Active-Mode Power Optimization in OFDMA-Based Wireless Networks

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***Abstract*—Energy efficiency is increasingly important for wireless cellular systems due to the limited battery resources of mobile clients. While modern cellular standards emphasize low client battery consumption, existing techniques do not explicitly focus on reducing power that is consumed when a client is actively communicating with the network. Based on high data rate demands of modern multimedia applications, active-mode power consumption should also be an important consideration for wireless system design and standards development. Recent work in this area shows that radio resource management schemes optimizing energy efficient metrics can provide considerable reduction in client power consumption. In this paper, we evaluate the performance of such techniques using realistic cellular system simulation model. Specifically, we focus on the emerging fourth generation IEEE 802.16m standard. Our simulation results indicate that energy efficient techniques continue to provide considerable power savings, even when accounting for realistic system parameters and channel environments.**

I. INTRODUCTION

Adoption of wireless technology has become increasingly widespread as new high data rate broadband wireless standards emerge, allowing for improved access to services and applications previously only supported through fixed broadband systems. The increasing importance of energy efficiency for wireless systems is dictated by relatively slow progress in battery technology [1] and the growing quality of service requirements of multimedia applications. The gap between available and required battery capacity is becoming especially significant for small form-factor mobile devices, where wireless power comprises a significant portion of the total platform power budget. Addressing this growing gap requires aggressive improvements in all aspects of wireless system design, ranging from low power silicon and power management techniques on mobile platforms, to developing support in the wireless network for reducing client energy consumption.

The parallel evolution of personal, local and metropolitan area networks provides the wireless clients with a wide choice of which infrastructure to use for a given application. The Institute of Electrical and Electronics Engineers (IEEE) 802.16 work group and the 3rd Generation Partnership Project (3GPP) are introducing fourth generation metropolitan wireless standards. Originally, IEEE 802.16 [2] has been designed for fixed clients, whereas its current version [3] enables support for mobile clients as well. Given the importance of power consumption for battery constrained devices, client power saving and improved energy efficiency is an important objective for the future 4G standards [4].

The power-bandwidth optimization techniques investigated in this paper are aimed at improving the active mode energy efficiency properties of wireless mobile devices. Active mode power consumption is important for reliable uplink transmissions due to significant transmit power required to overcome path loss degradation and poor efficiency of radio frequency (RF) power amplifiers. Consequently, focusing on reducing active power consumption can increase the battery life of mobile clients, which is crucial for the deployment of next generation high data rate wireless networks. The results reported in this paper are focused on the IEEE 802.16 standards but are equally applicable to other OFDMA-based cellular standards, such as 3GPP Long Term Evolution (LTE).

II. BACKGROUND AND PREVIOUS WORK

Contemporary wireless standards support reductions in client power consumption through maximizing sleep/idle periods at the clients. However, as mentioned, they do not explicitly focus on active mode power consumption. Given the battery-limited power budget of mobile devices and the high-data rate demands of multimedia applications, active mode power consumption is also expected to become an important consideration for wireless system design and standards development.

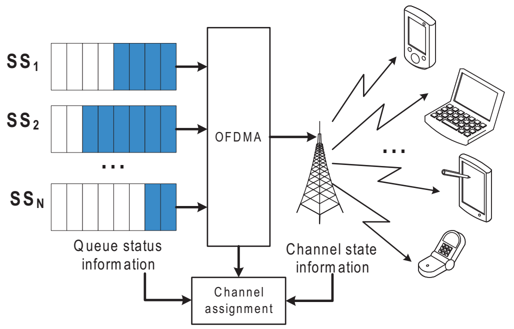

Fig. 1. General power-bandwidth optimization scheme.

Surprisingly, little scientific attention is paid to the problem of client power optimization in the active mode. Here we note that the network may utilize additional techniques, that go beyond simply controlling the transmit power per link, to improve battery consumption for mobile devices [5]. One such solution is to develop resource allocation algorithms at the base station that minimize subscriber stations power consumption (see Fig. 1). Joint power and resource optimization for wireless cellular systems has been investigated in recent work summarized below.

In [6] the problem of energy efficient transmission in wireless networks is studied for flat fading OFDMA channels. Although cellular channels are frequency selective, the assumption of flat fading channels is a good representation for the case where OFDMA systems use distributed or randomized sub-carrier sub-channelization. Here, the effective channel is roughly similar across all sub-channels and hence may be modeled by flat fading assumptions. The work in [7] extends the results of [6] for the frequency-selective wireless channels.

In [8] the aspects of the cross-layer system design for energy efficient wireless communication are summarized. A general information-theoretic approach to the energy efficient communication is presented. Several energy efficient resource optimization algorithms accounting for both active and circuit power consumption are presented. The paper in [9] focuses energy efficient transmissions for interference-limited cellular systems. Low complexity solutions to energy efficient resource optimization are proposed in [10], which significantly reduces the computational complexity associated with earlier iterative approaches. Closed form solutions for link adaptation and resource allocation are developed by looking at time-averaged, steady state metrics.

The inherent limitation of the above power optimization research is that it considers a static, steady state network environment.

References [11] and [12] propose dynamic energy optimal solutions by using a simplified model for a wireless system under dynamic varying load. Accounting for dynamic traffic characteristics is also an important consideration for the future wireless networks. In this work, however, we concentrate on the simpler static scenario from [10] as it is analytically tractable and conduct performance evaluation of the low complexity energy efficient algorithms. In Section III the system model is considered and the algorithm is detailed. Section IV describes the methodology we use for the performance evaluation and Section V presents the obtained results. The summary is given in Section VI.

III. ENERGY EFFICIENT SYSTEM MODEL

For the sake of simplicity in this section we consider the following system model. There are one base station (BS) and N subscriber stations (SSs) or clients. We focus on the uplink channel only, as data transmission consumes much more SS power than reception. Channel time is broken into frames. Each frame is composed of K frequency sub-channels. Exactly one client may transmit its data at one sub-channel per one frame. However, one client may utilize more than one sub-channel (up to K) for its data transmission per one frame. Each client i transmits data on each sub-channel j with an attenuation factor g_{ij} given by the following matrix:

$$G = \left| \begin{array}{cccc} g_{11} & g_{12} & \cdots & g_{1K} \\ \cdots & \cdots & \cdots & \cdots \\ g_{i1} & g_{i2} & \cdots & g_{iK} \\ \cdots & \cdots & \cdots & \cdots \\ g_{N1} & g_{N2} & \cdots & g_{NK} \end{array} \right|$$

It is assumed that attenuation factors are known at the BS. The task of the resource allocation algorithm is to assign frame sub-channels (or quanta of resources) to clients with pending data packets. Currently, we assume that the packet buffer of a client is always full. The attenuation factors should be taken into account to minimize the subsequent power consumption. Information about sub-channel assignment is sent to SSs in the downlink and SSs transmit their packets according to that assignment.

In order to derive a power-optimal resource allocation algorithm, the energy efficient metric is introduced in [10]. Energy efficiency of the client n in the time frame t is the total data size sent by this client by the time t ($M_n[t]$) divided by the consumed energy ($E_n[t]$)

$$u_n[t] = \frac{M_n[t]}{E_n[t]}. \tag{1}$$

Due to the fact that the frames have equal size, (1) could be rewritten as

$$u_n[t] = \frac{T_n[t]}{P_n[t]}, \tag{2}$$

where $T_n[t]$ is the data rate of client; $P_n[t]$ is the total consumed power. The $T_n[t]$ and $P_n[t]$ may be calculated recursively by

$$T_n[t] = T_n[t-1] + r_n[t], \tag{3}$$

$$P_n[t] = P_n[t-1] + p_n[t], \tag{4}$$

where $r_n[t]$ is the data rate of the client n at the frame t; $p_n[t]$ is the consumed power by the client n at the frame t.

Thus, energy efficiency shows how many data bits are sent by a client per a Joule of consumed energy (bpJ). The task of an energy efficient algorithm is to schedule client transmissions to maximize a particular energy efficient criterion. Two energy efficient criteria may be considered:

1) An arithmetic-mean criterion

$$U_{AM}[t] = \sum_{n=1}^{N} u_n[t]. \tag{5}$$

2) A geometric-mean criterion

$$U_{GM}[t] = \sum_{n=1}^{N} \log\left(u_n[t]\right). \tag{6}$$

Define C_n^* to be the set of sub-channels assigned to the client n. Total sub-channel allocation is therefore

$$C = \bigcup_{i=1}^{N} C_i^* . \tag{7}$$

An energy efficient algorithm creates such an allocation C that energy efficient criterion is maximized

$$C : \lim_{t\to\infty} U(C, r, p, t) \to \max . \tag{8}$$

In [10] it is shown that energy efficient criterion tends to its maximum if sub-channel allocation is defined as

$$C_n^* = \{k \,|\, J(n,k) > J(m,k), \forall m \neq n\}, \forall n, \tag{9}$$

where $J(n,k)$ depends on the selected criterion.

$J(n,k)$ is then calculated for the

1) arithmetic-mean criterion as

$$J(n,k) = \frac{r_{nk}[t]}{T_n[t-1]} - u_n[t-1]\frac{p_{nk}[t]}{P_n[t-1]}, \tag{10}$$

2) geometric-mean criterion as

$$J(n,k) = \frac{r_{nk}[t]}{T_n[t-1]} - \frac{p_{nk}[t]}{P_n[t-1]}, \tag{11}$$

where $r_{nk}[t]$ is the data rate of the client n at the frame t on the sub-channel k; $p_{nk}[t]$ is the power consumed by the client n at the frame t for the data transmission on the sub-channel k.

It is important that values $r_{nk}[t]$ and $p_{nk}[t]$ are calculated by the BS before the sub-channel allocation and consequently before the actual transmission of clients. Value p_{nk} is assigned by the BS and SS transmits data with the assigned power. An estimation of r_{nk} could be calculated using Shannon's law

$$r_{nk}[t] = f \log_2\left(1 + \frac{g_{nk} \cdot p_{nk}}{\sigma^2}\right), \tag{12}$$

where f is the signal frequency band; σ^2 is the noise power.

Summarizing, the algorithm from [10] could be described as follows.

1) The BS calculates $J(n,k)$ metric for all the clients at all sub-channels.
2) For each sub-channel the BS determines a client with maximum $J(n,k)$ value and assigns the sub-channel to this client.
3) Information about sub-channel assignment is sent to the clients.
4) The SSs transmit data in the assigned sub-channels.

The described low complexity energy efficient algorithm has the property of increasing the selected energy efficient criterion up to some suboptimal value with time. Nevertheless, this algorithm does not take packet delay into consideration. Moreover, if a channel does not change much, i.e. each client has nearly the same attenuation factors for all the sub-channels, this algorithm selects one client for all the sub-channels during a frame. As such, we modified the basic energy efficient algorithm implicitly taking packet delay into consideration.

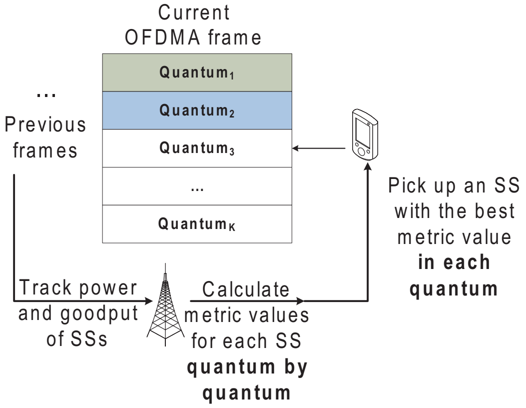

Fig. 2. Modified energy efficient algorithm operation.

The modified low complexity energy efficient algorithm (see Fig. 2) may schedule different clients within a frame, hence up to K SSs could transmit simultaneously. Therefore, despite the full-buffer assumption the potential mean traffic delay is considerably reduced. The proposed modified algorithm predicts power/goodput in the current frame, accounting for the already scheduled quanta of resources.

IV. SYSTEM LEVEL SIMULATOR METHODOLOGY

We now come to the performance evaluation of the modified low complexity energy efficient algorithm described in the previous section. According to [4] the cellular system is modeled as a network of 19 cells with central target cell surrounded by interfering cells. Each cell is hexagonal, with cell radius R determined by the link budget. The System Level Simulator (SLS) creates N_c cells, and each cell may have S sectors each with a boresight direction (ϕ_{BS}) and a frequency (F_{BS}). The network is planned with A frequency allocations, yielding a frequency reuse pattern of $S \times A$. The parameters in Table I describe the network configuration.

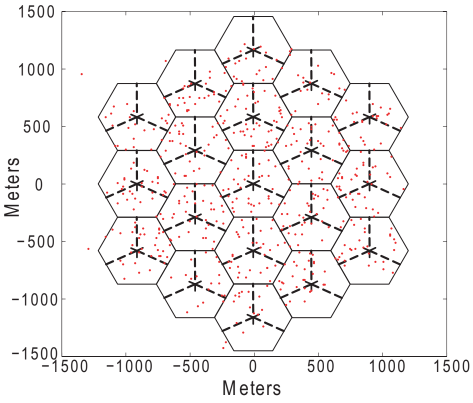

Fig. 3. Example SSs layout.

The SLS assumptions are compliant with IEEE 802.16 Evaluation methodology [4]. In particular, Fig. 3 shows an

TABLE I
GENERIC NETWORK CONFIGURATION

Parameter	Description	Value
N_c	Number of cells	19
S	Number of sectors/cell	3
$N_s = S \times N_c$	Total number of sectors	57
R	Cell radius	0.5 km
ϕ_{BS}	Orientation (boresight angle) of each sector as defined by 3GPP-3GPP2	$S = 3 : \phi_{BS} = 30, 150, 270$
A	Number of frequency allocations in the network (frequency reuse)	1

example of client layout within the considered system model. The SSs are placed randomly inside the simulated cellular system and are then associated with the BSs. We restrict our further explorations to the universal frequency reuse 3 × 1 pattern, where the same frequency allocation is deployed in all sectors throughout the network. Below we compare the modified energy efficient algorithm with existing power control methods in place for 4G systems.

V. PRACTICAL FEATURES AND RESULTS

In our experiments we use the goodput, power and energy efficiency (EE) performance metrics to compare the energy efficient approach vs. the other 4G system profiles. A profile defines both a power control algorithm and a scheduling algorithm. In the simulations we use the optimization criterion of mean geometric over individual energy efficiencies and maximized it with the modified low complexity EE algorithm. The resulting CDFs are generally compared with those of the other 4G system profiles. We notice that currently the EE profile favors cell-center clients for the cost of the cell-edge clients. This is different from the results presented in [10]. It was established that such a performance difference is due to the huge variation of channel attenuation factors in the simulated wireless environment.

Total wireless power consumption at the client varies as a function of its state (see Fig. 4), whether idle or active. When the typical client is actively transmitting to the network, it not only consumes RF power in the power amplifier to communicate its signal reliably over the air (transmit power, p_{tx}), but also additional power in the electronic circuitry (circuit power, p_c), which is greater than its idle power consumption (p_i). It can be seen that the overall energy consumption of the client is not only affected by the useful power needed for reliable communication, but also the overhead energy consumed due to power consumed in circuit electronics.

The optimal energy efficient transmission rate is affected by which components of the transmit power dominate the power budget. In practice the idle power is expected to be much less than the circuit power of a client. In our simulations we set the parameters shown in Table II [13].

We now concentrate on providing the general performance comparison with the SLS tool described in the previous section. We investigate the performance of the selected profiles, which are: SMST power control + PF scheduler, ST power control + PF scheduler, FP power control + PF scheduler and EE power control + EE scheduler. ST is a fixed Signal to Interference plus Noise Ratio (SINR) target method, where power is adjusted at the client to ensure a fixed SINR at receiver for all clients. SMST is a variable SINR target [14], where each client has an SINR target depending on its location. Cell-center clients can have a higher SINR target, whereas cell-edge clients have a lower SINR target.

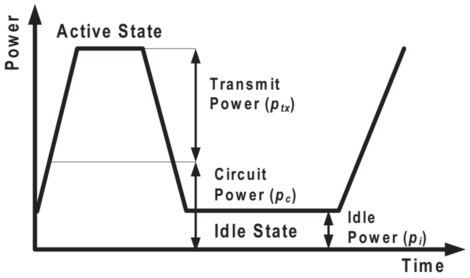

Fig. 4. Typical client power profile.

TABLE II
SIMULATED NETWORK CONFIGURATION

System Parameter	Value
Carrier Frequency	2.5 GHz
System Bandwidth	10 MHz (1024 FFT size)
Power Control	Energy efficient (EE), Simplified maximum sector throughput (SMST), SINR target (ST), Full-Power (FP)
Number of Clients/Sector	10
Scheduling	Low complexity EE, Proportional Fair (PF)
Circuit Power p_c	100 mW
Idle Power p_i	10 mW
Maximum Transmit Power	23 dBm
Channel Model	ITU-Ped B, 3 kmph
Sub-channel Permutation	DRU

We observe the individual goodput (see Fig. 5) for the Distributed Resource Unit (DRU) sub-channelization scheme (6 resource quanta). In Fig. 6 and Fig. 7 the corresponding CDFs for individual client power and energy efficiency are given. We notice that the EE profile results in the minimal client power and thus provides the highest energy efficiency.

Although we do not include detailed results in this paper, we have shown through extensive simulations that the low complexity schemes perform close to near optimal iterative schemes from [7] even with realistic system and channel assumptions. Our results also report the average goodput gain of up to 36%, average power gain of up to 88% and average energy efficiency gain of up to 91% [13].

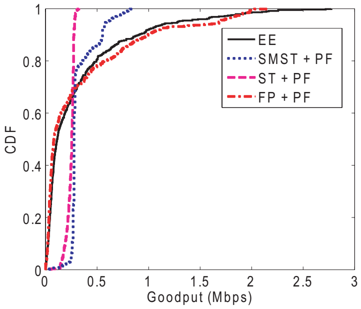

Fig. 5. Empirical goodput CDFs for DRU permutation.

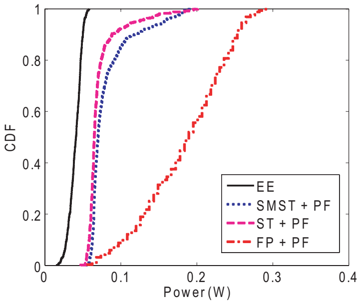

Fig. 6. Empirical power CDFs for DRU permutation.

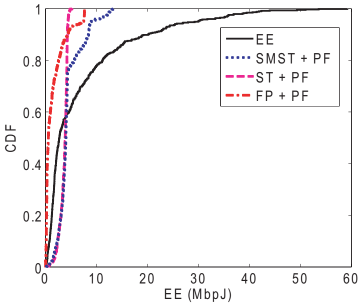

Fig. 7. Empirical EE CDFs for DRU permutation.

VI. CONCLUSION

In this paper we studied the system level performance of energy efficient power and resource optimization for OFDMA-based wireless cellular networks. The IEEE 802.16m evaluation methodology was used to investigate a reference 4G system and realistic system parameters, channel environment and implementation considerations were addressed. In particular, low complexity energy efficient schemes were evaluated. Performance comparison with existing state of the art throughput efficient power optimization schemes was also considered.

Through extensive simulations we showed that the energy efficient schemes demonstrate significant power savings across the cell (greater than 70%), and are more energy efficient in terms of bits/Joule metric for cell-center clients. The performance for cell-edge clients requires further improvement, which may be provided through use of ”fairer” metrics. In this paper we have shown results assuming ideal amplifier efficiencies. Simulations show that energy efficient schemes perform well with practical amplifier efficiencies in the range of 10-20%.

The system level performance characterization of energy efficient wireless transmission techniques studied in this paper appears to be the first of its kind and indicates significant promise for this research area. Future extensions of this work need to focus on more advanced system models and algorithms. In particular, the full-buffer assumption, used in this paper needs to be relaxed and traffic models for multi-media services need to be included. Queuing models, arrival flows and traffic-aware energy efficient scheduling must also be included. It should also be noted that IEEE 802.16m standard now provides specific hooks for mobile devices to initiate active mode power savings. The results reported herein were important towards enabling this feature in the standards [13].

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