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Interest-aware energy collection & resource management in machine to machine communications

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ABSTRACT

The emerging paradigm of Machine to Machine (M2M)-driven Internet of Things (IoT), where physical objects are not disconnected from the virtual world but aim at collectively provide contextual services, calls for enhanced and more energy-efficient resource management approaches. In this paper, the problem is addressed through a joint interest, physical and energy-aware clustering and resource management framework, capitalizing on the wireless powered communication (WPC) technique. Within the proposed framework the numerous M2M devices initially form different clusters based on the low complexity Chinese Restaurant Process (CRP), properly adapted to account for interest, physical and energy related factors. Following that, a cluster-head is selected among the members of each cluster. The proposed approach enables the devices of a cluster with the support of the cluster-head to harvest and store energy in a stable manner through Radio Frequency (RF) signals adopting the WPC paradigm, thus prolonging the operation of the overall M2M network. Each M2M device is associated with a generic utility function, which appropriately represents its degree of satisfaction in relation to the consumed transmission power. Based on the distributed nature of the M2M network, a maximization problem of each device's utility function is formulated as a non-cooperative game and its unique Nash equilibrium point is determined, in terms of devices' optimal transmission powers. Considering the devices' equilibrium transmission powers, the optimal charging transmission powers of the cluster-heads are derived. The performance of the proposed approach is evaluated via modeling and simulation and under various topologies and scenarios, and its operational efficiency and effectiveness is demonstrated.

1. Introduction

Wireless communication systems and networks have grown explosively in recent past due to the increasing popularity of devices like smart phones, tablets with powerful multimedia capabilities and applications, sensors, actuators, vehicles, human-wearables, etc. The Wireless World Research Forum envisions in 2020 seven trillion wireless devices will be serving seven billion people [1]. According to CISCO prediction [2], the monthly global mobile data traffic will be 49 exabytes by 2021, and the annual mobile data traffic will exceed half a zettabyte. Key part of the evolving wireless communication environment is the Internet of Things (IoT), which presents an emerging topic of great technical, social and economic significance. Projections for the impact of IoT on the Internet and economy are impressive. Recent statistics anticipate as many as *100* billion connected IoT devices and a global economic impact of more than $11 trillion by 2025 [3]. The emerging paradigm of Machine to Machine (M2M)-driven IoT will differ fundamentally from that in the classic internet that focused on human to human communication. M2M communications will feature orders of magnitude more nodes, most of which will be extremely low-power or self-powered devices.

1.1. Related work

Among the key concerns related to the IoT applications is the prolongation of the mobile M2M devices' battery life, towards guaranteeing the operation of the IoT system for a longer time period. Therefore, in the vast majority of the IoT applications, the energy efficient communication and the stable energy supply to them have become among the primary objectives in resource allocation. The latter becomes even more critical due to the growing proliferation of M2M devices, which are often deployed in areas where frequent human access or battery replacement is not always feasible [4].

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Aiming at improving the energy efficient communication among the M2M devices, and in parallel overcoming the wireless access congestion problem, the joint clustering of devices and resource management arises as a promising solution. Various M2M devices clustering methods have been proposed in the recent literature based on different criteria, such as M2M devices' achievable signal to interference plus noise ratio [5], transmission delay [6], etc. The induced hierarchy for management and control via the clustering methods provide an immediate and intuitive benefit [24–26]. Furthermore, the concept of data priority has been adopted towards devising energy efficient and congestion mitigated clustering algorithms thus improving the energy efficient transmission of the M2M devices for the IoT applications. The authors in [7] propose a data-centric clustering algorithm of the M2M devices in a resource constrained M2M network by prioritizing the quality of the overall data transmitted by the individual devices. Following the concept of data priority, a healthcare IoT application is studied in [8], where the criterion of health-based priority of the transmitted data is utilized towards performing M2M devices' clustering. In [9] the problem of energy-efficient clustering is studied by jointly considering cluster formation, transmission scheduling and power control while the problem of energy efficient transmissions of M2M devices has been studied in [10] considering an existing clustering in the M2M network. More specifically, the authors allow the cluster-head to coordinate the congestion within the existing cluster via assigning weights to the M2M devices based on various criteria, such as data priority, energy availability, and M2M devices' mobility. In [11], a primitive joint interest, energy and physical-aware framework for coalitions' formation among the wireless IoT devices and an energy-efficient resource allocation in M2M communication networks is introduced. Despite the promising results obtained, the main drawback of this approach is that it only emphasizes on the energy efficient communication among the devices, while their available energy/battery is fixed and they are not capable of harvesting additional energy from the RF signals.

In parallel of devising clustering algorithms to improve the energy efficiency, the stable energy supply to the M2M devices is of great importance to prolong their battery life, as well as the operational life of the overall IoT network. Towards this direction, the Wireless Powered Communication (WPC) technique has emerged as a promising alternative to the conventional battery-powered operation and/or the energy harvesting technique based on natural energy sources such as solar or wind. The M2M devices participating in an IoT application, whether battery-free or not, can benefit by adopting the WPC technique, due to the fact that they can harvest and store energy in a stable manner from the Radio Frequency (RF) signals via dedicated neighbor devices, e.g., cluster-heads, during the wireless energy transfer (WET) phase. Then, the saved energy can be further exploited via adopting energy efficient transmission techniques, as the one discussed before, and transmit their information signals to the cluster-head or evolved NB (eNB) during the wireless information transmission (WIT) phase [12]. Several research works have been proposed in the literature dealing with the energy utilization efficiency via adopting the wireless powered communication technique and devising intelligent resource management frameworks. In [13], a joint time allocation and power control framework is proposed towards maximizing network's energy efficiency under different conditions, such as the initial battery energy of each mobile device and the minimum system throughput constraints. The maximization problem of the uplink sum-rate network's performance is studied in [14], while adopting the WPC technique and via jointly determining the optimal energy and time resource allocation for the multiple mobile devices. This work has been extended in [15] considering additional constraints, such as infinite or finite capacity energy storage. Furthermore, the problem of joint subcarrier scheduling and power allocation via jointly adopting the orthogonal frequency division multiplexing (OFDM) and WPC techniques has been studied in [16] towards maximizing system's sum-rate. Also, the problem of energy-efficient resource management in a distributed manner has been thoroughly studied in the literature, considering either single control parameter (e.g., power control) [17–19] or multiple control parameters (e.g., power and rate control) [20] considering complex networking paradigms [21].

Though the aforementioned: (a) clustering approaches for supporting energy efficient communication among M2M devices and (b) resource management efforts, while adopting the WPC technique, present significant results towards improving the overall system's energy efficiency and M2M devices' battery saving, their main drawbacks are:

a. Their joint effect in prolonging M2M devices' battery life has not been studied and exploited yet and
b. Their main goal is to optimize system's welfare, thus they cannot be properly adapted to device-centric paradigms, where the goal of the devices is to optimize device's perceived satisfaction from the allocated resources.

Last but not least, it should be noted that as the IoT represents a vision in which the Internet extends into the real world embracing everyday objects, physical items are no longer disconnected from the virtual world and aim at collectively provide contextual services. Therefore the Internet of Things comprises a digital overlay of information over the physical world, where objects and locations, along with device purpose and interest become interrelated. This paper aims at exactly dealing with these challenging issues and filling the corresponding gap in the literature.

1.2. Paper contribution

Specifically, to overcome the aforementioned drawbacks, in this paper, it is the first time in the literature to the best of our knowledge that a joint interest and energy-aware devices' clustering methodology and a resource management framework adopting wireless powered communication (WPC) technique in M2M communication networks for supporting IoT applications is proposed. The basic contributions and differences of our proposed approach and framework in this paper are summarized as follows.

1. A joint interest, physical and energy-aware cluster formation mechanism is proposed based on the Chinese Restaurant Process (CRP) [15] in order to create clusters among the numerous M2M devices. In a nutshell, the fundamental novelties of the proposed cluster formation mechanism are:
   (a) the overall combined communication interest among the M2M devices is determined based on three factors, i.e., interest of interaction among the M2M devices regarding the examined IoT application, physical proximity and energy availability, while the vast majority of the literature considers only the two latter factors in order to create clusters among the devices and
   (b) the adoption of the CRP admission control policy towards creating the clusters, which consists of closed formulas with low implementation complexity and therefore presents a realistic solution.
2. The use of WPC technique in M2M networks enables the devices in each cluster to harvest energy from the RF signals of the cluster-head. The fundamental benefits of incorporating the WPC technique in M2M networks are: (a) the elimination of the need for frequent manual replacement and recharging, (b) higher throughput, (c) prolongation of devices' lifetime and (d) low network operating cost. Moreover, instead of and in con-