Cooperative and Non-Cooperative ARQ Protocols for Microwave Recharged Sensor Nodes

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Cooperative and Non-Cooperative ARQ Protocols for Microwave Recharged Sensor Nodes

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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 battery needs not be replaced. Power is delivered to the sensor 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 three automatic retransmission request (ARQ) protocols that may be used in GAP4S to yield reliable and fair data transmission from the sensor nodes to the base-station. Two of the protocols take advantage of cooperative communication, whereby neighboring sensor nodes help during the retransmission process. The analysis presented on the saturation throughput of the ARQ protocols helps quantify the gain achievable when cooperative communication is used in GAP4S in a variety of working conditions.

I. INTRODUCTION

The advantages and potential impact of wireless networks are widely acknowledged nowadays. The commercial introduction of wireless LAN's, as well as the ongoing research activities in ad-hoc wireless networks and — more recently — wireless sensor networks, point at the widespread and increasing interest in these networks.

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]. Conventional sensor networks require wired links between the sensing element (sensor) and a central processing unit, where all the signal processing takes place. In this case they are more commonly known as control networks [2]. Unfortunately, the wiring process is often expensive, time-consuming, fault-prone, and potentially dangerous [3].

Both the recent development of relatively inexpensive and low-power wireless micro-sensors and various significant advances in wireless networking have paved the way to wireless sensor networks [4]–[13]. Some of the many benefits of wireless sensor networks include a reduced installation cost, ability to rapidly reconfigure the data acquisition, and safe deployment in inhospitable physical environments such as disaster areas, toxic locations, and remote geographic regions. The wireless networking of these sensors allows them to organize themselves in jointly accomplishing large sensing tasks, thus greatly improving the accuracy of the information provided to the user. For example, it is possible for a class of sensors to focus on particular aspects that are pointed out by another class of sensors, and to route their data to sink nodes or end-users outside the inspected area. In some instances, sensors are capable of establishing and maintaining their communication networks, and provide missing data by coordinating themselves to recover from failures. In summary, the sensor network dynamically adapts itself to and interacts with the environment, sharing resources between the sensors and working in a power efficient way.

An interesting step forward in this field is represented by maintenance-free solutions, e.g, solutions where sensor or battery replacement is not required. 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 sensors, densely and uniformly distributed over the area of interest. At the sensor, the foreseen power dissipation level is below 100 μW to avoid the use of batteries and permit energy-scavenging or harvesting [11] directly from the environment. To cope with the resulting short transmission range, ad-hoc multi-hop networking is envisioned among the highly dense sensors. In addition, the

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large number of sensors permits cooperative interactions for data fusion.

The Generic Autonomous Platform for Sensor Systems or *GAP4S* project [14] at UTD is in many respects complementary to the two above-mentioned efforts. It is indicated for those applications in which energy harvesting from the environment is neither possible, nor efficient, nor sufficient. The power consumption at the sensor node is above the harvesting level. Such a power level is provided by a (mini) base-station that remotely recharges the sensor 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 one time, the radius of the footprint may range up to hundred meters. Communication from the sensor to the base-station takes place on a radiofrequency (RF) channel. As a result, the provided power allows for relaxed requirement on RF accuracy on the channel from the sensor to the base-station. For example, VCO instead of PLL can be used at the sensor node. The MW signal generated by the base-station is also used to distribute slot synchronization, transmit acknowledgments, and other control packets to the sensor nodes. The base-station may use smart antennas to ensure best power provisioning and full-duplex connectivity to the sensor nodes.

The objective of this paper is to propose and compare *fair* and *reliable* data protocols for GAP4S. Fairness is accomplished by giving 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 retransmission protocol (ARQ). The objective is accomplished taking into account the effect of path loss on both recharging and transmission wireless operations. The main philosophy adopted here is to keep the sensor node as simple as possible. The base-station is responsible for scheduling collision-free transmissions and retransmissions of the sensor nodes, and guaranteeing fairness. For scheduling retransmissions, three ARQ protocols are considered, trading performance for implementation complexity at the base-station. The first is a conventional ARQ, whereby transmission from the sensor node to the base-station is repeated until successfully completed. The other two protocols take advantage of *cooperative radio communication*. In simple terms, cooperative communication is accomplished by requesting a node — other than the source — to retransmit the data frame when the first transmission is not successful. Cooperative communication provides a way to *borrow* energy from other nodes to accomplish a successful data delivery. The next paragraph provides a short description of cooperative communication.

Radio networks are inherently different from wired ones, in that radio by its nature is a broadcast medium. When a node in the network transmits to a neighboring node, not only the destination node, but also other nodes within earshot receive the same signal. This phenomenon is conventionally treated as interference in the physical layer and — unless scheduling in time or frequency is provided — as collision in the MAC layer. In essence, the broadcast nature of the wireless link, as well as the fading channel that is typical of the radio transmissions, have been historically treated as a nuisance. Methods based on cooperative radio communication can turn this liability into an advantage [15]–[20]. Wireless nodes that are within earshot can cooperate by making use of the received interference and improve the overall capacity of the wireless links. The essence of the idea lies in that the destination benefits from data frames arriving via two statistically independent paths, a concept known as *spatial diversity* in wireless communications. It is believed that cooperative communication may 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 the paper, a performance comparison is carried out among the three protocols, in terms of achievable saturation throughput. The comparison is achieved by varying a number of system parameters: transmission power, footprint size, path loss exponent, and antenna gain at the base-station. Results indicate that higher throughput, or equivalently lower power consumption for a target throughput is achievable by the two cooperative protocols, when compared to the conventional ARQ protocol.

II. GAP4S DESCRIPTION

This section provides a brief description of the GAP4S architecture.

Fig. 1 gives a pictorial description of the GAP4S architecture. A number of 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 mini base-station, i.e., the footprint size of the base-station. Each sensor node

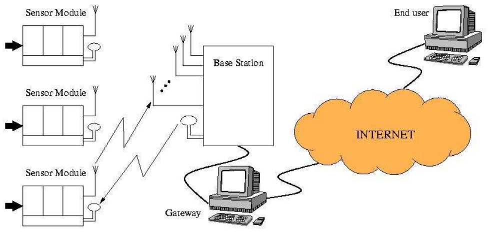

Fig. 1. GAP4S system architecture

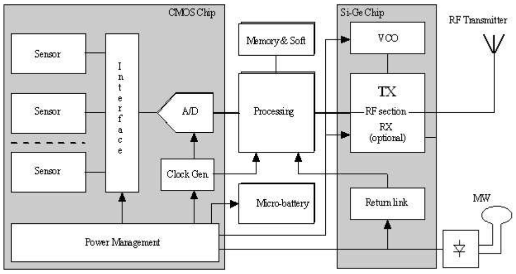

Fig. 2. GAP4S sensor node: block diagram

sends generated data to the base-station via a RF wireless uplink channel. Each sensor node recharges its battery via the received MW power that is continuously radiated by the base-station. A simple modulation of the MW link enables data transfer from the base-station to the sensor nodes (downlink channel). The chosen RF data communication and data link protocol must ensure both reliable delivery of sensor data to the base-station and low-power consumption at the sensor nodes. The general philosophy followed to accomplish this double objective is to use dumb sensor nodes and restrict all the network intelligence at the base-station. The sensor node and the base-station architectures are described next.

Fig. 2 shows the block diagram of the generic sensor node[1]. A variable number of sensors may be connected to the multi-functional sensor interface. The interface is capable of suitably handling signals coming from different sensor categories. Namely, the interface can process voltages, currents or capacitance and resistance modulations. Sensor electronic signals are then amplified by a digitally controlled gain factor. If any filtering action is required, the analog interface may host filters on demand. The A/D converter is software programmable and permits to change the resolution from 8 to 12-bits and to adapt the conversion rate from low frequency up to 40 MHz. The power management module is integrated with the sensors, the analog interface and the data converter. The power management module controls the battery charge and discharge, determines the frequency of the main clock for an optimum power use, incorporates the DC-DC converter for recharging the battery (using the MW signal from the base-station) and manages the RF module. The micro-battery is currently a commercially available component. The power management module operates its functions on the basis of expected charge-discharge operative conditions. The signal processing and memory modules are based on existing low-power commercial component. The VCO RF modules are integrated using a sub-micron Si-Ge BiCMOS technology. The return link module recovers the slot synchronism and extracts messages transmitted by the base-station over the MW channel. An *optional* module may be added to the sensor node to provide the RF reception capability that is required by two of the data link protocols discussed in Section III.

The base-station receives data from the sensor nodes on the RF channel. A directional antenna may be used at the base-station to improve the received signal to noise ratio (SNR). Continuously, the base-station radiates recharging power to the sensor nodes using the MW channel. The radiated recharge power is constrained to safety levels. The MW signal is modulated 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 sensor data is collected reliably and fairly from across the entire set of sensor nodes, despite 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.

III. THREE ARQ PROTOCOLS FOR GAP4S

This section describes three Automatic Retransmission Request (ARQ) protocols that may be used in the GAP4S to overcome transmission errors. It is assumed that transmission errors may occur only on the uplink RF channel, as the sensor node power budget limits the SNR. Transmission errors on the downlink MW channel are negligible due to the relatively high power of the MW signal.

The three ARQ protocols take into account the unique nature of the GAP4S architecture, whereby the base-

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[1] An integrated prototype of the sensor node is currently under development [21], [22]

station — characterized by non-stringent power constraints — remotely recharges the sensor nodes, broadcasts slot synchronization, polls sensor nodes for collision free uplink transmissions, and sends acknowledgments.

A. *ARQ-NC Protocol*

The ARQ-NC is a non cooperative protocol, i.e., a conventional ARQ protocol. Upon request, the sensor node transmits its data to the base-station (single hop communication). The data frame contains data encoded using an error detection and correction code. Upon the reception of a data frame either with errors that can be corrected, or no detected errors, the base-station replies with a positive ACK frame. Upon reception of a frame with detected errors that cannot be corrected, the base-station sends a NAK frame to the sensor node. In turn the sensor node retransmits the data frame until reception at the base-station is successful. Available options for this protocol are stop and wait, go back N, selective repeat, etc. [23].

B. *ARQ-C Protocol*

The ARQ-C protocol takes advantage of the broadcast nature of the sensor node transmission by using *spatial diversity* to reach the base-station. Fig. 3 sketches how the ARQ-C protocol works. When the data frame transmitted by the 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*[2] 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 and/or require a lower power to transmit 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 make use of multiple cooperating nodes helping the same source. Assume that the density of the sensor nodes is high. It is likely that a number of sensor nodes may 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, thus 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 to overhear and transmit by the base-station via the recharging MW channel.

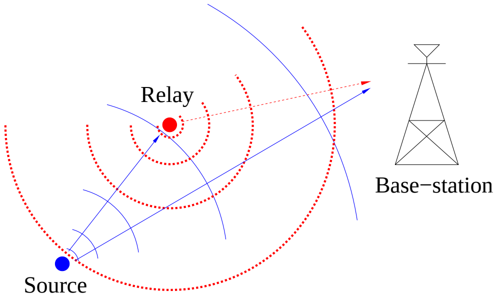

Fig. 3. Cooperation between two sensor nodes

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 chose cooperating nodes at each retransmission attempt.

C. *ARQ-C^N Protocol*

The ARQ-C^N protocol is a recursive version of the ARQ-C protocol. Fig. 4 sketches how the ARQ-C^N protocol works. The source transmits to the base-station. Relay i overhears and stores the data frame. If the data frame is not correctly received at the base-station, relay i retransmits the frame. This time, during the retransmissions, relay j overhears and stores the data frames. If the data frame is not correctly received at the base-station at the end of the retransmission attempt performed by relay i, relay j retransmits the frame. The procedure continues recursively, possibly requiring the cooperation of additional relay nodes, until the frame is received correctly at the base-station.

The rationale behind this recursive protocol is the assumption that the relay node is chosen to have (a) a higher probability of successful (re)transmission than the one of the source (or previous relay) and/or (b) to require a lower power to transmit the data frame to the base-station. Thus, when retransmission is required, the data

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[2] The optional RF reception module is required at sensor nodes.

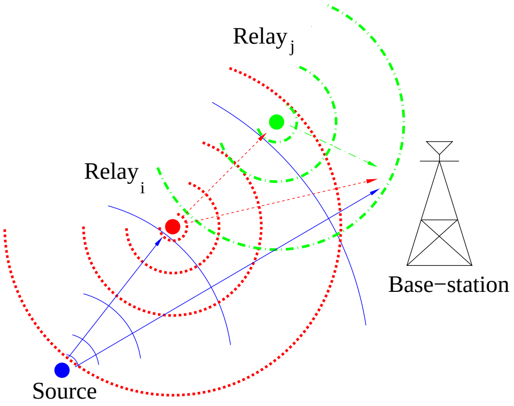

Fig. 4. Collaborations among three sensor nodes

frame *migrates* to sensor nodes that are more likely to produce a successful transmission. For each data frame transmission, the sequence of the relay nodes is chosen by the base-station. Once again, the base-station may choose that in a probabilistic way, according to some predefined distribution values. The complexity at the base-station in this case is slightly higher than the one of the ARQ-C protocol, as the migration of each data frame must be tracked. If necessary, in order reception of frames may be enforced by the base-station. In this protocol too, the required intelligence is entirely residing at the base-station. Sensor nodes are ordered to overhear and transmit by the base-station via the recharging MW channel.

A final note on the similarities and differences between the ARQ-C^N protocol and the store and forward. The similar aspect is that the data frame may reach the base-station via a multi-hop route. The difference is that the former remains a layer 2 protocol, while the latter is a layer 3 solution based on routing tables stored at the sensor nodes.

IV. ASSESSING SATURATION THROUGHPUT OF THE ARQ PROTOCOLS

This section attempts to assess the saturation throughput that is achieved by the three retransmission protocols discussed in the previous section. The saturation throughput (S) defines the throughput values ($\leq S$) that can be sustained by the system under two constraints: the average power consumption at each sensor node cannot exceed the power recharge rate, and fair access is granted to all sensor nodes in the area surrounding the base-station. It is assumed that other system aspects are not limiting the system throughput, e.g., the channel and electronics bandwidth, buffer capacity, network latency, QoS, etc.

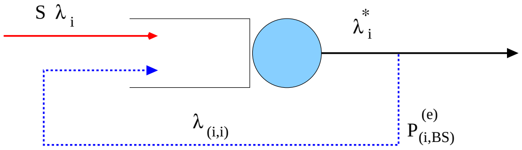

Fig. 5. ARQ-NC: flow model

The sensor nodes and the base-station are stationary. The battery recharge characteristic at each sensor node is ideal, i.e., linear and indefinitely rechargeable. The relative data traffic intensity from each sensor node is known.

The base-station determines which are the cooperating nodes for each source (ARQ-C and ARQ-C^N protocols only). The cooperating nodes are chosen to maximize the saturation throughput, as explained next.

The problem of maximizing the throughput with the three different protocols can be formulated using a flow model that relies on the following input and variables.

Input:

- N: the set of sensor nodes,
- P_{BS}: the recharge power radiated on the MW channel by the base-station,
- P_i^{rec}: the amount of recharge power radiated by the base-station that reaches sensor node i,
- $d_{i,j}$: distance between sensor node i and j,
- $d_{i,BS}$: distance between sensor node i and the base-station,
- E_{b_i}: energy transmitted per bit at sensor node i,
- L: number of bits per data frame,
- $P^{(e)}_{(i,j)}$: data frame error probability from sensor node i to j,
- $P^{(e)}_{(i,BS)}$: data frame error probability from sensor node i to the base-station.

Variables:

- $S\cdot\lambda_i$: traffic intensity generated at sensor node i. λ_i ([data frames/s]) is a predefined constant, $S \in \Re$.

A. ARQ-NC Protocol

Fig. 5 shows the flow model used for the ARQ-NC protocol. The figure represents the transmission queue at sensor node i. With probability $P^{(e)}_{(i,BS)}$ the data frame transmission is not successful, in which case the frame remains in the transmission queue for the next retransmission attempt. λ_i^* is the relative total flow of frames transmitted by sensor node i, i.e., both transmissions and retransmissions. The problem of maximizing the throughput can be formulated as follows:

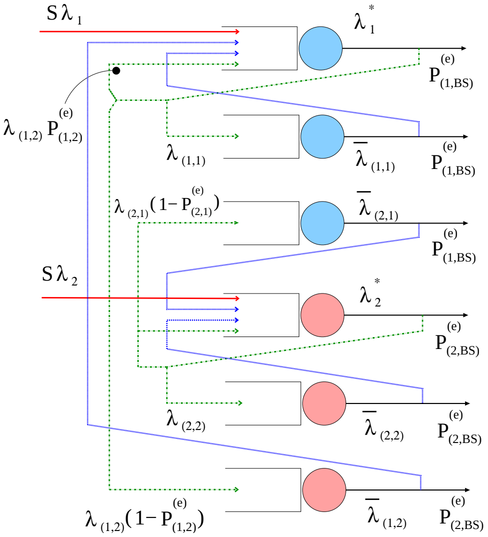

Fig. 6. ARQ-C: flow model

$$max : S \tag{1}$$

Subject to:

$$(\lambda_i^* \cdot L \cdot E_{b_i}) \leq P_i^{rec} \qquad \forall i \in N \tag{2}$$

$$\lambda_i^* = \frac{S \cdot \lambda_i}{1 - P^{(e)}_{(i,BS)}} \qquad \forall i \in N \tag{3}$$

Eq. 2 ensures that the received recharge power at each sensor node is sufficient to sustain the total number of transmissions. Eq. 3 expresses the total number of transmissions per unit of time.

B. ARQ-C Protocol

Fig. 6 shows the flow model used for the ARQ-C protocol. In this model multiple queues are used at each sensor node. Each sensor node i has a separate queue to deal with data frames that correspond to the situation where sensor node i is the relay for another node, including the case when sensor node i is being the relay for itself. After a transmission error at sensor node i, flow λ_i^* is divided into all the possible relay nodes, i.e., $\lambda_{(i,j)}$ represents the amount of data frames that suffered an error and require (through the centralized control at the base-station) sensor node j to be the relay. $\lambda_{(i,j)}$ is measured in data frames per second. Obviously, sensor node j can be the relay only if the transmission from sensor node i to sensor node j is error free. $\overline{\lambda}_{(i,j)}$ is the flow of data frames successfully reaching sensor node j from sensor node i. Notice that with this model the total number of data frames transmitted per unit of time at sensor node i is $\lambda_i^* + \sum_j \overline{\lambda}_{(i,j)}$. The problem of maximizing the throughput can be formulated as follows:

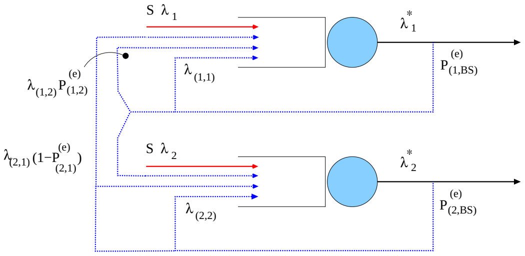

Fig. 7. ARQ-C^N: flow model

$$max : S \tag{4}$$

Subject to:

$$(\lambda_i^* + \sum_j \overline{\lambda}_{(i,j)}) \cdot L \cdot E_{b_i} \leq P_i^{rec} \qquad \forall i \in N \tag{5}$$

$$\lambda_i^* = S \cdot \lambda_i + \sum_j (P^{(e)}_{(i,j)} \cdot \lambda_{(i,j)}) + + \sum_j (P^{(e)}_{(j,BS)} \cdot \overline{\lambda}_{(j,i)}) \qquad \forall i \in N \tag{6}$$

$$\overline{\lambda}_{(i,j)} = (1 - P^{(e)}_{(i,j)}) \cdot \lambda_{(i,j)} \qquad \forall i,j \in N \tag{7}$$

$$\sum_j \lambda_{(i,j)} = P^{(e)}_{(i,BS)} \cdot \lambda_i^* \qquad \forall i \in N \tag{8}$$

Eq. 5 balances the total energy used to transmit data frames and the energy received from the base-station. Eq. 6 expresses the total number of data frames that sensor node i has to transmit/retransmit. This is the sum of three terms: new data frames, data frames that the base-station designated to be retransmitted by relay j but were not successfully received at sensor node j, and data frames that node i has to retransmit because the retransmission operated by relay j was not successful. Eqs. 7 and 8 are flow conservation constraints.

C. ARQ-C^N Protocol

Fig. 7 shows the flow model used for the ARQ-C^N protocol. Since at each retransmission the relay can take further advantage of another relay, only one queue at each sensor node is needed in this model. Equations for this protocol are similar to the previous case.

$$max : S \tag{9}$$

Subject to:

$$(\lambda_i^* \cdot L \cdot E_{b_i}) \leq P_i^{rec} \qquad \forall i \in N \tag{10}$$

$$\lambda_i^* = S \cdot \lambda_i + \sum_j (P_{(i,j)}^{(e)} \cdot \lambda_{(i,j)}) + \\ + \sum_j ((1 - P_{(j,i)}^{(e)}) \cdot \lambda_{(j,i)}) \quad \forall i \in N \tag{11}$$

$$\sum_j \lambda_{(i,j)} = P_{(i,BS)}^{(e)} \cdot \lambda_i^* \quad \forall i \in N \tag{12}$$

Eq. 10 balances the total energy used to transmit data frames and the energy received from the base-station. Eq. 6 expresses the total number of frames that sensor node i has to transmit/retransmit. This is the sum of three terms: new data frames, data frames that the base-station designated to be retransmitted by relay sensor node j but were not successfully received at sensor node j, and frames that relay i has to retransmit because the retransmission operated by relay j was not successful. Eq. 12 is a flow conservation constraint.

V. PERFORMANCE

This section reports various saturation throughput results achievable by the three retransmission protocols in a number of anticipated GAP4S scenarios. Results are presented after a short description of the assumptions made on the wireless channels.

A. Wireless Channel Assumptions

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 is modeled as

$$E_{b_r} = E_{b_t} \cdot \frac{G_T \cdot G_R}{(4\pi \cdot d/\lambda)^n} \tag{13}$$

where:

- E_{b_r}, E_{b_t}: energy per bit at the receiver and transmitter, respectively,
- G_T, G_R: transmitter and receiver antenna gain, respectively,
- d: distance between the transmitter and the receiver,
- λ: wavelength at the channel center frequency,
- n: path loss exponent, $n = 2$ in free space, typically $2 \leq n \leq 4$ for environments with structures and obstacles [24], [25].

Fading is assumed to be slow and flat Rayleigh; i.e., the fading coefficients are considered constant over a single frame transmission, and the fading experienced by each frame transmission is statistically independent of the fading experienced by any other frame transmission. The instantaneous signal to noise ratio of the RF channel at receiver j given a transmission from transmitter i is:

$$\gamma_{(i,j)} = \frac{E_{b_r}}{N_0} \cdot \alpha_{(i,j)}^2 \tag{14}$$

where:

- E_{b_r}: energy per bit at the receiver, calculated using Eq. 13,
- N_0: noise spectral density of the Additive White Gaussian Noise (AWGN), proportional to the Boltzmann constant and the absolute temperature,
- $\alpha_{(i,j)}$: a Rayleigh distributed random variable used to model the Rayleigh fading magnitude between transmitter i and receiver j, $E[\alpha_{(i,j)}^2] = 1 \ \forall i, j$.

It is assumed that the MW downlink channel is error free. On the RF uplink channel, sensors send data into, 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 $\gamma_{(i,j)}$ and the code (if any) used to add redundancy to the transmitted data. The probability of detecting an erroneous codeword $P_{(i,j)}^{(block)}$ when a coded data frame, i.e. a codeword, is sent from transmitter i to receiver j is upper bounded by the following expression [17], [26]

$$\zeta = \min \left\{ 1, \sum_{D=D_f}^{\infty} a(D) \cdot P(D|\gamma_{(i,j)}) \right\} \tag{15}$$

$$P_{(i,j)}^{(block)} \leq 1 - \int_0^{\infty} (1 - \zeta)^B \cdot p(\gamma_{(i,j)}) d\gamma_{(i,j)} \tag{16}$$

where:

- B: number of data bits in each block (data plus CRC bits), i.e., number of trellis branches in the codeword,
- D_f: free distance of the code [27],
- $a(D)$: spectrum of the code [28], i.e., number of codewords of weight D,
- $P(D|\gamma_{(i,j)})$: probability that a wrong path at distance D is selected,
- $p(\gamma_{(i,j)})$: probability density function of the instantaneous SNR.

It is assumed that binary PSK with soft decoding is employed, in which case

$$P(D|\gamma_{(i,j)}) = Q(\sqrt{2 \cdot D \cdot \gamma_{(i,j)}}) \tag{17}$$

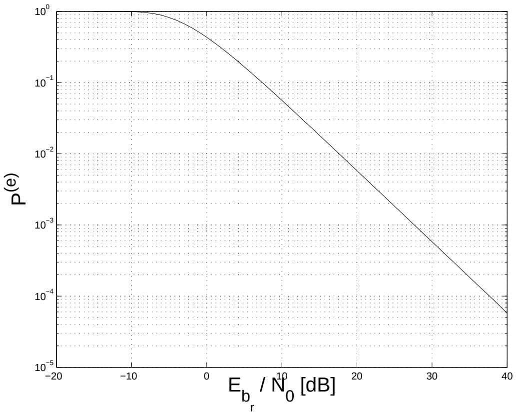

Fig. 8. Error probability ($P^{(e)}$) as a function of E_{b_r}/N_0

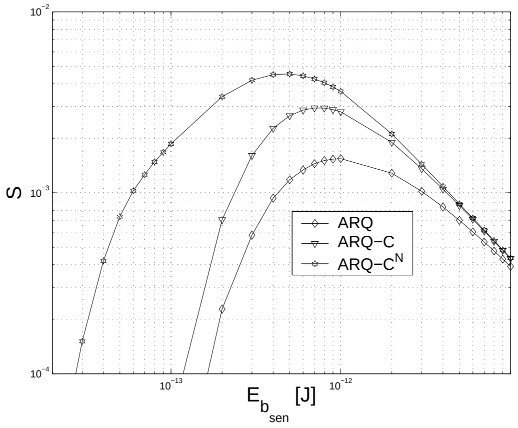

Fig. 9. Saturation throughput (S) versus energy per bit transmitted at the sensor nodes ($E_{b_{sen}}$). $R = 50$ m, $G = 50$, $n = 3.5$

where $Q(\cdot)$ is the Marcum Q function [29] and D is the weight of the codeword.

The CRC is used to detect the case of an erroneous decoding of a codeword, in which case a retransmission is requested. We assume that the CRC is able to detect all erroneous codewords, therefore the data frame error probability, i.e., the probability that a retransmission is requested is $P_{(i,j)}^{(e)} = P_{(i,j)}^{(block)}$.

B. Numerical Results

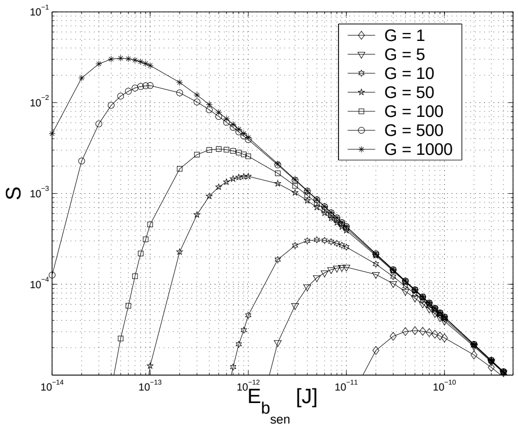

Fig. 10. ARQ-NC: saturation throughput (S) versus energy per bit transmitted at the sensor nodes ($E_{b_{sen}}$). $R = 50$ m, $n = 3.5$

Numerical results are obtained using the GAP4S frequencies, i.e., 433 MHz for the uplink and 2.4 GHz for the downlink. Data frames are fixed and carry $B = 128$ bits (data plus CRC), that are encoded into 256 bit codewords using a rate-compatible punctured convolutional code (RCPC) with rate 1/2, parent code rate of 1/4, puncturing period of 8, and memory of 4 [28]. The frame error probability versus E_{b_r}/N_0 for this RCPC is shown in Fig. 8. The recharge power that is constantly radiated by the base-station is $P_{BS} = 10\ W$. It is assumed that the energy received by the sensor antenna is fully transfered into its battery, and circuitry losses are negligible. It is assumed that the energy consumption at the sensor node is due to transmissions. The consumption of the other sections, e.g., analog-digital conversion, processing, power management, receiver, is neglected. Traffic is uniform, i.e., $\lambda_i = 1$, $\forall i \in N$.

Saturation throughput is computed by solving the formulations presented in Section IV using ILOG Cplex [30]. Average values are computed 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. The base-station is at the center of the footprint. The polar coordinates of each sensor with respect to the base-station are randomly chosen using a uniform distribution of the angle in the $[0, 2\pi)$ interval, and a uniform distribution of the magnitude in the $(0, R]$ interval.

Fig. 9 shows the saturation throughput (S) of the three retransmission protocols as a function of the energy transmitted per bit at every sensor node ($E_{b_{sen}}$). The ARQ-C and ARQ-C^N protocols reach saturation throughput values that may be more than twice the values achieved by the ARQ-NC protocol.

Figs. 10, 11, and 12 plot S versus $E_{b_{sen}}$ for the ARQ-NC, ARC-C and ARQ-C^N protocol, respectively. A number of base-station RF antenna gains (G) are considered. Intuitively, the value of S grows with increasing values of G for all of the three protocols. Cooperative communication is found to be more effective when the antenna gain is small, e.g., $G \leq 10$. The reason is that while the antenna gain at the base-station increases, the

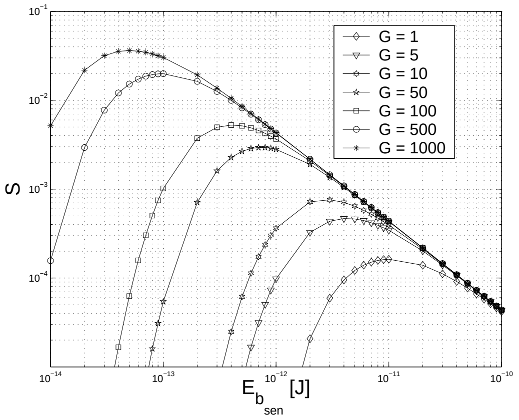

Fig. 11. ARQ-C: saturation throughput (S) versus energy per bit transmitted at the sensor nodes ($E_{b_{sen}}$). $R = 50$ m, $n = 3.5$

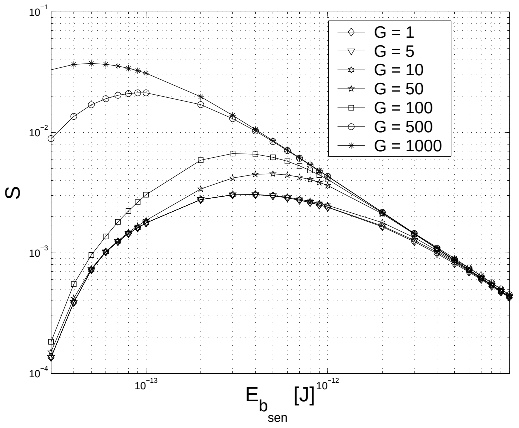

Fig. 12. ARQ-C^N: saturation throughput (S) versus energy per bit transmitted at the sensor nodes ($E_{b_{sen}}$). $R = 50$ m, $n = 3.5$

RF antenna gain at the sensor node remains constant and equal to one, which favors transmission to the base-station when compared to transmission to cooperative sensor nodes.

Fig. 13 plots S as a function of the signal to noise ratio that is received at the base-station (SNR_{BS}). In this case, every sensor node must adjust its transmitted energy per bit to obtaining the indicated SNR_{BS}. In this case too, the two cooperative protocols may achieve higher values of S when compared to the ARQ-NC protocol.

The results in Table I document the effect of both the footprint radius (R) and the path loss coefficient (n) on S for the three protocols. For all the results in the table, $G = 50$. Results in the top part of the table are obtained using $E_{b_{sen}}$= 1E-11 J. Results in the top-left part are obtained using $n = 3.5$. Results in the top-right part are obtained using $R = 50$ m. Results in the bottom part of the table are obtained using SNR_{BS}=-5 dB. Depending on the surrounding environment — which may affect the value of n — the size of the footprint spans from tens to hundred meters. The two cooperative ARQ protocols yield always higher saturation throughput than the one achieved by the non cooperative ARQ.

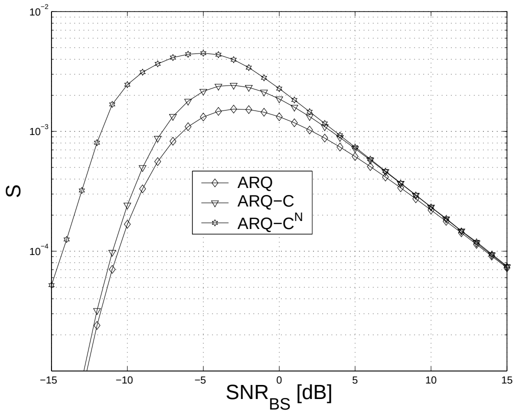

Fig. 13. Saturation throughput (S) versus signal to noise ratio received at the base-station (SNR_{BS}).$R = 50$ m, $G = 50$, $n = 3.5$

VI. CONCLUSION

The paper described the GAP4S architecture: a maintenance-free wireless sensor network. Three ARQ protocol options (two of which rely on cooperative communication) were proposed to yield reliable data delivery in GAP4S. The saturation throughput of the ARQ protocols was computed by solving a linear problem that characterizes the amount of cooperative communication offered by the sensor nodes.

In a variety of anticipated scenarios, it was found out that the two ARQ protocols based on cooperative communication may more than double the saturation throughput, or equivalently, the required power to operate the system is half when compared to the non cooperative ARQ protocol. With relatively low microwave signal levels (10 W) it is possible to reach footprint sizes in the 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.

Based on these encouraging results, further study is going to be carried out on cooperative ARQ protocols applied to sensor networks. For instance, it is interesting to find the transmission scheduling strategies at the base-station and the medium access control protocols that are best suited for GAP4S.

TABLE I

SATURATION THROUGHPUT (S) AS A FUNCTION OF THE FOOTPRINT RADIUS (R) AND PATH LOSS COEFFICIENT (n)

	$E_{b_{sen}}$=1E-11 J, $G = 50$, n=3.5					$E_{b_{sen}}$=1E-11 J, $G = 50$, $R = 50$ m				
	$R = 10$ m	$R = 20$ m	$R = 50$ m	$R = 80$ m	$R = 100$ m	$n = 2$	$n = 2.5$	$n = 3$	$n = 3.5$	$n = 4$
ARQ-NC	0.121	1.07E-2	3.90E-4	4.84E-5	1.19E-5	154.8	2.184	3.07E-2	3.90E-4	3.33E-7
ARQ-C	0.122	1.07E-2	4.32E-4	7.28E-5	2.28E-5	154.9	2.185	3.08E-2	4.32E-4	1.14E-6
ARQ-C^N	0.124	1.09E-2	4.35E-4	8.29E-5	2.99E-5	154.9	2.185	3.08E-2	4.35E-4	2.97E-6
	SNR_{BS}=-5 dB, $G = 50$, n=3.5					SNR_{BS}=-5 dB, $G = 50$, $R = 50$ m				
	$R = 10$ m	$R = 20$ m	$R = 50$ m	$R = 80$ m	$R = 100$ m	$n = 2$	$n = 2.5$	$n = 3$	$n = 3.5$	$n = 4$
ARQ-NC	102.5	0.801	1.31E-3	4.89E-5	1.02E-5	1.27E7	5985.4	2.803	1.31E-3	6.14E-7
ARQ-C	177.1	1.384	2.27E-3	8.44E-5	1.77E-5	1.45E7	7715.4	4.189	2.27E-3	1.11E-6
ARQ-C^N	337.4	2.636	4.32E-3	1.61E-4	3.37E-5	1.57E7	8741.4	5.856	4.32E-3	2.83E-6

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