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Distributed Control of Wireless Power Transfer Subject to Safety Constraints

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Abstract: The deployment of networks composed of several radio frequency (RF) based wireless power transfer nodes will be an indispensable component of future Internet of Things (IoTs). The natural objective of such networks, so called the wireless power transfer networks (WPTNs), is to charge the energy receiver devices wirelessly as quickly as possible; i.e. maximizing the transmitted power. However, a safe-charging WPTN must also comply with the RF exposure regulations and keep electromagnetic radiation (EMR) under a predefined threshold. In this paper we consider the problem of maximizing the transmitted wireless power to the energy receivers with subject to the safety constraints. We introduce two fully-distributed charging algorithms where the energy transmitters communicate only with the sensors in their communication range to obtain their measurements, perform simple computation steps to adjust their power levels and and in turn satisfy safety constraints without any global information.

Keywords: Distributed optimization, Networks of sensors and actuators, Control of networks, Wireless power transfer networks, Electro-magnetic radiation safety.

1. INTRODUCTION

In today's world, the provision of energy to Internet of Things (IoT) is becoming a prominent issue due to the increasing number of the connected devices. As of now, many appliances are still powered using power cords. On the other hand, low-power wireless embedded systems, such as wireless sensor networks (WSNs), are powered using batteries. However, batteries do not provide a promising solution to get rid of power cords due to their severe drawbacks: (i) they increase the size and the cost of the hardware; (ii) its impracticle to implant battery-powered hardware in human body; (iii) replacing batteries or recharging them is quite demanding for the the sustainable operation and (iv) they are quite harmful for the environment.

Fortunately, advancements in electronics enabled circuits capable of harvesting energy from the radio frequency (RF) waves Gao et al. (2014); meanwhile the power requirements of the low-power electronic devices have been reduced to a few μW Smith (2013). As a consequence of these advancements, it is now feasible to transfer the electromagnetic energy, using the electric field of the RF waves as an energy delivery medium, from a power source to receiver devices over the air; so called the RF-based *wireless power transfer* (WPT). Apart from conventional radio-frequency identification (RFID) tags, RF-based WPT is now sufficient enough to provide energy to computational RFIDs (CRFIDs)—a new class of tiny computers based on the RFID technology and capable of sensing, computing and communicating without batteries using only the harvested RF energy. These battery-less systems have already started to allow several interesting applications, e.g. wireless cameras Naderiparizi et al. (2015). Without doubt, the interest in the battery-less systems is rising that will reveal several interesting research problems and challenges in this domain Gollakota et al. (2014).

For the provision of sufficient energy to the any kind of battery-less devices, deployment of networks composed of several WPT nodes will be a prerequisite. Conceptually, energy transmitters (ETs) in these dedicated *wireless power transfer networks* (WPTNs) Liu et al. (2016b) are capable of controlling their transmission power levels in order to charge nearby energy receiver (ER) devices over the air collaboratively. The natural objective of the WPTNs is to charge ERs as quickly as possible; i.e. to maximize the transmitted power and in turn the harvested energy. However, a safe-charging WPTN must guarantee that none of its users are exposed to harmful electromagnetic radiation (EMR) and it must comply with the RF exposure regulations Liu et al. (2016a).

1.1 Contributions

In this paper we consider a WPTN in which extra sensor nodes are deployed to measure EMR values at specific locations. We focus on the problem of maximizing the transmitted power to the ERs with subject to the safety constraints, i.e. the measured EMR values from the sensors do not exceed a pre-defined EMR threshold value. To this end, we propose two distributed charging algorithms where ETs communicate only with the sensors in their communication range to obtain their EMR measurements, perform simple computation steps to adjust their power levels and in turn satisfy safety constraints without global

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information. In particular, the main contributions of this paper are:

- To the best of our knowledge, this is the first study that provides feedback-based distributed algorithms the for safe wireless charging. In particular, satisfying safety constraints using feedbacks from sensors has never been studied in the distributed setting before.
- In the current literature, safety solutions are based on mathematical models that represent the EMR distribution. Therefore, in theory, they can satisfy safety constraints. However, it is impossible to estimate the EMR value since the transmitted power is random due to environmental effects Liu et al. (2016a). Since our solutions use real EMR measurements from the sensors, they always guarantee the safety of the WPTNs in practice.
- The proposed algorithms are simple and easy to implement. Each ET requires *only* local knowledge about the ERs inside its power transmission range and communicates *only* with the sensors inside its communication range. In turn, multiple ETs can update their power levels simultaneously, without communicating with the other ETs, making the proposed solutions very attractive from a practical point of view.

2. RELATED WORK

Although the relationship between EMR and health impairments has not been proved conclusively, it is widely accepted that being exposed to small radiation levels over long time periods raises the risk of cancer Ahlbom et al. (1998). To this end, several institutions established exposure limits for the radiation power Kalialakis and Georgiadis (2014). From algorithmic point of view, considerable research efforts for WPTNs have been devoted to optimize the harvested power Krikidis (2014), energy outage Huang and Lau (2014) and charging delay Fu et al. (2013). However, none of these studies considered the safety issues in WPTNs.

Quite recently, the safety challenges in RF-based WPTNs have started to receive the attention from the researchers Liu et al. (2016a). We are aware of two studies in the literature that focused on safe WPT. In Dai et al. (2014a), the authors provided a centralized formulation to maximize the total transmitted power meanwhile satisfying the EMR safety constraints at each point in a pre-defined 2D deployment area. Later on, the same authors considered handling the same problem in the distributed setting Dai et al. (2014b). However, their distributed solution is quite complex and consist of several phases. Since trying to satisfy the EMR safety at each point in the pre-defined 2D area introduces infinite number of constraints, the authors first reduce the number of constriants by forcing ETs to implement a distributed redundant constraint reduction algorithm. After this step, the 2D area is splitted into several small squares in such a way that the ETs inside these square reqions can calculate the local linear programming (LP) solution independently by only considering the constraints in these squares. Namely, instead of performing a centralized LP, the authors allow to perform LP inside the independent squares and then merge the

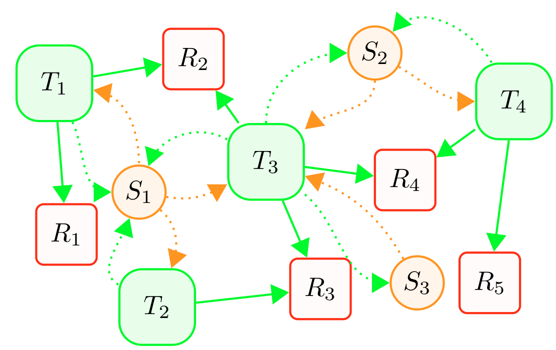

Fig. 1. A representative graph-theoretical view of a Wireless Power Transfer Network (WPTN). Energy transmitters are denoted by T_i, energy receiver devices are denoted by R_j and sensor nodes are denoted by S_k.

results to obtain the main LP solution. A crucial drawback of these two studies is that the proposed solutions satisfy EMR constraints in practice if and only if the proposed EMR model reflects the real wireless power propagation perfectly. In contrast, our solutions do not require communication among ETs; they rather require the ETs to communicate with the real sensors that can provide real EMR measurements. Moreover, they allow ETs to perform little number of computation steps to adjust their power levels. In addition, since our algorithms consider the real measurements from sensors, they will always guarantee safety constraints in practice.

3. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we present an analytical system model based on the studies Govindan et al. (2011); Zhou et al. (2012); Naderi et al. (2015). We model a WPTN in a 2D plane (room) using a directed graph G, as depicted in Fig. 1. We list our assumptions, definitions and introduce the notation as follows:

I) The WPTN is assumed to be composed of several stationary RF-based ETs, each denoted by $T_i \in T$.

II) P_i denotes the output power of the transmitter T_i. Formally, there is a minimum power level denoted by $P_{\min}$ and a maximum power level denoted by $P_{\max}$ so that

$$P_{\min} \le P_i \le P_{\max} \tag{1}$$

III) WPTN is assumed to be composed of stationary ERs, each denoted by $R_j \in R$.

IV) Each energy transmitter can charge the energy receivers inside its power transmission *coverage*, denoted by C_i. As depicted by the directed connections in graph G, T_1 in Fig. 1 can charge R_1 and R_2 which are assumed to be the elements of the set C_i.

V) The power received by energy receiver $R_j \in C_i$ from energy transmitter T_i is inversely proportional to the square of the distance d_{ij} between T_i and R_j; shown as

$$P_{ij} \propto \frac{\gamma P_i}{(d_{ij} + \beta)^2} \tag{2}$$

where γ and β are constants dependent on the environment and the hardware of the energy receivers