Paper

Improvement of LTE Downlink Channel Estimation Performance by Using an Adaptive Pilot Pattern

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Abstract—This paper proposes an adaptive pilot pattern to improve channel estimation performance for LTE downlink system with high mobility. The downlink pilot positions are predefined in the time and frequency domain with fixed pilot pattern in LTE standard. However, that pilot structure is not efficient in a fast time varying channel, and leads to a decrease of channel estimation performance. The authors propose and evaluate the performance of LTE downlink channel estimation using an adaptive pilot scheme to optimally use pilot tones over time varying channels. It is shown that only seven bits of additional wide-band feedback per frame and per user are required to optimally support adaptive pilot pattern. Simulation results show that the proposed method allows high performance in terms of throughput and channel estimation error. This analysis shows that LTE downlink throughput could be increased over 4%.

Keywords—channel estimation, LTE, MIMO, OFDM, pilot pattern.

1. Introduction

Long Term Evolution (LTE) is a new communication technology based on Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink (DL) and Single Carrier Frequency Division Multiple Access (SCFDMA) in the uplink (UL). Additionally, LTE downlink transmission model is based on multiple antenna architecture on the transmitter and receiver side [1]. Orthogonal Frequency Division Multiplexing (OFDM) has been widely applied in wireless communication systems due to its high data rate transmission and its robustness to multipath channel delay [2], [3]. However, OFDM system is very sensitive to Doppler frequency shift caused by high mobility of receiver. In such case, the channel changes within one OFDM symbol and the orthogonality between subcarriers is broken resulting the intercarrier interference (ICI). Hence, the system performance may be considerably degraded. In order to mitigate ICI in LTE system, several channel estimation techniques have been proposed [4]–[7]. Channel estimation is done using pilots inserted in the transmitted OFDM symbol. The design of a channel estimator is based on two fundamental problems:

- the amount of pilot symbols to be transmitted,
- the complexity of the estimator.

In LTE system, the pilots have static positions as defined in the Release 8 for both Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) scheme [8]. Consequently, this LTE pilot scheme seems not optimal in terms of throughput because the amount of the pilot symbols according to channel time selectivity.

In the literature, much work has been carried out in terms of pilot arrangement in OFDM systems. Two methods classes are available for pilot arrangements. One is based on regular patterns, where pilot symbols are equally-spaced in time and/or frequency domain, whereas the other relies on irregular patterns.

The optimal spacing design of pilot symbols for OFDM systems has been investigated by several studies over the past ten years. In literature, several methods have been designed for regular pilot lattices that satisfy a suitable Nyquist criterion [9], [10]. These regular patterns are not suitable for systems in which pilot tones are not equi-powered or channel is time varying process [11]. Recently, irregular pilot arrangements were shown to be optimal in the mean squared error (MSE) sense for certain classes of time varying channels [12], [13].

In this paper the authors show how to use an adaptive pilot scheme to optimally use LTE pilot tones over time domain. These new pilot schemes improve the system performance and correct the loss of throughput in time varying channel.

This paper is organized as follows. Section 2 presents MIMO OFDM system model. In Section 3, the LTE pilot design is introduced. Adaptive pilot design is described in Section 4. In Section 5, the authors investigate the feedback requirements for the proposed adaptive pilot-symbol pattern. The system simulation results are presented in Section 6.

2. MIMO OFDM System Model

In this section, the transmission model suitable for further derivation is introduced. Let us consider the block diagram of MIMO OFDM system with $\mathrm{N_t}$ transmit antennas, $\mathrm{N_r}$ receive antennas and N subcarriers (see Fig. 1). Generated OFDM signals are transmitted through a number of antennas in order to achieve diversity.

In MIMO OFDM system shown in Fig. 1 (in SISO OFDM systems $\mathrm{N_t} = 1$), the authors assume that the duration of

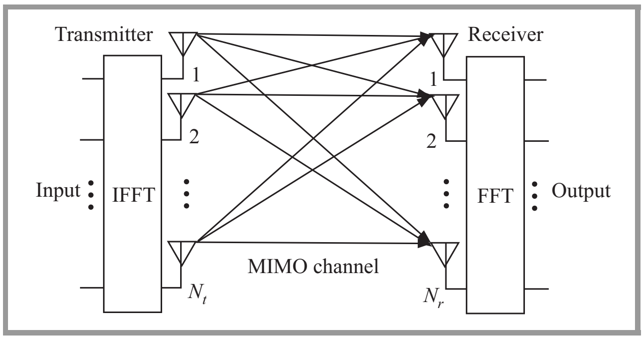

Fig. 1. Block diagram of MIMO OFDM system.

the cyclic prefix is long enough to avoid intersymbol interferences (ISI).

A received symbol vector at a discrete time index n transmitted over a flat and time-variant MIMO channel can be written as:

$$Y_k^q(n) = \sum_{p=1}^{\mathrm{N_t}} H_{k,k}^p . X_k^p(n) + \underbrace{\sum_{p=1}^{\mathrm{N_t}} \sum_{\substack{i=1 \\ i\neq k}}^{\mathrm{N}} H_{k,i}^p . X_i^p(n)}_{ICI} + W_k^p(n), \quad (1)$$

where $X_k^p(n)$ is the transmitted symbol over the k-th subcarrier from the p-th antenna at time index n, $Y_k^q(n)$ is the received symbol over the k-th subcarrier from the q-th antenna at time index n. $H_{k,i}^p$ denotes a frequency channel response between the k-th and i-th subcarrier. Intercarrier interference can be neglected for time invariant channels and time varying channels with moderate mobility.

The time-frequency pilot scheme used in a MIMO environment is based on orthogonal pilots, which is one of the innovation used by LTE. When null subcarriers are employed, the pilots corresponding to the other antennas pilots have to be turned off (null subcarriers) to avoid interference between antennas [15].

3. LTE Pilot Scheme

In LTE standard, pilot symbols are transmitted during the first and fifth OFDM symbol of each slot when the short cyclic prefix (CP) is used and during the first and fourth OFDM symbol when the long CP is used [8]. The frequency spacing between two successive pilot symbols is 6 subcarriers. Figure 2 illustrates LTE pilot scheme for SISO case.

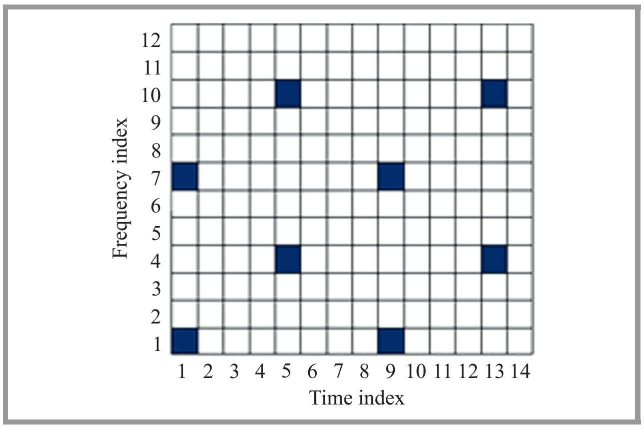

Fig. 2. Pilot structure for LTE system.

The authors propose a novel concept called useful throughput to characterize throughput D_u available to data transmission by taking into account the number of data subcarriers and pilot subcarriers in a frame of K OFDM symbols. The pilot symbols causes degradation in terms of useful throughput (data symbols), which can be expressed as:

$$D_u = \frac{\text{Number of data tones}}{\text{Number of tones}} D, \quad (2)$$

where D and D_u are the original throughput (data + pilot symbols) and useful throughput (data symbols), respectively.

Consequently for the purpose of comparison, the ratio between D and D_u is derived for LTE regular pattern and proposed scheme:

$$\frac{D_u}{D}(\text{LTE regular pattern}) = 1 - \frac{\mathrm{N_p}}{4\mathrm{N}}, \quad (3)$$

where N and $\mathrm{N_p}$ are OFDM number of subcarriers and number of pilot subcarriers, respectively.

4. Adaptive Pilot Design

An adaptive pilot scheme is proposed to achieve high throughput gains. This dynamic pilot scheme investigates time selectivity of the channel to reduce the number of pilot symbols used. When the channel does not change during the K OFDM blocks transmission, the first OFDM block for the transmission of pilot subcarriers is used and the same channel estimation during transmission of the following $(K-1)$ blocks is kept. This approach allows varying the amount of the pilot symbols according to channel time selectivity. For the purpose of comparison, Fig. 3 shows a classical LTE regular pattern and proposed irregular pattern.

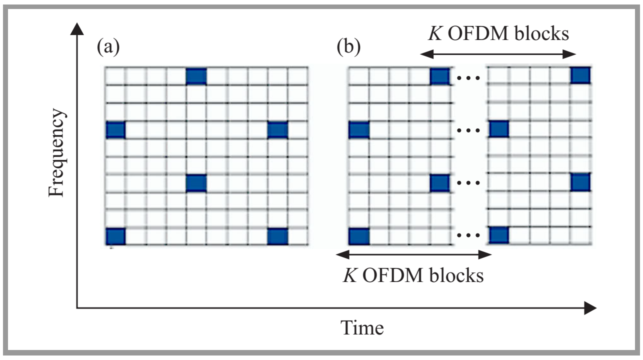

Fig. 3. Comparison between LTE: (a) regular pattern, (b) proposed pattern.

Good bit error rate (BER) performance can be achieved by the proposed pattern if K satisfies the following inequality

$$K.T \leq T_{coh}\,, \tag{4}$$

where T is the time duration of one OFDM symbol and T_{coh} is channel coherence time. The Doppler spread f_d, and the coherence time T_{coh}, are reciprocally related over Rayleigh fading channel [14]:

$$T_{coh} \approx \frac{9}{16.\pi.f_d}\,. \tag{5}$$

Therefore, K is an integer chosen to satisfy the inequality:

$$K \leq \frac{9}{16.\pi.f_d.T}\,. \tag{6}$$

An optimal choice of K is:

$$K = \left\lceil \frac{9}{16.\pi.f_d.T} \right\rceil. \tag{7}$$

The ceiling of a number is shown by $\lceil . \rceil$.

Consequently for the purpose of comparison, the ratio between D and D_u is derived for regular pattern and proposed scheme:

$$\frac{D_u}{D}\,(\text{LTE regular pattern}) = 1 - \frac{\mathrm{N_p}}{4\mathrm{N}}\,, \tag{8}$$

$$\frac{D_u}{D}(\text{adaptive pattern}) = 1 - \frac{\mathrm{N_p}}{K.\mathrm{N}} = 1 - \frac{1}{6K}\,. \tag{9}$$

Figure 4 shows that the throughput gain of proposed adaptive pattern is significant:

$$\text{throughput gain} = \frac{1}{6}\left(\frac{1}{4} - \frac{1}{K}\right)D\,. \tag{10}$$

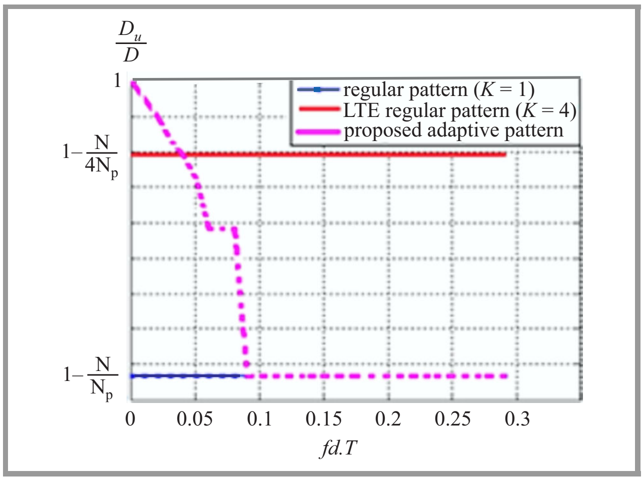

Fig. 4. Normalized throughput versus $f_d.T$ for different pattern configurations.

From Fig. 4, the two cases can be expressed and compared:

- **LTE high performance $f_d.T \leq 0.04$ ($K \geq 4$)**

The best performance for LTE is realized at low speeds up to 15 km/h. However, in LTE high performance ($f_d.T \leq 0.04$), mobile speed between 15 km/h and 120 km/h can be supported with high performance [15]. In this case, proposed scheme improves the normalized useful throughput ($f_d.T \leq 0.04$). Especially, throughput gain exceeds 4% for moderate time varying channels ($f_d.T \leq 0.01$).

- **LTE low performance $f_d.T > 0.04$ ($K < 4$)**

The maximum speed which LTE is designed to manage acceptable performance varies from 120 to 500 km/h ($f_d.T > 0.04$) [15]. In such case, the channel changes within one OFDM symbol, and higher pilot density is needed for channel estimation. The pilot symbols in LTE structure are not dense enough. Proposed scheme has a throughput decrease in order to allow high channel estimation performance. To allow the transmitter to update the pilot pattern, a feedback is required between the receiver and transmitter.

5. Feedback

In this section, the feedback requirement for adaptive pilot-symbol pattern in LTE is considered. The LTE radio frame has a length of 10 ms, and OFDM symbol time duration is $T \approx 72\ \mu$s. The Doppler frequency is given by

$$f_d = \frac{v}{\mathrm{c}} \cdot f_0\,, \tag{11}$$

where f_0 is a carrier frequency, v is a mobile velocity and c is speed of light. The K value is given by Eqs. (7) and (11) as follows:

$$K = \left\lceil \frac{9.\mathrm{c}}{16.\pi.f_0.v.T} \right\rceil. \tag{12}$$

κ is a group with finite number of elements of all possible K values

$$\kappa\left\{K = \left\lceil \frac{9.\mathrm{c}}{16.\pi.f_0.T} \right\rceil \text{knowing that } v \in \left[0 - 300\ \mathrm{km/h}\right]\right\}. \tag{13}$$

Knowing that LTE frequency f_0 varies from 600 MHz to 3.8 GHz, the number of elements of κ is less than 127.

Since the K value is needed by the eNodeB (emitter) to update periodically the pilot pattern. This information can be reported by the user equipment back to an eNodeB for every frame, knowing that LTE radio frame has a length of 10 ms.

The extra feedback requirement caused by the proposed adaptive pilot pattern is less than 7 bits ($\log_2 127 = 7$) reported by the receiver to an eNodeB every 10 ms (UL). In other words, significant improvements in downlink throughput (more than 4% for low moving speed terminals) can be obtained at the expense of only 0.7 kb/s throughput loss in the UL throughput.

For the purpose of comparison between throughput gain in DL and throughput loss in UL, in Table 1 the throughput gain for different velocities are shown.

Table 1
Comparison between throughput gain in DL and throughput loss caused by feedback requirement in UL (DL throughput = 300 Mb/s, UL throughput = 75 Mb/s)

Mobility	Throughput gain (DL)	Throughput loss (UL)
$v = 3$ km/h, $f_d = 7$ Hz ($f_d.T = 0.001$)	+12 Mb/s	–0.7 kb/s
$v = 15$ km/h, $f_d = 35$ Hz ($f_d.T = 0.005$)	+11 Mb/s	–0.7 kb/s
$v = 30$ km/h, $f_d = 70$ Hz ($f_d.T = 0.01$)	+9 Mb/s	–0.7 kb/s
$v = 120$ km/h, $f_d = 280$ Hz ($f_d.T = 0.04$)	0	–0.7 kb/s

6. Performance Evaluation

In this section, the simulation results of the proposed pattern are presented and the throughput gain of a system is compared using proposed adaptive pilot pattern, against a system using fixed pilot pattern defined by LTE standard.

A typical LTE system shall support users moving with velocities up to 500 km/h, which corresponds a Doppler frequency of approximately 1150 Hz at a carrier frequency of 2.5 GHz, the duration of one OFDM symbol is $T = 72$ μs. OFDM system is simulated using the parameters on DL LTE.

For the purpose of comparison between fixed pilot pattern in LTE and proposed pattern, in Table 2 an useful throughput for different velocities is presented.

Table 2
Comparison between LTE pattern and proposed pattern in terms of normalized useful throughput

Mobility	Throughput gain
$v = 3$ km/h, $f_d = 7$ Hz ($f_d.T = 0.001$)	4%
$v = 15$ km/h, $f_d = 35$ Hz ($f_d.T = 0.005$)	3.7%
$v = 30$ km/h, $f_d = 70$ Hz ($f_d.T = 0.01$)	3%
$v = 120$ km/h, $f_d = 280$ Hz ($f_d.T = 0.04$)	0%

According to Table 2 and Fig. 5, throughput gain of the proposed pattern shall achieve more than 4% over time varying channels with moderate mobility ($v < 3$ km/h).

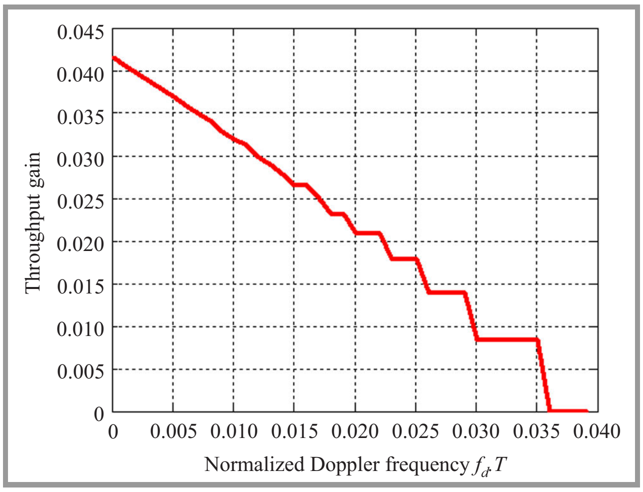

Fig. 5. Throughput gain versus $f_d.T$.

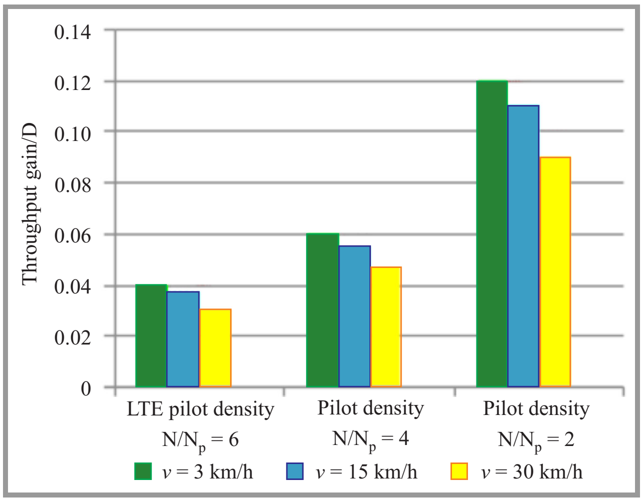

Fig. 6. Normalized throughput gain for different pilot densities.

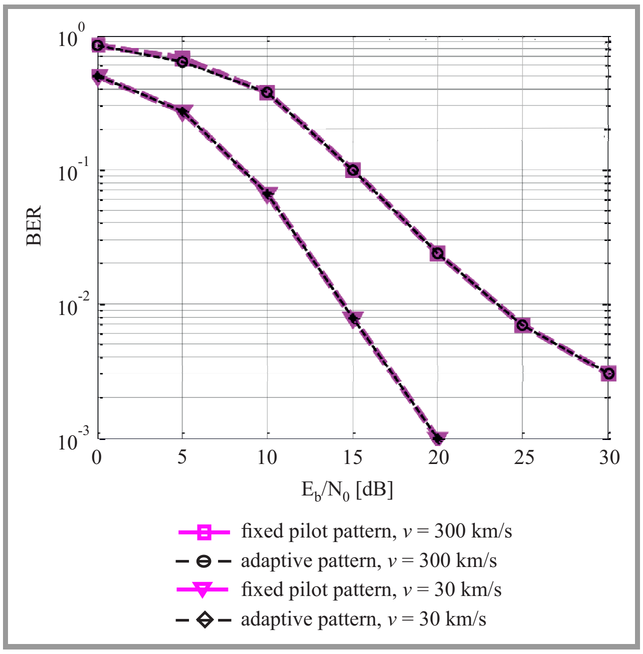

Fig. 7. BER versus E_b/N_0 curves.

Figure 6 shows that the adaptive pattern performs better than LTE regular pattern in terms of throughput gain when $f_d.T$ is less than 0.04. When $f_d.T$ is greater than 0.04, LTE regular pattern seems performing better than adaptive pattern in terms of throughput gain, but it has inferior performance in terms of channel estimation because channel is time varying inside one OFDM block (LTE low performance).

To evaluate channel estimation performances, the authors consider an OFDM system with $N = 256$ subcarriers of which 8 serve as pilot tones ($N_p = 8$), and a variant multipath channel model with 4 paths according to Jackes model ($L = 4$, $N_p > L$) and 4-QAM modulation. It can be seen in Fig. 7 that the proposed adaptive pattern has the same performance as LTE regular pattern.

7. Conclusion

Fixed pilot scheme used by LTE standard causes degradation in terms of useful throughput over moderate time varying channels. Moreover, it can contribute to low performance over fast time varying channel. The proposed adaptive pilot design is specifically tailored to optimally use pilot tones over time varying channels. The adaptive pilot patterns that adjust density of the pilot symbols in time domain to time selectivity of channel. This study has demonstrated the effectiveness of adaptive pilot schemes for MIMO OFDM channel estimation. Furthermore, the proposed adaptive patterns improve throughput gain compared to LTE fixed pilot pattern.

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