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A modified vacation queueing model and its application on the Discontinuous Reception power saving mechanism in unreliable Long Term Evolution networks

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ABSTRACT

In this paper, Discontinuous Reception, a power saving mechanism in Long Term Evolution wireless networks, is analytically investigated in the presence of transient faults by using an unreliable $M/G/1$ queue with multiple vacations. System failures may occur either due to transient faults in the mobile device or due to wireless link errors. When a failure occurs, the device may request the retransmission of the packet after a recovery period. In such a case, the power consumption will be further increased. Steady state analysis is presented, and decomposition results are discussed. Energy and performance metrics are obtained, and used to provide useful numerical results.

1. Introduction

Wireless networks have enjoyed an exponential growth and wireless communication has become an essential part of modern life. Many new wireless applications demand higher data rates and consume more energy than in the recent past. However, wireless devices are always powered by batteries, which have limited lifetime and constrain their use and the growth of wireless networks.

Recent advances in wireless communications are marked by the development of Fourth Generation (4G) technologies such as 3GPP LTE (3rd Generation Partnership Project Long Term Evolution) [1]. As LTE increases data rates by a factor of 50 compared to 3G, wireless device batteries are still about the same size, so substantial improvements in power usage are necessary to operate at these very high rates and wide frequency bands. These savings come from improvements in the hardware, the system architecture, and the protocols used. Consequently, power saving mechanisms are becoming increasingly important for next-generation wireless networks. In order to improve client's operation period without recharging the battery of the device, 3GPP LTE defines the Discontinuous Reception (DRX) mode [1].

In DRX mode, the User Equipment (UE, the mobile device) powers down most of its circuitry for a predefined period (DRX cycle) when there are no packets to be received. A DRX cycle consists of a sleep period, during which the UE is unavailable, and an on-period (or a listening period), during which the UE monitors new packet arrivals in the evolved Node B (eNB, the base station) by receiving an indication message conveyed via a control channel. If the UE receives a positive indication message implying that newly arrived packets are buffered and ready for transmissions, it wakes up to receive the buffered packets. Otherwise, it immediately goes back to sleep to prevent redundant power consumption.

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Wireless/mobile systems are notorious for the highly time-varying and unreliable wireless channels due to the propagation effects such as multipath fading, shadowing, and path loss. Moreover, mobile devices often suffer from transient faults such as memory or software faults. Faults are generally classified either as transient or as permanent (see [2]). A transient fault will eventually disappear without any apparent intervention (a restart of the device is usually enough in case of a software fault, whereas a failed wireless link becomes again operational soon), whereas a permanent one remains until it is removed by some external agency. In this work we consider only transient faults that recur unpredictably. Transient faults cause system failures and a traditional way to increase reliability is repetition.

However, retransmission schemes in modern wireless networks employ forward error correction (FEC), a technique used for controlling errors in data transmission. Under such schemes, the total number of retransmissions (until successful transmission) can be reduced substantially. Clearly the repetition of the transmission process will increase the power consumption and thus, a cross-layer investigation of the effect of failures on power consumption is critical.

1.1. Related work in energy saving in wireless systems

Several analytical studies have been conducted in the literature regarding the performance of DRX. Yang et al. [3] provided a Markov chain model to investigate the performance of the DRX in UMTS (which is the predecessor technology of 3GPP LTE) systems. There, the DRX mechanism was modeled as an $M/G/1$ queue with multiple vacations. In [3] the authors derived the Laplace transform of the downlink packet delay and the power saving factor. Yang et al. [4] proposed a semi-Markov model where packet arrivals followed the European Telecommunications Standards Institute (ETSI) bursty packet traffic model, while more recently Baek and Choi [5] studied a discrete time model to analyze DRX in 3GPP LTE by taking into account both the downlink and the uplink traffic. Mancuso and Alouf [6] analyzed a queueing model for the behavior of users and base stations in continuous connectivity, while Anisimov et al. [7] provided a comparison between the DRX in LTE-Advanced and the sleep mode that is employed in the IEEE 802.16m standard.

In order to maximize energy efficiency, a traffic-based DRX cycle adjustment scheme was proposed by Yu and Feng [8] to adjust the DRX parameters according to traffic estimation. A partially observable Markov decision process was employed to conjecture the traffic status and to provide the selection policy for DRX parameters. Zhou et al. [9] modeled an adjustable DRX power saving mechanism under bursty packet data traffic by using a semi-Markov process. Their analytical results, which were validated against simulations, showed that DRX in LTE achieves better power saving gains over DRX in UMTS, at the price of a prolonging wake up delay. Finally, Yeh et al. [10] provided a comparative analysis of energy saving methods in 3GPP and 3GPP2 standards.

Power saving modes in systems other than the LTE have also been studied; hereafter we cite some of these studies. A queueing-based modeling framework was used for the analysis of power saving of IEEE 802.16e in [11–14]. The power saving operation of the Cellular Digital Packet Data (CDPD) system was studied using queueing theory in [15,16]. Sleep mode operation of the IEEE 802.11 protocol was investigated in [17], while the energy efficiency in Wireless Sensor Networks (WSN) using vacation models was studied in [18–20].

1.2. Related work in energy saving in wired systems

Clearly, much study has been devoted to power saving in wireless networks where the nodes are battery operated. As indicated in [21], the radio transceiver, which is the dominant source of energy consumption within a node, consumes almost the same amount of energy when it exchanges packets and when it is in the idle mode. Therefore, switching off the transceiver can result in meaningful energy savings. Furthermore, the authors in [22] introduced a novel energy efficient algorithm to find and maintain routes in mobile ad-hoc networks. This work was motivated by learning algorithms and the concept of smart packets from previous research on cognitive packet networks [23].

In contrast to wireless networks, wired networks, which are massive consumers of power have recently drawn attention. The authors in [24] examined some approaches, which were used for dynamically managing wired packet networks, in order to minimize energy consumption, while meeting users' quality of service (QoS) needs. Their approach was based on automatically turning on/off link drivers and/or routers in response to changes in network load.

In [25,26], analytical models based on G-networks [27], were developed to incorporate the effects of user traffic, the overhead in QoS and the energy consumption introduced by the control traffic, that will be needed to carry out the rerouting decisions. Building on these works, they also examined in [28] the use of a gradient-based algorithm for QoS and power minimization in wired networks. Two distinct schemes, the conventional shortest-path routing and an autonomic energy aware routing algorithm [29], were investigated as the starting point for the gradient algorithm.

Recently, Gelenbe [30,31] proposed the Energy Packet Network (EPN), which stores and forwards quantized energy units to and from a large range of devices. The theoretical framework was based on G-networks. Finally, Gelenbe and Lent [32] studied ways to reduce energy consumption in information and communication technology systems while preserving acceptable levels of QoS.

1.3. Our contribution

In this work, we investigate the performance of the DRX power saving mode in LTE systems under the presence of transient faults such as transient software faults of the device and wireless link errors. Clearly none of the studies presented