Energy Cooperation for Sustainable IoT Services within Smart Cities

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***Abstract*—In this paper, we consider energy cooperation in an Internet of Things (IoT) smart city scenario. We assume the presence of interconnecting energy harvesting IoT gateways (GWs), that are endowed with energy harvesting capabilities and whose role is to collect and aggregate data from field sensing devices. Energy cooperation complements and balances the energetic needs to those devices that are neither connected to the power grid, nor satisfactorily served by energy harvesting due to the instability of ambient energy arrivals. The proposed solution entail energy transfers from energy rich gateways to energy scarce ones, i.e., those which are not connected to the power grid. To identify the optimal energy transfer/allocation scheme, we formulate a convex optimization problem that finds the optimal solution for heterogeneous smart systems. With this energy allocation technique, the gateways are unlikely to run out of energy during operation and the gap between energy offer and demand among interconnected gateways is kept to a minimum. We also quantify the performance of the proposed energy transfer policies as a function of network parameters, including: the amount of traffic generated by sensing devices, the number of smart services in the system, and the number of gateways that are connected to the power grid.**

***Index Terms*—Energy harvesting; energy cooperation; energy consumption; Smart City; Smart services; Internet of Things.**

I. Introduction

IoT technologies are becoming a major driver for the industry and affect our everyday life through a number of services. For example, a 2009 survey conducted in Republic of Korea has counted 228 types of smart services, classified in many categories including, among others: administration, transportation, medical care, environment, crime and disaster prevention, education, tourism, sport, and work production [1]. Public protection and disaster relief (PPDR) is a key service encompassing critical applications handling direct threats to life, individual or public health and safety, property, and the environment [2]. Often, these applications are highly dependable: service outages have severe effects and should be avoided. This means that energy provisioning is key for the design of smart services. Yet, at the same time it is predicted that 50 billion IoT devices will be interconnected by 2020 [3]; thus, the reduction of their energy footprint is also important.

IoT systems play a significant role in forming Smart Cities (SCs), that are expected to be home to most of the future society and can be defined as [4]: “well defined geographical areas, where technologies such as Information and Communications Technology (ICT), logistics, energy production, and so on, interact to create benefits to the citizens in terms of well being, easier and faster access to services, inclusion/participation, environmental quality, and intelligent development”. The integration of ICT within SCs, in particular, IoT technologies, makes it possible to build smart decision making systems based on real-time awareness, bringing together people, processes and knowledge. All the smart system components have to be intelligently interconnected [5]. Moreover, the construction of this large-scale smart system involves environmental issues, meaning that ICT solutions have to rationally consume energy, and to be as much self-sustainable as possible.

Energy cooperation between wireless communication nodes was considered in [6], where energy sources and relay nodes possess energy harvesting capabilities and exploit them in an attempt to maximize the end-to-end throughput. A few works have investigated energy cooperation among base stations (BS). The authors of [7] propose an energy allocation scheme for energy harvesting BSs. A convex formulation is posed and the obtained energy allocation policies are compared against an assignment problem solved through the Hungarian method. A similar scenario was considered in [8], where the set of BSs send out the harvested energy through a common aggregator and the solution for optimal power allocation and energy transfer is obtained for a weighted-sum-rate maximization problem. A framework with two energy harvesting BSs that have limited storage was studied in [9]. Two cases were considered: (i) the energy arrival profile is known in advance; or (ii) energy arrival statistics is not available. Online, offline, and hybrid algorithms were compared for both cases.

In this work, we consider smart services to be interconnected among each other, exploring an energy cooperation scheme to increase the energy sustainability and therefore reliability of IoT scenarios. Specifically, smart services are enabled by gateways (GW) that collect and process data from IoT sensors and objects. GWs are sink nodes that can be thought of as routers in residential scenarios. Examples may be smartphones that collect and aggregate data from wearable biomedical sensors, smart city gateways collecting pollution, traffic, or parking data from cameras or road-side sensing units [10]. Therefore, the power sources for IoT gateways are diverse and depend on the gateway’s type and/or the considered application. The GW energy consumption is related to its data collection task and the transmission of the aggregated data to the base station via, e.g., time division multiple access (TDMA) scheduling [11]. Hence, the overall gateway energy consumption depends on the amount of served IoT devices and their throughput. Typically, gateways are connected to the electrical grid and equipped with a backup battery to provide resilience to power network outages. In this work, we additionally consider that gateways have energy harvesting (EH) capabilities. EH allows increasing the energy sustainability of a system, but, at the same time, they provide a volatile energy supply due to the intermittent nature of ambient energy. For instance, solar energy arrival is not homogeneous over a day and depends on the solar panel size, deployment site, and orientation. Other works have also studied this feature; for example, the solar gateway *CerfCube* for habitant monitoring presented in [12], consumes about 2.5 W and is equipped with a solar panel that provides 60-100 W but only during sunny days; thus, also a rechargeable battery has to be accounted for. The authors of [13] propose an aquatic environmental monitoring framework where gateways and sensors are powered by solar panels. The proposed design was successfully integrated at Moreton Bay, Brisbane (Australia) to monitor a segment of the Australian Coral Reef.

The main contribution of this paper is the integration of these aforementioned topics and technologies into a single optimization framework to come up with a SC scenario that intelligently provides services, but at the same time is aware of its carbon footprint and tries to reduce it as much as possible.

The combination of energy cooperation with EH and IoT systems is the scenario that is considered in this work, and is sketched in Fig. 1. IoT smart services are represented by gateways. Some of them are only powered by solar panels (for instance, applications in rural areas), termed *offgrid*. Others are also connected to the electrical grid, i.e., *ongrid* (for example, GWs located in buildings). The energy arrival profile for the solar energy is derived from [14]. Moreover, gateways are equipped with a backup battery that allows energy storage and prevents the system from sudden operation stops due to power grid outages.

All the gateways are connected to a central node called the *energy router*, which determines the energy allocation among GWs and implement the needed energy transfers. This nomenclature is taken from [7]. Through the interconnected grid, energy is exchanged from high battery level GWs to energy scarce ones. The IoT gateway load is generated randomly following a uniform distribution in a range that includes different available communication technologies that are suitable for IoT applications. Hence, an energy allocation optimization problem is formulated, with the objective of prolonging the life-time and the energy sustainability of the system.

Numerical results are provided to demonstrate the effectiveness of the proposed energy cooperation policy. In particular, we investigate the impact of key parameters on the system sustainability, including the number of gateways that are connected to the energy router, the amount of data traffic generated by the field sensor nodes, and the fraction of GWs connected to the power grid. We compare the energy cooperation scenario with the case where no energy cooperation scheme is used, and compare the average battery level for both scenarios.

The rest of this paper is organized as follows. In Section II, we outline our proposed system model. The formulation of the energy allocation problem is presented in III. Numerical results are discussed in Section IV that shows the effectiveness of the energy cooperation scheme and the dependency from different parameters. Finally, the conclusions are drawn in Section V.

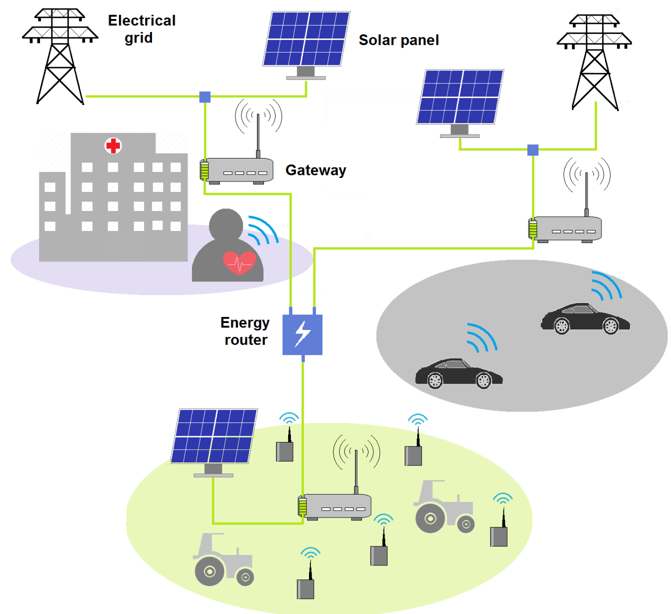

Fig. 1 – Energy framework for interconnected smart services.

II. System Model

We consider a system of N gateways (set $\mathcal{N}$) with energy harvesting capabilities, serving n associated IoT devices. Gateways are divided into two sets: connected to the power grid (set $\mathcal{N}_{\text{ongrid}}$) and only depending upon harvested solar energy (set $\mathcal{N}_{\text{offgrid}}$). Time t is slotted, i.e., $t = 1, 2, \ldots,$ with the slot duration implicitly assumed to be equal to one hour. The gateway energy consumption is modeled following [15]. The model takes into account the energy consumption for receiving k bits of data and aggregating m messages:

$$E_{\text{RX}}(k) = E_{\text{elec}} \cdot k \,, \tag{1}$$

$$E_m(m, k) = m \cdot k \cdot E_{\text{DA}} \,, \tag{2}$$

where E_{elec} and E_{DA} are the energy for the activation of the data receiving circuit board and the energy required for the aggregation of a single message of unit length, respectively. Hence, the total power consumption of a gateway $i \in \mathcal{N}$, E_i^{con}, amounts to the sum of communication and aggregation terms, that is,

$$E_i^{\text{con}} = n \cdot E_{\text{RX}}(k) + E_m(m, k) \,, \tag{3}$$

where the energy consumption is eventually connected to the number of sensing nodes n that are associated to the gateway, and the individual data rate of each sensor node.

The energy transfer among gateways is performed following the same technique used in [7]. Energy losses are considered and depend on the distance ℓ between source and destination gateways, the resistivity of the wire connecting them (denoted as ρ, measured in Ω mm^2/m) and its cross sectional area (A, mm^2) [16]:

$$R = \frac{\rho l}{A}\,. \tag{4}$$

In the considered scenario, the connection among gateways is established via the energy router through a star topology. Different topologies shall be explored in future work. For the numerical results, the distances between the energy router and gateways are uniformly distributed at random, on a square area. Therefore, energy links between gateways have also random length.

Solar energy harvesting is accomplished with a reference model inspired by a real-world device, i.e., Panasonic N235B photovoltaic technology, in which each solar module has a size of $0.44\,\mathrm{m}^2$ and is equipped with 25 solar cells. The SolarStat tool was used to obtain the energy arrival profile $p(t)$ across an entire day considering the city of Los Angeles as the deployment site [14]. This energy profile is reshaped for each gateway, taking into account different installation environmental conditions for the solar panels, in particular attenuations that may occur due to nearby buildings or trees. This variability in the energy harvesting model is taken into account as follows. $A_i^h(t)$ is the amount of harvested energy in time slot t for gateway i [7]: it depends on the energy profile $p(t)$ (equal for all gateways) and $r(0,s)$, which is sampled from a uniform probability distribution function in the open interval $(0,s)$, where s embodies the correlation among the harvested energy profiles across gateways:

$$A_i^h(t) = r(0,s)p(t)\,. \tag{5}$$

The energy level of a gateway battery changes at each time slot t due to energy arrivals (energy harvesting process), the energy obtained from the power grid, the GW energy consumption (reception and aggregation of data) and the amount of transferred energy among gateways. Specifically, the battery level of gateway $i \in \mathcal{N}$ evolves according to the following update equation:

$$E_i(t+1) = E_i(t) - E_i^{\mathrm{con}}(t) + E_i^{\mathrm{tr}}(t) + A_i^h(t) + A_i^g(t) \tag{6}$$

where $E_i(t)$ is the amount of energy at time slot t, $E_i^{\mathrm{con}}(t)$ is the energy consumption calculated according to (3) in that time slot, $E_i^{\mathrm{tr}}(t)$ is the amount of energy to be transferred or received to/from other gateways (if a gateway is an energy *provider*, then $E_i^{tr}(t) < 0$, otherwise, the gateway is an energy *consumer* and $E_i^{tr}(t) > 0$). Values $A_i^h(t)$ and $A_i^g(t)$ represent the amount of energy harvested and obtained from the power grid, respectively. For gateways $i \in \mathcal{N}_{\mathrm{offgrid}}$, which are not connected to the power grid, we have $A_i^g(t) = 0$, if $i \in \mathcal{N}_{\mathrm{ongrid}}$ then $A_i^g(t) \geqslant 0$. The battery has a finite capacity $C_{\max}$ and two predefined thresholds: upper and lower, denoted by $C_{\mathrm{th}}^{\mathrm{up}}$ and $C_{\mathrm{th}}^{\mathrm{low}}$, respectively. These thresholds are used to define the behavior of a gateway in terms of the amount of energy that it is allowed to transfer or receive. Specifically, in each time slot t, gateways can precisely define their roles in the energy cooperation scheme depending on the energy battery level and these energy thresholds. Hence, the behavior of gateway $i \in \mathcal{N}$ is set in the following way [7]:

$$\begin{cases} E_i(t) \geq C_{\mathrm{th}}^{\mathrm{up}} & \text{gateway } i \text{ is an } \textit{energy provider} \\ E_i(t) < C_{\mathrm{th}}^{\mathrm{low}} & \text{gateway } i \text{ is an } \textit{energy consumer}\,. \end{cases} \tag{7}$$

If a gateway $i \in \mathcal{N}_{\mathrm{ongrid}}$ is an energy provider, the amount of energy that it can transfer in time slot t is calculated as the difference between its current battery level and the upper threshold, i.e., $E_i(t) - E_{\mathrm{th}}^{\mathrm{up}}$. Instead, if a gateway $j \in \mathcal{N}_{\mathrm{offgrid}}$ is identified as an energy consumer, then the amount of demanded energy is obtained as the difference between the lower threshold and its current battery level: $E_{\mathrm{th}}^{\mathrm{low}} - E_i(t)$.

III. Optimization Problem

To increase the sustainability of the system under study, we formulate an optimization problem, whose solution consists of an energy allocation policy that transfers energy from energy providers to energy consumers. The sets of energy providers and consumers are denoted here as $\mathcal{N}_{\mathrm{prov}} = \{1,..,P\}$ and $\mathcal{N}_{\mathrm{cons}} = \{1,..,C\}$, respectively. The available energy to transfer from providers to consumers is captured by matrix $\boldsymbol{B} = [b_{ij}]$, where element b_{ij} represents the amount of energy available from provider i to consumer j. If i is an energy provider, element b_{ij} accounts for the energy that this node can transfer, namely, $E_i(t) - C_{\mathrm{th}}^{\mathrm{up}}$, which is corrected by a coefficient k_{ij} depending on the distance between i and j, which takes into account energy losses. Vector $\boldsymbol{d} = [d_j]$ represents the energy demand of energy consumers.

We now write an objective function that aims at reducing the imbalance between energy demand and supply, so that energy is allocated (and used) as efficiently as possible across the whole system. As we shall see shortly, a well balanced energy allocation also reduces the overall energy that is purchased from the power grid. The optimization problem is formulated as follows:

$$\min_{\boldsymbol{X}} \quad \sum_{j=1}^{C}\left(\sum_{i=1}^{P} x_{ij} b_{ij} - d_j\right)^2 \tag{8a}$$

$$\text{subject to:} \quad 0 \leq x_{ij} \leq 1, \qquad \forall i \in \mathcal{N}_{\mathrm{prov}}, \forall j \in \mathcal{N}_{\mathrm{cons}}, \tag{8b}$$

$$\sum_{j=1}^{C} x_{ij} \leq 1, \qquad \forall i \in \mathcal{N}_{\mathrm{prov}}, \tag{8c}$$

where $x_{ij} \in [0,1]$ are the decision variables, which represent the fraction of the available energy b_{ij} that is allocated from provider $i \in \mathcal{N}_{\mathrm{prov}}$ to consumer $j \in \mathcal{N}_{\mathrm{cons}}$, in matrix notation $\boldsymbol{X} = [x_{ij}]$. The first constraint represents the fact that x_{ij} is a fraction of the available energy b_{ij}, and the second one means that the total amount of energy that a certain provider i transfers to consumers j cannot exceed the total amount of available energy at this provider.

The optimal solution of the problem $\boldsymbol{X}^* = [x_{ij}^*]$ returns the optimal energy allocation between providers and consumers, meaning that any provider i can transfer energy to more than one consumer j at a time, and any consumer j can receive energy from multiple providers i. Due to the convex nature of the formulation, the problem can be solved using standard

TABLE I – Simulation Parameters

Parameters	Values
Number of deployed gateways N	20
Number of sensor nodes per GW	$[1000, 10000]$
Energy per received bit $E_{\rm elec}$	$5\,{\rm nJ/bit}$
Energy to aggregate m messages E_{DA}	$5\,{\rm pJ/bit}$
Number of aggregated messages m	10
Cable resistivity ρ	$0.023\,\Omega{\rm mm}^2/{\rm m}$
Cable cross-section A	$10\,{\rm mm}^2$
EH correlation coefficient s	2
Energy battery capacity $C_{\max}$	[24.4-57.7]Wh
Upper threshold C_{th}^{up}	$0.7C_{\max}$
Lower threshold C_{th}^{low}	$0.3C_{\max}$

methods, the Matlab toolbox CVX [17] has been used to this purpose.

IV. Numerical results

In this section, we numerically evaluate the proposed energy trading model. Simulations are performed as follows: every time slot t, GWs energy battery levels are updated following (6); then, every GW decides upon its energy role using (7) and, after that, matrices $\boldsymbol{B}$ and $\boldsymbol{D}$ are calculated. Finally, the solution $\boldsymbol{X}^*$ of the optimization problem in (8) is found and the energy transfer among gateways is performed thanks to the energy router, see Fig. 1. The numerical results that follow show a performance comparison between two scenarios: system *with* and *without* energy cooperation.

For the simulations, the sensor node data rate is picked randomly in the range $[1\,{\rm kb/s} – 1\,{\rm Mb/s}]$ sampled from a uniform probability distribution function. This rather wide range of data rates is selected to mimic the diversity of technologies that are expected to coexist in future smart cities. A few technologies that may be amenable for the provisioning of smart services are: SigFox ($<$ 0.1 kb/s) [18], LoRa - $0.3 - 50$ kb/s [19], Z-Wave - $9.6/40/100$ kb/s [20], NFC - $106, 212, 424$ kb/s [21], ZigBee - 250 kb/s [22], Bluetooth - 1 Mb/s [23]. Gateways are randomly distributed following a uniform distribution within an area of $1\,{\rm km} \times 1\,{\rm km}$ and each gateway is equipped with a Li-Ion battery with capacity in the range $[24.4 – 57.7]$Wh. The remaining simulation parameters are listed in Table I. All presented results are averaged over $3,000$ simulation instantiations.

To quantify the effectiveness of our energy cooperation model, we define the *energy outage ratio* metric, representing the number of depleted gateways, i.e., those whose energy battery level is not enough for the gateway to function, over the total number of gateways in the system; the goal is to minimize this metric, reducing as much as possible the number of gateways that run out of energy. The results in Fig. 2 are obtained using $|\mathcal{N}_{\rm ongrid}| = 10$, a random number of sensor nodes per GW in the range $[1,000 – 10,000]$ (see Table I) and a data rate in the range $[1\,{\rm kb/s} – 1\,{\rm Mb/s}]$. The figure plots on average the dynamical changes of the energy outage ratio values for the system over a day with and without energy cooperation. When no energy cooperation is accounted for (termed “Without EC” in the figure) the energy outage ratio is relatively high (i.e., up to 50% of the gateways run out of battery). When our optimization is used (“With EC”), no

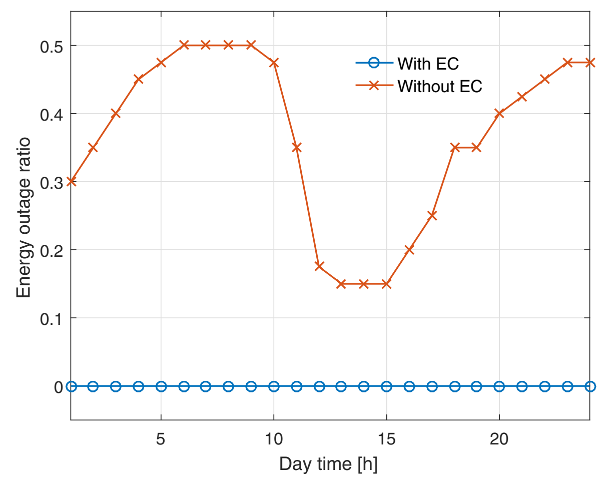

Fig. 2 – Energy outage ratio across an entire day.

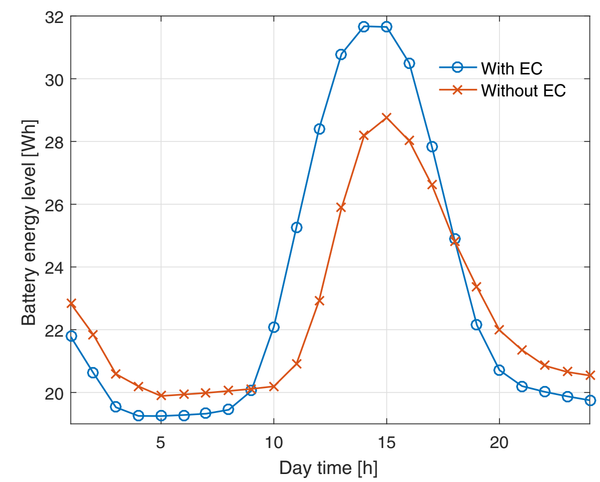

Fig. 3 – Average gateway battery level across an entire day.

gateway runs out of energy across the entire day and this is due to two reasons: 1) energy rich gateways transfer some of their excess energy to energy poor ones and 2) ongrid gateways assist those that are offgrid, by transferring energy towards them whenever the energy that can be harvested from the environment is insufficient.

The same simulation settings are used in Fig. 3, where the average gateway battery level is plotted across a full day for the two cases: with and without energy cooperation. Without energy cooperation, the average battery level is higher from 6:00 pm to 9:00 am. In fact, during such hours the harvested energy from the sun is negligible and the application of energy transfer among gateways reduces the battery level of all of them. This does not happen without EC, where ongrid gateways maintain a high battery level that on average is better than using EC during this time period.

The next figures show the role of some of the system parameters. First, we explore the impact of the number of gateways that are connected to the energy router. The results in Fig. 4 are obtained using $|\mathcal{N}_{\rm ongrid}| = 10$, a random number of sensor nodes per GW in the range $[1,000 – 10,000]$, and

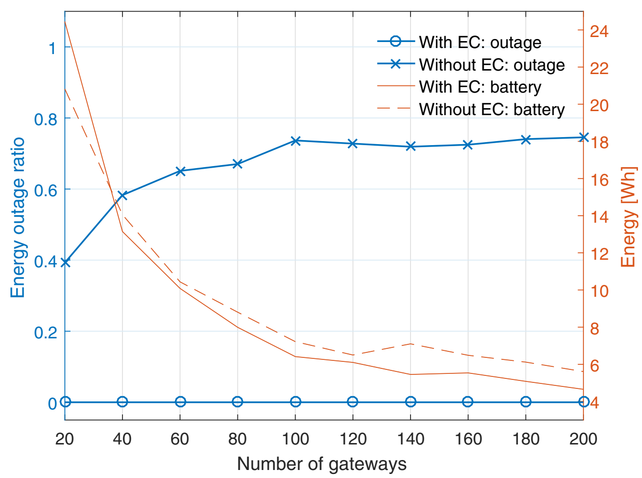

Fig. 4 – Energy outage ratio performance varying the number of gateways N.

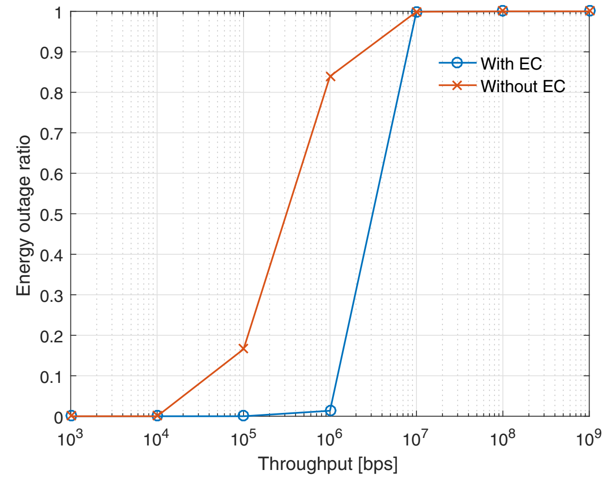

Fig. 6 – Energy outage ratio varying sensor nodes throughput.

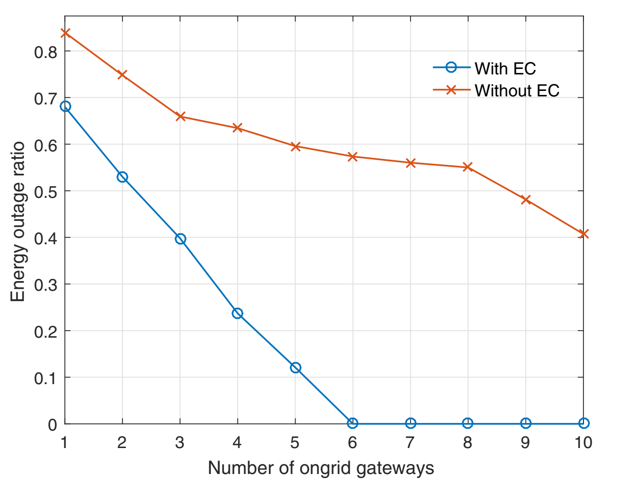

Fig. 5 – Energy outage ratio evaluation increasing the number of ongrid GWs.

a throughput in the range $[1\,\mathrm{kb/s} – 1\,\mathrm{Mb/s}]$. As expected, an increase in the number N of gateways deployed in the system, without a corresponding increase in the number of ongrid ones, when EC is not applied leads to a worse performance, i.e., the number of depleted gateways gets higher and the energy outage ratio correspondingly increases. Nevertheless, the system becomes fully energy sustainable applying EC even when N is equal to 200. The average battery energy level in the system with EC is however smaller than without EC, due to the energy losses in the energy transfer process.

In Fig. 5, we plot the energy outage ratio as a function of the number of GWs that are connected to the grid. Results are obtained using the same settings as for Fig. 3. As expected, increasing the number of ongrid GWs provides a gradual decrease of the energy outage ratio when there is no EC. But increasing the ongrid GWs is especially beneficial when EC is applied. In that case, as the number of ongrid gateways gets larger than five, no energy gateways run out of energy any longer.

Finally, we study how the number of depleted gateways depends on the sensor nodes data rate, which spans over the range $[0.1\,\mathrm{kb/s} – 10\,\mathrm{Gb/s}]$. In this case, we also explore considerably high data rates as our aim is to identify the full extent of the benefits provided by EC. The remaining parameters are $N = 20$, $|\mathcal{N}_{\mathrm{ongrid}}| = 10$ and a uniformly distributed random number of sensor nodes per GW in the range $[1,000 – 10,000]$ is considered. The results are presented in Fig. 6 and show that for the case without EC and a data rate smaller than $10\,\mathrm{kb/s}$ the energy outage ratio is zero, therefore no energy cooperation is needed for these values. However, in the range $[10\,\mathrm{kb/s} – 10\,\mathrm{Mb/s}]$, EC performs better providing a gain of about 25%. If the data rate is higher than $10\,\mathrm{Mb/s}$, then the system cannot be energy sustainable, and all gateways will be depleted, no matter whether EC is used.

V. Conclusions

In this work, we considered a Smart City scenario represented as a set of interconnected IoT gateways that offer smart services by collecting and aggregating data from IoT sensing devices. Gateways are endowed with energy harvesting capabilities, which in this study means that they are equipped with a solar panel and an energy storage (rechargeable battery). Energy cooperation is utilized to provide energy sustainability to the system through the transfer of energy from gateways with a high battery level to those whose battery is about to deplete. For this scenario, an optimal energy allocation was found, solving a convex problem with the goal to reduce the imbalance between available energy in gateway batteries and energy demand in the system. We analyzed the effectiveness of the proposed energy allocation strategy, comparing it against the case where energy cooperation is not allowed, and also checking the impact of several system parameters, such as number of gateways that are connected to the energy router, the number of ongrid gateways and the data rate of sensor nodes. Numerical results show that, with energy cooperation, the system is fully energy sustainable for many system configurations, showing a substantial improvement against a scenario where cooperation is not allowed.

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