Asymmetry in Energy-Harvesting Wireless Sensor Network Operation Modeled via Bayesian Games

Elvina Gindullina and Leonardo Badia
University of Padova, Dept. of Information Engineering, via Gradenigo 6B, 35131 Padova, Italy
email: {elvina.gindullina, badia}@dei.unipd.it

***Abstract*—We consider the management of an energy harvesting wireless sensor network, inspired by game theory so as to obtain a distributed multi-agent operation. In particular, we focus on asymmetries in the nodes energetic capabilities, and how do they impact on the resulting performance. We frame the problem as a repeated Bayesian game with asymmetric players and incomplete information, where also the private information available at each node is asymmetric. We find out that instead of a proportionally fair resource utilization, such a situation ends up in an even more unbalanced situation, which leads to an inefficient management where certain nodes are utilized beyond their fair share. Future research directions are identified so as to recover information about asymmetries from the strategic gameplay of the sensors and thus enable a better management.**

***Index Terms*—Wireless sensor network; energy harvesting; battery management; Bayesian games; repeated games**

I. Introduction

Energetic sustainability of a wireless sensor network (WSN) is one of the main requirements of its operation, since battery-powered sensors have a finite energy reserve. At the same time, energy demand for wireless nodes is ever increasing worldwide. One solution aims at increasing both robustness and environmental sustainability of sensor networks can be represented by energy harvesting mechanisms. [1]

This still presents several challenges related to the design of efficient policies for wireless sensor networks [2], [3], since nodes are usually programmed to carry out tasks without coordination. Depending on the rules set and making a decision on which sensor is associable to a certain task, there may still be inefficiencies. No node can be active to provide service, or multiple nodes are simultaneously active, which represents an energetic wastage. This is further complicated by the lack of information about the energy levels of the nodes. If a node is delegated to a task, but due to high battery stress it gets depleted, that task will be unsolved even though another sensor could have carried it out.

One possible solution is to approach the problem from the standpoint of game theory, so as to model multi-agent interactions with different objectives [4]. Relevant to this paper, [5] applies a game theoretical approach for battery-powered WSN in which the battery state of a sensor is private information; it computes a Bayesian Nash equilibrium that is found and compared with the perfect-information game. In [6] game-theoretic approach is applied to analyze multi-channel and multi-access schemes. Authors prove the Pareto-optimality of the Nash equilibrium of the system and offer an online-learning algorithm for the multi-channel and multi access system. Authors of [7] consider the WSN as Bayesian for warning notifications to avoid energy overuse in bottleneck nodes in a clustered solar-powered network. All these papers consider a symmetric case, e.g., with identical battery storage.

This work has received funding from the European Union Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 675891 (SCAVENGE).

In general, game theory is used for distributed optimization under the assumption that nodes are all rational but they are also assumed to be identical and perfectly coordinated, so that the functioning conditions are equivalent for all of them. In reality, there may be several differences in environmental conditions for energy harvesting of each sensor; for example, sensors can be equipped by solar panels with different orientations, or they can significantly differ in their circuitry or battery type. Past activity history of each sensor, and private information about the surrounding environment, also affect the ability of the sensor to operate. Each sensor performs differently in managing and transmitting data, and battery stress can change considerably. Another cause of asymmetry can be that a sensor may or may not have complete information about the energy level performance of other players.

Specifically, we study a case of non-identical energy harvesting sensors that perform some tasks (transmissions of packets with variable size) assigned to a common service available to all of them, but distributedly managed as a participatory activity. We formulate the analysis as a repeated Bayesian game with asymmetric players. We consider the operation of the WSN by discussing the implications of asymmetries in the nodes' characteristics for energy harvesting (such as a battery capacity), and also we investigate the effect of having some information as private. One sensor updates its belief based only on the history of the game, while the other makes its decisions taking into consideration the information about the capacity and the energy state of the other player.

The ideal management of such a network would be to still exploit the nodes proportionally to their capabilities. However, since the management is distributed and the nodes do not have full awareness of the entire network, this principle may cease to be applicable. Thus, we use the model of the Bayesian game with asymmetric players as a way to quantify the resulting unfairness. We performed some simulations and showed that this situation does not lead to the ideal game performance proportion, but is still more balanced in comparison with the strategy, when all sensors are unaware of asymmetries.

Future research directions are identified to avoid these imbalances; for example, a proper belief update rule can be designed so that in the long run the nodes are able to acquire the knowledge they lack, or at least to estimate it.

II. MODEL

We consider a WSN virtually playing a repeated Bayesian two-player game with asymmetric players. Each game round represents the decision of each sensor about whether to pursue a given task. Players are denoted as j and k, respectively. Each task is also associated with the amount of energy for its transmission. We consider the transmission of data packets as the tasks that the sensors try to accomplish, in which case the amount of energy is a direct consequence of the packet size. However, the approach can be easily generalized to other kinds of tasks as well. The decision about whether to transmit the packet or not is also based on current and average energy level of the other sensor in the network [5]. The key point of this decision-making process is that, according to a Bayesian game setup, players may not have full knowledge about the scenario and therefore create themselves $beliefs$ to handle the situation. The decisions they make are actually based on expectations (averages) of their beliefs [4].

For our problem, we assume that node k is fully aware of the network operation, while node j represents an entire room full of LIFO policies. We use these notations:

e_l^i - level of energy of sensor $l \in \{j, k\}$ at round i
e_l^{max} - capacity of sensor l's battery, with $l \in \{j, k\}$
$\overline{e_l}$ - average energy level of sensor $l \in \{j, k\}$
e_q^i - amount of energy required to transmit data at round i.
a_l^i - energy arrival at node $l \in \{j, k\}$, at round i.

In the repeated Bayesian game players care about the future consequences of their current behavior. Every stage a sensor has to decide whether to spend energy or store it. In the former case, the level of energy in stage $i+1$ will be:

$$e_j^{i+1} = max(0, e_j^i - e_q^i + a_j^i) \quad (1)$$

If the sensor makes the decision to store energy, then the energy level of its battery will be corrected only by an amount of the arrival energy and will be:

$$e_j^{i+1} = min(e_j^i + a_j^i, e_j^{max}) \quad (2)$$

In a single-device system, sensor transmits only if the energy state of the battery is greater than a threshold, or in other words, sensor j transmits, only if $e_j^i \geq e_{th}$, where e_{th} is a given energy threshold [5]. If μ_j is a probability that the energy level of sensor j is greater than its threshold in the i round, or in other words, a probability, that the sensor has enough energy to transmit, then any $\widetilde{\mu}_j > \mu_j$ will allow the transmission:

$$\begin{cases} \mu_j = 1 & e_j \geq e_{th} \\ \mu_j = 0 & e_j < e_{th} \end{cases} \quad (3)$$

If we consider the situation with several sensors in the WSN, the performance analysis is to be distributed, and each sensor has to transmit less data in total, than in a single-device system. It can be proven that in this case the threshold is corrected by the probability that another sensor also transmits the data packet. Let μ_k be a probability that the energy level of sensor k is greater than its threshold in the i round, then:

$$\begin{cases} \mu_j = 1 & e_j \geq \frac{e_{th}}{1-\mu_k} \\ \mu_j = 0 & e_j < \frac{e_{th}}{1-\mu_k} \end{cases} \quad (4)$$

We now consider that information about the opponent's energy level and the capacity of the battery is not symmetric. We denote the information about the current energy level e_j^i and the capacity of the battery e_j^{max} of sensor j as a common knowledge. The information about the energy levels of the sensor k (e_k^i, e_k^{max}) is private. Therefore, sensor k is able to make decisions guided by the rules of the rational behavior, taking into consideration energy levels of both sensors. In particular, the probability that sensor k should increase its transmission rate if the energy level of sensor j may not be enough for transmitting an incoming data ($e_j \geq e_{th}$) packet, and monotonically increase if the value of the threshold increases over the energy level of sensor j in the $i-1$ round. In addition, the higher energy level of the sensor k, then the higher probability that sensor k will transmit the data packet in the next round only if the battery has enough resources or $\overline{e_q} > e_k^{i-1}$. Based on this, we bring the following

Proposition 1. The strategy of sensor k in the i stage is:

$$\mu_k^i = min([\overline{e_q} > e_j^{i-1}] \cdot \frac{\overline{e_q}}{e_j^{i-1}} + [\overline{e_q} > e_k^{i-1}] \cdot \frac{e_k^{i-1}}{e_k^{max}}, 1) \quad (5)$$

where threshold $\overline{e_q}$ is calculated by using the statistical information about the data packets sent in the $t = (0, ..., i-1)$.

In comparison with sensor k, sensor j operates based only on the information about its own energy level and the history of the game. Similarly with [8], we denote the history of sensor k actions as $h_k^i = (a_k(t_0), ..., a_k(t_{i-1}))$, where $a_j(t_i) \in A_i = \{transmit, not\ transmit\}$ is an action of sensor j. We identify the system of belief updates for sensor j about the distribution probability of sensor k, i.e., sensor j updates its belief about the energy state is under or below its threshold of the sensor k by using Bayes rule from round i to $i+1$. Let $\mu_j(\theta_k|h^i)$ be belief of sensor j about the energy level of sensor k at round i, where $\theta_k = e_k^i \geq e_k^{th}$, then the posterior distribution will take form:

$$\mu_j^i(\theta_k|h_k^i) = \frac{\mu_k^i(\theta|h_k^i)P(a_k(t_i)|h_k^i)}{\sum \mu_k^i(\theta_k|h_k^i)P(a_k(t_i)|\theta_k|h_k^i)} \quad (6)$$

where $P(a_k(t_i)|e_k^i > e_k^{th}|a_j(t_i), h_k^i)$ is the probability that the action will be observed in the i round. From this equation we see that to update the belief, the whole history h_k^i of sensor k has to be taken into account to calculate the probability a given action $a_k(t_i)$ is played.

In our game, both sensors choose an action simultaneously at the beginning of each game. And sensor k make strategic decision expressed in (5), and sensor j every round updates beliefs using the Bayes' rule, as per equation (6). The performance of such a system will be presented in the next section.

III. SIMULATION AND NUMERICAL RESULTS

We consider a two - sensor WSN, described by parameters previously outlined. Sensors have different battery capacities and the system has a single data queue that represents the source for tasks to be performed by nodes. Each round a data packet arrives to be transmitted with random energy consumption e_q^i.

We compare 2 scenarios of belief update and how they affect the fairness of the game. Firstly, *scenario 1*: when two

TABLE I – SIMULATION PARAMETERS

Parameters	Values
Capacity of S_j	0..20
Capacity of S_k	20
Energy consumption in i round e_q	1..5
Arrival amount of energy in i round a_j^i, a_k^i	1..4
Energy arrival rate α, β	0.6

sensors transmit randomly with probability $\mu_j = 0.5$ and $\mu_k = 0.5$ respectively, at each round i. We do not update beliefs about the energy level of the opponent player. In *scenario 2* we introduce the belief update rule about sensor k and the behavior rule of sensor k with respect to the energy levels of both sensors, proposed in the previous section. We vary the value of e_j^{max} to reveal dependence between chosen strategy and fairness of the game. We expect that in the ideal situation the sensor with bigger capacity transmits more data amount, or by other words, to observe the directly proportional relationship between balance in throughput and capacity of a sensor's battery if the strategy is good enough.[1]

Note that throughput depends on three components: amount of lost data, total energy consumption for data transmitted by sensor k and j. Fig.1 demonstrates three scenarios:

– ideal scenario, when no data loss is observed and each sensor transmits data according to its capacity of the battery, for example if $e_j^{max}/e_k^{max} = 0.5$, then k and j transmit 2/3 and 1/3 of total data amount respectively.

– *scenario 1*, in which each sensor transmits data randomly.

– *scenario 2*, in which one sensor transmits data according energy state and capacity information of the opponent sensor, obtaining each time slot, and the opponent sensor transmits data updating its belief about energy state of the first sensor by cumulating the history h_k^i of its transmission.

If sensors transmits data randomly with $\mu_k = \mu_j = 0.5$, when both sensors decide to transmit the data packet or to drop it, we obtain an asymmetry reflected in the results (Fig.1: data losses curves). Moreover, *scenario 2* demonstrates significantly smaller amount of data losses in comparison with the *scenario 1*.

Furthermore, from Fig. 1 we can notice, that in both scenarios if $e_k^{max}/e_k^{max} \geq 0.5$, performance and data losses of both sensors are equalized. Both scenarios do not provide the balanced performance, but *scenario 1* is slightly more rational, when $e_k^{max}/e_k^{max} < 0.5$, because sensor k takes into consideration in its strategy the capacity of sensor j. In particular, if $e_k^{max}/e_k^{max} = 0.1$, then in *scenario 1* 40 % of total data amount will be lost, 40 % is transmitted by the sensor with the higher capacity and 20% is transmitted by the sensor with the lower capacity. In *scenario 2*, 10 % of data will be lost, 80 % will be sent by a sensor with the battery with higher capacity and 10 % with the lower capacity. Note that in the ideal situation it should be equal to 0 %, 95 % and 5 % respectively. Thus, the results found prove that the knowledge about the asymmetric property of the system makes its performance more balanced and robust.

IV. CONCLUSIONS

We consider a wireless sensor network consisting of two asymmetric sensors, powered by batteries with different capacities. We investigate the role of asymmetries by means of game theory. We focused on an unbalanced scenario, where, for example, one sensor knows the asymmetric property of the system by knowing the energy state and the capacity of the second sensor, whereas the other one does not know. We assume that the ideal scenario for such a system is transmitting data by each sensor proportionally to their battery capacities.

We studied the interaction between sensors as an instance of a Bayesian game, iteratively updated to better estimate the prior. We obtained that if both sensors do not take into account the asymmetric property of the system at all, then the system is less balanced. The same happens if one sensor knows about the asymmetry and exploits it in its strategy. In addition, we demonstrated that these strategies are not effective and ignore the asymmetric property of energy harvesting WSN if the relation between sensors capacities is more than 0.5.

For the future work, it is useful to consider asymmetries not only in the battery capacity, but also in energy arrival rates, leakage rate and other parameters. Another possibility is to develop appropriate rules of interaction between asymmetric sensors in energy harvesting WSNs with the proportion of performance close to the ideal scenario, meaning that each sensor transmits data proportionally with its battery capacity.

[1] Source code is available upon request from the authors

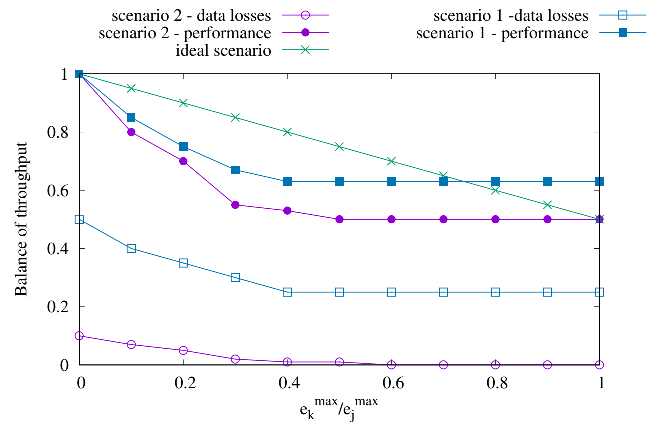

Fig. 1 – Numerical Results

REFERENCES

[1] J.A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics", *IEEE Perv. Comput.*, Vol. 4, pp. 18-27, 2005

[2] I. Ahmed, M. M. Butt, C. Psomas, A. Mohamed, I. Krikidis and M. Guizani, Survey on Energy Harvesting Wireless Communications: Challenges and Opportunities for Radio Resource Allocation,*Elsevier Computer Networks*, Vol. 88, pp. 234-248, 2015.

[3] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover and K. Huang "Energy harvesting wireless communications: A review of recent advances" *IEEE Journal on Selected Areas in Communications* 33 (3), pp. 360-381, 2015

[4] H. Shi, W. Wang, N. Kwok and S. Chen, "Game Theory for Wireless Sensor Networks: A Survey" *Sensors*, 12(7), pp. 9055-9097, 2012

[5] F.-Y. Tsuo, H.-P. Tan, Y. Chew, and H.-Y. Wei. "Energy-aware transmission control for wireless sensor networks powered by ambient energy harvesting: A game-theoretic approach" In *IEEE ICC*, 2011

[6] J. Zheng, H. Zhang, Y.Cai, R. Li. "Game-Theoretic Multi-Channel Multi-Access in Energy Harvesting Wireless Sensor Networks" *IEEE Sensors*, vol. 16, no. 11, pp 4587 - 4594, 2016

[7] T.Zou, S. Lin, Q. Feng and Y.Chen "Energy-Efficient Control with Harvesting Predictions for Solar-Powered Wireless Sensor Networks" *Sensors*, vol. 16, no. 53, 2016

[8] A.V. Guglielmi and L.Badia, "Bayesian game analysis of a queuing systemwith multiple candidate servers", *Proc.IEEE CAMAD*, 2015