Self-Optimizing Strategies for Interference Coordination in OFDMA Networks

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Abstract

This paper investigates self-optimizing schemes for interference management in downlink of Orthogonal Frequency-Division Multiple Access (OFDMA) networks: power control, fractional frequency reuse and dynamic fractional load. While the first two schemes are based on continuous power control, the third scheme is based on switching off frequency sub-bands thus dynamically varying the cell capacity and creating frequency reuse patterns. Distributed solutions based on the distributed gradient descent method are developed. Coordination between enhanced eNode Bs (eNBs) is achieved via information exchanged on the X2 interface. The scheduling gain for a Raleigh-fading channel is modeled and incorporated in the solution. Numerical simulations of a large scale Long Term Evolution (LTE) network show the potential benefits of the self-optimization schemes, with significant performance gains brought by the dynamic fractional reuse scheme. [1]

Index Terms

Self-Optimization, OFDMA, Interference Coordination, fractional frequency reuse, fractional load

I. Introduction

Self-organizing networks (SON) in Radio Access Networks (RAN) is a recent management paradigm that is considered as a means to empower the network by embedding autonomic features. SON mechanisms allow to increase the network performance, to simplify its management and to reduce its cost of operation. Main organizations and standardization bodies such as 3rd Generation Partnership Project (3GPP) ([1], [2]) have picked up this topic, and SON mechanisms encompassing self-configuration, self-optimization and self-healing are expected to become widely commercially available with the introduction of 4-Generation networks such as LTE-Advanced and Worldwide Interoperability for Microwave Access (WiMAX) 802.16m.

Although self-configuration features already exist (e.g. in the first LTE deployed networks), self-optimization features are still discussed in standardization bodies and require important research efforts prior to their successful implementation. Self-optimization aims at adapting the network to variations in traffic, in propagation conditions and to modification in the operating conditions such as the introduction of a new service. Recently, the use of SON features in a general policy management framework has been suggested, in which SON entities are used as a means to enforce high level operator policies introduced in the management plane, and are translated into low-level objectives guiding coordinated SON entities. Hence SON entities can be triggered by traffic or load increase, performance degradation and alarms, but also by policies. It is noted that the problem of coordinating simultaneous SON processes is an open and challenging problem that needs to be addressed in order to to allow the deployment of SON mechanisms. Among the important self-optimization mechanisms in RANs are interference coordination, ([3], [4]) mobility management, and energy saving ([5]). Many problems need further investigation to fully benefit from SON in RAN, in areas where little material has been published. Examples are autonomous cell outage management [6], and coverage-capacity optimization [7].

[1]This work has been partially carried out in the framework of the FP7 UniverSelf project under EC Grant agreement 257513

This paper investigates self-optimization for Inter-Cell Interference Coordination (ICIC) in an OFDMA network. Inter-cell interference can dramatically degrade cell performance and perceived Quality of Service (QoS), particularly at cell edge. We are interested in distributed solutions that can be implemented in a flat architecture (e.g. LTE and LTE-Advanced architecture). To coordinate interference between neighboring cells eNBs need to exchange information. In the case of LTE for example, signaling between eNBs can be exchanged over the X2 interface. Different contributions have been reported in the literature, such as inter-cell scheduling ([8], [9]), dynamic frequency reuse ([3]) and dynamic beam-forming ([10]). This paper investigates three related self-organizing schemes for mitigating interference (see Figure 1), with the aim at drawing guidelines for efficient network engineering. The solution adopted should be a trade-off between network performance gain and the technological complexity associated with the solution implementation. The first scheme adjusts the transmission power of the entire bandwidth, and is denoted hereafter as **Power Control (PC)**. The second scheme considers a dynamic **Fractional Frequency Reuse (FFR)**, also known in the literature as *soft frequency reuse*. The third scheme, denoted as dynamic **Fractional Load (FL)** considers switching off certain frequency sub-bands which is equivalent to reducing the cell capacity (see [11] for the static FL). All three self-optimizing problems are tackled using a distributed gradient descent method, and heuristics for solving them are proposed. Signaling load and performance of the different power allocation strategies are analyzed. Interference mitigation is performed in a slow time scale (of the order of a second) by the ICIC scheme and by the scheduler with a fast time scale of the order of a millisecond.

Contributions with respect to previous works are twofold: algorithms for power adaptation using closed form expressions that incorporate the scheduling gain [7], [12], and a study of the optimal utility function in order to maximize network performance.

This paper is organized as follows: Section II presents self-organizing ICIC algorithms. The dynamic power control problem in an OFDMA network is stated and a general distributed algorithm is presented. Section III describes the system model of a downlink OFDMA network we are considering, and provides the closed-form formulas that are necessary for the power control algorithm. In Section IV we simulate the proposed algorithm in a 42 Base Stations (BSs) dynamic network simulator, and demonstrate the important resulting gains in both mean throughput and Block Call Rate (BCR). Some insight on the relative performance of the various ICIC schemes is given. Section V concludes the paper.

II. Algorithms for Interference Coordination

Two algorithms are presented here for the FFR and FL ICIC schemes. The PC scheme can be seen as a special case of the FFR with a single sub-band (see Fig. 1). The two algorithms follow the same principle: eNBs exchange some information with their neighbors and adjust their power dynamically to maximize the global network utility $U = \sum_s U_s$, with U_s the utility of BS s. There are N_{BS} eNBs, the frequency resource is divided into N_b sub-bands, and $P_s^{(b)}$ denotes the power emitted by s on a Physical Resource Block (PRB) of band b.

A. FFR scheme

The optimization problem is written as follows in Table I, where P_{tot} is the maximal power a BS can transmit, γ - the minimal proportion of P_{tot} that a BS must transmit and N_{PRB} - the number of PRBs in a sub-band. Let

maximize U
subject to $0 \leq P_s^{(b)} \leq P_{max}$, $1 \leq s \leq N_{BS}$, $1 \leq b \leq N_b$
and $\gamma P_{tot} \leq N_{PRB} \sum_{b=1}^{N_b} P_s^{(b)} \leq P_{tot}$, $1 \leq s \leq N_{BS}$

TABLE I
FFR maximization problem

$\mathcal{P} = \mathcal{P}_1 \times ... \times \mathcal{P}_{N_{BS}}$ denote the set of power allocations that satisfy the constraints, which is a product of convex sets.

Let $\pi_s(t) \in \mathbb{R}^{N_b}$, $t \in \mathbb{N}$ denote the power allocation of BS s at time t. We can then use the distributed algorithm introduced in [13] for the power allocation. For $1 \leq s \leq N_{BS}$:

$$\pi_s(0) \in \mathcal{P}_s \ , \ \pi_s(t+1) = \left[\pi_s(t) + \mu \vec{\nabla}_s U(\pi_s(t))\right]^+ \quad (1)$$

where $\vec{\nabla}_s$ is the gradient with respect to $(P_s^{(b)})_{1\le b\le N_b}$, $\mu > 0$ -a small constant,and $[.]^+$ -the projection on $\mathcal{P}_s$. Furthermore, (1) converges to a local optimum of U, see [13]. While there is no guarantee that a local optimum is good, we have observed that on typical instances of the problem, the difference of utility between a local optimum and the global optimum is about 1%.

B. FL scheme

The FL scheme can be considered as the discrete form of the previous problem: where P_{min}, P_{max} are two fixed

maximize U
subject to $P_s^{(b)} \in \{P_{min}, P_{max}\}$, $1 \le s \le N_{BS}$, $1 \le b \le N_b$
and $N_{b\,min} \le \#\{b \vert P_s^{(b)} = P_{min}\} \le N_{b\,max}$, $1 \le s \le N_{BS}$

TABLE II
FL MAXIMIZATION PROBLEM

power levels. We say that sub-band b is "on" in eNB s if $P_s^{(b)} = P_{max}$ and is "off" if $P_s^{(b)} = P_{min}$ and $N_{b\,min}$, $N_{b\,max}$ are the minimum and maximum number of "on" bands respectively. It is noted that the special case with $P_{min} = 0$ corresponds to the dynamic FL scheme where only a portion of the resources are allocated at each time step (i.e. iteration of the algorithm). This case is of particular interest due its simpler implementation. However, it will be shown that having $P_{min} = 0$ limits the system performance. Furthermore we say that turning on or off a sub-band is admissible if the resulting power allocation satisfies the constraints on the number of "on" sub-bands. To solve the discrete problem we propose the algorithm in Table III, for each time step t, for $1 \le s \le N_{BS}$. It is

$b_{off} = \arg\min_{b,(\pi_s(t))_b = P_{max}} (\vec{\nabla}_s U(\pi_s(t)))_b$
$b_{on} = \arg\max_{b,(\pi_s(t))_b = P_{min}} (\vec{\nabla}_s U(\pi_s(t)))_b$
Turn on b_{on} and turn off b_{off} if it is admissible
and $(\vec{\nabla}_s U(\pi_s(t)))_{b_{on}} > 0$ and $(\vec{\nabla}_s U(\pi_s(t)))_{b_{off}} < 0$
Else turn on b_{on} if it is admissible and $(\vec{\nabla}_s U(\pi_s(t)))_{b_{on}} > 0$
Else turn off b_{off} if it is admissible and $(\vec{\nabla}_s U(\pi_s(t)))_{b_{off}} < 0$
Else keep the same power allocation

TABLE III
FL ALGORITHM

noted that while this algorithm represents a heuristic rule, it is easy to implement and performs relatively well in practical settings.

III. OFDMA NETWORK SYSTEM MODEL

A. Signal to Interference plus Noise Ratio (SINR)

Let $h_{s\to i}$ denote the signal attenuation between BS s and user i. The SINR of user i served by eNB s on a PRB of sub-band b is denoted by $S_{s,i}^{(b)}$ and is calculated as follows:

$$S_{s,i}^{(b)} = \frac{h_{s\to i} P_s^{(b)}}{N_0^2 + \sum_{s' \in \mathcal{N}_s} h_{s'\to i} P_{s'}^{(b)}} \tag{2}$$

with $P_s^{(b)}$ being the power transmitted by eNB s on a PRB of band b, $\mathcal{N}_s$ the set of neighbors of s and N_0^2 - the thermal noise. The attenuation is given by the following model:

$$h_{s\to i} = \frac{A}{(d_{s\to i})^\beta} \chi_{s\to i} \tag{3}$$

$d_{s\to i}$ is the distance between eNB s and user i, A and β are two constants and $\chi_{s\to i}$ - the shadowing which is modeled by a log-normal random variable.

B. Scheduling gain

The fast-fading follows a Rayleigh model. The instantaneous throughput of user i at time t_m on PRB p belonging to sub-band b, $r_{i,t_m}^{(p)}$ is given by:

$$r_{i,t_m}^{(p)} = \Phi(S_i^{(b)} \xi_{i,t_m}^{(p)}) \tag{4}$$

where Φ is a quality table which maps instantaneous SINR into bitrate, and $\xi_{i,t_m}^{(p)}$ is an exponentially distributed random variable with mean 1. Furthermore, we assume that $\left(\xi_{i,t_m}^{(p)}\right)_{i,t_m,p}$ are all independent. We introduce Ψ, the throughput of a user alone on a sub-band:

$$\Psi(S_{s,i}^{(b)}) = N_{PRB} \int_0^{+\infty} \Phi(x S_{s,i}^{(b)}) e^{-x} dx \tag{5}$$

We define BS s utility U_s as the α-fair utility introduced in [14], where $\alpha \geq 0$:

$$U_s = \begin{cases} \displaystyle\sum_{i=1}^{N_u(s)} \log(d + r_i) & , \quad \alpha = 1 \\ \displaystyle\sum_{i=1}^{N_u(s)} \frac{(d + r_i)^{1-\alpha}}{1-\alpha} & , \quad \alpha \neq 1 \end{cases} \tag{6}$$

where r_i is the mean throughput allocated to user i, $N_u(s)$ - the number of users served by eNB s and $d > 0$ - a small constant to avoid singularity at 0. The case $\alpha = 2$ is of particular interest as we will demonstrate later on. We can then use the results in [13] to obtain the gradient of the network utility with respect to the BSs powers. Let $s' \in \mathcal{N}_s$, in the Round Robin (RR) case:

$$r_i = \frac{1}{N_u(s)} \sum_{b=1}^{N_b} \Psi\left(S_{s,i}^{(b)}\right) \tag{7}$$

$$\frac{\partial U_s}{\partial P_s^{(b)}} = \frac{1}{N_u(s)} \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} \frac{S_{s,i}^{(b)}}{P_{s,i}^{(b)}} \Psi'\left(S_{s,i}^{(b)}\right)}{(r_i + d)^\alpha} \tag{8}$$

$$\frac{\partial U_s}{\partial P_{s'}^{(b)}} = \frac{1}{N_u(s)} \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} -\frac{h_{s'\to i}(S_{s,i}^{(b)})^2}{h_{s\to i} P_s^{(b)}} \Psi'\left(S_{s,i}^{(b)}\right)}{(r_i + d)^\alpha} \tag{9}$$

In the Proportional Fair (PF) case we have:

$$r_i = \sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^k}{k+1} \Psi\left(\frac{S_{s,i}^{(b)}}{k+1}\right) \tag{10}$$

$$\frac{\partial U_s}{\partial P_s^{(b)}} = \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^k S_{s,i}^{(b)}}{(k+1)^2 P_{s,i}^{(b)}} \Psi'\left(\frac{S_{s,i}^{(b)}}{k+1}\right)}{(r_i + d)^\alpha} \tag{11}$$

$$\frac{\partial U_s}{\partial P_{s'}^{(b)}} = \sum_{i=1}^{N_u(s)} \frac{\sum_{b=1}^{N_b} \sum_{k=0}^{N_u(s)-1} \binom{N_u(s)-1}{k} \frac{(-1)^{k+1} h_{s'\to i}(S_{s,i}^{(b)})^2}{(k+1)^2 h_{s\to i} P_s^{(b)}} \Psi'\left(\frac{S_{s,i}^{(b)}}{k+1}\right)}{(r_i + d)^\alpha} \tag{12}$$

It is noted that Φ, Ψ and Ψ' can be calculated beforehand and used in the form of quality tables, hence the gradient calculation is computationally light. It is also noted that equation (10) is only a lower bound when the SINR of a user is not the same on all bands, and a rigorous justification is found in [12]. It is also noted that the same approach could be extended to frequency selective Raleigh-fading channels using the formulas in [15].

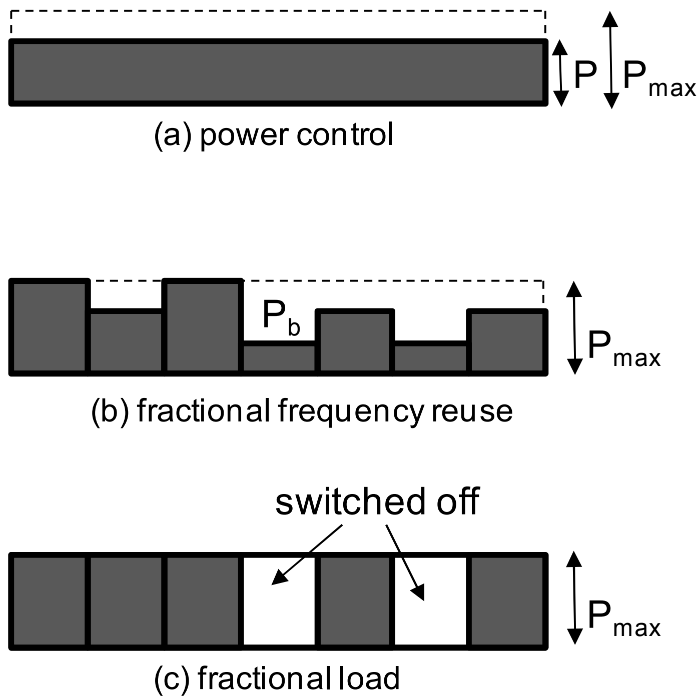

Fig. 1. Interference mitigation schemes

C. Choice of α

The α parameter in (6) has an important role in the ICIC schemes: it determines how much weight is given to cell-edge users, since a higher α favors users who have a smaller mean throughput. We choose $\alpha = 2$ here, that is $U_s = -\sum_{i=1}^{N_u(s)} \frac{1}{d+r_i}$. The corresponding utility is linked to the cell load, which is generally shown to be the key metric when analyzing cell capacity using queuing theory results. This hypothesis is verified numerically in Section IV.

D. Signaling load and delay

Every $1s$, each BS s calculates and transmits $\frac{\partial U_s}{\partial P_{s'}^{(b)}}$, $1 \leq b \leq N_b$ to all its neighbors $s' \in \mathcal{N}_s$. The transmission occurs through the so-called X2 interface. Assuming that each BS has 6 neighbors, 4 frequency bands, and that the each derivative is coded on 32 bits, we have that the signaling load is 768 bits/s per BS which is very small compared to the available capacity on the X2 interface. Furthermore, a delay of $50ms \ll 1s$ on the X2 interface is expected, hence the delay has no impact on our algorithm.

IV. Simulation

This section describes simulation results of the self-optimizing ICIC schemes using a semi-dynamic LTE network simulator. The simulator performs correlated Monte-Carlo snapshots with a time resolution of a second. The principle of such a simulator is described in [16], and it allows to assess the performance of large network size, with 42 eNBs in the present study. Simulation parameters are listed in Table IV.

Four ICIC schemes are considered: the FFR and PC and two cases for the FL, with $P_{min} = 0$ and $P_{min} = 0.1 \times P_{max}$, denoted as “FL 1/0” and “FL 1/0.1” respectively. We add the reference case which does not use interference coordination, and is denoted as “no ICIC” in the figures. We choose $\alpha = 2$ for the comparison of the four algorithms. We define the BCR as the percentage of users rejected by admission control, namely, users who arrive when the BS has reached the maximum number of active users.

Figure 2 compares the BCR attained by the different algorithms. We can see that all the algorithms decrease the BCR noticeably, with the PC and FFR performing the best, showing that considering continuous power allocation brings considerable gains in comparison with discrete power allocations. It is noted that the gains are considerable in terms of BCR. Figure 3 compares the mean File Transfer Time (FTT), and Figure 4 - the cumulative distribution

Simulator parameters	
Spatial resolution	$25m \times 25m$
Total simulated area	$1km \times 1km$
Time resolution	$1s$
Simulation time	$3000s$
User speed	$5km/h$
File size	$10Mbytes$
Number of sub-bands	8
Network bandwidth	$2MHz$
Number of stations	42
Cell layout	14 eNB's $\times$ 3 sectors
$(N_{b\,min}, N_{b\,max})$ for FL 1/0.1	$(4, 8)$
$(N_{b\,min}, N_{b\,max})$ for FL 1/0	$(6, 8)$
α	2
γ	5%
Maximum eNB transmit power	$30W$
Service Type	FTP
Scheduler Type	PF
Thermal noise	$-174dBm/Hz$
Path loss	$128 + 37.6\log_{10}(d)$ dB, d in km
Shadowing standard deviation	$6dB$
Max number of active users in a BS	20

TABLE IV
MODEL PARAMETERS

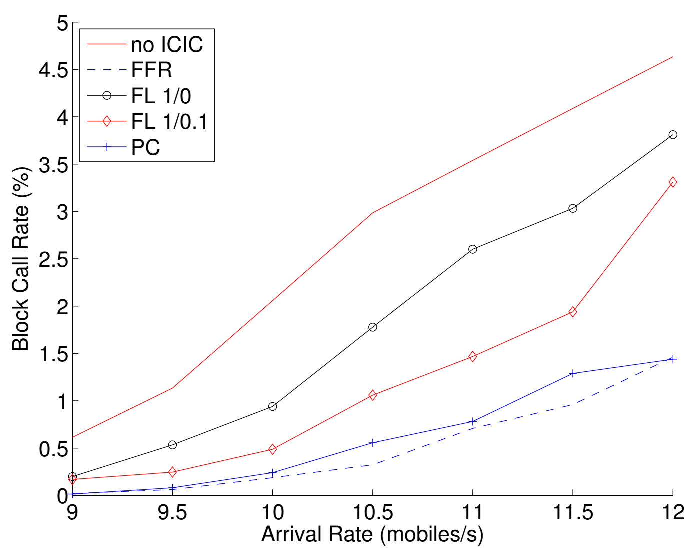

Fig. 2. BCR of ICIC strategies

function (c.d.f) of the FTT. Noticeable gains are demonstrated, with the FFR performing the best. It is also noted that for both Key Performance Indicators (KPIs), the FL 1/0.1 outperforms the FL 1/0 significantly, meaning that it is more beneficial to emit at low power on some bands rather than completely shut them off. Another important information is that the difference between the c.d.f curves is more noticeable in the high FTT region, namely the ICIC schemes mainly benefit cell-edge users.

Figure 5 and Figure 6 show the BCR and mean FTT respectively as a function of α. For the two KPIs, the optimal point lies close to 2, which confirms the reasoning behind the choice of $\alpha = 2$.

V. CONCLUSION

This work has presented distributed SON schemes for interference coordination in OFDMA networks: the PC scheme which adapts the transmitted power for the entire frequency bandwidth, the dynamic FFR scheme which

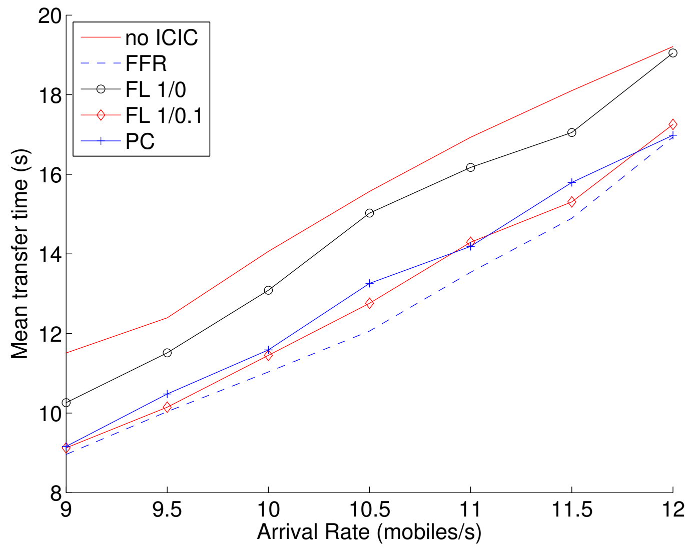

Fig. 3. Mean FTT of ICIC strategies

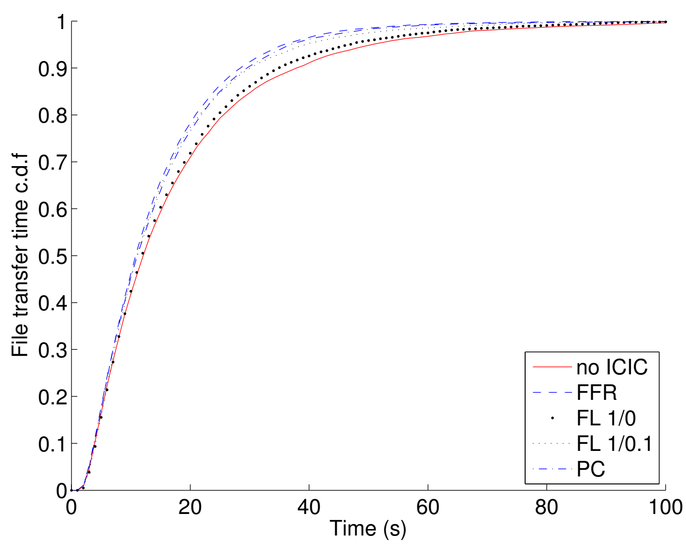

Fig. 4. c.d.f of FTT, $\lambda = 11$

adapts the power on different frequency sub-bands and the FL scheme in which frequency sub-bands can be switched off or can be allocated a value for the transmitted power. The proposed algorithms are fully distributed, using information available from neighboring cells and closed form formulas, making it both computationally light and suitable for practical implementations. The four ICIC schemes bring noticeable performance gains in both FTT and BCR, and the FFR is able to reduce the BCR from 5% to 1.5%, which constitutes a considerable performance increase indeed.

It has been applied to a large-scale network simulator, showing important gains over a full power allocation, in both BCR and cell-edge user throughput. The FFR and the PC provide the best performance while the FL is technologically simpler to implement. The FL $1/0.1$ is better than the FL $1/0$, showing that it can be beneficial not to switch off bands completely.

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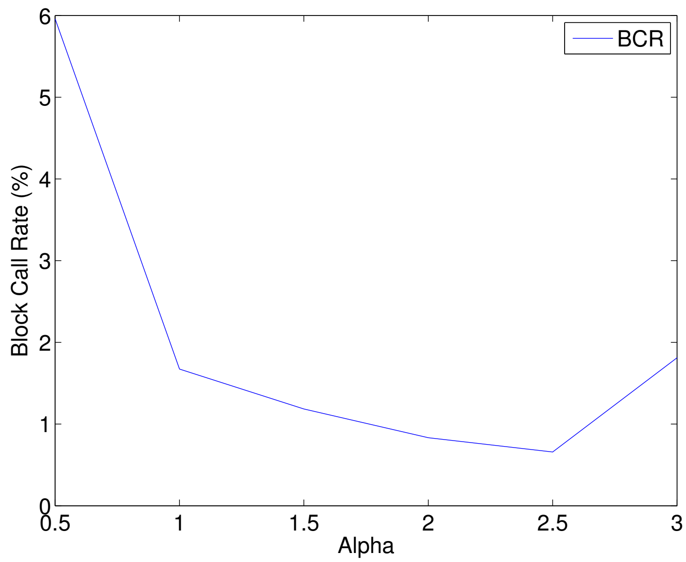

Fig. 5. BCR for different values of α, $\lambda = 11$

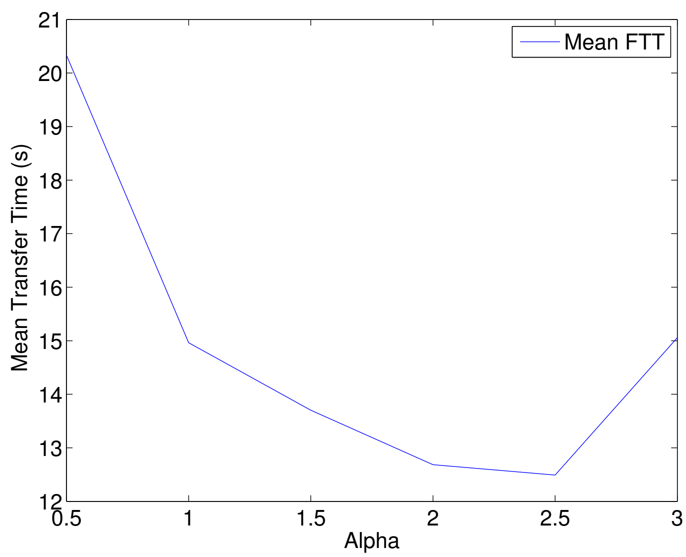

Fig. 6. Mean FTT for different values of α, $\lambda = 11$

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