Capacity Maximizing ICI Canceling Windows for OFDM in Time-Varying Channels

Jae Yeun Yun*, Sae-Young Chung, and Yong H. Lee
Dept. of EECS. Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
e-mail : yeuny@stein.kaist.ac.kr

Abstract— **The rate-t/k ($t \leq k$) OFDM systems with the intercarrier interference (ICI) canceling windows are presented by generalizing the existing rate-$1/k$ system and the capacity lower bounds of these systems for time-varying frequency selective channels are analyzed. Based on the capacity analysis, the optimal windows maximizing the capacity lower bounds are designed numerically with an assumption that the channel is flat fading. The effects of ICI canceling windows on the capacity lower bounds are examined through numerical simulations and the results indicate that considerable performance improvement can be achieved by employing the proposed windows, as compared with the conventional systems with/without windowing when the channel varies very rapidly.**

Index Terms– OFDM, inter-carrier interference (ICI), windowing, time-varying channel, capacity

I. Introduction

It has been recognized that the performance of an orthogonal frequency division multiplexing (OFDM) system can be severely degraded if the channel varies within an OFDM symbol period. This happens because such a fast varying channel causes intercarrier interference (ICI). To compensate for the ICI, various techniques have been introduced including the frequency- and time-domain equalization (see, e.g., [1] and references therein), the ICI self-cancellation [2]-[4] and the frequency-domain partial response coding (PRC) [5], [6]. Among these approaches to ICI mitigation, the equalization would be the most common, but its implementation tends to require heavy computation when the channel varies fast. The ICI self-cancellation schemes are based on the use of a frequency-domain coding or a time-domain windowing, which are rate-$1/k$ techniques and effective in decreasing the receiver complexity. However, these ICI canceling schemes reduce the spectral efficiency by a factor of k. The PRC stems from the partial response signaling for single-carrier systems [7]. It does not sacrifice the spectral efficiency, but often needs maximum-likelihood sequence estimator (MLSE) to minimize the performance loss—this increases the receiver complexity.

In this paper, we present the rate-t/k ($t \leq k$) OFDM systems with time-domain windowing by generalizing the rate-$1/k$ system in [4], where the rate-t/k system employs the first t subcarriers of every k subcarriers. For these systems, the capacity lower bounds are derived for the time-varying channels and the optimal time-domain windows are developed by maximizing these bounds. The derivation is based on partitioning of the $M \times M$ channel matrix $\mathbf{H}$ into $t \times t$ submatrices (blocks) where t divides M. Under the assumption that only the off-diagonal blocks of $\mathbf{H}$ cause ICI, the windows are designed to mitigate the effect of those blocks. As a result, the off-diagonal blocks can be ignored in designing the receiver, and the computational burden is reduced.

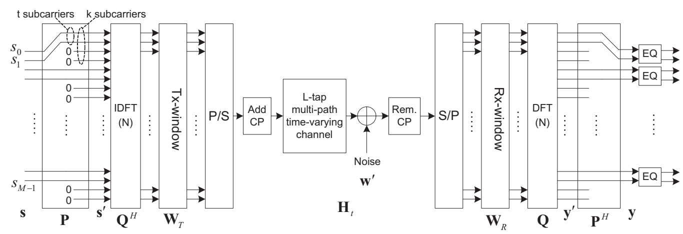

Fig. 1. A rate-t/k OFDM system with a time-domain windowing.

It is observed that the rate-t/k OFDM system can be viewed as multiple-input multiple-output (MIMO) systems with interferers; and its capacity lower bound is given by the capacity expression of MIMO systems [12]. Given a signal-to-noise ratio (SNR), the capacity lower bound is maximized through a numerical procedure. When the rates are less than 1 ($t < k$), the resulting windows make the spectrum of each signal subcarrier, after suffering Doppler spread, have almost zero value at the frequency of the other signal subcarriers, as rate-$1/k$ systems in [4]. Through comparing the systems with various rates, usefulness of ICI canceling schemes are examined, and the results indicate that the proposed rate-t/k ($t < k$) systems can provide the higher spectral efficiency when channel varies very rapidly.

The following notation is used throughout the paper: $\text{diag}(a_0, \cdots, a_{k-1})$ represents a diagonal matrix whose diagonal entries are $a_0, \cdots, a_{k-1}$. $[\mathbf{A}]_{p,q}$ denotes the (p,q)-th element of a matrix $\mathbf{A}$.[1] $\mathbf{I}_t$ and $\mathbf{0}_{t\times k}$ stand for a t-by-t identity matrix and a t-by-k null matrix, respectively. $(\cdot)_N$ denotes a modulo-N operation. $E[\cdot]$ denotes expectation and $tr[\cdot]$ stands for matrix trace.

This work was supported in part by the University Information Technology Research Center Program of the government of Korea.
*Corresponding author.

[1]If $\mathbf{A}$ is an M-by-N matrix, $0 \leq p \leq M-1$ and $0 \leq q \leq N-1$.

1-4244-0355-3/06/$20.00 (c) 2006 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

II. SYSTEM MODEL

Fig. 1 illustrates a rate-t/k OFDM system with a time-domain windowing. The M-dimensional input vector $\mathbf{s}$ is multiplied by the N-by-M up-sampling matrix $\mathbf{P}$, where N is the number of OFDM subcarriers, $M/N(= t/k)$ is the code rate, and $\mathbf{P}$ is a block diagonal matrix with identical blocks $\sqrt{k/t} \cdot [\mathbf{I}_t \ \mathbf{0}_{t\times(k-t)}]^T$. The resulting N-dimensional vector, $\mathbf{Ps}$, is multiplied by the N-point IDFT matrix $\mathbf{Q}^H$ and the transmit window matrix $\mathbf{W}_t = \text{diag}(w_{t,0}, \cdots, w_{t,N-1})$, sequentially, and passed through an L-tap multi-path time-varying channel. Here, $[\mathbf{Q}]_{p,q} = (1/\sqrt{N}) \cdot e^{-j\frac{2\pi}{N}pq}$ and it is assumed that $tr[\mathbf{W}_t\mathbf{W}_t^H] = N$ to constrain the transmission power. At the receiver, before the DFT operation, the signal vector is multiplied by the receiver window matrix $\mathbf{W}_r = \text{diag}(w_{r,0}, \cdots, w_{r,N-1})$ and, after DFT and down-sampling, the received vector $\mathbf{y}$ is expressed as

$$\begin{aligned} \mathbf{y} &= \mathbf{P}^H\mathbf{Q}\mathbf{W}_r\mathbf{H}_t\mathbf{W}_t\mathbf{Q}^H\mathbf{Ps} + \mathbf{P}^H\mathbf{Q}\mathbf{W}_r\mathbf{w}' \qquad (1a) \\ &= \mathbf{Hs} + \mathbf{w}, \qquad (1b) \end{aligned}$$

with $\mathbf{H} \equiv \mathbf{P}^H\mathbf{Q}\mathbf{W}_r\mathbf{H}_t\mathbf{W}_t\mathbf{Q}^H\mathbf{P}$ and $\mathbf{w} \equiv \mathbf{P}^H\mathbf{Q}\mathbf{W}_r\mathbf{w}'$ in the last equality, which are the frequency-domain channel matrix and noise vector, respectively. Here, $\mathbf{w}'$ is an N-dimensional zero-mean additive white Gaussian noise (AWGN) vector and $\mathbf{H}_t$ is N-by-N time-domain channel matrix whose (p, q)-th element is given by

$$[\mathbf{H}_t]_{p,q} = \begin{cases} h(p; (p-q)_N) & \text{if } 0 \le (p-q)_N \le L-1 \\ 0 & \text{otherwise,} \end{cases} \qquad (2)$$

where $h(n; l)$ represents the l-th tap of the sampled channel impulse response at the n-th sample of an OFDM symbol. The M-by-M frequency-domain channel matrix $\mathbf{H}$ is partitioned as follows:

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}(0,0) & \cdots & \mathbf{H}(0, M/t-1) \\ \vdots & \ddots & \vdots \\ \mathbf{H}(M/t-1, 0) & \cdots & \mathbf{H}(M/t-1, M/t-1) \end{bmatrix} \qquad (3)$$

where $\mathbf{H}(u, v)$ is a t-by-t block. To rewrite (1) in terms of blocks in (3), the vector $\mathbf{y}$, $\mathbf{s}$ and $\mathbf{w}$ are partitioned into sub-block vectors. Specifically, let $\mathbf{y} = [\mathbf{y}^T(0), \cdots, \mathbf{y}^T(M/t-1)]^T$, $\mathbf{s} = [\mathbf{s}^T(0), \cdots, \mathbf{s}^T(M/t-1)]^T$, and $\mathbf{w} = [\mathbf{w}^T(0), \cdots, \mathbf{w}^T(M/t-1)]^T$. Here, $\mathbf{y}(u)$, $\mathbf{s}(u)$ and $\mathbf{w}(u)$ are the t-dimensional vectors representing the u-th blocks of $\mathbf{y}$, $\mathbf{s}$ and $\mathbf{w}$, respectively. Then, the u-th block of $\mathbf{y}$ in (1) can be written as

$$\mathbf{y}(u) = \mathbf{H}(u, u)\mathbf{s}(u) + \sum_{v=0, v\ne u}^{M/t-1} \mathbf{H}(u, v)\mathbf{s}(v) + \mathbf{w}(u). \qquad (4)$$

Consequently, the overall system with an M-by-M channel matrix is partitioned into M/t sub-systems, each of which has a t-by-t channel matrix. We assume that only the off-diagonal blocks cause interference—not only diagonal elements of $\mathbf{H}$ but diagonal blocks will be treat as signal terms at the receiver. By defining interference and noise terms as $\mathbf{v}(u) = \sum_{v\ne u} \mathbf{H}(u, v)\mathbf{s}(v) + \mathbf{w}(u)$, (4) is given by

$$\mathbf{y}(u) = \mathbf{H}(u, u)\mathbf{s}(u) + \mathbf{v}(u). \qquad (5)$$

At the receiver, $\mathbf{s}(u)$ in (5) can be detected using techniques such as the maximum likehood (ML) [8] and V-BLAST detectors [9]. Due to the fact that the complexity of MIMO detectors mainly depends on the number of simultaneously transmitted symbols, t is chosen to be a small number. When $t \le 4$, an ML detector based on the sphere decoding algorithm has practical complexity [8]. Throughout this paper, the diagonal blocks $\{\mathbf{H}(u, u)\}$ is assumed to be perfectly known at the receiver,[2] while it is unknown at the transmitter.

III. CAPACITY LOWER BOUND

Examining (5) as a MIMO system, it can be observed that (5) represents a MIMO system with interferers, so we naturally introduce the capacity formula of a MIMO system [12]. To derive the capacity, we introduce the following assumptions:

A1) The input vector $\mathbf{s}$ is the circularly symmetric Gaussian random vector with covariance $\mathbf{R}_s = \mathbf{I}_M$.

A2) The noise vector $\mathbf{w}$ is also the circularly symmetric Gaussian random vector with covariance $\mathbf{R}_w = \sigma^2\mathbf{I}_N$.

A3) All multi-paths of the channel are mutually uncorrelated and each time-domain channel tap, $h(n; l)$, is an wide-sense stationary random process having the Rayleigh distribution. Specifically, we assume that

$$E[h(n; l)h^*(n'; l')] = \sigma_l^2 r(n-n') \cdot \delta(l-l'), \qquad (6)$$

where $r(n)$ is a time-domain autocorrelation function of the channel defined as $r(n) = E[h(m+n; l)h^*(m; l)]/\sigma_l^2$ and σ_l^2 denotes a mean power of the l-th channel tap. It is also assumed that the channel power is normalized to satisfy $\sum_l \sigma_l^2 = 1$.

Under the above assumptions, the interference $\mathbf{v}(u)$ in (5) is independent from $\mathbf{s}(u)$. In contrast, $\mathbf{v}(u)$ is not Gaussian because it is a linear combination of products of Gaussian random processes. But, $\mathbf{v}(u)$ can still be approximated as Gaussian giving a lower bound of the capacity [13].[3] Given the covariance $\mathbf{R}_{v(u)} = E[\mathbf{v}(u)\mathbf{v}^H(u)]$, the capacity lower bound of the u-th sub-system is written as

$$C_u = E\left[\frac{1}{k}\log_2 \det\left(\mathbf{I}_t + \mathbf{H}(u, u)\mathbf{H}^H(u, u)\mathbf{R}_{v(u)}^{-1}\right)\right] \qquad (7)$$

with expectation over the distribution of $\mathbf{H}(u, u)$. The capacity lower bound of the overall system is then $C = (t/M) \cdot \sum_{u=0}^{M/t-1} C_u$. Here, the effect of the cyclic prefix (CP) is ignored because, in practice, an OFDM symbol duration (T_s) is set to be much larger than CP duration (T_g) to minimize a spectral loss caused by CP. In this paper, it is assumed that T_s is fixed at sufficiently large value satisfying $T_g \ll T_s$.

[2] Efficient channel estimation techniques for OFDM systems over time-varying channels have been proposed in [10], [11].

[3] To observe tightness of this lower bound, we simulate the actual capacity numerically when $t = 1$. It is observed first by a numerical simulation that the interference is well approximated to have the Laplace distribution, with which the actual capacity is calculated. The result indicates that difference between the lower bound and the actual capacity is small. From this, we roughly conclude that the lower bound is expected to be reasonably tight.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

After some calculation outlined in Appendix, $\mathbf{R}_{v(u)}$ is given by

$$\mathbf{R}_{v(u)}=\frac{k^2}{t^2}\mathbf{Q}_t\mathbf{W}_r\left\{\sum_{l=0}^{L-1}\sigma_l^2\mathbf{W}_{t,l}\left(\frac{N}{k}\mathbf{R}'-\mathbf{R}\right)\mathbf{W}_{t,l}^H+\frac{t}{k}\sigma^2\mathbf{I}_N\right\}\mathbf{W}_r^H\mathbf{Q}_t^H. \quad (8)$$

Here, the (p,q)-th elements of N-by-N matrices $\mathbf{R}$, $\mathbf{R}_s$, and $\mathbf{W}_{t,(l)}$, and t-by-N matrix $\mathbf{Q}_t$ are defined as

$$[\mathbf{R}]_{p,q} = r(p-q)\cdot\sum_{n=0}^{t-1}e^{j\frac{2\pi}{N}(p-q)n}, \quad (9)$$

$$[\mathbf{R}_s]_{p,q} = [\mathbf{R}]_{p,q}\cdot\delta(p-q+m\cdot N/k), \quad (10)$$

$$\mathbf{W}_{t,(l)} = \text{diag}(w_{t,(-l)_N},\cdots,w_{t,(N-1-l)_N}), \quad (11)$$

$$[\mathbf{Q}_t]_{p,q} = 1/\sqrt{N}\cdot e^{-j\frac{2\pi}{N}pq}, \quad (12)$$

respectively. Since $\mathbf{R}_{v(u)}$ is not relevant to u, we simply denote $\mathbf{R}_{v(u)}$ as $\mathbf{R}_v$. Meanwhile, the distributions of $\mathbf{H}(u,u)$ are also the same for all u because the channel is assumed as Gaussian and there are only phase differences among them. Consequently, all the sub-systems have the same capacity lower bound, and this lead to $C = C_0$ without loss of generality. From the equality $\mathbf{H}(0,0) = (k/t)\cdot\mathbf{Q}_t\mathbf{W}_r\mathbf{H}_t\mathbf{W}_t\mathbf{Q}_t^H$, the capacity lower bound of overall system is given by

$$C = E\left[\frac{1}{k}\log_2\det\left(\mathbf{I}_t+\frac{t^2}{k^2}\mathbf{Q}_t\mathbf{W}_r\mathbf{H}_t\mathbf{W}_t\mathbf{Q}_t^H \times\mathbf{Q}_t\mathbf{W}_t^H\mathbf{H}_t^H\mathbf{W}_r^H\mathbf{Q}_t^H\mathbf{R}_v^{-1}\right)\right] \quad (13)$$

with expectation over the distribution of $\mathbf{H}_t$.

IV. Designing windows

In this section, windows that maximize C in (13) are designed for a given SNR $= 1/\sigma^2$. To simplify design procedure, we have the following assumptions:

- The transmit and receive windows are the same and have real values: $\mathbf{W}_t = \mathbf{W}_r \equiv \mathbf{W}$.
- The channel is a flat fading channel: $L = 1$.

To model the time variation of the channel, it is assumed that the channel follows the Jakes model [14]: $r(n-n') = J_0(2\pi f_dT_s(n-n')/N)$, where $J_0(x)$ is the zeroth-order Bessel function of the first kind and f_dT_s denotes the Doppler frequency normalized by the subcarrier spacing. It should be noted that $r(n-n')$ depends on f_dT_s. Since the transmitter can hardly know the f_dT_s of a serving user, f_dT_s is also a random variable in designing the windows. Then, expectation in (6) becomes

$$E[h(n;l)h^*(n';l')] = \sigma_l^2E[J_0(2\pi f_dT_s(n-n')/N)]\cdot\delta(l-l'), \quad (14)$$

where the expectation in right side hand (RHS) is over a distribution of f_dT_s. Defining $\mathbf{R}'$ and $\mathbf{R}'_s$ as modified versions of $\mathbf{R}$ and $\mathbf{R}_s$ in (9) and (10) according to (14), respectively, the covariance of $\mathbf{v}(u)$ for a flat fading channel is given by

$$\mathbf{R}'_v = \frac{t^2}{k^2}\mathbf{Q}_t\mathbf{W}\left\{\mathbf{W}\left(\frac{M}{t}\mathbf{R}'_s-\mathbf{R}'\right)\mathbf{W}^H+\frac{t\sigma^2}{k}\mathbf{I}_N\right\}\mathbf{W}^H\mathbf{Q}_t^H. \quad (15)$$

The optimal window, which maximizes the capacity lower bound under the above assumptions, is the solution of the following optimization problem.

$$\max_{\mathbf{W}} \quad C_{flat} \quad (16a)$$

$$\text{s.t} \quad tr[\mathbf{W}\mathbf{W}^H] = N, \quad (16b)$$

where

$$C_{flat} = E\left[\frac{1}{k}\log_2\det\left(\mathbf{I}_t+\frac{t^2}{k^2}\mathbf{Q}_t\mathbf{W}\mathbf{H}_t\mathbf{W}\mathbf{Q}_t^H \times\mathbf{Q}_t\mathbf{W}^H\mathbf{H}_t^H\mathbf{W}^H\mathbf{Q}_t^H\mathbf{R}_v'^{-1}\right)\right]. \quad (17)$$

However, it is formidable to find the closed form solution to (16). So we introduce a numerical procedure alternatively. First, expectations in (14) and (17) are approximated using sampling (Monte-Carlo) methods. It is assumed that f_dT_s has uniform distribution over $(0,\ 0.5]$. For practical situation of the time-varying channel environments, this region is sufficient. Second, the constrained nonlinear optimizer is employed to find the solution.[4] The optimizations are performed for several rate-t/k systems; rate-$1/1$, $1/2$, $2/2$, $2/4$, $3/4$, and $4/4$. We have tried many randomly selected initial points to the optimizer and it appears that most of resulting C_{flat}'s converge to the same value.

Fig. 2 exhibits the optimized windows in the case that $N = 64$ and a SNR is 25dB. The conventional window for the rate-$1/2$ system in [4] (Design A) is also plotted for comparison. In the figure, the optimal windows for systems with the effective rate-1 ($t = k$) have flat shapes close to 1, and the optimal windows for systems with the effective rate less than 1 ($t < k$) have shapes similar to the conventional window in [4], which is designed to maximize a signal-to-interference ratio.

Fig. 3 shows the simulated power spectrums of the signal transmitted through the 0-th subcarrier[5] when $N = 64$ (after the receiver windowing and before the down-sampling), the channel was a flat fading channels with $f_dT_s = 0.3$, and there was no noise. In the figure, the powers of 0 to $t-1$ subcarriers are of the signals and the ones of the remaining subcarriers are of intercarrier interferences. For the systems with the effective rate less than 1, considerable ICI suppressions are obtained by the windows, while, for the systems with the effective rate-1, there are only slight reductions of ICI. Comparing the result of the proposed window for the rate-$1/2$ system with that of the existing window in [4], we can notice that the proposed window is designed to further suppress only the ICI powers impairing the other signal subcarriers—only even numbered subcarriers are used after down-sampling at the receiver. This tendency is also observed for the results of the other rate-t/k ($t < k$) systems, and it may imply that the proposed windows are more effectively designed to suppress ICI than the existing window in [4].

[4]The constrained nonlinear optimizer named 'fmincon' of MATLAB is employed.

[5]The power spectrums of the other signal subcarriers are the frequency shifted versions of the Fig. 3.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

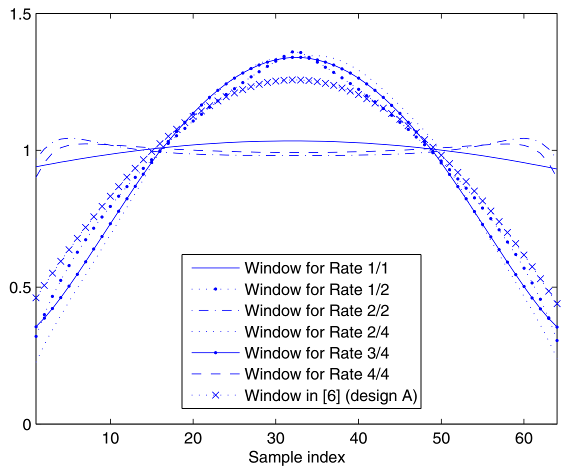

Fig. 2. The the proposed windows for rate-t/k OFDM systems when $N = 64$ and a SNR is 25dB.

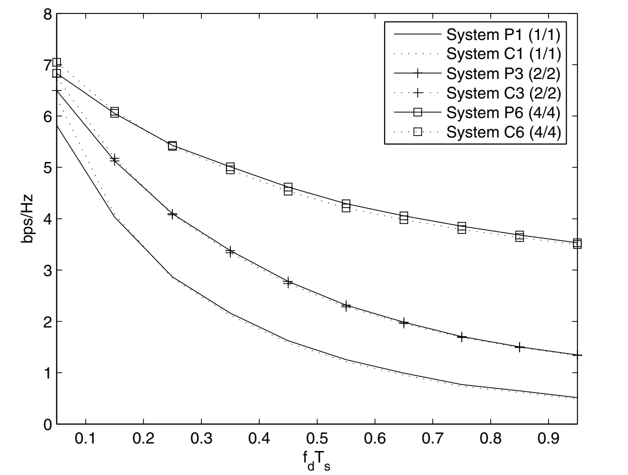

Fig. 4. The capacity lower bound versus $f_d T_s$ for effective rate 1 systems.

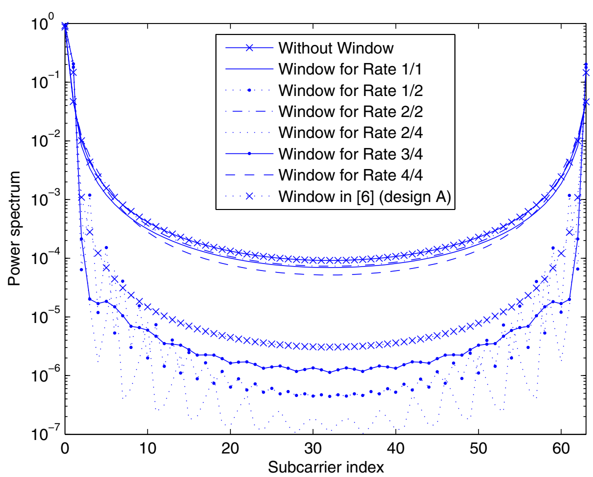

Fig. 3. The power spectrums of the signal transmitted through the 0-th subcarrier after receiver windowing when $N = 64$ and $f_d T_s = 0.3$.

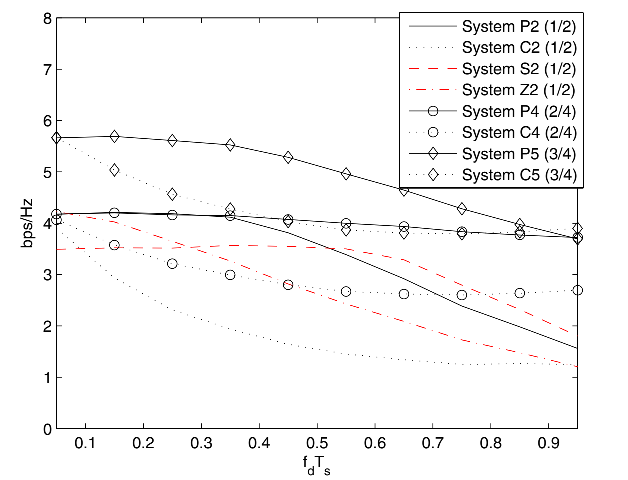

Fig. 5. The capacity lower bound versus $f_d T_s$ for effective rate less than 1 systems.

V. Numerical Simulations

The effects of the proposed and existing windows on OFDM systems have been examined through numerical simulations by evaluating the capacity lower bound of $C = (t/M) \cdot \sum_{u=0}^{M/t-1} C_u$ using (7). The simulation environments were as follows: the number of subcarriers $N = 64$, the channel was a 8-tap channel with equal-gain power profile generated by the Jakes model where $f_d T_s$ varied from 0.05 to 0.95, and SNR = 25dB. Various systems were simulated to compare the performance:

- System P1-P6 : The rate-$1/1$, $1/2$, $2/2$, $2/4$, $3/4$, and $4/4$ systems with the designed windows in Section IV, respectively.
- System C1-C6 : The same rate systems as System P1 to P6 without windowing, respectively.
- System S2 : The rate-$1/2$ system with the window in [4] (Design A).
- System Z2 : The system with the rate-$1/2$ frequency-domain ICI canceling code in [2].

Fig. 4 shows the capacity lower bounds of systems having an effective rate-1. As expected, windowing does not provide the improved capacity, and this means that windowing can not mitigate ICI sufficiently when $t = k$. Since the systems with $t = k$ do not spend bandwidth efficiency to mitigate ICI, they exhibit high performance in low $f_d T_s$ region. However, as $f_d T_s$ increases, ICI degrades performance seriously.

Fig. 5 presents the capacity lower bounds of systems having effective rate less than 1. In the figure, systems having the proposed windows exhibit much improved performance over systems without windowing, and this means that the proposed windows provide considerable ICI suppression in the case $t < k$. Moreover, the proposed rate-$1/2$ system, System P2, outperforms System Z2 within the whole range of $f_d T_s$, and shows improved performance over System S2 when $f_d T_s \leq 0.5$. While System P2 performs worse than System S2 when $f_d T_s > 0.5$, it is because the proposed window is optimized for $f_d T_s \in (0,\ 0.5]$. On the other hand, the rate t/k $(t < k)$ systems have performance limit even in low $f_d T_s$ region because these basically have rates less than 1.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

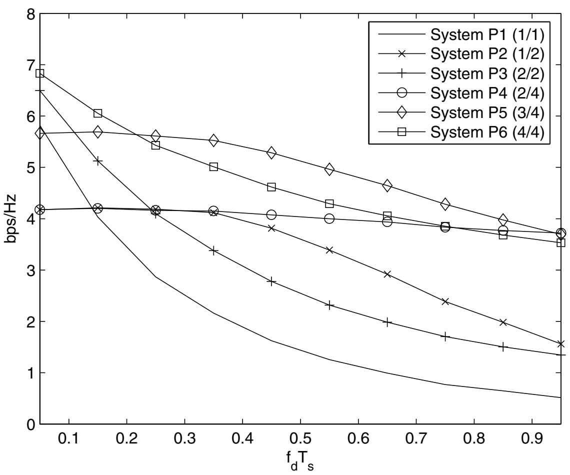

Fig. 6. The capacity lower bound versus f_dT_s for systems having the proposed windows

Fig. 6 exhibits the capacity lower bounds of System P1-P6. This figure is plotted to examine the utility of ICI canceling systems with $t < k$. For fair comparison, system pairs having the same t are considered because each pair of systems have the similar receiver complexity—rate-$1/1$ and $1/2$, rate-$2/2$ and $2/4$, and rate-$4/4$ and $3/4$ are compared pairwisely. The results show that there is a cross point of performance for each pair, and it means that, if a system needs to be operated within f_dT_s region above the cross point (when f_dT_s is high), it is better to utilize rate-t/k ($t < k$) systems with the proposed windows. Meanwhile, it is also observed that the higher capacity can be obtained as t increases at a cost of the receiver complexity.

VI. Conclusion

The rate-t/k ($t \le k$) OFDM systems with time-domain windows are presented and the capacity lower bounds of these systems for time-varying frequency selective channels are analyzed. Based on the capacity analysis, the optimal windows maximizing the capacity lower bounds are designed numerically under the assumption that the channel is flat fading and compared to existing ICI canceling schemes. It is observed that the proposed windows show sufficient ICI mitigation performance for rate-t/k ($t < k$) systems, while windowing is not necessary for rate-k/k systems. Simulation results demonstrate that the proposed windows can provide performance improvements over the existing ICI canceling schemes. Moreover, by comparing the rate-t/k ($t < k$) systems having windowing with the rate-t/t systems, usefulness of ICI canceling schemes are examined. The results indicate that the proposed rate t/k ($t < k$) systems can provide the higher spectral efficiency when the channel varies very rapidly.

Appendix

A. Derivation for (8)

Let $\mathbf{K}_u = \sum_{v \neq u} E[\mathbf{H}(u,v)\mathbf{H}^H(u,v)]$ and $\mathbf{Z}_u = E[\mathbf{w}'(u)\mathbf{w}'^H(u)]$. Defining $\mathbf{H}' \equiv \mathbf{Q}\mathbf{W}_r\mathbf{H}_t\mathbf{W}_t\mathbf{Q}^H$, we can write the (p,q)-th element of $\mathbf{K}_u$ as

$$[\mathbf{K}_u]_{p,q} = \frac{k^2}{t^2} \sum_{v \neq u} \sum_{s=0}^{t-1} E\left\{ [\mathbf{H}']_{uk+p,vk+s} \cdot [\mathbf{H}']^*_{uk+q,vk+s} \right\}. \quad \text{(A1)}$$

Here, $\mathbf{H}'$ is derived as

$$[\mathbf{H}']_{p,q} = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} w_{r,n} w_{t,(n-l)_N} h(n;l) e^{-j\frac{2\pi}{N}lq} e^{j\frac{2\pi}{N}(q-p)n}. \quad \text{(A2)}$$

Substituting (A2) into (A1), we have

$$[\mathbf{K}_u]_{p,q} = \frac{k^2}{t^2N^2} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \sum_{l=0}^{L-1} \sigma_l^2 r(T(n-n')) \times w_{r,n} w_{t,(n-l)_N} w^*_{r,n'} w^*_{t,(n'-l)_N} \sum_{s=0}^{t-1} e^{j\frac{2\pi}{N}s(n-n')} \times e^{j\frac{2\pi}{N}(-np+n'q)} \left\{ \frac{N}{k} \delta\left(n-n'+m\cdot\frac{N}{k}\right) - 1 \right\}, \quad \text{(A3)}$$

where m is an arbitrary integer. Similarly, the (p,q)-th element of $\mathbf{Z}_u$ is derived as

$$[\mathbf{Z}_u]_{p,q} = \frac{k\sigma^2}{tN} \sum_{n=0}^{N-1} |w_{r,n}|^2 e^{j\frac{2\pi}{N}(q-p)n}. \quad \text{(A4)}$$

Converting (A3) and (A4) into matrix representation, (8) is obtained.

References

[1] L. Rugini, P. Banelli, and G. Leous, "Simple equalization of time-varying channels for OFDM," *IEEE Comm. Lett.*, vol. 9, pp.619-621, July 2005.
[2] Y. Zhao and S.-G. Häggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems," *IEEE Trans. on Commun.*, vol. 49, pp.1185-1191, July 2001.
[3] J. Armstrong, "Analysis of new and existing methods of reducing intercarrier interference due to carrier frequency offset in OFDM," *IEEE Trans. on Commun.*, vol. 47, pp.365-369, Mar. 1999.
[4] A. Seyedi and G. Saulnier, "General ICI self-cancellation scheme for OFDM systems," *IEEE Trans. Vehicular Tech.*, vol. 54, pp.198-210, Jan. 2005.
[5] Y. Zhao and S.-G. Häggman, "Intercarrier interference compression in OFDM communication systems by using correlative coding," *IEEE Commun. Lett.*, vol. 2, pp.214-216, Aug. 1998.
[6] H. Zhang and Y. Li, "Optimum frequency-domain partial response encoding in OFDM system," *IEEE Trans. on Commun.*, vol. 51, pp. 1064-1068, July 2003.
[7] J. G. Proakis, *Digital Communications*, 3rd ed., New York: McGraw-Hill, 1995.
[8] H. Vikalo, B. Hassibi, "On the sphere-decoding algorithm II. Generalizations, second-order statistics, and applications to communications," *IEEE Trans. on Signal Proc.*, vol. 8, pp. 2819-2834, Aug. 2005.
[9] G. J. Foschini, G. D. Golden, R. A. Valenzuela, "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," *IEEE Journal of Selected Areas in Commun.*, vol. 17, pp. 1841-1852, Nov. 1999.
[10] Y. Choi, P. Voltz, and F. Cassara, "On channel estimation and detection for multicarrier signals in fast and selective rayleigh fading channels," *IEEE Trans. on Commun.*, vol. 49, pp.1375-1387, Aug. 2001.
[11] A. Stamoulis, S. Diggavi, and N. Al-Dhahir. "Intercarrier interference in MIMO OFDM," *IEEE Trans. on Signal Proc.* vol. 50, pp.2451-2464, Oct. 2002.
[12] A. Lozano and A. M. Tulino, "Capacity of multiple-transmit multiple-receive antenna architectures," *IEEE Tr. Inform. Theory*, vol. 48, pp.3117-3128, Dec. 2002.
[13] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, New York: Wiley, 1990.
[14] W. C. Jakes, Jr., *Microwave Mobile Communications*, New York: Wiley, 1974.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.