Ad Hoc Networks 36 (2016) 214–228

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Tag-based cooperative data gathering and energy recharging in wide area RFID sensor networks

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ARTICLE INFO

Article history:
Received 8 January 2015
Revised 29 June 2015
Accepted 1 July 2015
Available online 14 July 2015

Keywords:
RFID sensor networks
Mobile data gathering
Wireless energy recharging

ABSTRACT

The Wireless Identification and Sensing Platform (WISP) conjugates the identification potential of the RFID technology and the sensing and computing capability of the wireless sensors. Practical issues, such as the need of periodically recharging WISPs, challenge the effective deployment of large-scale RFID sensor networks (RSNs) consisting of RFID readers and WISP nodes. In this view, the paper proposes cooperative solutions to energize the WISP devices in a wide-area sensing network while reducing the data collection delay. The main novelty is the fact that both data transmissions and energy transfer are based on the RFID technology *only*: RFID mobile readers gather data from the WISP devices, wirelessly recharge them, and mutually cooperate to reduce the data delivery delay to the sink. Communication between mobile readers relies on two proposed solutions: a *tag-based relay* scheme, where RFID tags are exploited to temporarily store sensed data at pre-determined contact points between the readers; and a *tag-based data channel* scheme, where the WISPs are used as a virtual communication channel for real time data transfer between the readers. Both solutions require: (i) clustering the WISP nodes; (ii) dimensioning the number of required RFID mobile readers; (iii) planning the tour of the readers under the energy and time constraints of the nodes. A simulative analysis demonstrates the effectiveness of the proposed solutions when compared to non-cooperative approaches. Differently from classic schemes in the literature, the solutions proposed in this paper better cope with *scalability* issues, which is of utmost importance for wide area networks.

1. Introduction

The integration of radio frequency identification (RFID) systems and wireless sensor networks (WSNs) has greatly attracted the interest of industrial and research communities during the last decade [1]. Early attempts in the direction of unifying identification and sensing operations were based on the hybrid coexistence of both technologies within a common framework [2,3]. Recently, the advancements of RFID technology opened a completely new scenario where passive tags are augmented with sensing capabilities [4]. This is the case of the Wireless Identification and Sensing Platform (WISP) that definitely gave birth to RFID sensor networks (RSNs) for joint identification and sensing purposes. WISP devices harvest energy from the RF signal generated by a reader and use it to power a fully programmable micro control unit (MCU) and the sensor. Some contributions testify to the remarkable potentialities of WISPs in small environments such as smart home [5] and e-health [6,7] applications. Moreover, equipping the WISP with

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http://dx.doi.org/10.1016/j.adhoc.2015.07.001
1570-8705/

a capacitor for long-run sensing activities [8] paves the way for a wider range of applications hitherto restricted to traditional WSNs, such as data logging or environmental sensing in large spaces. For instance, WISP devices can be used for forest monitoring, fire detection, environment security and tracing of agriculture products to assure the products quality in extended cultivated lands [9,10].

The effective deployment of large RSNs is challenging due to the specific features of the involved “smart tags”. WISP devices use the RFID interface to exchange data, with the communication burden totally on the reader. This is a notable advantage w.r.t. sensor nodes, whose energy is mainly consumed in the transceiver section. On the other hand, the drawback of an RFID interface is that no direct WISP-to-WISP communication is possible and, thus, information cannot be multi-hop forwarded to the sink. Moreover, WISP tags are completely passive devices; they need an RFID reader to be recharged and they store the RF harvested energy in a capacitor. The discharge of the capacitors with the time depends on the sensing rate, and typically guarantees a very limited lifetime of the tag, which thus requires to be periodically recharged. This aspect plays a key role to enable RSNs also for long-run applications and has been investigated in the literature referring to a wireless rechargeable sensor network [11]. Noteworthy, differently from classic rechargeable sensor devices, which require additional hardware for wireless power transfer [12], a sensor-enabled tag uses the RFID communication interface also for energy harvesting, with a consequent reduction in costs and complexity per single node [13].

We focus on large-scale RSNs and propose solutions that foresee simple low-cost RFID mobile readers to keep the WISP devices charged while cooperating to transfer data to the sink and reduce the collection delay. Differently from other solutions in the literature, our proposals exclusively rely on the RFID technology for both data transmissions and energy transfer. Having a single technology reduces network deployment costs and makes the proposed solutions independent from third parties such as network providers. This is important for the scenarios considered in this paper where alternative communication technologies are hardly available. For instance, cellular communication technologies are scarcely deployed in isolated areas (e.g., cultivated lands, forest areas) and coverage issues may rise. As a consequence, the opportunity of designing ad-hoc communication networks, autonomously from alternative technologies, is essential to guarantee an efficient, reliable and scalable solution in the scenarios of study in this paper. Moreover, the memory of the tag can be used as a temporary data storage which guarantees the persistence of the medium and can enable novel approaches, overcoming limitations of classic technologies. For instance, it allows devices to exchange data in a given area even if they are momentarily out of the communication range. In these cases, a direct communication (whatever the used technology such as Zigbee [14]) would be lost.

The problem of recharging WISPs while collecting data from them can be modeled as a Multiple Traveling Salesmen Problem with Deadlines [15], where multiple mobile elements follow disjoint tours to guarantee that all sensors are visited by only one mobile element and that all recharging deadlines are met. This problem is well-known to be NP-hard and various heuristics have been proposed in literature to solve it [16–18]. Unfortunately, these solutions typically rely on anchor points to collect data from nearby sensors via multi-hop communication or assume long-range communications between mobile chargers; such assumptions do not hold for the reference scenario studied in this paper, so novel customized solutions are required that meet the technological constraints of RFID sensor tags. In fact, since no WISP-to-WISP communications are possible, the only way to collect the information from a WISP device is through an RFID reader located sufficiently close to the WISP. Moreover, in the reference wide area RSN scenarios, we believe that *scalability* is of utmost importance to guarantee the network maintenance and reliability on a large scale. Classical schemes proposed in the literature for data collection, energy replenishment or joint data collection and energy replenishment in rechargeable WSNs often suffer from scalability limitations. Differently, the solutions that we propose for RSNs have the important advantage of being scalable with the size of the network and the number of deployed WISP devices.

For an efficient implementation of the proposed techniques for cooperative data collection and recharging in wide area RSNs, the following aspects will be specifically designed in the paper:

- *Network clustering*: The WISP devices are clustered so that each mobile reader serves only one cluster. The proposed cluster formation methodology is based on the energy constraints of the WISPs and aims to keep the number of mobile readers low while perpetual network operation is guaranteed through periodical WISP recharging.
- *Mobile reader movement tour definition*: Two types of mobile readers are defined, the so-called *cluster reader*, designated to gather data from the cluster and recharge the associated WISPs, and the *bus reader*, that transports data between clusters to the sink. The movement tours for both types of mobile readers are accurately studied to reduce the traveled paths and the data collection delay, both on an intra-cluster and an inter-cluster basis.
- *Communication between mobile readers*: The cluster readers recharge the WISPs, gather the sensed data, and deliver them to the bus readers. The data transfer between cluster and bus readers is implemented through two proposed solutions. In the *tag-based relay (TBR)* scheme, each cluster reader temporarily stores the data collected from its cluster in a large-memory passive tag [19], called *relay*. Then, in a “delay tolerant” mode, the bus reader picks up the data stored in the relays and carries it to the sink. In the *tag-based data channel (TDC)*, WISPs are used as a sort of “virtual communication channel” for data transfer between cluster and bus readers [20]. This unconventional use of the RFID technology for data communication allows for “real time” communication between RFID readers, thus enabling cooperative solutions without the need for additional hardware deployment in the mobile readers and, therefore, reducing their complexity. The readers’ tour synchronization is therefore required since the cluster and the bus reader must simultaneously be in proximity to the tag used for data exchange.

The effectiveness of the proposed solutions is evaluated in a broad range of simulation scenarios for wide area networks and compared with approaches that do not foresee