Energy Efficient Operation of a Wireless Communication System

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Abstract

Recently, the enhancement of existing and the introduction of novel energy efficient algorithms for mobile users of wireless communication systems is receiving increasing attention. The research is equally important to improve the energy efficiency of both reception and transmission of data. In this work, we propose a relatively simple wireless communication system model to compare the performance of different energy efficient mechanisms and techniques for joint power control at the mobile station and scheduling at the base station.

Index Terms: Energy efficiency, uplink transmission, scheduling, system-level simulator.

I. Introduction

Currently, wireless communication systems proliferate and their coverage ranges increase. Consequently, the number of network users grows, where the majority is constituted by the mobile devices. Due to the limited power budget of the latter (which is determined by the battery capacity [1]), the improvement and the introduction of novel energy efficient techniques is of increasing importance. This would allow Mobile Stations (MSs) to save their energy both during reception and during transmission of data [2].

In this work, we consider energy efficient techniques used at the MS data transmission stage. As such, we introduce the system model based on the well-developed IEEE 802.16 [3] technology. However, the model may be easily tailored to another prominent wireless technology, LTE (Long-Term Evolution).

The rest of the paper is organized as follows. In Section II we detail the system model and summarize the energy efficient uplink techniques in Section III. We then compare various techniques in Section IV and conclude in Section V.

II. System model derivation

IEEE 802.16 technology defines the interaction between Base Station (BS) and its MSs at two lower layers: Physical and Media Access Control (MAC) layers. We introduce wireless communication system model based upon recommendations [4], [5]. Below we detail a set of relevant assumptions, which is split into three classes: communication system topology, wireless signal propagation, and MS operation. We address each of these groups in what follows.

A. Communication system topology

Consider wireless communication system topology as follows.

Assumption 1. *System structure.* The system is composed of a set of N_C neighboring cells. The cell shape is a regular hexagon with the cell radius R. A BS is placed in the center of each cell (see Figure 1).

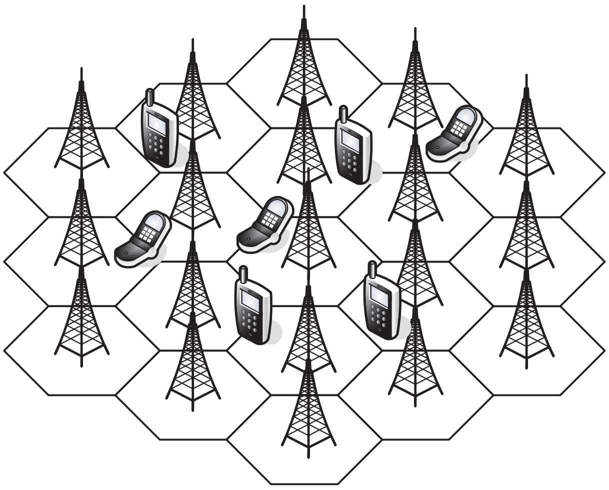

Fig. 1. Communication system topology

Consider cell configuration as follows.

Assumption 2. *Cell configuration.* Each cell is split into three sectors of 120^o. Each sector is put into correspondence a dedicated antenna at the respective BS.

At the network design stage, a frequency reuse pattern is selected. Currently, several patterns are exploited as per [3], [5]. Consider frequency reuse pattern as follows.

Assumption 3. *Frequency reuse pattern.* Each sector exploits the same frequency range.

For the subsequent BS and MSs placement, their coordinates should be set. Therefore, consider placement grid parameters as follows.

Assumption 4. *Placement grid parameters.* We set the offset of the placement grid as:

$$a = \frac{10\frac{\sqrt{3}}{2}R}{N_{SS}}, \tag{1}$$

where N_{SS} is the number of points on $X(Y)$ axis. Importantly, MSs and BS may be placed only at the grid line intersections.

After the placement grid is set, the MSs distribution is performed across the cells. Consider MSs distribution pattern as follows.

Assumption 5. *MSs distribution pattern.* The coordinates of each MS are generated randomly, according to the uniform distribution. After the MS coordinates have been generated, it is assigned to a particular BS. The BS assignment is performed according to the ”signal/noise” ratio (SNR, Signal to Noise Ratio). We use the following expression to obtain the SNR values:

$$SNR = \frac{P_i g_i}{\sigma^2}, \tag{2}$$

where P_i is the transmit power of ith MS; g_i is the signal attenuation coefficient for ith MS; σ^2 is the variance of the noise.

Assumption 6. *System synchronization.* System time is divided into equal time intervals, called frames. Frames are enumerated with non-negative integers, where frame number f corresponds to the time interval $[f-1, f)$. We further refer to frame number f as frame f for brevity. The frame boundaries are known to all the system users.

B. Wireless signal propagation

In practice, the transmitted wireless signal is susceptible to various degradation factors, which decrease its power and increase distortion. Signal distortion type strongly depends on the wireless environment, where the signal has been communicated. In order to account for the variety of degradation factors, we introduce the following assumptions.

Assumption 7. *Signal propagation environment.* Wireless communication system operates in a metropolitan area. As such, the environment model should account for the below degradation factors.

Signal attenuation due to its propagation (path loss) is calculated as follows for an MS moving at the pedestrian speed:

$$PL_{ITU-OIP}(d) = 49 + 40\log_{10}(d) + 30\log_{10}(f), \tag{3}$$

where d is the distance between the BS and the MS; f is the carrier frequency.

Signal attenuation due to its propagation (path loss) is calculated as follows for an MS moving at the vehicular speed:

$$PL_{ITU-V}(d) = 80 - 18\log_{10}(\Delta H_{BS}) + 40(1 - 4\Delta H_{BS}/1000)\log_{10}(d) + 21\log_{10}(f), \tag{4}$$

where ΔH_{BS} is the BS height over the average metropolitan rooftop level.

Beside signal attenuation due to its propagation, signal shadowing should be accounted for as follows:

$$S_{i,j} = aX_j + bY_{i,j}, \tag{5}$$

where $a^2 = b^2 = 0.5$; i, j is the MS and the BS number respectively; X, Y are the random variables generated according to the Gaussian distribution with zero mean.

Additionally, we account for the signal power degradation due to penetration through various obstacles. The respective degradation factor is a random variable generated according to the Gaussian distribution with zero mean and the variance of 8.

Assumption 8. *Channel noise.* The communication channel is impaired by additive white Gaussian noise.

C. MS operation

Assumption 9. *Input arrival flow.* Each MS in the system has a single connection with the BS for its uplink data transmission. The system is studied in saturation conditions. As such, the outgoing packet buffer of each MS is always full.

Additionally, we assume the following regarding the uplink traffic types.

Assumption 10. *Traffic types.* Uplink traffic types of all the MSs in the system are similar and correspond to low-priority flows (e.g., Best Effort [3]).

We note that in this paper the channel reservation mechanisms are not considered. As MSs operate in the full-buffer conditions, they may use the ”piggybacking” mechanism. Therefore, the uplink transmission of a packet also contains information about how much data is still remaining in the outgoing buffer. Consequently, the BS has up-to-date information about the bandwidth demands of its MSs.

The scheduler at the BS controls the uplink data transmission. The produced schedule is broadcasted to all the MSs of a particular sector and the subsequent data transmission strictly follows this schedule. Slot is the minimal resource quantum that may be allocated to an MS for its uplink data transmission. Each data packet is divided into resource blocks. The transmission of each block takes exactly one slot.

The current condition of the wireless environment considerably impacts the transmission data rate. Less severe degradation of the wireless channel allows more information to be transmitted per time unit. When degradation increases, the transmission data rate should be decreased to control the error probability. In order to achieve the required error probability regardless of the varying channel state, the Modulation and Coding Schemes (MCSs) are used. In Table I, we summarize the MCSs defined by IEEE 802.16 wireless standard.

TABLE I
MODULATION AND CODING SCHEMES

Modulation scheme	Code rate	$SINR$ value, dB
$QPSK$	$1/2$	5
	$3/4$	8
$16-QAM$	$1/2$	10.5
	$3/4$	14
$64-QAM$	$1/2$	16
	$2/3$	18
	$3/4$	20

Additionally, the table contains the values of $SINR$ (Signal to Interference plus Noise Ratio) corresponding to a particular MCS.

Importantly, our wireless communication system model shares many features with the state-of-the-art system-level simulators. At the same time, it has much lower complexity and is easier to operate. The comparison of the considered models is given below in Table II.

TABLE II
COMPARISON OF MODELS

Parameter	Model from [6]	Model from [7]	Our model
Number of cells	19	19	19
Bandwith, MHz	10/20	10	10
Channel model	ITU	ITU	ITU
HARQ support	yes	yes	no
Duplexing	TDD/FDD	TDD	TDD
Fast fading	yes	yes	no
BS antenna height	20	20	20

III. ENERGY EFFICIENT UPLINK TRANSMISSION

IEEE 802.16 family of standards defines a set of mechanisms that may be used to reduce energy expenditure of the uplink transmission by an MS. However, the specific guidelines on how to use these mechanisms are not given by the standard. In this paper, we consider adaptive power control at the MS side and energy efficient scheduling at the BS side. The joint use of these techniques may reduce the energy consumption of the wireless communication system.

Currently, several baseline algorithms for power control and scheduling are known. As an example, we study ”Target SNR” power control algorithm and ”Proportional Fair” scheduler. Consider these approaches in more detail. The main idea of the ”Target SNR” power control of the MS transmitter is to maintain a certain ”signal/noise” ratio at the BS.

The main feature of the ”Proportional Fair” scheduler is to guarantee approximately the same data rate for all the MSs of a particular sector (if all the traffic flows have equal priority, see Assumption 10) [8]. The features of the considered baseline algorithms are the implementation simplicity and the independence between the scheduler and the power control. In what follows, we compare the advanced algorithms and contrast them against the baseline approaches.

As an alternative to the baseline algorithms, we consider joint power control and scheduling targeting at energy efficiency increase. In this work, we follow [9] to define energy efficiency of ith MS as:

$$u = \frac{R_i}{P_{C,i} + P_{T,i}}, \tag{6}$$

where R_i is the amount of transmitted data bits; $P_{C,i}$ is the circuit power consumed by the MS; $P_{T,i}$ is the transmit power consumed to send R_i bits. Consequently, energy efficiency indicates how many data bits may be communicated per one Joule of energy.

Here we focus on the approaches that allow to maximize either of the two energy efficient criteria. The former criterion is termed the mean arithmetic and is given by:

$$\varepsilon[T_f] = \sum_{n=1}^{N} u_n[T_f], \tag{7}$$

where N is the number of MSs in the system; $u_n[T_f]$ is the energy efficiency of nth MS.

The latter criterion is termed the mean geometric and is given by:

$$V[T_f] = \sum_{n=1}^{N} \log u_n[T_f]. \tag{8}$$

According to [10], to maximize the mean arithmetic criterion, at the scheduling stage the subsequent resource slot should be granted to the MS, which has the maximum of the following scheduling metric:

$$J(n,k) = \frac{r_k[t]}{P_n[t-1]} - u_n[t]\frac{p_k[t]}{P_n[t-1]}, \tag{9}$$

where $J(n,k)$ is the mean arithmetic energy efficient metric of nth MS at kth sub-channel (or, set of sub-carriers); $r_k[t]$ is the data rate of the MS at kth sub-channel of frame t; $P_n[t-1]$ is the transmission power spent by nth MS in frame $t-1$; $p_k[t]$ is the transmission power spent by the MS at kth sub-channel of frame t.

The use of the mean arithmetic criterion allows to allocate resources to the MSs, which have the maximum energy efficiency, that is, have better wireless channel conditions than the other MSs.

To maximize the mean geometric criterion, at the scheduling stage the subsequent resource slot should be granted to the MS, which has the maximum of the following scheduling metric:

$$J'(n,k) = \frac{r_k[t]}{T_n[t-1]} - \frac{p_k[t]}{P_n[t-1]}, \tag{10}$$

where $J'(n,k)$ is the mean geometric energy efficient metric of nth MS at kth sub-channel; $T_n[t-1]$ is the amount of data transmitted by nth MS in frame $t-1$.

The use of the mean geometric criterion allows to allocate resources to the MSs with higher fairness, than when the mean arithmetic criterion is followed.

In order to exploit the above scheduling approach, the data rate and the transmit power of an MS in the current and the previous frames should be evaluated. At the first step of the algorithm, it is assumed that both the consumed power and the amount of transmitted data bits are given by the Shannon's formula for SNR equal to one. For the subsequent data rate evaluation, the following expression may be used:

$$r_k[t] = \max(B \log_2(\frac{P[t-1]Bg_k[t]}{T[t-1]\sigma^2 \log_e 2}), 0), \tag{11}$$

where B is the channel bandwidth; $g_k[t]$ is the attenuation factor at kth sub-channel of frame t; σ is the noise level.

We now describe the MS power selection mechanism. Consider the "signal/noise" ratio at a particular sub-channel as the function of the data rate as:

$$SNR_{nk} = S(r_{nk}[t]), \tag{12}$$

where SNR_{nk} is the "signal/noise" ratio of nth MS at kth sub-channel; $r_{nk}[t]$ is the estimated data rate of nth MS at kth sub-channel of frame t. Consequently, in order to transmit with the data rate of $r_{nk}[t]$, the "signal/noise" ratio should be greater than or equal to SNR_{nk}. The function $S(r_{nk}[t])$ may be derived using the Shannon's formula.

The transmit power of nth MS at kth sub-channel of frame t may be obtained by the following expression:

$$p_{nk}[t] = \frac{SNR_{nk}[t]\sigma^2}{g_{nk}[t]} = \frac{S(r_{nk}[t])\sigma^2}{g_{nk}[t]}, \tag{13}$$

where $SNR_{nk}[t]$ is the "signal/noise" ratio of nth MS at kth sub-channel of frame t; $r_{nk}[t]$ is the estimated data rate of nth MS at kth sub-channel of frame t; σ is the noise level; $g_{nk}[t]$ is the attenuation factor of nth MS at kth sub-channel of frame t.

IV. Comparison of uplink energy efficient techniques

Consider the following energy efficient techniques, each of which is a combination of a power control algorithm at the MS side and a scheduling algorithm at the BS side:

1) "Proportional Fair" scheduler at the BS and "Target SNR" power control at the MS;
2) Energy efficient scheduler (maximizing the mean arithmetic criterion, EE AM) at the BS and adaptive power control at the MS;

3) Energy efficient scheduler (maximizing the mean geometric criterion, EE GM) at the BS and adaptive power control at the MS.

In order to compare the selected techniques, we note that for ”Target SNR” power control energy efficiency and throughput essentially depend on the value of the target SNR. As such, the optimal target SNR level should be established that is a function of the total number of MSs. In Figure 2, we plot the overall throughput over a particular sector as a function of the target SNR for different numbers of MSs. Firstly, we observe that as target SNR increases, the overall throughput also grows. However, at the certain target SNR value, the throughput growth stops, which means that the highest MCS is now used to transmit data.

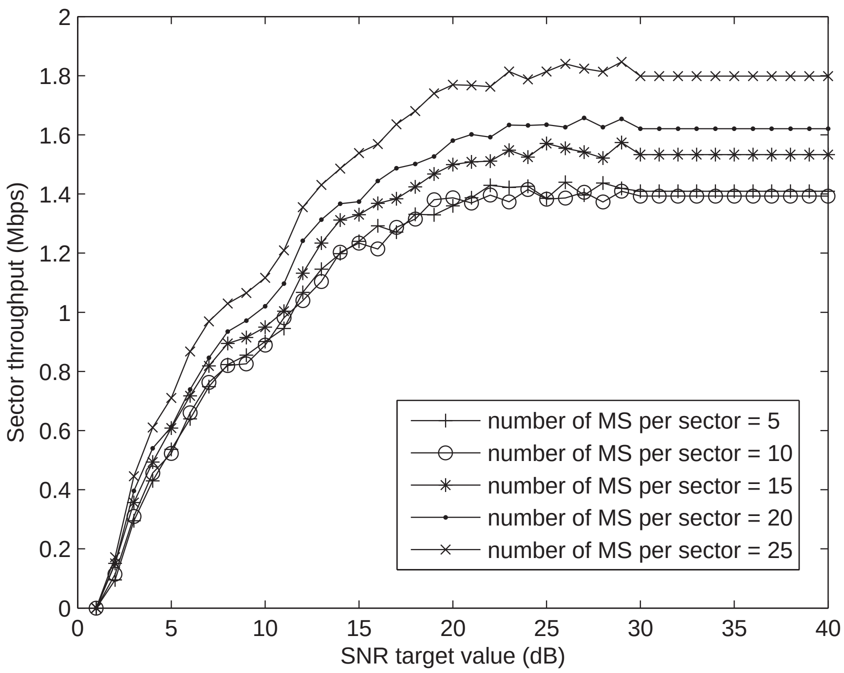

Fig. 2. Throughput dependence on target SNR

In Figure 3, we study the dependence of energy efficiency on the target SNR. From this plot, we derive the optimal target SNR values for the given number of MSs per sector.

After the optimal target SNR value has been established, we compare various energy efficient techniques of joint power control and scheduling. In Figure 4, we plot the overall throughput over a particular sector as a function of the total number of MSs. We observe that the highest throughput is achieved when the mean arithmetic criterion is used. This is explained by the fact that only the MSs with the favorable channel conditions are allocated the resource. The lowest throughput is achieved when ”Proportional Fair” scheduler is used together with ”Target SNR” power control, as these algorithms fail to account for the wireless channel conditions.

In Figure 5, we plot the dependence of energy efficiency on the number of MSs per sector for various energy efficient techniques. As before, the highest energy efficiency is achieved when the mean arithmetic criterion is used, whereas the lowest energy efficiency corresponds to the joint use of ”Proportional Fair” scheduler and ”Target SNR” power control. The use

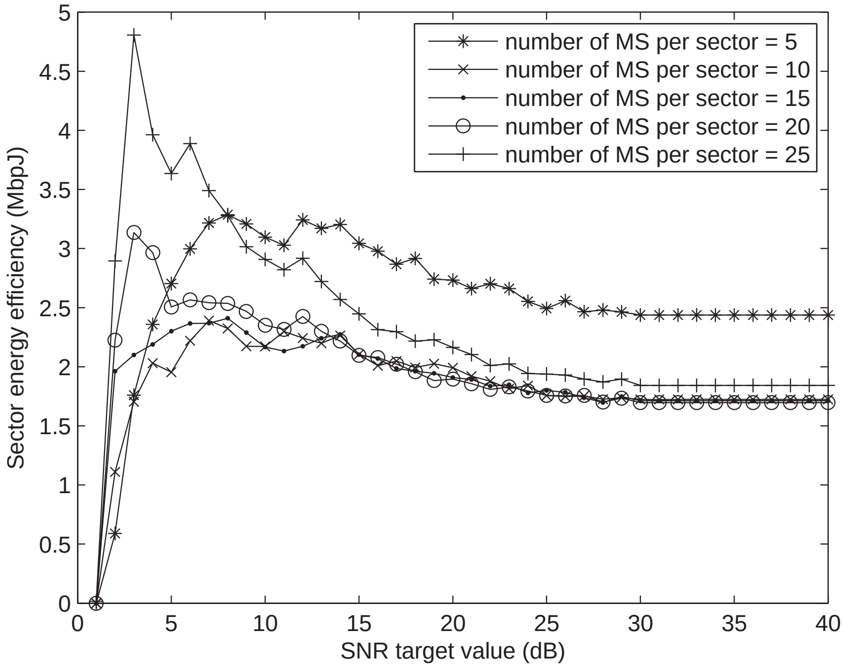

Fig. 3. Energy efficiency dependence on target SNR

of the mean geometric criterion results in the moderate energy efficiency increase because of improved MSs fairness.

Indeed, if user fairness is concerned (e.g., in terms of individual MS throughput, see Figure 6), the situation reverts. As such, the use of ”Proportional Fair” scheduler guarantees approximately even distribution of the resource across the MSs. Consequently, the least fair is the combination of the mean arithmetic criterion and adaptive power control.

V. Conclusions

In this paper, we considered different energy efficient techniques comprising a power control algorithm at the mobile station and a scheduling algorithm at the base station. We compared the performance of these approaches with our own simplified system-level simulator. In particular, we addressed throughput, energy efficiency, and fairness. We indicated significant energy efficient improvements contrasting the advanced schemes against their baseline counterparts. We conclude that the combination of energy efficient scheduler (maximizing the mean geometric criterion) at the base station and adaptive power control at the mobile station has desirable practical properties by allowing to balance performance and fairness.

Acknowledgments

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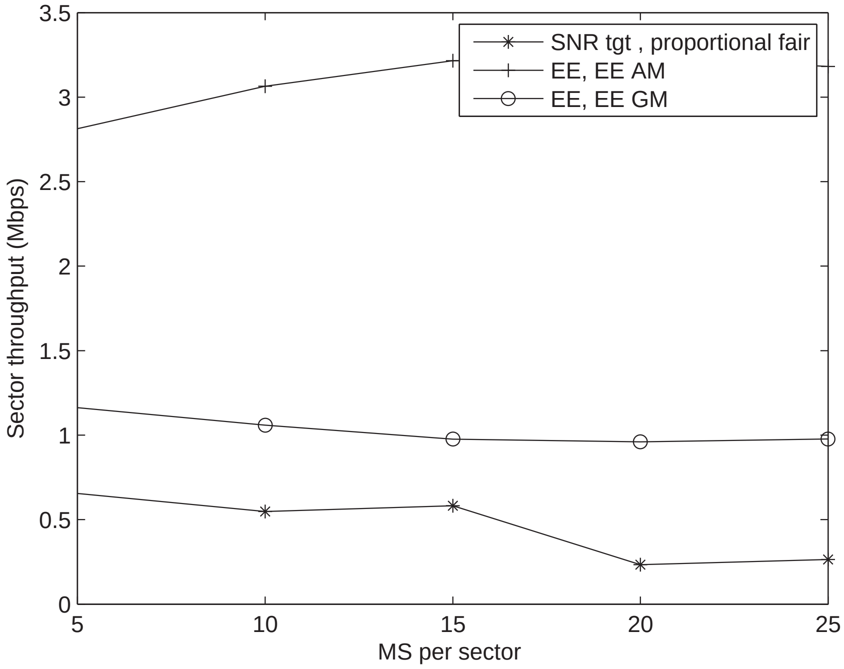

Fig. 4. Throughput for various energy efficient techniques

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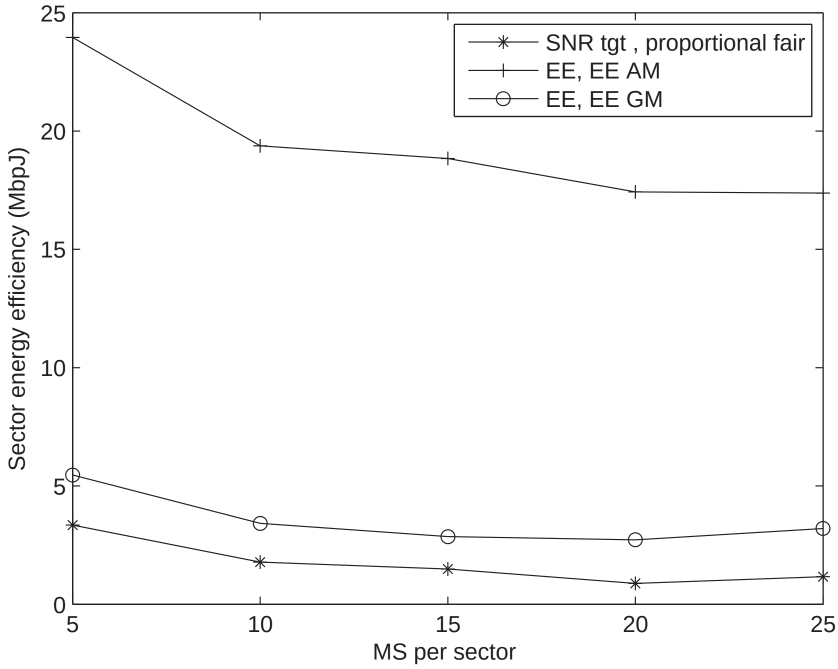

Fig. 5. Energy efficiency for various energy efficient techniques

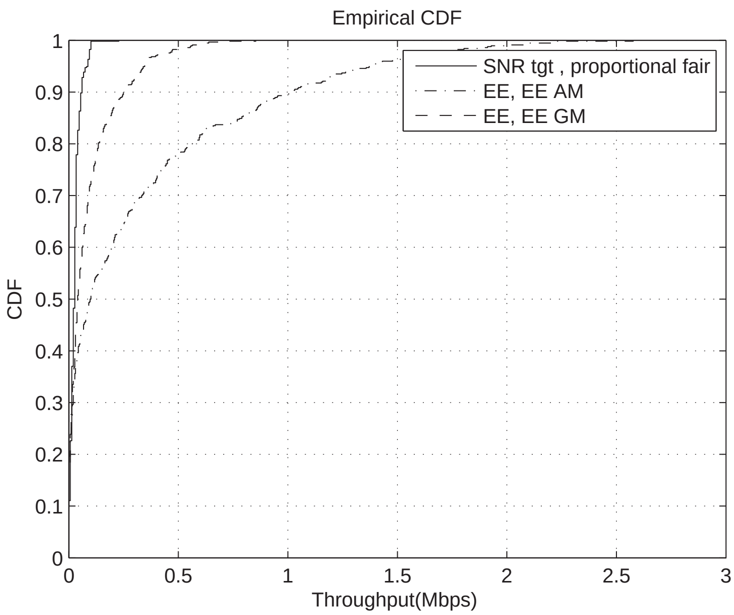

Fig. 6. Empirical throughput cumulative distribution functions