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Performance analysis of sleep mode mechanisms in the presence of bidirectional traffic

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A B S T R A C T

Short battery life being a major impediment to a more widespread use of wireless devices, industry standards like WiMAX and 3GPP Long Term Evolution (LTE) embed power saving mechanisms in their protocol stack. Trading in network delay performance for extended battery life, these mechanisms require a careful balance to optimize overall network performance. Therefore, this paper assesses the impact of these mechanisms on network delay performance and battery life, thereby refining existing performance studies of the power saving mechanisms. In particular, this paper explicitly takes into account presence of both downlink and uplink traffic and their influence on the power saving mechanism. This contrasts with previous studies, where the analyses only accounted for downlink traffic. We obtain numerically efficient procedures to compute packet delay as well as energy efficiency characteristics under Markovian traffic. Then, performance of power saving is investigated by some numerical examples. Our results clearly indicate that uplink traffic heavily impacts the energy efficiency of the power saving mechanism.

1. Introduction

The IEEE 802.16e standard [1] backed by the WiMAX Forum [2] and the Long Term Evolution (LTE) [3] of the Universal Mobile Telecommunications System (UMTS) are emerging standards that have the potential to become the major standard for broadband wireless communication in the near future. These standards regulate communication between mobile subscriber stations (MSSs) and base stations (BSs) – user equipment (UE) and evolved Node-Bs (eNB) in LTE terminology – in a metropolitan area wireless network.

Short battery life is one of the main impediments to a more widespread use of wireless devices. Hence, understandably, a lot of research is directed at solving or at least mitigating this problem. Foremost this can be done by improving on the efficiency of batteries, but lately there is also a lot of interest in including energy-saving measures in the communication protocols themselves. On that account, it is no wonder that various energy-saving elements are incorporated in both WiMAX and LTE. Energy saving mechanisms are referred to as sleep mode and idle mode in WiMAX [4] and as discontinuous reception (DRX) in LTE [5].

In WiMAX, a MSS in sleep mode is still registered to a BS and still performs hand-off procedures. In contrast, idle mode operation (which is optional in current WiMAX standards) goes further and allows the MSS to be completely switched off and unregistered with any BS, while still receiving broadcast traffic. In LTE, DRX can be initiated when the UE is registered with an eNB (RRC_CONNECTED: radio resource control connected state) or when it is not (RRC_IDLE: radio resource control idle state). In the former case, the UE scans the neighboring eNBs when it detects signal quality degradation with respect to the serving eNB and performs handover when required by the signal quality. In this paper, we mainly consider the sleep mode mechanism and DRX in RRC_CONNECTED. In either case, the MSS (or UE) turns itself off for predetermined periods

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of time which are negotiated with the BS (eNB). In accordance with WiMAX terminology, these periods are referred to as 'sleep windows' in the remainder of this paper.

Three sleep mode classes are defined by the WiMAX standard. When in Power Saving Class I, the sleep window is progressively doubled in size from a prenegotiated minimum to a prenegotiated maximum value. Having reached the maximum sleep window length, this sleep window is repeated uninterruptedly, until traffic arrives. This class is considered to be suitable for best-effort and non-real-time traffic. Class II features fixed-length sleep windows, that is the same sleep window size is repeated continuously until there is uplink or downlink traffic to be transmitted. This class is typically employed for UGS (unsolicited grant services) traffic. Finally, Class III negotiates only a one-time sleep period. This is typically used for management traffic, when the MSS knows when upcoming traffic is to be expected.

Although Class I is most interesting from a modeling point of view, the analysis in this paper is general enough to encompass all three classes. In particular, our model assumes that a general sequence of sleep window sizes t_i, $i \geqslant 1$, has been negotiated between MSS and BS. In addition, this sequence is kept fixed during the entire operation of the system, instead of being negotiated at every start of a sleep period.

For LTE, the DRX cycle is initiated if there is neither download nor upload traffic for a predefined amount of time or a predefined number of frames. The choice of the lengths of the sleep windows differs considerably from WiMAX. First, LTE powers down the UE for short periods, a small sleep window is chosen. If there is still no traffic after a predefined number of these short sleep windows, DRX switches to longer sleep windows. Choosing a short window size first, allows the UE to wake up fast in case of unexpected data arrival immediately after the DRX cycle is enabled. As shown further, the general sequence of sleep window sizes introduced above, is sufficiently general to study DRX for any fixed parameter setting. As such, this paper presents a unified analysis of power saving operations in WiMAX and LTE, i.e. one that allows to compare the two sleep-mode updating mechanisms. Of course, WiMAX and LTE represent two very approaches to MAC layer protocol design, and we do not claim to have a unified model that captures both WiMAX and LTE.

1.1. Literature review

Power saving mechanisms have received a lot of interest lately from the performance modeling community, most authors focusing on the sleep mode mechanism of WiMAX. In [4], the average energy consumption of the MSS is obtained in case of Poisson downlink traffic, as well as an approximate expression for the mean packet delay. Retaining the Poisson assumption, Zhang and Fujise [6] investigate the energy consumption of the MSS accounting for both downlink and uplink traffic. For DRX, Bontu and Illidge [5] calculate the energy consumption of the UE for Poisson traffic. These authors also calculate the average delay that is experienced by a packet that arrives during a sleep window.

An accurate assessment of the delay experienced at the BS (or eNB) buffer however, requires a queueing model. For IEEE 802.16e, Han and Choi [7] model the BS buffer as a continuous-time finite-capacity queue with a Poisson arrival process and deterministic service times. A semi-Markov chain analysis leads to expressions for the mean packet delay and the mean energy consumption by the MSS. The analysis in [8] is based on an $M/G/1/K$ queueing model with multiple vacations and exhaustive service. For queueing systems with vacations, the server leaves for a vacation whenever there are no packets in the queue. If there are no packets in the queue upon returning from the vacation, the server immediately leaves for another vacation, and so on [9]. Clearly, the vacations can be used to model the sleep windows of the MSS. As the buffer space is finite, [8] also studies packet loss at the BS. Similar work can also be found in [10], where the length of a vacation is assumed to depend on the previous vacation length.

Predating UMTS, Cellular Digital Packet Data (CDPD) also provides a power saving mechanism. As in LTE and contrasting with IEEE 802.16e, the subsequent sleep windows do not increase in length, apart from the first sleep window which is shorter. The system can therefore be modeled as a queueing system with multiple vacations and exceptional first vacation length. See [11] where CDPD sleep mode is investigated for finite buffers and Poisson traffic. Delay, loss and energy efficiency are investigated. In addition to queueing models, Lin and Chuang [12] assess the performance of CDPD sleep mode by simulation.

Investigation of optimal sleep window lengths have not been limited to the restrictions imposed by the various standards. For example, an alternative to the exponential increase of the sleep windows is evaluated by simulation in [13]. Finally, in our previous work on the sleep mode mechanism of WiMAX [14,15], we considered a general D-BMAP arrival process, and we found that traffic correlation, which was hitherto neglected in almost every study, has an important impact on the sleep mode performance.

The present paper investigates the effects of the presence of uplink traffic on the performance of the sleep mode operation, which is another aspect that has received little attention in existing studies. In [6], uplink traffic has been given attention, although in that paper it was restricted to Poissonian traffic only and performance assessment was limited to energy efficiency. A simulation study taking both uplink and downlink traffic into account is found in [22]. A preliminary version of this paper can be found in [16], on which we extend in the present work by providing a.o. an analysis of the packet delay distribution and two new practical scenarios, while in [17] an analysis with more restrictions on the arrival process and the nature of uplink/downlink correlations is presented.

The influence of uplink traffic is considerable, as the MSS immediately ceases the sleep mode operation whenever there is uplink traffic to be transmitted. Thus, during uplink transmission, there is neither extra sleep mode delay experienced by incoming downlink traffic nor any power saving, as the communication circuitry is already switched on. We jointly model both the uplink activity and the downlink traffic by a finite but otherwise general Markovian background process and derive buffer content