lambda_\infty(P_T) = \sup_{x, \tilde{F}(\cdot)} e^{-x} \sum_{k=1}^{\infty} \frac{x^k}{k!} C_k(\tilde{F}(\cdot)). \qquad (9)$$

The above optimization requires choosing the optimal target a posteriori distribution $\tilde{F}$. A good choice of target distributions, from our preliminary analysis, is the class of fading distributions with roll-off δ.

We can also at the same time evaluate what happens when no channel state information is used. For such cases, we show that the maximum asymptotic stable throughput (AST) has a similar form

$$\lambda_\infty^o(P_T) = \sup_x e^{-x} \sum_{k=1}^{\infty} \frac{x^k}{k!} C_k(F(\cdot)).$$

Note that the prior channel distribution F is used in contrast to $\tilde{F}$ when CSI is used.

We are now ready to state a theorem that highlights the key advantage of opportunistic ALOHA.

Theorem 1 ([28]) *The asymptotic throughput with CSI is lower bounded by the spreading gain G for all P_T. In particular,*

$$G \le \lambda_\infty(P_T) \le G + G/\beta, \quad \forall P_T, \beta > 1$$

In contrast, The asymptotic throughput without CSI diminishes with P_T, i.e., $\lambda_\infty^o(P_T) \to 0$ as $P_T \to 0$.

The significance of the above theorem is that substantial throughput can be realized with arbitrarily small transmitter power at each node. Such a claim is due to the fact that there are a large number of nodes, and always some nodes have a good channel. In other words, opportunistic ALOHA exploits multiuser diversity.

4. CONCLUSION

We have proposed SENMA, an architecture for large low power sensor network. The key feature of SENMA is the addition of mobile agents that shifts processing complexities away from sensors. As a result, SENMA offers considerable advantage in energy efficiency over the flat ad hoc network architecture. We also proposed a joint design of PHY/MAC layer that leverages advantages of mobile agents and exploits the inherent node redundancies. A wide range of design options at different levels of the protocol stack are being explored for SENMA and for specific applications.

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