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Energy-efficient scheduling and grouping for machine-type communications over cellular networks

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ABSTRACT

In this paper, energy-efficient scheduling and grouping for battery-driven machine-type devices in cellular networks is investigated. We introduce a scheduling-based cooperation incentive scheme which enables machine nodes to organize themselves locally, create machine groups, and communicate through group representatives to the base station. This scheme benefits from a novel scheduler design which takes into account the cooperation level of each node, reimburses the extra energy consumptions of group representatives, and maximizes the network lifetime. As reusing cellular uplink resources for communications inside the groups degrades the Quality of Service (QoS) of the primary users, analytical results are provided which present a tradeoff between maximum allowable number of simultaneously active machine groups in a given cell and QoS of the primary users. Furthermore, we extend our derived solutions for the existing cellular networks, propose a cooperation-incentive LTE scheduler, and present our simulation results in the context of LTE. The simulation results show that the proposed solutions significantly prolong the network lifetime. Also, it is shown that under certain circumstances, reusing uplink resource by machine devices can degrade the outage performance of the primary users significantly, and hence, coexistence management of machine devices and cellular users is of paramount importance for next generations of cellular networks in order to enable group-based machine-type communications while guaranteeing QoS for the primary users.

1. Introduction

Information and Communications Technology (ICT) can play an important role in smart cities in order to improve the services that support urban dwelling like security, healthcare, public transportation, remote working and education, entertainment, and communications [1,2]. For example, due to ever increasing portion of old-aged people in the societies, ICT can provide a wide-range of health-care applications in order to monitor the status of citizens right from their homes by smart sensors [3]. The number of smart devices is expected to be nearly 50 billion by 2020, based on the estimation from Ericsson [4], and these devices are expected to be able to communicate autonomously. Machine-to-machine (M2M) communications means the inter-communications of machine devices without human intervention, and aims at enabling ubiquitous connectivity among uniquely identifiable smart physical objects that are capable of sensing or acting on their environment [5]. Among different enablers, cellular M2M, also known as machine-type communications (MTC), is expected to play a critical role in the market since cellular networks are penetrated deeply into almost all locations, provide easy-to-use cost-efficient communications anywhere by ubiquitous coverage and roaming capability [6–8]. M2M networks are generally characterized by the massive number of concurrent active

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devices, low-payload data transmission, and vastly diverse Quality-of-Service (QoS) requirements [9]. The continuing growth in demand from machine-type communications [10], the fact that most smart devices are battery driven and long battery-lifetime is crucial for them, and the inefficiency in current cellular infrastructure for providing energy-efficient small data communications [11] have triggered many research projects to see how current cellular standards must be revisited in order to provide large-scale yet efficient machine-type communications [12–17].

In this paper, lifetime-aware MTC scheduling over cellular networks is investigated. Aiming at maximizing the network lifetime, we first investigate joint scheduling and transmit power control scheme for machine-type communications. Then to offload the base station (BS) and prevent congestion, we present a cooperation incentive scheme which reimburses the extra energy consumptions for the helper nodes. Furthermore, we extend the derived solutions for existing cellular networks. Finally, we analyze the impact of underlying intra-group communications on the uplink transmission of primary users.

The main contributions of this paper include:

1) Present a lifetime-aware cooperative machine-type communications framework for future cellular networks with dense MTC deployment.
2) Present a cooperation-aware scheduler which reimburses the extra energy consumptions of the helper nodes and maximizes the network lifetime. Investigate the application of the proposed scheduler for existing LTE networks.
3) Present a distributed grouping scheme for machine-type devices deployed in cellular networks.
4) Explore analytically the tradeoffs between maximum allowable number of overlay machine groups in a cell and the interference level at the primary user.

The remainder of this article is organized as follows: Section 2 presents the related works. The system model is introduced in Section 3. In Section 4, the cooperation incentive scheduler is presented. In Section 5, distributed grouping is presented. In Section 6, a cooperation-incentive MTC scheduler for LTE networks is investigated. The impact of intra-group M2M communications on QoS of primary users is investigated in Section 7. Simulation results are given in Section 8. Concluding remarks are presented in Section 9.

2. Related works and motivation

2.1. Cellular-access for machine-type subscribers

The continuing growth in demand from machine-type subscribers for small data communications poses significant challenges to the existing cellular networks [9]. Random Access Channel (RACH) in the Long-Term Evolution (LTE) networks is the typical way for machine nodes to connect to the BS [18]. This channel carries random access preambles that users randomly choose from a set of available preambles and send to the base station. Since the total number of available preambles is limited, collisions and energy wastages are likely to happen in the case of massive concurrent access requests [17]. Several solutions, including Access Class Barring (ACB) [19,20], prioritized random access [21,22], and connectionless MTC [23,24] are studied in literature to reduce congestion in an overload condition. ACB, which has been originally specified for access control to the air interface in LTE and LTE-A, can be used as an effective and efficient tool to prevent congestion when massive concurrent access occurs. In this scheme, the BS regularly broadcasts the access probabilities of different classes of machine nodes, e.g. p_i for the ith class. Then, each machine node in class i which has data to transmit will decide with probability p_i to content for channel access or to go to the back-off mode with probability $1-p_i$. In prioritized random access schemes [21,22], the available preambles are divided among different classes of users, and hence, each class of users has only access to a limited set of preambles. Then, in the case of overload situations the emergency and high priority messages can be served without QoS degradation. To further reduce the probability of congestion in the RACH of LTE, machine nodes with limited data packet size can send data directly to the BS without connection establishment [23,24]. The capacity limits of RACH for serving machine-type communications and a survey of improved alternatives are studied in [25].

The surge in both traffic and signaling load [26], not only negatively impacts the Radio Access Network of LTE but also severe signaling overload is expected to happen at the Evolved Packet Core of LTE [27]. In [28], the scalability of MTC and Internet of Things (IoT) on LTE mobile networks is investigated and it is shown that some MTC categories, e.g. asset tracking, could be substantially challenging as the IoT scales up on LTE networks. Then, efficient scheduler design with reduced signaling overhead is of paramount importance for future M2M-enabled cellular networks [17].

2.2. Towards energy efficient MTC over cellular networks

To curb undesirable energy wastage and extend the battery lifetime of machine devices, a variety of energy-conserving measures have been developed, including discontinues reception (DRX), group-based MTC, device complexity reduction, and energy-efficient MTC scheduling.

2.2.1. Discontinues reception

DRX has been specified in LTE for energy saving by allowing User Equipment (UE) to switch off its receiver and go to the sleep mode. During the sleep period, UE cannot receive packets from the base station, and hence, DRX can introduce delays in data reception. To maximize the energy saving gain and keep the aforementioned delay bounded, the DRX parameters are to be designed carefully [29]. DRX design for machine-type communications is investigated in [30,31], and it is shown that such operation can significantly prolong the battery lifetimes of machine nodes deployed in LTE networks. The accurate design of On and Off periods by considering different QoS requirements and traffic characteristics of MTC constitutes an interesting and open area for further research [32].