System-Level Evaluation of a Downlink OFDM Kalman-Based Switched-Beam System with Subcarrier Allocation Strategies

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***Abstract*—In this paper, we propose a novel frequency scheduling strategy for an OFDM switched-beam system. We deal with dynamic frequency allocation based on the distance of the user from the serving base station (BS) or on the power of the channel response received by the user. The key idea is to reduce the interference among the neighboring cells. To do so, we consider a time-space-frequency allocation scheme where users are assigned with the appropriate set of subcarriers according to their serving beam at any given time. We evaluate the performance of the proposed frequency allocation scheme when Kalman filtering is used for joint channel estimation and beam selection. A system-level simulator is developed which computes the signal to interference ratio (SIR) for a reference mobile user with different resource allocation strategies. Previously obtained link-level throughput vs. signal to noise ratio (SNR) results are then translated into a system-level cumulative distribution function (cdf) of the user throughput. Link-level frame error rate (FER) results suggest that the proposed Kalman-based OFDM switched-beam system offers high performance over slow fading channels. System-level SIR results show that the proposed frequency scheduling scheme reduces significantly the interference. Our scheme enhances the system throughput compared to other allocation schemes.**

***keywords*— OFDM, switched beams, link-level, system-level, dynamic frequency allocation.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) has recently been the topic of intensive research due to its ability to cope with severe fading conditions without complex time equalization. It is suited for supporting high data rates over frequency-selective channels by splitting streams into lower rate streams which are simultaneously transmitted over a number of flat-faded narrowband channels.

The multi-carrier nature of OFDM provides the flexibility to be combined with other techniques such as adaptive modulation and power allocation [1] to enhance the system capacity and maintain the desired quality of service. Recently, adaptive resource allocation for OFDM has gained a great interest to allow for the efficient use of wireless frequency resources. In conventional systems, resources were allocated in a predetermined way. However, mobile terminals experience different channel conditions at any given time instant for different subcarriers [2]. In fact, the subcarriers which are experiencing a deep fade for one user may be in a favorable state for another. Therefore, dynamic resource allocation is crucial to enhance the system capacity and to improve the spectrum efficiency. Many papers have proven that the use of adaptive resource allocation can significantly improve the system capacity and combat interference [3, 4, 5].

Many approaches have been studied to mitigate the intercell interference through frequency scheduling strategies. In [3], interference avoidance and interference averaging methods were presented to combat co-channel interferences in IEEE 802.16 OFDMA networks. The first approach was implemented by dynamically allocating frequencies to the neighbor cells. The key idea of the interference averaging approach was maintaining the interference at a constant level.

Frequency planning strategies can also be used. Therefore, different frequency reuse factors can be considered [6]. For OFDM systems, a frequency reuse factor (FRF) of 1 is often considered, which may create co-channel interference [4]. In [4] and [5], a novel frequency reuse scheme was introduced. Subcarriers were divided into two groups, the super group was assigned to the center cell area and the regular group was partitioned into three sectors and assigned to the cell boundary. Each user is associated with one area according to its distance to the serving BS or according to its estimated experienced signal to interference plus noise ratio (SINR).

Here, we present a new frequency scheduling approach for OFDM switched-beam systems. We then evaluate the performance of an OFDM Kalman-based switched-beam system which uses our novel subcarrier allocation strategy and compare it with the performance obtained using other allocation strategies. We use the Kalman-based joint channel estimation and beam selection procedure initially proposed in [7], already shown to perform better over slow fading channels compared to other estimation methods.

We consider a multi-user environment with three-sector cells. For each sector, the available subcarriers are divided into two major groups according to the power of the channel response for each user. One group is assigned to users with high power channel responses, who are more likely to be located near the BS, and are therefore denoted as cell center users (CCU). The other subcarrier group is assigned to the remaining users, called cell edge users (CEU). The mobiles use the appropriate subcarrier group depending on the channel response power. If known, the location of the user could also be used instead of the channel response. In this paper, we have looked into both options. The results obtained show that the proposed frequency scheduling scheme results in a lower interference level compared to the use of a static frequency allocation strategy.

The paper is organized as follows. In section II, we describe the system model and the system-level simulator. The novel allocation strategy is detailed in section III. In section IV, we present our simulation results. Final conclusion and remarks are provided in section V.

II. System Model

To evaluate the performance of the OFDM switched-beam scheme, we consider a link-level to system-level translation approach. Let us first describe, in this section, the link-level model and then the system-level one.

A. Link-Level Model

For link-level simulations, we consider an OFDM downlink Multiple-Input Single-Output (MISO) system with switched beams where a single BS is transmitting to one user. Data streams are duplicated as many times as the number of antennas. Then they are multiplied by the corresponding beam weight before being processed by the Inverse Fourier Transform (IFT) block. The resulting k^{th} symbol, corresponding to the a^{th} antenna, $\mathbf{s}_a(k)$, is given by [7]:

$$\mathbf{s}_a(k) = \sum_{b=1}^{B} w_{a,b}\mathbf{t}_b(k), \tag{1}$$

where $w_{a,b}$ corresponds to the a^{th} antenna weight used to steer the transmitted signal to the b^{th} beam direction. $\mathbf{t}_b(k)$ is given by $[t_{b,1}(k), ..., t_{b,i}(k), ..., t_{b,N}(k)]^T$, where N and i denote, respectively, the number of subcarriers and the i^{th} subcarrier index, and $[.]^T$ denotes a column vector.

During a pilot symbol, the channel is estimated based on Kalman filtering using a particular pilot sequence [7]. Pilot symbols consist in overlapping phased pilot sequences transmitted to the user in the available beams for all subcarriers. The serving beam is the one which has the highest channel power. The link-level module provides FER results.

B. System-Level Model

For system-level evaluation, we develop a simulator tool which generates a multi-cell multi-user environment with three-sector cells. It uniformly populates a grid layout of N_{cell}^2 hexagonal cells. Each sector is covered by a uniform linear antenna array to generate B beams. The system-level performance is evaluated in the center cell. SIR measurements are collected over several snapshots for a mobile of interest which is randomly chosen in the center cell.

For a fixed system load C, which is defined as the number of users per cell, we compute the interference received at the mobile of interest. The interference signal includes intracell interference and intercell interference. The SIR is given as follows:

$$SIR = \frac{S_0}{\sum_{i=1}^{C \times N_{cell}^2 - 1} S_i}, \tag{2}$$

where S_0 denotes the desired signal and S_i denotes the i^{th} interfering signal. In fact, the mobile of interest receives S_i from the BS serving the i^{th} interferer.

The received power from a BS at a mobile user [8] is expressed as:

$$S_i = \frac{S 10^{(\frac{\zeta}{10})} \rho^2 a_L(\theta, \theta_b)}{r^{\alpha}}, \tag{3}$$

where S is the BS transmitting power per user, ζ is a zero-mean Gaussian random variable describing the shadowing factor and ρ is the fading attenuation. r is the distance between the mobile and the serving BS and α is the pathloss exponent. The factor $10^{(\frac{\zeta}{10})}\rho^2$ can be approximated by the equivalent shadowing factor $10^{(\frac{\eta}{10})}$. $a_L(\theta, \theta_b)$ is the antenna array pattern. θ is the angle that the mobile forms with the antenna-array normal and θ_b designates the steered beam direction.

The system performance is obtained by translating link-level results into meaningful system-level performance measures.

III. Frequency Allocation Strategies

A. Proposed Frequency Allocation Strategy

Here, we propose a proper frequency allocation scheme for OFDM switched-beam systems which aims at reducing the interference. We consider a full frequency reuse pattern where the available subcarriers are reused in each cell. However, this strategy exhibits co-channel interference among the users of adjacent cells since they use simultaneously the same subcarriers.

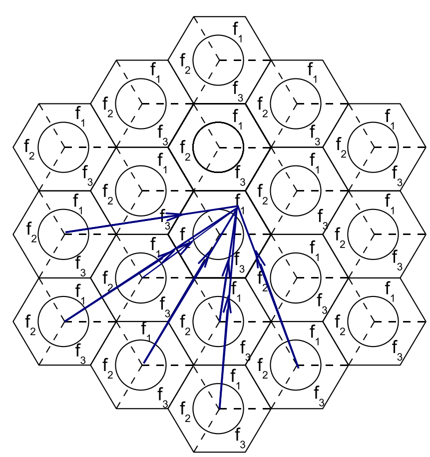

Fig. 1. Frequency reuse pattern for multi-cell OFDM systems.

To reduce this effect, [9] proposed a fractional frequency reuse (FFR) scheme where the spectrum is divided into two groups, the super group and the regular group. The first group is confined in the center cell area with a reuse factor of one. The second group is confined in the cell boundary with a reuse factor of $1/3$. We use this group partition approach to distinguish CEU and CCU in our multi-cell system.

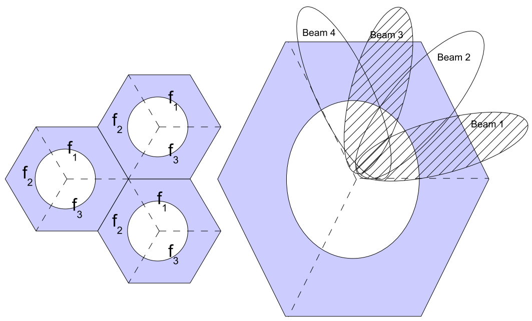

Fig. 2. Frequency assignment for a multi-cell switched-beam OFDM system.

To mitigate the co-channel interference problem, we divide the spectrum into three partitions corresponding to the three sectors, f_1, f_2 and f_3. Fig. 1 illustrates the frequency reuse pattern for the proposed multi-cell structure and the interfering sectors. The user in sector 1 at the center cell is interfered by the signals from sectors 1 in the cells designated by the arrows [5]. In addition, a channel-dependent subcarrier scheduling scheme is applied for each sector, such that users are partitioned into two groups based on their distance to the serving BS, depending on the power level of the channel that includes the effect of pathloss and shadowing. The CEUs and CCUs share the available subcarriers in each sector.

We also introduce a beam frequency allocation scheme in our strategy. In each sector i, f_i is shared between the CEUs and CCUs of each beam. As shown in Fig. 2, considering a switched-beam system with four beams, beams 1 and 3 (dashed beams) use the same subcarrier set. Hence a CEU (grey area) in beam 1 interferes with a CEU in beam 3, and similarly for CCUs (white area).

The users are dynamically distributed into CEUs and CCUs considering a parameter that we refer to as path gain threshold [12]. In our scheme, the path gain threshold consists in the received signal power. When the received signal is less than the threshold, the user is treated as a CEU, otherwise it is considered as a CCU.

To summarize, the subcarriers are first split in three sets, one for each sector of any given cell. The subcarriers of a given sector are further split in two sets, one for the CEUs and another for the CCUs. Finally, the CEU and the CCU subcarriers are split into two sets, one set for beams 1 and 3, and another for beams 2 and 4.

B. Benchmark Frequency Allocation Strategies

To evaluate the performance of our frequency allocation scheme, we compare it to two other strategies.

We first compare it to a frequency allocation scheme which uses the beam frequency allocation approach [13]. Unlike our scheme, the available subcarriers are statically assigned to users according to their serving beam (no CCUs nor CEUs). For this scheme (static), we consider two fixed frequency sets where users in beams 1 and 3 use the same frequency set and hence interfere, and similarly for users in beams 2 and 4.

Then we compare our proposed strategy to the frequency scheduling technique presented in [4]. We apply this strategy to our OFDM switched beam system. Unlike our scheme, the frequency allocation method in [4] uses the distance between the user and the serving BS to divide users into CEUs and CCUs. When the user distance to the serving BS is less than the threshold, the user will be considered as a CCU and will be served with the appropriate frequency group. Otherwise, it will be treated as a CEU. In this strategy, we do not consider a beam-frequency allocation approach.

TABLE I
LINK-LEVEL PARAMETERS

Parameter	Value	Parameter	Value
Bandwidth	5 Mhz	Frame size in bits	15352
Operating frequency	5 Ghz	Number of antennas	4
Full-band information bit rate	8 Mbps	Number of beams	4
OFDM symbol duration	16μs	Pilot rate	10%
Transmitted frames	5000	Convolutional encoder rate	$\frac{1}{2}$

TABLE II
SYSTEM-LEVEL PARAMETERS

Parameter	Value	Parameter	Value
Number of Iterations	100000	Number of cells	121
Antenna elements	4	Number of paths	3
Shadowing factor	8 dB	Pathloss exponent	4

IV. SIMULATIONS RESULTS

A. Simulation Parameters and Assumptions

The performance of the proposed Kalman-based channel estimation scheme is evaluated in two steps.

Link-level simulations were conducted for both slow and fast Rayleigh fading channels with 3 kmph and 60 kmph speeds, respectively. The OFDM modulator converts the 16-QAM symbols into 64 parallel data streams, each assigned to one subcarrier. Each stream is multiplied by the serving beam weight and transmitted over the four antenna branches [7]. Then the proposed frequency allocation structure is evaluated by system-level simulations. C mobile users are uniformly distributed over a multi-cell multi-user environment. We assume that at most one user is served by each beam at any given time and that the BS serves all users with the same power. Tables I and II summarize the simulation parameters.

B. Numerical Results

Link-Level Simulations: The evaluation of the Kalman-based method is performed through comparison with other estimation techniques based on pilot subcarrier multiplexing. These techniques consider beam-specific pilots which are periodically multiplexed on the available subcarriers [10]. The reference estimators are 1) the spline frequency-interpolator, which uses piecewise polynomials to reconstruct a continuous channel response at non-pilot subcarriers, 2) the time-interpolator, based on zero-forcing for equalization (TI_ZF) [11], which computes the time channel response by applying an IFFT to the frequency channel coefficients at pilot subcarriers and 3) the Minimum Mean Square Error (MMSE) estimator.

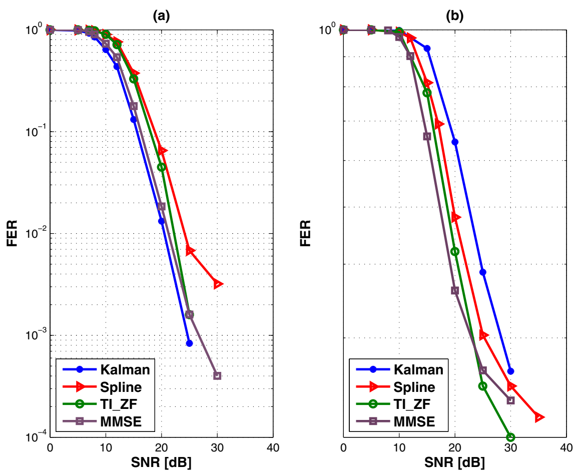

Fig. 3. FER vs. SNR for the estimation schemes over (a) slow fading channel and (b) fast fading channel.

The link-level performance is illustrated via FER curves. Fig. 3 shows that the Kalman method outperforms the three considered estimation methods for a slow fading channel. This is due to the tracking of the channel conditions by the Kalman estimator. For fast fading channels, our method performs worse than the other estimators because of the inaccuracy of the channel model at high speeds. However, the targeted applications are more likely at the low speed range we consider in the remainder of the paper.

System-Level Simulations: For the system-level performance analysis, we compute the SIR for a reference mobile in the center cell at different cell loads. The system-level capacity is expressed in terms of user throughput versus the cell load. To get the system-level capacity for the considered subcarrier allocation strategy, we translate the link-level FER results versus SNR into system-level throughput using the SIR values obtained by the multi-cell system-level simulation tool. Here we deal with the proposed frequency allocation schemes detailed in section III.

For our frequency allocation scheme, we use the path gain threshold which is related to the received signal from the serving BS. This threshold ranges from 0 to 10 dB [12] and corresponds to a particular proportion of CEUs and CCUs (we present results for 0 dB and 3 dB thresholds where 38% and 50% of users are, respectively, considered as CEUs). Figs. 4 and 5 show that the dynamic scheme significantly improves the performance of the system in terms of interference reduction compared to the static strategy. As shown in Fig. 6, the use of our novel dynamic scheme results in an enhanced system capacity. Our method gives more than double the average throughput per user of the static frequency allocation method.

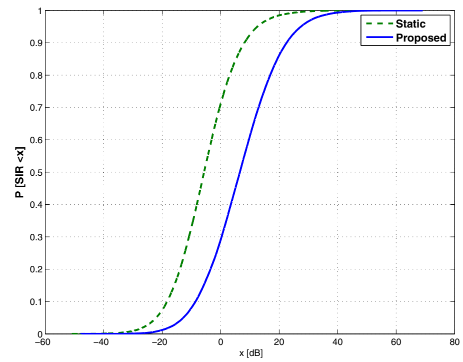

Fig. 4. CDF of the SIR for a cell load of 12 users.

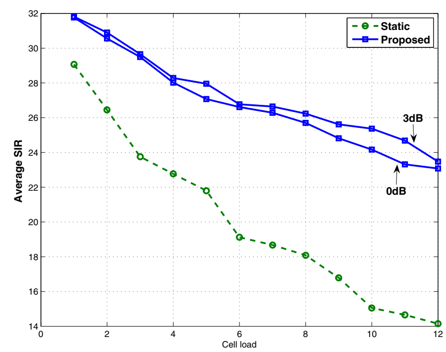

Fig. 5. Average SIR for static and dynamic allocation strategies.

We also compare our scheme with the frequency allocation strategy presented in [4]. Here we use the mobile distance to the serving BS to divide users into CEUs and CCUs for both methods. The distance threshold is set to 800 m for a 1 km radius cell. To compare performance, we look at the outage probability and the average SIR. As shown in Fig. 7, our scheme outperforms the scheme proposed in [4] in terms of outage probability. As for interference reduction, our scheme performs better as shown in Fig. 8 due to space frequency allocation according to the users distribution in each beam.

From the SIR values and the link-level throughput, we obtain the average user throughput per cell for both the proposed scheme and the scheme presented in [4]. In Fig. 9, we see that our strategy gives better performance in terms of average throughput per user. The reuse pattern used in our strategy noticeably reduces the intercell interference since it introduces a spatial dimension to the subcarrier allocation strategy.

V. Conclusion

In this paper, we treated the dynamic subcarrier allocation concept in the particular context of OFDM switched-beam systems. A Kalman-based channel estimator was considered

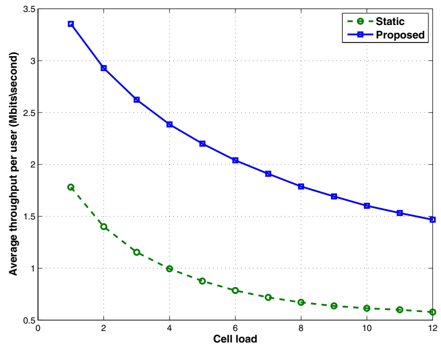

Fig. 6. Average throughput per user for static and dynamic subcarrier allocation strategies.

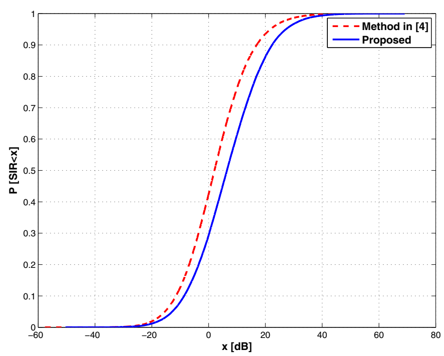

Fig. 7. CDF of the SIR for a cell load of 12 users.

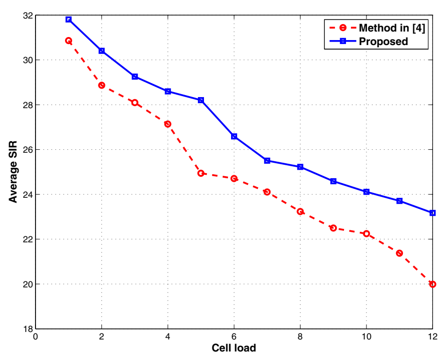

Fig. 8. Average SIR for different cell loads.

to jointly estimate the channel and select the serving beam. To evaluate the performance of the proposed frequency allocation scheme, we developed a system-level simulator which computes the SIR for a mobile of interest. These SIR results are then translated into system-level capacity measurements. The Kalman channel estimator was shown to give better results in terms of FER for slow fading channels. We tested the performance of the proposed dynamic scheme and compared it to two other frequency allocation strategies. The first one statistically divides the available frequencies between the beams. The second one is dynamic and divides users into CCUs and CEUs depending on the distance to the serving BS. Our scheme outperforms the two schemes since it dynamically distributes the available frequencies depending on the user channel response or position and it introduces a spatial dimension to the subcarrier allocation strategy.

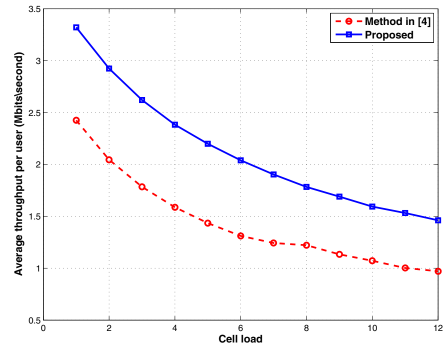

Fig. 9. Average throughput per user for a switched-beam OFDM system.

Acknowledgment

This work was supported by a Canada Research Chair on Wireless Communications and by the Cooperative Research and Development Program of NSERC and Ericsson Canada.

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