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

Paolo Monti, Marco Tacca and Andrea Fumagalli
The OpNeAR Lab, Erik Jonsson School of Engineering and Computer Science
The University of Texas at Dallas, Richardson, TX 75080
Email:{pxm017500,mtacca,andreaf}@utdallas.edu

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 [1]. Wireless sensor networks offer many benefits [2]–[5], including a reduced installation cost, ability to rapidly reconfigure the data acquisition, and safe deployment in inhospitable physical environments.

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 total power dissipation level is below 100 μW. At these power levels it may be possible to energy-scavenge or harvest [3] 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 requested.

The Generic Autonomous Platform for Sensor Systems or *GAP4S* project [6] 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 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 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 both code redundancy and automatic repeat request (ARQ) protocol. The approach adopted here is to keep the sensor node as simple as possible. The base-station is responsible for both scheduling collision-free transmissions and retransmissions at the sensor nodes, and guaranteeing fairness. Sensor nodes that are within earshot of each other are allowed to cooperate in securing successful uplink transmission towards the base-station. It is well-known that co-operative radio communication improves the overall capacity of wireless links [7], [8]. The essence of the idea lies in that the destination (e.g., the base-station) benefits from data frames arriving via multiple statistically independent paths, i.e., spatial diversity. Cooperative communication is believed to bring several advantages to wireless networks in general, and it may become especially attractive for nodes that have strict power constraints.

In this work, 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

---

This research was supported in part by NSF Grants No. CNS-0082085, CNS-0435429 and ECS-0225528.

0-7803-8938-7/05/$20.00 (C) 2005 IEEE

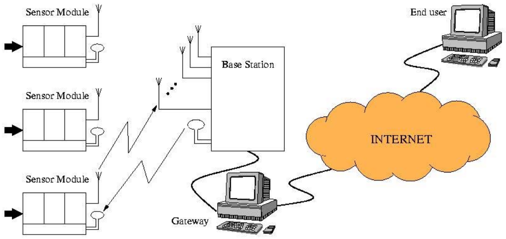

Fig. 1. GAP4S architecture

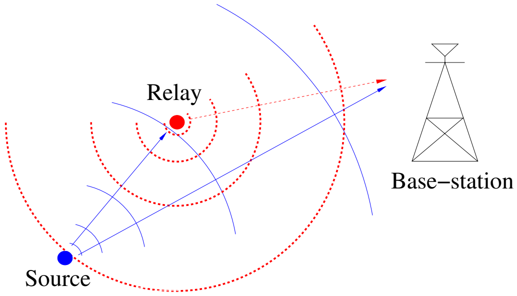

Fig. 2. Cooperation between two sensor nodes

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* optimized to improve the way 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 is available in [9].

Fig. 1 gives a description of the GAP4S architecture. The sensor nodes are assumed to be stationary. 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 all directions. The radiated recharge power may be constrained to safety levels. A 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 data is collected reliably and fairly from across the entire set of sensor nodes, irrespective of 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 task is to use dumb and low power-consumption sensor nodes and implement all the network intelligence at the base-station.

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

A simple cooperative ARQ protocol — $ARQ-C$ for short — is described in this section. In what follows, it is assumed that the MW downlink channel 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 that the frame retransmission be performed by 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 $ARQ-C$ protocol the base-station broadcasts the following information: the identification of the source node that transmits next, the data frame to be transmitted, and the node that is chosen to be the relay for the current data transmission. If either the relay does not overhear the source transmission successfully, or the relay retransmission attempt is unsuccessful, the base-station begins a new transmission round, i.e., it broadcasts again the identification of source, data frame and relay.

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, more importantly, its own power budget. The $ARQ-C$ protocol in GAP4S may 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 $ARQ-C$ solution is not to be confused with the conventional packet 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 chooses a cooperating node to perform the retransmission attempt.

IV. COMPUTING TRANSMISSION POWER LEVELS AT SENSOR NODES

In the remainder of the paper, the objective is to increase the saturation throughput from the sensor nodes to the base-station. The main limiting factor for throughput is the power made available to the sensor nodes. The power usage is determined by two factors, i.e., the chosen per-bit transmission

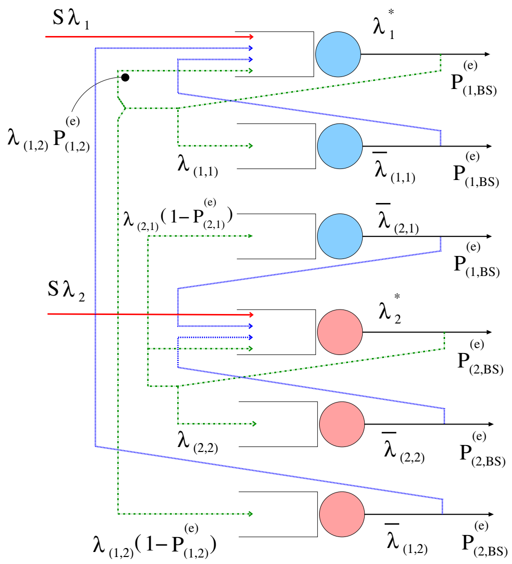

Fig. 3. ARQ-C: two-node transmission flow model

energy and the amount of per-node frame retransmissions. Taking into account these few observations, the base-station may choose the relay node for each frame transmission using the following flow model.

The transmission flow model for the $ARQ-C$ protocol is shown in Fig. 3. Let $p_{(i,j)}$ be the probability that the base-station selects node j (in the figure, $j = 2$) to be the relay for source i (in the figure, $i = 1$). The flow model captures four mutually exclusive transmission sequences. ($\mathcal{A}$) The frame transmission at source i is successful. The departure rate for this case is $\lambda_i^*(1 - P^{(e)}_{(i,BS)})$. ($\mathcal{B}$) The frame transmission at source i is not successful and relay j cannot help with the retransmission. This is the case when relay j does not successfully overhear the transmission at source i. The flow rate for this case is $\lambda_i^* P^{(e)}_{(i,BS)} p_{(i,j)} P^{(e)}_{(i,j)}$. ($\mathcal{C}$) The frame transmission at source i is not successful and the subsequent frame retransmission at relay j is successful. The flow rate for this case is $\lambda_i^* P^{(e)}_{(i,BS)} p_{(i,j)}(1 - P^{(e)}_{(i,j)})(1 - P^{(e)}_{(j,BS)})$. ($\mathcal{D}$) The frame transmission at source i is not successful and the subsequent frame retransmission at relay j is not successful. The flow rate for this case is $\lambda_i^* P^{(e)}_{(i,BS)} p_{(i,j)}(1 - P^{(e)}_{(i,j)}) P^{(e)}_{(j,BS)}$. At the end of ($\mathcal{A}$) and ($\mathcal{C}$) the base-station may request the transmission of a new data frame. At the end of ($\mathcal{B}$) and ($\mathcal{D}$) the base-station must start a new transmission sequence for the unsuccessful data frame. The following equations are derived: $\lambda_{(i,j)} = \lambda_i^* p_{(i,j)} P^{(e)}_{(i,BS)}$, $\overline{\lambda}_{(i,j)} = \lambda_{(i,j)}(1 - P^{(e)}_{(i,j)})$.

A rigorous formulation of the maximum saturation throughput (S) based on this flow model is given in [9]. The energy flow constraint is taken into account by ensuring that the power consumption at node i does not exceed the power received through the MW signal radiated by the base-station. The power consumption at node i consists of data frame transmission power, proportional to $\lambda_i^* + \sum_j \overline{\lambda}_{(j,i)}$, and data frame reception power, proportional to $\sum_{j \neq i} \frac{\lambda_{(j,i)}}{P^{(e)}_{(j,BS)}}$. Other consumption factors are ignored in the formulation. The formulation in [9] is linear (LP) when the transmission power levels at the sensor nodes are given as input. When the transmission power level at each sensor node is a variable to optimize — i.e., 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, it becomes a good relay candidate for many other sensor nodes. However, if the energy per bit is chosen too high the maximum number of frames that can be transmitted per time unit by the sensor node may become severely limited by its power constraint. It may even become impossible for the node to help others.

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

To efficiently solve this non-linear problem, a heuristic is proposed that finds a suitable 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 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 sustain a higher than average energy per bit transmission. The challenge is to increase the energy per bit of these sensor nodes gradually, in order to allow cooperation to still take place.

First, an initial solution is found, using a given distribution of the energy per bit values at the sensor nodes, i.e., $\{E^{(1)}_{b_i}, i \in N\}$, where N is the set of sensor nodes. Using $\{E^{(1)}_{b_i}, i \in N\}$ the LP formulation in [9] is easily solved. From the LP solution one can calculate the energy that is dissipated for transmission at sensor node i, i.e., $\lambda_i^* + \sum_j \overline{\lambda}_{(j,i)}$. At the k^{th} iteration, the power constraint equation at sensor node i is

$$\left(\sum_{j \neq i} \frac{\lambda_{(j,i)}}{P^{(e)}_{(j,BS)}} \right) \cdot L \cdot E_b^{(Rx)} + \left(\lambda_i^* + \sum_j \overline{\lambda}_{(j,i)} \right) \cdot$$
$$\cdot L \cdot \left(E^{(k)}_{b_i} + X^{(k)}_{Eb_i} \right) = P_i^{rec} \quad \forall i \in N, \qquad (1)$$

where $E_b^{(Rx)}$ is the energy required to receive one bit when the sensor node acts as a relay, L is the number of bits in the data frame, P_i^{rec} is the recharging power, and $X^{(k)}_{Eb_i}$ is the excess energy per bit — i.e., the energy received but not used by node i. Solving (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 in $(0, 1]$. 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 [9] is solved again.

The above step is repeated until the value of the saturation throughput S cannot be further improved.

V. RESULTS

This section reports saturation throughput values that are obtained for the $ARQ - C$ protocol. Saturation throughput values are measured in packets per second. For comparison, values are reported for two cases: *(i)* the transmission energy per bit is a given input, *(ii)* the energy per bit is optimized using the heuristic of 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. A path loss coefficient of $n = 3.5$ is used. Fading is assumed to be Rayleigh slow and flat; 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 [9].

It is assumed that the MW downlink channel is error free. On the RF uplink channel, data frames are augmented with a cyclic redundancy code (CRC). 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 SNR and CRC. The probability of detecting an erroneous codeword is upper bounded in [8]. The CRC is used to detect the case of an erroneous codeword decoding, in which case retransmission is required. We assume that the CRC is able to detect all erroneous codewords. It is assumed that binary PSK with soft decoding is employed.

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 [10]. The recharge power 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 transferred 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. It is assumed that the energy per bit necessary to overhear a transmission is negligible, i.e., $E_b^{(Rx)} = 0\ J$. The consumption of the other modules at the sensor node, e.g., analog-digital conversion, processing, power management, receiver, is neglected. Traffic is uniform, i.e., $\lambda_i = 1, \forall i \in N$.

The saturation throughput is computed by solving the LP formulation in [9] using ILOG Cplex. Two initial distributions of the transmission power levels at the sensor nodes are considered: *(i)* scenario A: the transmission energy per bit (E_b) is the same at each sensor node, *(ii)* scenario B: the transmission energy per bit at each sensor node is chosen to yield the same time-average signal to noise ratio (SNR) received 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.

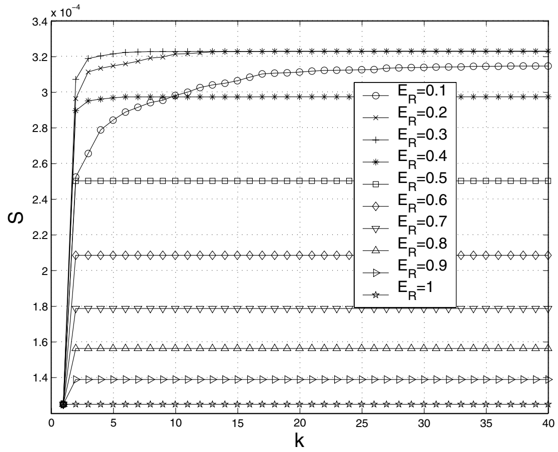

Fig. 4. Scenario A: saturation throughput (S) vs. number of iterations (k)

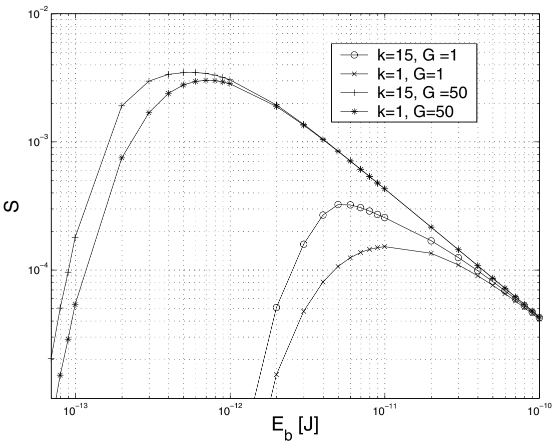

Fig. 5. Scenario A: saturation throughput (S) vs. $\{E_{b_i}^{(1)} = E_b, \forall i \in N\}$

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 an initial transmission energy per bit $E_b = 5 \cdot 10^{-12}$. As anticipated, when E_R is close to 1, the result found by the heuristic is not satisfactory. 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 other plots in the paper.

Fig. 5 reports a set of results that are obtained using scenario A. Two antenna gains, $G = 1$ and $G = 50$, are used at the base-station[1]. For each gain, two curves are plotted: ($k = 1$) is the solution found before running the heuristic, i.e., all the

---

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

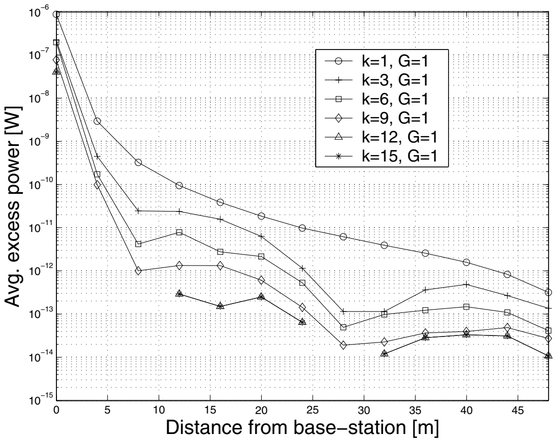

Fig. 6. Scenario A: average excess power vs. distance between sensor node and base-station

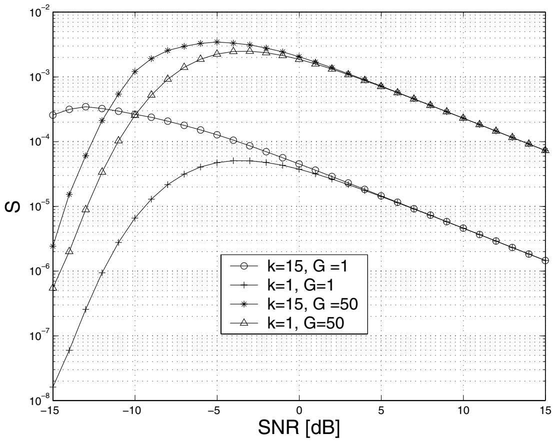

Fig. 7. Scenario B: saturation throughput (S) vs. the initial value of SNR at the base-station

sensor nodes use the same E_b, and ($k = 15$) is the solution found by the heuristic at the $15^{\rm th}$ iteration. The throughput gain obtained by the heuristic is clearly visible when E_b is small.

In Fig. 6 the sensor node excess power is plotted as a function of the sensor node distance from the base-station . These values are derived from the excess energy $\{E_{b_i}^{(k)}, i \in N\}$. The distribution of excess power is shown at iterations $k = 1, 3, 6, 9, 12, 15$. The initial value ($k = 1$) is $E_b = 5 \cdot 10^{-12}$. Tangible changes take place during the first few iterations only. The curves for $k = 12$ and 15 appear segmented as they show the non-zero values only.

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 $15^{\rm th}$ iteration. The heuristic yields tangible gain when $G = 1$.

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

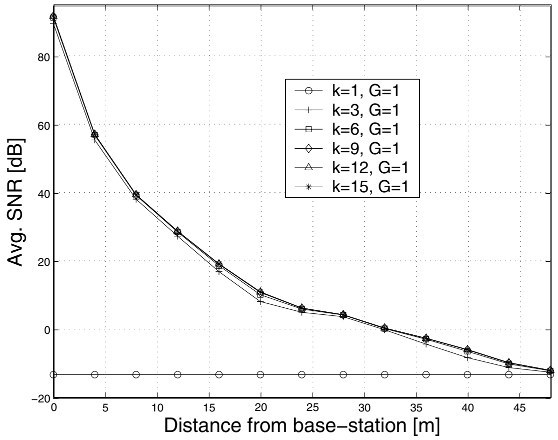

Fig. 8. Scenario B: average SNR vs. distance between sensor node and the base-station

VI. CONCLUSION

The paper described the microwave recharged wireless sensor network GAP4S. A cooperative ARQ protocol for GAP4S was presented. 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 solution found yields fair access to all sensor nodes and provides reliable communication against transmission errors.

With a 10 W microwave signal radiated by the base-station it is possible to reach footprint sizes up to hundred meters. With this transmission range, GAP4S applications may include building, airport, and monument monitoring and control, 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 COMNET*, vol. 38, no. 4, pp. 393–442, March 2002.
[2] “http://www.janet.ucla.edu/wins.”
[3] “http://bwrc.eecs.berkeley.edu/research/pico_radio/.”
[4] “http://www-mtl.mit.edu/research/icsystems/uamps.”
[5] “http://users.ece.gatech.edu/∼weilian/sensor.”
[6] “https://www.fastlane.nsf.gov/servlet/showaward?award=0225528.”
[7] A. Sendonaris, E. Erkip, and B. Aazhang, “User Cooperation Diversity–Part I: System Description,” *IEEE Trans. on Comm.*, pp. 1927–1938, November 2003.
[8] M. Janani, A. Hedyat, T. Hunter, and A. Nosratinia, “Coded Cooperation in Wireless Communications: Space-Time Transmission and Iterative Decoding,” *IEEE Trans. on Sig. Proc.*, vol. 52, no. 2, pp. 362–371, February 2004.
[9] M. Tacca, P. Monti, and A. Fumagalli, “Cooperative and Non-Cooperative ARQ Protocols for Microwave Recharged Sensor Nodes,” in *Proc. EWSN’05*, February 2005, pp. 45–56.
[10] J. Hagenauer, “Rate-Compatible Punctured Convolutional Codes (RCPC Codes) and their Applications,” *IEEE Trans. on Comm.*, vol. 36, no. 4, pp. 389–400, April 1988.