System-Level Evaluation of a Downlink OFDM Switched-Beam System with Kalman-Based Joint Channel Estimation and Beam Selection

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Abstract— **In this paper, we evaluate the performance of an OFDM switched-beam system based on Kalman filtering for joint channel estimation and beam selection. For this purpose, we develop a system-level simulator which computes the Signal to Interference Ratio (SIR) for a reference mobile user. For a given system capacity in terms of average number of users per cell, the resulting SIR distribution collected from a large number of system-level snapshots translates the link-level throughput vs. SNR results into a system-level cumulative distribution function (cdf) of the user throughput from which different meaningful system-level performance measures such as the average throughput can be computed. Simulations suggest that the proposed Kalman-based OFDM switched-beam system offers improved performance over slow fading channels in terms of link-level frame error rate (FER) and system-level capacity or average throughput per user or cell.**

I. Introduction

Today, smart antennas are successfully used to mitigate the interference and multipath fading effects and to enhance the communication capacity and quality by introducing spatial diversity [1]. Indeed, they enhance the performance of wireless communication systems by providing each individual user with the appropriate serving beam. There are two major approaches for smart-antenna beamforming. The first one is adaptive and based on tracking the mobile user when moving over the cell area [2]. The other approach, the switched beam, consists in selecting one beam pattern for each user from preset fixed beam patterns. The first scheme requires adaptive algorithms to select the serving beam by assigning time-dependent weights [3], which makes its implementation complex and costly. However, switched-beam beamforming is more practical due to its simplicity of implementation in existing networks.

The main task of a switched-beam system is the beam selection process using an accurate and fast converging algorithm in order to assign to each user the appropriate beam. The beam selection process has been the object of intensive research interest. In [4], two approaches were proposed to select the serving beam based on pilot aided channel estimation. The first approach considers SNR maximization and the second one is based on beam power measurements. However, few works addressed the issue of beam selection in the particular context of Orthogonal Frequency Division Multiplexing (OFDM). This technique has gained enormous interest due to its implementation simplicity and its resistance to fading problems by providing high data rates over frequency selective channels. Besides, OFDM eliminates intersymbol interference by the insertion of a cyclic prefix at the beginning of each OFDM symbol. In [5] and [6], a new approach for beam selection was proposed where the best serving beam is selected at the mobile terminal. The authors adopted the OFDM structure to jointly estimate the downlink channel and select the serving beam based on a specific pilot scheme. In [5], beams are separated using overlapping pilots related to each antenna element. A subcarrier-multiplexing pilot scheme was later used in [6]. This approach considers beam-specific pilots which are periodically multiplexed on the available subcarriers. At the receiver side, the highest-power beam is selected for the next transmission cycle.

More recently, an OFDM structure was used to select the serving beam in [7]. Two adjacent beams which have the same delayed path signal and the highest power are selected from a set of predefined fixed beams. Then the two beams are combined using an adaptive beamforming algorithm. However, this combined method is complex to implement.

In our work, we focus on switched-beam beamforming which offers a good tradeoff between performance and complexity. The beam-selection method proposed in [5] is based on frequency interpolation and Kalman filtering for OFDM switched-beam systems. Although this technique is promising, it has not been evaluated at the system level. The main objective of this work is to study the performance of the OFDM switched-beam system in [5] when applied to a multi-cell multi-user environment. To evaluate this approach, we develop a system-level simulator which takes into account the propagation properties of the environment, the user mobility and the interfering signals for link-to-system level translation. We compare this technique to other estimation techniques based on subcarrier-multiplexing pilot schemes (See [11] and references there in). The results obtained show that the proposed Kalman-based estimator offers improved performance over slow fading channels in terms of link-level FER or

system-level throughput per cell or user.
The paper is organized as follows. In section II, we describe the system model. The system-level evaluation procedure is presented in section III. Section V explains the link-to-system-level performance mapping tool and some simulation results. Final conclusion and remarks are provided in section V.

II. System Model

An OFDM downlink Multiple-Input Single-Output (MISO) system with switched beam is considered. The BS sends B data streams to B users. Each user is allocated a specific beam. Before OFDM modulation, data is preprocessed using an encoder, an interleaver and a mapper. Each data stream is duplicated as many times as the number of antennas. Then they are multiplied by the corresponding beam weight before being processed by the OFDM conventional Inverse Fast Fourier Transform (IFFT) block. The resulting symbol corresponding to the a^{th} antenna [5], $\mathbf{s}_a(k)$ is given by:

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

where $w_{a,b}$ and k correspond to the a^{th} antenna weight used to steer the transmitted signal to the b^{th} beam direction and to the k^{th} OFDM symbol, respectively. For data symbols, we assign $x = d$ and for pilot symbols we assign $x = p$.
$\mathbf{t}_b^x(k) = [t_{b,1}^x(k), ..., t_{b,i}^x(k), ..., t_{b,N}^x(k)]$, where N and i denote, respectively, the number of subcarriers and the i^{th} subcarrier index.
At the receiver, data is deinterleaved and decoded after OFDM demodulation. During a pilot symbol, $\mathbf{t}_b^p(k)$, the channel is estimated based on Kalman filtering. 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 next OFDM data symbol $\mathbf{t}_b^d(k)$ will be transmitted over the selected beam which is fed back by the receiver to the BS.

III. System-Level Evaluation

A. Simulator Setup

Our simulator is composed of a system-level module to evaluate the SIR. The link-level module described in the previous section provides statistics such as FER.
The system-level simulator generates a multi-cell multi-user environment with three-sector cells. We consider a grid layout of $N_{cells} \times N_{cells}$ hexagonal cells uniformly populated with mobile users. The mobile of interest is randomly chosen in the center cell.
Each sector is covered by B beams generated by a uniform linear antenna array composed of M antenna elements. The antenna array pattern [8] is defined as:

$$\begin{aligned} a_L(\theta) &= a_{EF}(\theta) \times a_{AF}(\theta) \quad (2) \\ &= \cos^2(\theta) \times (|\sum_{m=0}^{M-1} \exp(-jm2\pi d/\lambda \sin(\theta))\,|^2)/M, \end{aligned}$$

where $a_{EF}(\theta)$ is the element factor of a half-wave-dipole element ($d = \lambda/2$), $a_{AF}(\theta)$ defines the array function and θ is the angle that the mobile forms with the antenna-array normal.
The serving cell is the one which is emitting with the highest power.

B. Interference computation

For a specified capacity C which is defined as the average number of users per cell, we evaluate the system performance in terms of SIR measurements. The received interference signal at the mobile of interest includes intracell interference and intercell interference. The SIR expression is given by:

$$SIR = \frac{S_0}{\sum_{i=1}^{C\times N_{cell}^2-1} S_i}, \quad (3)$$

S_0 denotes the received signal by the desired mobile and S_i denotes the i^{th} interferer signal. In fact, the mobile of interest receives S_i from the BS assigned to the i^{th} interferer.
The received power from a BS at a mobile user [9] is expressed as:

$$S_i = \frac{S10^{(\frac{\zeta}{10})}\rho^2 a_L(\theta)}{r^\alpha}\,\chi, \quad (4)$$

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 $10^{(\frac{\eta}{10})}$. χ is an activity factor which equals 1 with probability p_{af} and $\chi_{fraction}$ otherwise. When an interferer is active, it contributes with all the transmitted power. Otherwise, it contributes with a power fraction allocated to pure signalling.

IV. Simulation Results

A. Simulation Scenario

Link-Level Simulations: In order to evaluate the proposed beam selection scheme, link-level simulations were conducted considering slow and fast Rayleigh fading corresponding, respectively, to 3 kmph and 60 kmph mobile speeds. The OFDM block diagram used for simulations is composed of a Viterbi encoder, an interleaver and a mapper to convert signals to 16-QAM symbols. The OFDM modulator converts the mapped symbols into 64 parallel data streams each assigned on one subcarrier. Each stream is duplicated four times as the number of antenna branches, then multiplied by the corresponding beam weight. Finally a cyclic prefix of $\frac{1}{4}$ the OFDM length is added.
The channel model was presented in [10]. It has 3 paths with an exponentially decaying power profile. The beam channel seen by one user in each subcarrier is modeled as an auto-regressive AR(2) process. Table I summarizes the link-level simulation parameters.

TABLE I

LINK-LEVEL PARAMETERS

Parameter	Value	Parameter	Value
Bandwidth	5Mhz	Frame size in bits	15352
Operating frequency	5Ghz	Number of antennas	4
Full-band information bit rate	8 Mbps	Number of beams	4
OFDM symbol duration	$16\mu s$	Pilot rate	10%
Transmitted frames	5000	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

System-Level Simulations: To evaluate the performance of the proposed beam selection scheme with joint channel estimation, system-level simulations were conducted. The simulator tool uniformly populates an 11×11 grid of hexagonal cells with C users per cell, where C ranges from 1 to 12.

To compute the interference seen by the desired mobile, we consider a frequency allocation strategy detailed below. The frequency spectrum is shared by three sectors in the cell. Each sector uses 64 subcarriers which are divided between four beams. In the first sector, beam 1 and beam 3 share the same subcarriers, and hence interfere. Beam 2 interferes with beam 4, and so on for the remaining sectors.

For each mobile, the simulator determines the physical cell, then computes the center of the serving cell. The system-level simulation parameters are summarized in table II.

B. Numerical Results

The proposed scheme based on Kalman filtering was compared to other estimators based on subcarrier-multiplexing: spline frequency-interpolator, time-interpolator based on zero-forcing and Minimum Mean Square Error (MMSE). The first one uses piecewise polynomials to reconstruct a smooth and continuous channel response at non-pilot subcarriers. The second one computes the time channel response by applying an IFFT to the frequency channel coefficients at pilot subcarriers based on zero-forcing for equalization (TI_ZF) [11].

Link-level FER performance is evaluated in Fig. 1. For a slow fading channel, the Kalman-based estimator outperforms the three other estimators. For a fast fading channel, the proposed Kalman-based estimator performs worse than the other estimators due to the inaccuracy of the AR(2) channel model at high speeds. Fig. 2 shows the performance of the Kalman estimation scheme in terms of user throughput for both slow and fast fading channels.

For system-level evaluation, we compute the SIR for the desired mobile at a given cell capacity. Fig. 3 shows the cdf of the SIR for 12 users per cell. It presents the outage probability of the system. The average SIR is shown in Fig. 4.

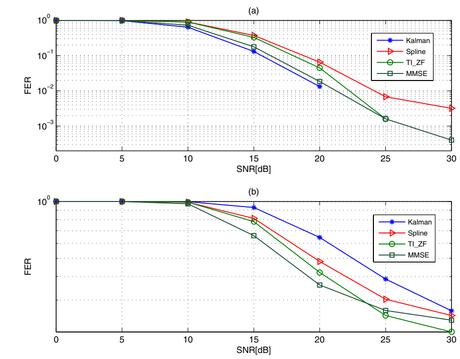

Fig. 1. Frame Error Rate for the estimation schemes for (a) slow fading channel and (b) fast fading channel.

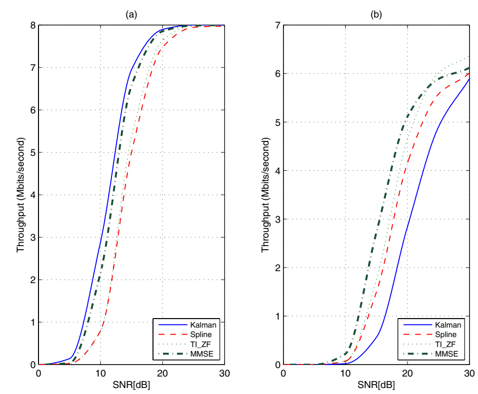

Fig. 2. User throughput for the estimation schemes over (a) slow fading channel and (b) fast fading channel.

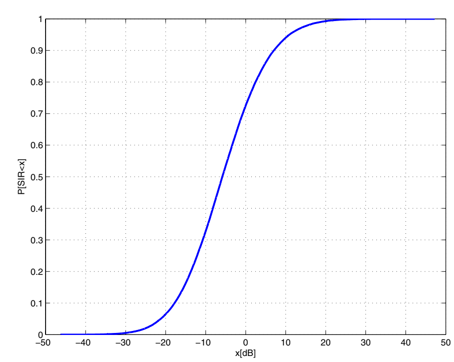

Fig. 3. Cumulative distribution function of the SIR for a capacity of 12 users per cell.

To evaluate the performance of the analyzed scheme, the simulator tool translates the link-level results above to the system level. For this purpose, we compute the cdf of the throughput per user. Fig. 5 illustrates the performance of the Kalman-based method for slow fading channels in comparison to other methods. The Kalman-based estimator is shown to outperform the reference methods in terms of average user and system throughput. The average throughput per user decreases

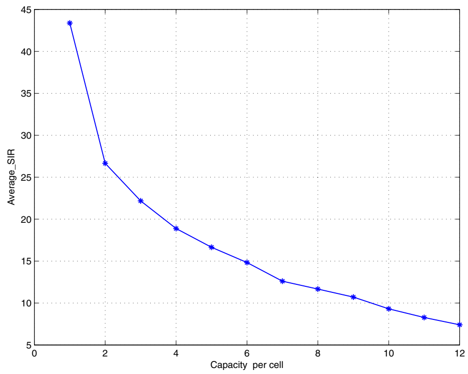

Fig. 4. Average Signal-to-Interference-ration for different cell capacities.

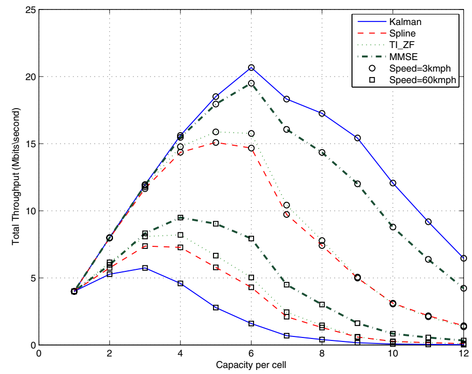

Fig. 7. Total throughput for slow fading and fast fading channels.

when the average number of users per cell increases. This fact is due to the increase of the number of interferers, as shown in Fig. 6. The average throughput per cell increases with the cell capacity reaching a maximum for 6 mobile users per cell then decreases as seen in Fig. 7. For fast fading channels, Kalman-based estimator performs worse than the reference estimators. We obtain a maximum capacity for 3 users per cell.

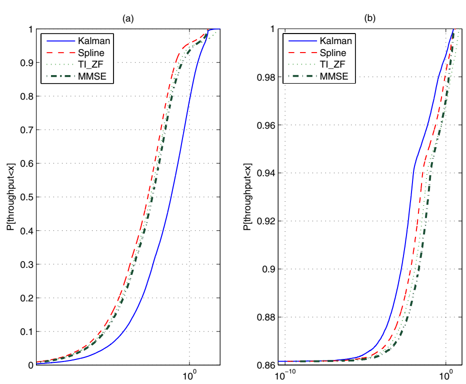

Fig. 5. Cumulative distribution function of the throughput for a capacity of 12 users per cell for (a) slow fading and (b) fast fading channels.

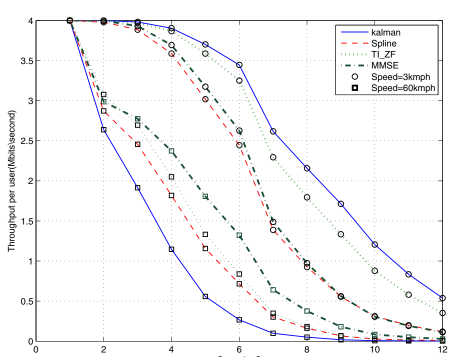

Fig. 6. User throughput for slow fading and fast fading channels.

V. Conclusion

In this work, we evaluated the system-level performance of a channel estimator based on Kalman filtering. For this purpose, we developed a system-level simulator which computed the SIR considering a reference mobile, then translated the link-level results which are expressed in terms of FER to the system-level. System capacity was evaluated by computing the average throughput per user and cell. The proposed Kalman-based estimator was shown to perform better over slow fading channels.

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