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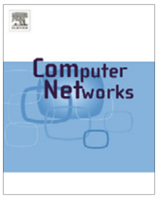

Analysis of power saving with continuous connectivity

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ABSTRACT

Always-on mobile users need high bandwidth channels with negligible access delay and limited power consumption. Such a *continuous connectivity* mode requires the management of high-speed channels, which can turn into substantial operational costs (i.e., power consumption rate) even in presence of low traffic, unless a power saving mechanism is enforced. In this paper, we analyze the impact of 3GPP-defined power saving mechanisms on the performance of users with continuous connectivity. We develop a model for packet transmission and operational costs. We model each downlink mobile user's traffic by means of an $M/G/1$ queue, and the base station's downlink traffic as an $M/G/1$ *PS* queue with multiple classes and inhomogeneous vacations. The model is validated through packet-level simulations. Our results show that consistent power saving can be achieved in the wireless access network, as high as 75% for mobiles and 55% for base stations.

1. Introduction

Thanks to technologies like WiMAX, HSPA, and LTE, today's mobile users can have a network performance experience similar to that provided by short range wireless LANs and even by wired DSL lines. The cost of providing such a service has been reported to be quite high for the network operator, e.g., of the order of tens of millions of dollars for a medium–small network with twenty thousand base stations [1]. However, most of the transmission cost might be dramatically reduced by using efficient power saving strategies in hardware, software and radio resource management domains.

We consider the case of users generating large volumes of traffic. These users browse the web, exchange email, share data on social networks, and access audio and video streaming applications. To shorten the delay to access the network as soon as new packets have to be exchanged, users need the continuous availability of a dedicated wideband data channel. This *continuous connectivity* requires frequent exchange of control packets, even in absence of data to be exchanged. So, unless power saving is enforced, a large amount of energy is required to control the high-speed connection.

The observation of current trends in the evolution of cellular standards, e.g., the evolution of 3GPP specifications, reveals that power saving is targeted via *sleep mode* operation, which will be mandatory in continuous connectivity at both user equipment (UE) and base station (evolved node B, namely eNB). However, sleep mode affects packet delay, thereby some constraints have to be considered when switching to power saving operations.

The literature presents various analytical and experimental studies on sleep mode in cellular networks, in particular on UE performance figures. The power saving mechanism for the UMTS UE has been evaluated in [2]. The performance of IEEE 802.16e power saving has been analytically evaluated in [3], where the authors use a semi-Markov chain approach. Other authors have used queueing theory to analyze the power saving. For instance, Seo et al. proposed an embedded Markov chain to model the system vacations in IEEE 802.16e, where the base station queue is seen as an $M/GI/1/N$ system [4]. An $M/G/1$ queue with repeated vacations has been proposed to

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model an 802.16e-like sleep mode and to compute the service cost for a single user download [5]. In a companion paper, we have analyzed the impact, on web traffic, of power saving mechanisms in continuous connectivity using a $G/G/1$ *PS* queue system [6]. In this paper, we adapt and extend the methodology of [5,6] to analyze multiple queues with a shared processor, without the restriction to web traffic.

Xiao proposed an analytical model, supported by simulations, for evaluating the performance of the UE in terms of energy consumption and access delay in both downlink and uplink [7]. Almhana et al. provide an adaptive algorithm that minimizes energy subject to QoS requirements for delay [8].

The work available in the literature does not tackle the base station viewpoint nor analytically capture the relation between cell load and service rate offered to the users. Conversely, we use an $M/G/1$ model to evaluate the behavior of each UE, and we compose the behavior of multiple $M/G/1$ queues into a single $M/G/1$ *PS* that models the eNB behavior. Then, we are able to analytically compute the cost reduction achievable thanks to sleep mode operations, and maximize this cost reduction both at the UE and the eNB under QoS constraints. In particular we refer to the 3GPP mechanism for downlink power saving in *Continuous Packet Connectivity* (CPC), namely the discontinuous reception (DRX) [9].

The importance of DRX in LTE and UMTS has been previously recognized in [10], where the authors model the DRX operation via a semi-Markov model for bursty packet data traffic. DRX advantages have been presented from the user viewpoint in [11], which proposes a very simple cost model over a detailed transmission model. Last, in [12], the authors use heuristics and simulation to show the importance of DRX for the UE.

The contribution of this paper is threefold: (i) we are the first to provide a complete queueing model for the behavior of users (UEs) and base stations (eNBs) in continuous connectivity, (ii) we provide a cost model that incorporates the different causes of power consumption, and (iii) we show how to use the model to minimize the power consumption rate under QoS constraints. Our model has been validated through packet-level simulations, and optimization results confirm that a dramatic economy of energy can be attained by correctly tuning the power saving parameters. UE costs can be reduced by a 75%, while eNB cost be lowered by more than 50%.

The paper is organized as follows: Section 2 reviews the concept of continuous connectivity. In Section 3 we derive a model for UE transmission activity and its cost. Section 4 extends the model to eNB. We validate the model in Section 5, and use it to compute the cost-QoS tradeoff at UE and eNB. Section 6 summarizes and concludes the paper.

2. Continuous connectivity

Consider a scenario in which user transmission activity is scheduled by the base station. Thereby the UE cannot transmit data unless the eNB grants a transmission opportunity. When using continuous connectivity, the UE should check the control channel continuously, and use it (in both uplink and downlink) for synchronization, power control, and traffic announcements. For instance, CPC has been defined by 3GPP for the next generation of high-speed mobile users, in which users register to the data packet service of their wireless operator and then remain online even when they do not transmit nor receive data for long periods [13]. A highly efficient sleep mode operation is thus strongly required, to allow disabling both transmission and reception of frames during idle periods. The UE, however, still has to transmit and receive control frames at regular pace, so that synchronization to the base station and power control loop can be maintained. Therefore, idle periods are limited by the mandatory control activity that involves the UE. To save energy, when there is no traffic for the user, the UE can enter a sleep mode in which it checks and reports on the control channels according to a fixed pattern, namely, only once every m time units (e.g., it listens to the control channel only one subframe out of m). This way, the energy consumption reduction at the mobile equipment is relevant, especially in case the transmitter is completely shut down during sleep mode operations. In change, the UE can transmit/receive new data only every m subframes.

However, in order to keep synchronization, the UE is always requested to listen to control channels every few tens of milliseconds, at most. Hence, the continuous connectivity cost can be sensibly higher than the cost incurred in WiMAX networks for instance, where no control channels are defined, and decoding the resource allocation table at the beginning of the downlink frame is not mandatory.

In 3GPP, DRX characterizes the downlink transmission behavior with sleep mode operations enabled. DRX allows the UE to save energy while monitoring the control information transmitted by the eNB over the High Speed Shared Control Channel. DRX affects data delivery, since no data can be dependably received without an associated control frame. In particular, 3GPP specifications define a DRX *long-cycle*, that is the total number of subframes in a listening/sleeping window out of which only one subframe is used for control reception. Valid values for this long-cycle are 4, 5, 8, 10, 16, and 20 subframes (i.e., using a 2 ms subframe in HSPA yields cycles of 8, 10, 16, 20, 32, and 40 ms). Note that the DRX long-cycle is activated only upon a timeout after the last downlink transmission. The timeout threshold specified in the standard can be $M = 2^{a+1}$ subframes, $a \in \{0, \ldots, 8\}$.

3. Power saving at the UE

Power saving at the UE is composed of the saving done in downlink and that done in uplink. In downlink, the UE decodes the control channel following the DRX pattern, and receives packets accordingly [13]. Uplink control transmissions follow a scheme similar to DRX, namely DTX (Discontinuous transmission). However, the DTX behavior depends on the activity of multiple physical channels [9]. Therefore, for sake of clarity and simplicity, we only focus on the DRX in the downlink, and leave the analysis of DTX in uplink for the future work. In particular, our model can be used for the downlink of systems using slotted operations, and specifically for HSPA [13] and LTE/LTE-Advanced [13,14]. We will show in Section 4