Optimized Transmission Power Levels in a Cooperative ARQ Protocol for Microwave Recharged Wireless Sensors

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***Abstract*— The Generic Autonomous Platform for Sensor Systems, or GAP4S, is a maintenance-free wireless sensor network in which the sensor node battery does not need to be replaced. Power is delivered to the sensor node via a microwave signal that is radiated by a base-station. The base-station also acts as the entry point to a wider communication network, e.g., the Internet.**

This paper describes an automatic repeat request (ARQ) protocol that may be used in GAP4S to yield reliable and fair data transmission from the sensor nodes to the base-station. The protocol takes advantage of cooperative communication, whereby neighboring sensor nodes help during the retransmission process. The transmission power level is optimized at each sensor node to increase the saturation throughput of the ARQ protocol.

I. INTRODUCTION

The deployment of sensor networks permits the distributed detection and estimation of various parameters related to a variety of commercial and military applications. Some applications include security, medical monitoring, machine diagnosis, chemical and biological detection [1]. Wireless sensor networks offer many benefits [2]–[6], including a reduced installation cost, ability to rapidly reconfigure the data acquisition, and safe deployment in inhospitable physical environments. The wireless networking of these sensor nodes allows them to jointly organize themselves in large sensing tasks, thus greatly improving the accuracy of the information provided to the user.

An interesting step forward in this field is represented by maintenance-free solutions, e.g, solutions whereby sensor node or battery replacement is not required. Two examples are the PicoRadio project at Berkeley and the μAMPS (with base-station) at MIT. Both projects aim at short, or very short transmission distance (2-10 m), low cost sensor nodes, and deployment of a large number of nodes, densely distributed over the area of interest. At the sensor node, the foreseen power dissipation level is below 100 μW. At these power levels it may be possible to energy-scavenge or harvest [4] directly from the environment, thus avoiding the use of conventional batteries. To cope with the resulting short transmission range, ad-hoc multi-hop networking is envisioned.

The Generic Autonomous Platform for Sensor Systems or *GAP4S* project [7] at the University of Texas at Dallas is in many respects complementary to the effort mentioned above. It is suitable for those applications in which the energy harvesting from the environment is neither possible, nor efficient, nor sufficient. The required power is provided by a (mini) base-station that remotely recharges the sensor node on-board battery via a microwave (MW) signal. For the purpose of both recharging from and transmitting directly to the base-station, the sensor nodes in the GAP4S architecture must be inside the footprint of the base-station — possibly mobile — that represents the entry point to a wider communication network, e.g., the Internet. At any time, the radius of the footprint may range up to hundred meters. The MW signal generated by the base-station is also used to distribute slot synchronization, and transmit acknowledgments and other control packets to the sensor nodes. The base-station may use directional receiving antennas to ensure best power provisioning and full-duplex connectivity to the sensor nodes. Communication from the sensor node to the base-station is single-hop and takes place on a radiofrequency (RF) channel.

The goal of this paper is to increase the sensor node to base-station saturation throughput in the power-constrained GAP4S architecture. This goal is accomplished by making use of a *fair and reliable* ARQ protocol, that is based on *cooperative* radio communication, combined with a transmission power level that is *individually* chosen at each sensor node. To clarify this claim some further explanation is necessary.

Fairness is accomplished by giving network access to each sensor node, proportionately to its generated data rate. *Reliable* data delivery against transmission errors is accomplished by means of code redundancy and an automatic repeat request (ARQ) protocol. The main philosophy adopted is to keep the sensor node as simple as possible. The base-station is responsible for scheduling collision-free transmissions and retransmissions at the sensor nodes, and guaranteeing fairness. The objective is accomplished by taking into account the effect of transmission impairments on both recharging and transmission wireless operations. Sensor nodes that are within earshot of the source are allowed to *cooperate* with one another, by making use of the received broadcast signal (intended for the base-station) and helping with the retransmission process (when necessary). It is well-known that cooperative radio communication improves the overall capacity of wireless links [8]–[11]. The essence of the idea lies in that the destination (the base-station) benefits from data frames arriving via multiple

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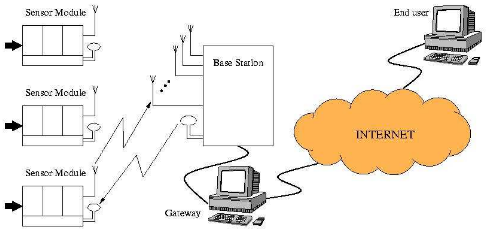

Fig. 1. GAP4S architecture

statistically independent paths, a concept known as spatial diversity. Cooperative communication is believed to bring several advantages to wireless networks in general, and it may become especially attractive for networks whose nodes have strict resource constraints, such as sensor networks. In this paper, cooperative communication is accomplished by requesting a node — other than the source — to retransmit the data frame when the first transmission is not successful. In a sense, cooperative communication provides a way to borrow energy from other nodes to accomplish successful data delivery. Due to the peculiarity of the GAP4S architecture, some sensor nodes may be subject to higher (lower) recharge rates than others. Taking this factor into account, the transmission power level at each sensor node is *individually* chosen to improve how the delivered energy is put to work at the sensor nodes.

II. GAP4S DESCRIPTION

This section provides a brief description of the GAP4S architecture. More information can be found in [12].

Fig. 1 gives a description of the GAP4S architecture. Wireless sensor nodes are distributed on either given fixed or mobile positions. Their positions are geographically restricted to a predetermined area surrounding a power-rich base-station, i.e., the footprint of the base-station. Each sensor node sends generated data directly to the base-station via a RF wireless uplink channel. A directional antenna may be used at the base-station to improve the received signal to noise ratio (SNR). Each sensor node recharges its battery via the received MW power that is continuously radiated by the base-station in an omnidirectional way. The radiated recharge power is constrained to safety levels. A simple modulation of the MW link provides the downlink channel from the base-station to the sensor nodes. The downlink channel enables to distribute slot synchronization, poll the sensor nodes for collision free uplink transmission, send ACK/NAK for received data frames, download software updates, and remotely program sensor nodes for the desired sensing operation. Unlike other solutions, downlink transmission is not costly to the sensor nodes as it occurs over the MW recharging channel. The base-station is also responsible for ensuring that sensed data is collected reliably and fairly from across the entire set of sensor nodes, despite their location. For this purpose it is necessary to design a data link protocol that makes the RF channel reliable and equally available to the sensor nodes. The general philosophy followed to accomplish this objective is to use dumb and low power-consumption sensor nodes and implement all the network intelligence at the base-station.

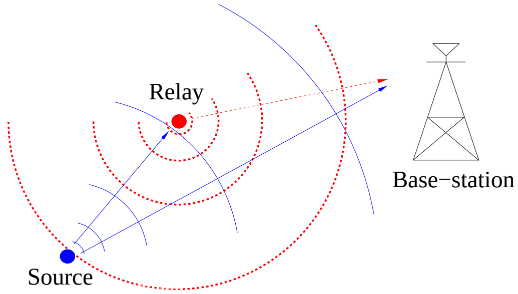

Fig. 2. Cooperation between two sensor nodes

III. THE ARQ PROTOCOL FOR GAP4S: $ARQ-C$

The cooperative ARQ protocol — $ARQ-C$ for short — takes advantage of the broadcast nature of the sensor node wireless transmission to reach the base-station. In what follows, it is assumed that the MW downlink is error free. Fig. 2 sketches how the $ARQ-C$ protocol works. When the data frame transmitted by a sensor node, (*the source*), is not successfully received, the base-station requests the frame retransmission by means of a second sensor node (*the relay*). The relay may have *overheard* the transmission of the source data frame, and stored the frame temporarily. If chosen wisely, the relay may increase the probability of delivering the data frame successfully, without requiring any further retransmission. From a different perspective, the relay may lower the transmission power level that is required to deliver the data frame to the base-station. In the $ARQ-C$ simplest version, if either the relay does not overhear the source transmission correctly, or the relay retransmission attempt is unsuccessful, the base-station requests that the source starts the data frame transmission anew.

The relay is viewed as a *cooperating node* in the effort of delivering the source data frame to the base-station. The cooperating node offers both space diversity and its own power budget. The $ARQ-C$ protocol in GAP4S can use multiple cooperating nodes to help the same source. Assume that a number of sensor nodes are suitable to act as cooperating nodes for the same source. For each retransmission attempt, one of these sensor nodes is chosen to be the relay. The base-station makes such choice, effectively creating a situation of load (and power) balancing among the sensor nodes. The base-station may choose in a probabilistic way, according to some predefined distribution values. Note that the required intelligence is entirely residing at the base-station. Sensor nodes are ordered when to overhear and when to transmit by the base-station via the recharging MW channel.

The above solution is not to be confused with the conventional store and forward solution. In fact, the latter is a layer 3 solution that requires routing tables at the sensor nodes. The former is a layer 2 solution in which the base-station is allowed to choose cooperating nodes at each retransmission attempt.

IV. COMPUTING THE TRANSMISSION POWER LEVELS AT THE SENSOR NODES

Fig. 3 shows the transmission flow model for the $ARQ-C$ protocol. To deal with the data frame retransmissions, sensor

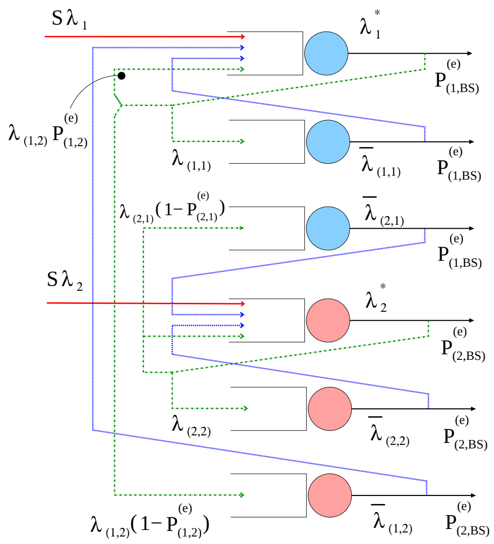

Fig. 3. ARQ-C: two-node transmission flow model

node j (in the figure, $j = 2$) has multiple queues. Each queue contains the data frames that node j retransmits on behalf of a given node i (in the figure, $i = 1$). Note that $i = j$ is permitted and represents the case of no cooperation. Upon a transmission error toward the base-station — occurring with probability $P^{(e)}_{(i,BS)}$ — at source i data frame rate λ^*_i is divided into all the possible relay nodes, i.e., $\lambda_{(i,j)}$ is the rate of data frames that are affected by a transmission error and require (through the centralized control at the base-station) relay j to attempt retransmission[1]. Sensor node j can indeed act as relay only if the transmission from sensor node i to sensor node j is error free — occurring with probability $(1 - P^{(e)}_{(i,j)})$. $\overline{\lambda}_{(i,j)}$ is the rate of data frames that successfully reach sensor node j from sensor node i, i.e., $\overline{\lambda}_{(i,j)} \leq \lambda_{(i,j)}$. The total rate of data frames transmitted at sensor node i is $\lambda^*_i + \sum_j \overline{\lambda}_{(i,j)}$.

An exact mathematical formulation to find the maximum saturation throughput (S) for the $ARQ-C$ protocol can be found in [12]. The formulation determines both the relays for each source i, and the rate of data frame retransmissions that is handled by relay j, i.e., $\lambda_{(i,j)}$. The energy flow constraint must be satisfied, i.e., at sensor node i the average transmission power — the product of the power used to transmit each data frame and $\lambda^*_i + \sum_j \overline{\lambda}_{(i,j)}$ — must be less than or equal to the power received through the MW signal radiated by the base-station. In the formulation, it is possible to reduce the number of relay candidates for sensor node i, by considering only sensor nodes j such that $P^{(e)}_{(i,j)} \leq P^{(e)}_{(i,BS)}$. The formulation in [12] is linear (LP) when the transmission power level at the sensor nodes is given as an input. When the transmission power level at each sensor node is a variable to optimize — the case being studied here — the formulation becomes non-linear.

The exact solution of the latter case is made difficult by the nature of the $ARQ-C$ protocol. When a sensor node is using a high energy per bit value to transmit data[2], it becomes a good relay candidate for many other sensor nodes. However, if the energy per bit is chosen too high while each data frame transmission has a lower error probability, the maximum number of frames that can be transmitted per time unit by the sensor node is severely limited by its power constraint. Consequently, the amount of effective cooperation may be very limited.

At each sensor node, a trade-off must be found between the error probability and the maximum number of transmitted data frames.

To solve this non-linear problem, a heuristic is proposed that finds a distribution of the transmission power levels at the sensor nodes. The heuristic is based on an iterative approach. The objective of the iteration is to reach a balance between the recharging rate and the (re)transmission power at every sensor node. Notice that sensor nodes which are closer to the base-station receive more recharging power. These sensor nodes can therefore sustain a higher energy per bit transmission than other sensor nodes. The challenge is to increase the energy per bit of the former sensor nodes gradually, in order to allow cooperation to still take place.

First, an initial solution is found, using a given distribution of the transmission energy per bit at the sensor nodes, i.e., $\{E^{(1)}_{b_i}, i \in N\}$, where N is the set of sensor nodes. With a predetermined transmission energy per bit at each sensor node, the LP formulation in [12] is easily solved. From the LP solution it is possible to calculate the energy that is dissipated for transmission at sensor node i, i.e., $\lambda^*_i + \sum_j \overline{\lambda}_{(i,j)}$. At the k^{th} iteration, the power constraint equation at sensor node i is

$$(\lambda^*_i + \sum_j \overline{\lambda}_{(i,j)}) \cdot L \cdot (E^{(k)}_{b_i} + X^{(k)}_{Eb_i}) = P^{rec}_i \qquad \forall i \in N, \quad (1)$$

where L is the number of bits in the data frame, P^{rec}_i is the recharging power, and $X^{(k)}_{Eb_i}$ is the excess energy per bit — i.e., energy received but not used. Solving Eq. 1 for $X^{(k)}_{Eb_i}$, a new value of the energy per bit is computed,

$$E^{(k+1)}_{b_i} = E^{(k)}_{b_i} + E_R \cdot X^{(k)}_{Eb_i} \quad \forall i \in N, \qquad (2)$$

where E_R is a constant value in the $(0, 1]$ range. The value chosen for E_R determines how gradually the energy per bit is increased at each iteration. With the new values $\{E^{(k+1)}_{b_i}, i \in N\}$, the LP formulation in [12] is solved again.

This step is repeated until the value of the saturation throughput S does not improve anymore.

V. RESULTS

This section reports saturation throughput values that are computed for the $ARQ-C$ protocol. For comparison, values

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[1] Notice that $\frac{\lambda_{(i,j)}}{\lambda^*_i}$ is equal to the value of the probability that the base-station chooses sensor node j to be the relay for source i.

[2] Each sensor node may both transmit its own data and retransmit other sensor nodes' data.

are reported for two cases: (1) the transmission energy per bit is a given input, and (2) the energy per bit is optimized using the heuristic described in Section IV.

The following assumptions are used. Both path loss and fading are taken into account in the RF uplink transmission. Only path loss is taken into account in the MW downlink recharging signal. The path loss coefficient $n = 3.5$ is used. Fading is assumed to be slow and flat Rayleigh; i.e., the fading coefficients are considered constant over a single frame transmission. The fading experienced by each frame transmission is statistically independent of the fading experienced by any other frame transmission. More details on the models used for path loss and fading can be found in [12].

It is assumed that the MW downlink channel is error free. On the RF uplink channel, data frames are augmented with a cyclic redundancy (CRC) code. Each block contains B bits (including the CRC bits). The probability of receiving a frame incorrectly (error probability) is a function of both the instantaneous signal to noise ratio and the code used to add redundancy to the transmitted data. The probability of detecting an erroneous codeword is upper bounded by the expression reported in [13]. It is assumed that binary PSK with soft decoding is employed. The CRC is used to detect the case of an erroneous codeword decoding, in which case a retransmission is requested. We assume that the CRC is able to detect all erroneous codewords.

Results are obtained using the GAP4S frequencies, i.e., 433 MHz for the RF uplink and 2.4 GHz for the MW downlink. Data frames have fixed length and carry $B = 128$ bits (data plus CRC). Each frame is encoded into 256 bit codewords using a rate-compatible punctured convolutional (RCPC) code with rate 1/2, parent code rate of 1/4, puncturing period of 8, and memory of 4 [14]. The recharge power that is constantly radiated by the base-station is set at $P_{BS} = 10\ W$. It is assumed that the energy received by the sensor antenna is fully transfered into its battery, and circuitry losses are negligible at the sensor node. It is assumed that the energy consumption at the sensor node is due to transmissions only. The consumption of the other modules at the sensor node, e.g., analog-digital conversion, processing, power management, receiver, is neglected. Traffic is uniform.

The saturation throughput is computed by solving the LP formulation in [12] using ILOG Cplex [15]. Two initial distributions of the transmission power levels at the sensor nodes are considered:

- Scenario A: the transmission energy per bit (E_b) is the same at each sensor node,
- Scenario B: the transmission energy per bit at each sensor node is set to yield the same time-average signal to noise ratio (SNR) at the base-station.

Results are averaged over 10 distinct instances of sensor node distribution. Each instance is obtained by randomly distributing 200 sensor nodes within a circular footprint of radius $R = 50$m. The base-station is at the center of the footprint. The polar coordinates of each sensor node with respect to the base-station are randomly chosen using a uniform distribution of the angle in the $[0, 2\pi)$ interval, and a triangular distribution of the magnitude in the $(0, R]$ interval, i.e., the density of sensor nodes is constant over the circular footprint.

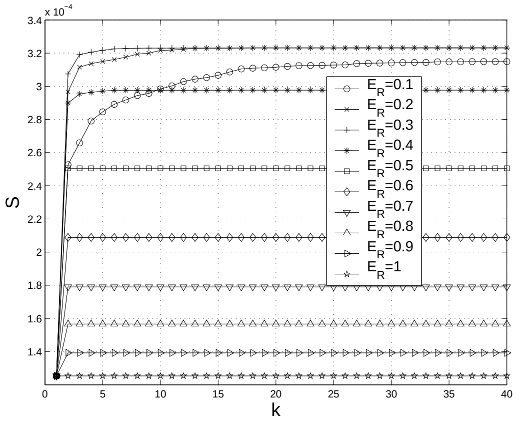

Fig. 4. Scenario A: saturation throughput (S) vs. number of iterations (k)

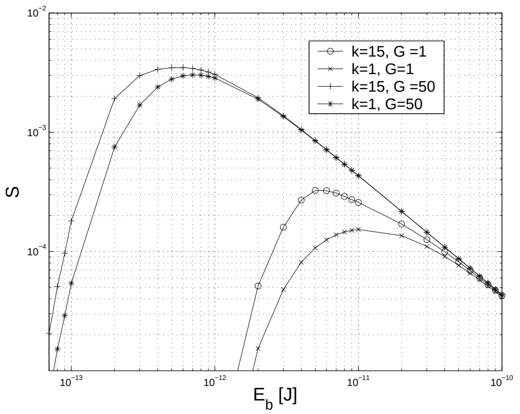

Fig. 5. Scenario A: saturation throughput (S) vs. $\{E_{b_i}^{(1)} = E_b, \forall i \in N\}$

Fig. 4 shows the increase of saturation throughput (S) with the number of iterations, for various values of E_R. The curves are obtained using an antenna gain at the base-station of $G = 1$ and a transmission energy per bit $E_b = 5 \cdot 10^{-12}$. When E_R is close to 1, the result found by the heuristic is not satisfactory. That is because the energy per bit at the sensor nodes that are close to the base-station is increased too quickly at the first few iterations. When E_R is close to 0, the saturation throughput increases slowly, thus requiring a large number of iterations. A good compromise is found for $E_R = 0.3$, which is the value chosen to obtain the next plots.

Fig. 5 reports a set of results that are obtained using scenario A. Two antenna gains are used at the base-station: $G = 1$ and $G = 50$[3]. For each gain, two curves are plotted: ($k = 1$) is the solution found before running the heuristic, i.e., all the sensor nodes use the same E_b, and ($k = 15$) is the solution found by the heuristic at the 15th iteration. A significant throughput gain is obtained by the heuristic when E_b is small.

In Fig. 6 the average excess power (derived from the excess energy, $\{E_{b_i}^{(k)}, i \in N\}$) of the sensor node is plotted versus the

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[3] When $G = 50$ the smart antenna main lobe of the radiation pattern must point at the transmitting sensor node.

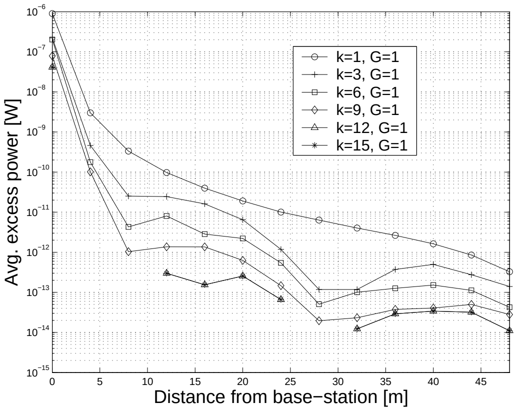

Fig. 6. Scenario A: average excess power vs. distance between sensor node and base-station

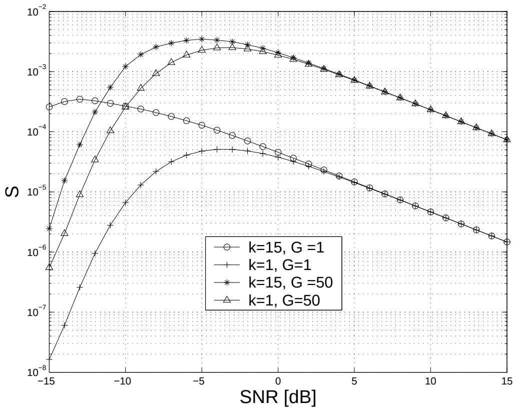

Fig. 7. Scenario B: saturation throughput (S) vs. the initial value of SNR at the base-station

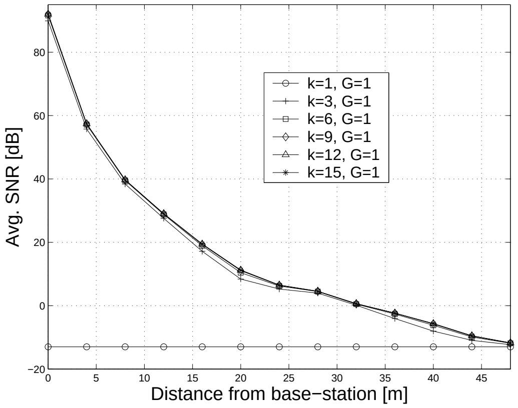

Fig. 8. Scenario B: average SNR vs. distance between sensor node and the base-station

distance between the sensor node and the base-station. The distribution is shown at the iteration number $k = 1, 3, 6, 9, 12, 15$. The initial value ($k = 1$) is $E_b = 5 \cdot 10^{-12}$. Significant changes take place during the first few iterations. After a relatively small number of iterations, changes are practically negligible. The curves for $k = 12$ and 15 appear segmented, as they show only the non-zero values.

Fig. 7 reports results that are obtained using scenario B. Two antenna gains are used at the base-station: $G = 1$ and $G = 50$. For each gain, two curves are plotted: ($k = 1$) is the solution found before running the heuristic, i.e., all the sensor nodes use the same SNR, and ($k = 15$) is the solution found by the heuristic at the 15^{th} iteration. The heuristic yields substantial gain when $G = 1$.

In Fig. 8 the average SNR at the base-station is plotted against the distance between the sensor node and the base-station. The distribution is shown at the iteration number $k = 1, 3, 6, 9, 12, 15$. The initial value ($k = 1$) is $SNR = -13$dB. After the third iteration, changes are practically negligible.

VI. CONCLUSION

The paper briefly described the microwave recharged wireless sensor network GAP4S. A cooperative ARQ protocol was proposed for the GAP4S architecture. The level of cooperation among the sensor nodes, and the transmission power at each individual sensor node were jointly optimized to improve the achievable saturation throughput of the ARQ protocol. The proposed solution yields fair access to all sensor nodes and provides reliable communication against transmission errors.

The obtained results indicate that with a relatively low level of the microwave signal radiated by the base-station (10 W) it is possible to reach footprint sizes up to hundred meters. Possible fields of applications for GAP4S span from building, airport and monument monitoring and control, to industrial and agricultural activities, personal safety, monitoring and alerting systems.

REFERENCES

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *Elsevier Computer Networks*, vol. 38, no. 4, pp. 393–442, March 2002.

[2] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy Efficient Protocol for Wireless Microsensor Networks," in *Proceedings of Hawaii Conference on System Sciences*, January 2000, pp. 4–7.

[3] "http://www.janet.ucla.edu/wins."

[4] "http://bwrc.eecs.berkeley.edu/research/pico_radio/."

[5] "http://www-mtl.mit.edu/research/icsystems/uamps."

[6] "http://users.ece.gatech.edu/∼weilian/sensor."

[7] "http://www.nsf.gov/awardsearch/showaward.do?awardnumber=0225528."

[8] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative Communication in Wireless Networks," *IEEE Communications Magazine*, 2004, accepted for publication.

[9] A. Sendonaris, E. Erkip, and B. Aazhang, "User Cooperation Diversity–Part I: System Description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, November 2003.

[10] ——, "User Cooperation Diversity–Part II: Implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, November 2003.

[11] E. Zimmermann, P. Herhold, and G. Fettweis, "The impact of cooperation on diversity-exploiting protocols," in *In Proceedings of 59th IEEE Vehicular Technology Conference (VTC Spring)*, May 2004.

[12] M. Tacca, P. Monti, and A. Fumagalli, "Cooperative and Non-Cooperative ARQ Protocols for Microwave Recharged Sensor Nodes," Universiry of Texas at Dallas, Tech. Rep. UTD/EE-02/2004, July 2004.

[13] M. Janani, A. Hedyat, T. Hunter, and A. Nosratinia, "Coded Cooperation in Wireless Communications: Space-Time Transmission and Iterative Decoding," *IEEE Transactions on Signal Processing*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[14] J. Hagenauer, "Rate-Compatible Punctured Convolutional Codes (RCPC Codes) and their Applications," *IEEE Transactions on Communications*, vol. 36, no. 4, pp. 389–400, April 1988.

[15] "http://www.ilog.com/products/cplex/."