Massive Wireless Energy Transfer: Enabling Sustainable IoT Towards 6G Era

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Abstract—Recent advances on wireless energy transfer led to a promising solution for powering future Internet of Things (IoT) devices enabled by the upcoming sixth generation (6G) era. In this paper, we overview the main architectures, challenges and techniques for efficient wireless powering. We emphasize on the suitability of Channel State Information (CSI)-free strategies when powering simultaneously a massive number of devices. We show that even without considering the energy resources required for CSI acquisition, the gains from operating with CSI decrease quickly as the number of powered devices increases, while distributed CSI-free strategies become even more advantageous by widening the energy coverage region with high reliability. Overall, advances in the system design and in resource allocation strategies are required for optimizing the energy supplying process, specially under the challenges imposed by future networks.

I. INTRODUCTION

The sixth generation (6G) era envisions a society that is data-driven, enabled by near-instant, unlimited wireless connectivity [1]. Such vision is shared by the Internet of Things (IoT) which promises to bring wireless connectivity to anything, ranging from tiny static sensors to autonomous objects, to communicate and collaborate over the Internet by circulating information directly among themselves and/or from the surrounding environment. While traditional machine-type communication (MTC) has relied on short-range wireless technologies, moving toward large-scale deployments requires broader interconnection capabilities such as that provided by cellular networks. The fifth generation (5G) of cellular networks introduces two new use cases orientated to support IoT, namely ultra-reliable low latency communications (URLLC) and massive MTC (mMTC). While 5G is the first generation aiming at MTC use cases, there is still lots of room for improvement with respect to the capability of dealing with an astonishing number of devices [2]. This trend is expected to be amplified with the advances of current generation and even more so towards 6G.

The vision 6G casts encompasses technological and societal development goals [1] in which low-emission, zero-energy, devices are key for a sustainable IoT network. In this context, massive IoT deployment becomes a major concern, due to the lack of energy efficient solutions for powering and keeping uninterrupted operation of such huge number of devices. Energy harvesting (EH) techniques provide an efficient method that avoids replacing or externally recharging batteries, a procedure that may be costly or impossible in hazardous environments, building structures or the human body [3]. Sustainable IoT is much broader than EH and energy efficiency. Nonetheless, we foresee EH as a key component of any future massive IoT network. According to the energy source, many types of EH schemes have been considered, based on solar, piezoelectric, wind, hydroelectric, or radio frequency (RF) signals. When RF signals are intentionally used for powering EH devices, we refer to a Wireless Energy Transfer (WET) process, which is the focus of this work. While harvesting energy from environmental sources is dependent on the presence of the corresponding energy source, WET provides key benefits in terms of being wireless, readily available in the form of transmitted energy, low cost, and having small form factor [4].
This article discusses benefits of massive WET for the IoT era, while commenting on related use cases and candidate enabling techniques such as Energy Beamforming (EB) \[5\] and Distributed Antenna Systems (DAS) \[6\]. Furthermore, we identify accurate channel state information (CSI) acquisition as a key limitation for powering wirelessly massive network deployments, and consequently introduce WET solutions that do not rely on CSI availability, thus CSI-free. We evince the suitability of CSI-free strategies where Power Beacons (PBs) are strategically deployed to charge EH devices, taking into account the practical features of typical EH circuitry, while providing fundamental insights towards designing practical massive WET systems.

II. WET FOR IoT

WET exploits the far-field radiative properties of electromagnetic waves to power wireless devices over short or moderate distances. With the continuous decrease in device operating power, as low as a few microwatts, and the recent developments in multiple-input multiple-output (MIMO) technology, we expect an increasing number of WET applications in the near future. IoT networks are expected to benefit from WET by taking advantage of \[7\]:

- battery charging without physical connections, which significantly simplify the servicing and maintenance of battery-powered devices;
- form factor reduction of the end devices;
- increase of durability and reliability of end devices thanks to their contact-free design;
- enhanced energy efficiency and network-wide reduction of emissions footprint.

The IoT paradigm intrinsically includes wireless information transfer (WIT), hence WET appears naturally combined with WIT. Thus, two architectures prevail \[5\]: \(i\) Wireless Powered Communication Network (WPCN), where WET occurs in the downlink in a first phase and WIT takes place in the second phase; and \(ii\) Simultaneous Wireless Information and Power Transfer (SWIPT), where WET and WIT occur simultaneously.

Fig. 1 shows some typical use cases for the above architectures in the IoT era, but practical networks could also include a mixture of the above schemes. Notice also that WET constitutes a fundamental and sensitive building block in these networks because: \(i\) WET duration could be significantly larger than WIT in order to harvest usable amounts of energy \[8\]. Actually, some use cases require operating under WET almost permanently while WIT happens sporadically, e.g., due to event-driven traffic; and \(ii\) nowadays the efficiency of the circuitry for energy and information transmissions are still very different, while typical information receivers can operate with sensitivities ranging from \(-130\) dBm to \(-60\) dBm receive signal power; an EH device needs up to \(-10\) dBm \[9\]. To overcome this, energy and information transceivers usually require different antenna and RF systems \[10\], and moreover can be performed either in an out-of-band or in-band manner \[10\]. While the out-of-band approach allows avoiding interference by transmitting the information and energy over different frequency bands, it requires additional spectrum resources. On the other hand, the in-band alternative alleviates the spectrum efficiency issue by allowing the information and energy to be transmitted over the same band in a time-division or even full-duplex manner \[11\].

Adopting WET as an efficient powering solution in the IoT era still encounters some challenges
III. Enabling Efficient WET and Challenges Ahead

Next, we discuss several techniques that seem suitable for enabling WET as an efficient solution for powering the future IoT networks, summarized in Fig. 2, besides other associated challenges.

A. Energy Beamforming (EB)

Using high-gain antennas to focus the energy in narrow beams toward the devices improves efficiency. For fixed LOS links, conventional large aperture antennas, such as dish or horn antennas, could be employed; whereas for mobile applications with a dynamic channel environment, an electronically steerable antenna array is more suitable [9], [10].

With EB, the energy signals at different antennas are carefully weighted to achieve constructive superposition at intended receivers. The larger the number of antennas, $M$, installed at the PB, the sharper the energy beams can be generated in some particular spatial directions. The number of beams is limited by $M$, thus, for efficiently reaching each of the $N$ EH devices with different energy beams, it is required that $N \leq M$.

Notice that EB requires accurate CSI, including both magnitude and phase shift from each of the transmit antennas to each receive antenna. When CSI is available, EB is capable of directing wireless energy by adapting to the propagation environment. However, CSI is difficult to acquire in practice in WET systems. On one hand, the scenario in which the PB sends training pilots and waits for a feedback from the EH devices is not desirable since:

- many simple EH devices do not have baseband signal processing capability to perform channel estimation; and
- accurate channel estimation consumes a significant amount of time and energy, which may erase the gains from EB; and moreover,
- the problem of reliable CSI feedback persists.

Alternatively, it seems appropriate that the EH devices send the training pilots, while the PB acquires CSI and then forms the energy beams. This reverse-link training becomes suitable for estimating CSI under large antenna arrays, since training overhead is independent of the number of transmit antennas. However, the EH devices still need carefully designed training strategies, such as the transmit power, duration, and frequency bands, to minimize the energy spent in scheduling and sending the training signals. Additionally, accurate channel reciprocity must hold, which is known to be sensitive to hardware impairments specially when devices at both link extremes are very different, while for some scenarios there is also the problem of receiver mobility which could lead to time-varying channels, making channel tracking difficult.

B. Distributed Antenna Systems (DAS)

End-to-end efficiency of EH systems decay quickly with distance between the PB and EH device because of the severe power attenuation. Thus, DAS (or distributed PB) are foreseen as potential enablers of future IoT networks since under suitable design they are capable of eliminating blind spots while homogenizing the energy provided to a given area, supporting ubiquitous energy accessibility. Additionally, separate PBs, each equipped with multiple transmit antennas, could alleviate the issue of CSI acquisition when forming efficient energy...
beams in multiple-users setups, since each PB may be responsible for the CSI acquisition procedure of a smaller set of EH devices [6]. Although, the prerequisite for optimal distributed EB is both frequency and phase synchronization, which is still very costly and challenging as discussed in Section III-A.

C. Resource Scheduling and Optimization

WPCN achieves performance comparable to that of a conventional non-WET network when intelligent policies for throughput maximization are applied [12]. When information and energy transmissions take place in the same network system, they should be conveniently scheduled to avoid co-channel interference and to optimize the overall system performance according to the metric of interest. In practice, real-time information/energy scheduling is a challenging problem because of time-varying wireless channels and the causal relationship between current WET process and future WIT.

Communication and energy scheduling can be performed in the spatial domain when energy and information transmitters are equipped with multiple antennas [3]. For instance, EB can be used by a PB to steer stronger energy beams to efficiently reach certain users while prioritizing their energy demands towards the information transmission phase. Besides, EB and space-division multiple access can be combined with dynamic time-frequency resource allocation to further enhance the system performance in WPCNs. Some other strategies that have been considered in the literature so far are input signal distribution optimization [2], cooperation [5], [10], Hybrid Automatic Repeat-reQuest (HARQ), power control [2], [13] and rate allocation [14].

D. Challenges Moving Towards Massive WET

Despite these recent advances in EB, DAS and their joint operation, not all challenges presented in Section II are yet fully addressed, much less with respect to future massive IoT networks. In this context, it is imperative to take into account the characteristics of mMTC, which are: i) small packets, potentially going down to a few bytes and low user data rates, e.g., around 10kb/s per user; ii) large number of users, e.g., up to 300,000 devices in a single cell; iii) battery constrained devices; and iv) sporadic user activity, e.g., mixed traffic models with periodic and event-driven traffic. Although the first assumption is favourable for devices relying on EH, the second assumption poses important challenges not only for the access but also for the CSI acquisition procedures (in addition to those mentioned in Subsection III-A), since in order to prevent interference and collisions during training, scheduling strategies may be necessary, draining important energy resources that may be too costly for energy-limited devices (third assumption). Moreover, the performance of CSI-based systems decays quickly as the number of user increases [15]. Therefore, in such massive deployment scenarios the broadcast nature of wireless transmissions should be intelligently exploited for powering a massive number of devices simultaneously with minimum or non CSI. The fourth assumption reinforces our previous comments in Section II on the necessity of efficient and carefully designs of WET since WIT is mainly sporadic. Additionally, EH hardware is affected by many non-linear impairments which are difficult to model analytically, but an efficient design must take them into account. Thus, not only the inherent characteristics of IoT networks must be considered but also the practical details of EH hardware implementations.

Next we present two study cases dealing with these challenges. We focus on WET scenarios with a large number of EH devices and analyse the performance of some CSI-free strategies, while considering practical EH hardware characteristics.
Fig. 4. Performance in terms of average harvested energy (AHE) and average energy outage probability per node (AEO), as a function of the number of EH devices when \( M = 4 \). The EH IoT nodes have been distributed uniformly in a circular area of radius 15m.

IV. HOW TO POWER A MASSIVE NUMBER OF DEVICES?

Next we discuss illustrative use-cases on single and multiple PBs (with multiple antennas each) using the CSI-free strategies shown in Fig. 3. The problem of CSI acquisition in multi-user WET systems is critical and limits the practical significance of any research work relying on perfect CSI. Therefore, we evaluate two different metrics: i) the average harvested energy per node (AHE) and ii) the average energy outage probability per node (AEO), which denotes the probability of not harvesting energy in a coherence block time. We assume sensors equipped with practical EH hardware characteristics [15]: i) \(-22\) dBm of sensitivity, which is the minimum RF input power required for EH; ii) \(-8\) dBm as saturation level, which is the RF input power for which the diode starts working in the breakdown region, and from that point onwards the output DC power keeps practically constant; and iii) 0.35 of energy conversion efficiency in the RF interval between sensitivity and saturation. We assume a log-distance path loss model with exponent 3, 26dB of average signal power attenuation at a reference distance of 1m or less, and a LOS parameter decreasing linearly with the distance from 15 to 0 in 10m.

A. Single Power Beacon in mMTC

This use-case illustrates that CSI-free strategies are agnostic to the number of devices in the network, contrary to CSI-based counterparts whose performance decreases rapidly as the network becomes more dense. The gap between CSI-free and CSI-based strategies is only noticeable for relatively small networks, although energy consumption for CSI acquisition is not being computed and therefore the actual gap is even smaller. Such conclusions are drawn from Fig 4, in which two CSI-based strategies are included as benchmark: OA – CSI, for which the antenna that provides the greatest amount of overall harvested energy is selected; and AA – CSI, for which instead of transmitting with the same power over each antenna, the PB pre-compensates through precoding vectors for the channel and EH hardware effects before transmission, such that the overall harvested energy at the entire set of EH devices is maximized. Notice that CSI-based results are idealistic, since we ignore the energy resources that would be required for CSI acquisition, and even the AA – CSI scheme could be unfeasible to implement in practice because of the computational complexity that involves finding the optimum precoding vectors when the number of users and/or antennas increases. Therefore, as \( N \) increases the CSI acquisition procedures and associated energy expenditures become a problem and limiting the practical benefits of the CSI-based schemes. Additionally, the AA – CSI scheme outperforms the AA (CSI-free) strategy only when powering a very small number of devices, and even for single PB the performance gap is not significant. The gap is even expected to decrease if \( M \), and/or spatial correlation increases [15]. Additionally, notice that even if the SA scheme does not provide much gain in terms of the average harvested energy, it does provide in terms of the energy outage, thus, it may be suitable for supporting uninterrupted operation of simple EH devices.

B. Multiple Power Beacons in mMTC

Next, we aim to evaluate the scalability of CSI-free strategies in a DAS composed of multiple PBs context. Thus, as an illustrative practical cases, we
assume either that \(i\) signals transmitted at different PBs are independent, or \(ii\) signals are fully correlated, which is possible under perfect synchronization (SYNC). The selection of the powering strategy is intricate already for the single PB scenario; the problem becomes even more complex in a multi-PB setup and therefore it is not straightforward to determine what is the most appropriate strategy. However, our results as shown in Fig. 5 indicated that the later alternative is not recommended as it lowers the performance, specially with respect to energy outage. Therefore, multiple PBs WET systems should be designed to avoid correlation of the powering signals. Interestingly, increasing the number of antennas attenuates this effect when operating under the SA scheme, while AA seems to be the most suitable strategy as it provides the largest average harvested energy with increase of the number of antennas, also having one of the best energy outage performances when WET signals are fully uncorrelated. In Fig. 6 when comparing top to bottom rows, we observe that using the AA scheme is the most beneficial for those EH devices in the neighbourhood of each PB, for which high reliability in delivering energy is guaranteed. However, those devices that are distant from all PBs benefit more from the SA strategy. The SA scheme allows homogenizing somewhat the energy outage performance in the plane, which would be appropriate in not extremely dense PB deployments. Notice that the SA strategy is the least harmed under full correlation of the powering signals, which is an extreme case but may not be completely avoided in practical setups. As commented before, such advantage increases with the number of antennas.

\[ \text{V. Conclusions} \]

WET is a promising solution for powering future IoT networks where a huge number of devices will require steady and uninterrupted operation as envisioned by 6G. In this work we show that EB and DAS alone may be inefficient for massive WET deployments due to overhead and increased energy consumptions imposed by CSI acquisition. We propose and emphasize the suitability of CSI-free strategies when powering simultaneously a large number of devices, while presenting numerical results for single and multi-PB deployments. Our results evince that combining DAS with an efficient CSI-free scheme allows enlarging the energy coverage region, thus, decreasing the maximum energy outage probability of all EH devices.

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