2011 17th Asia-Pacific Conference on Communications (APCC)
2nd – 5th October 2011 | Sutera Harbour Resort, Kota Kinabalu, Sabah, Malaysia

On Performance of Cooperative OFDM/TDM with Frequency-Domain Equalization in A Multipath Wireless Channel

Amir Ligata
Communication Department
IPSA Institute
Sarajevo, Bosnia and Herzegovina
amir.ligata@ipsa-institut.com

Haris Gacanin[†]
Motive Division
Alcatel-Lucent Bell N.V.
Antwerp, Belgium
haris.gacanin@alcatel-lucent.com

Fumiyuki Adachi
Graduate School of Engineering
Tohoku University
Sendai, Japan
adachi@ecei.tohoku.ac.jp

***Abstract*—Cooperative transmission, where spatially distributed users form a multi-antenna system and assist in forwarding the information from source to destination node, achieves the diversity gain of a multiple-input multiple-output (MIMO) system. Cooperative network based on OFDM has been proposed to cope with the channel frequency-selectivity but due to high peak-to-average power ratio (PAPR) of OFDM, expensive power amplifier are required. In this paper, we present cooperative network based on OFDM combined with time division multiplexing (OFDM/TDM) using minimum mean square error frequency-domain equalization (MMSE-FDE) in a frequency-selective fading channel. We theoretically analyze the network performance with respect to the bit error rate (BER). The conditional signal-to-interference plus noise ratio (SINR) expressions are derived based on Gaussian approximation of the residual inter-slot interference (ISI) after MMSE-FDE for the given set of channel gains. The average BER performance for OFDM/TDM is evaluated by Monte-Carlo numerical computation method using the derived theoretical expressions and confirmed by computer simulation. The results show that the lower BER is achieved with cooperative OFDM/TDM in comparison with OFDM based cooperative network because OFDM/TDM exploits both cooperative and frequency diversity gains.**

***Index Terms*—Cooperative networking, theoretical analysis, MMSE-FDE, OFDM/TDM.**

I. INTRODUCTION

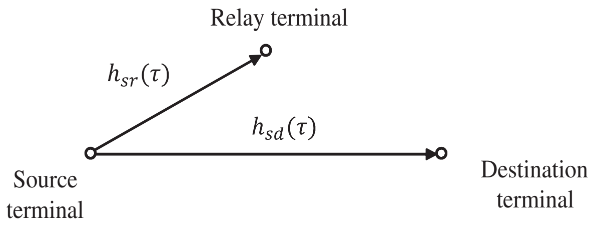
Multi-antenna systems are considered to be a good candidates to offer broadband data services in a limited available bandwidth. Their application, however, often encounters practical implementation problem if a large number of antennas is to be deployed. In order to overcome this problem, a new mode of transmit diversity, called cooperative diversity, was proposed based on user cooperation [1]-[2], where the antennas of the sender and the partners together form a multiple transmit antenna situation. A variety of algorithms have been developed to obtain cooperative diversity gain [3]-[8].

Cooperative network based on orthogonal frequency division multiplexing (OFDM) physical-layer access is an attractive solution to achieve the cooperative diversity while overcoming the wireless channel frequency-selectivity. However, the largest drawback of OFDM is its large PAPR that leads to a lower power efficiency of power amplifiers. OFDM combined with time division multiplexing (OFDM/TDM) can be used to reduce the PAPR to some extent [9]. At the OFDM/TDM transmitter, the inverse fast Fourier transform (IFFT) time window (i.e., OFDM/TDM frame) of OFDM is divided into K slots, which carries an OFDM signal with reduced number of subcarriers without the guard interval (GI) insertion. At the OFDM/TDM receiver, frequency domain equalization based on minimum mean square error criterion (MMSE-FDE) over the entire frame is applied to exploit the channel frequency-selectivity. Thus, the cooperative network based on OFDM/TDM using MMSE-FDE physical-layer access in a frequency-selective fading channel may be an attractive solution to achieve both cooperative and frequency diversity gains with a lower PAPR in comparison with cooperative network based on OFDM [10]. To the best of the authors knowledge the detailed analysis of such scheme has not been presented.

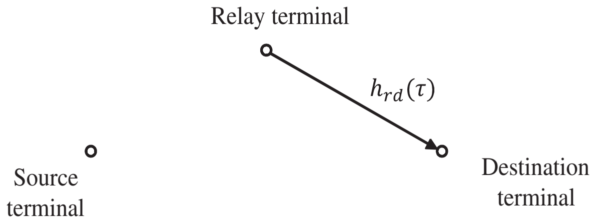
This paper presents a theoretical performance analysis of cooperative relay network based on OFDM/TDM using MMSE-FDE in a frequency-selective fading channel. We assume that the residual inter-slot interference (ISI) after MMSE-FDE can be approximated as a zero-mean Gaussian variable and derive the conditional signal-to-interference plus noise ratio (SINR) expressions for the given set of channel gains. The theoretical bit-error rate (BER) performance is evaluated by Monte-Carlo numerical computation method and confirmed by computer simulation. Our results show that the lower BER is achieved with cooperative OFDM/TDM in comparison with OFDM based cooperative network, since cooperative OFDM/TDM network exploits both frequency and cooperative diversity gains.

The remainder of this paper is organized as follows. Section II presents the network model. Performance analysis in Sect. III. In Sect. IV, numerical results and discussions are presented. Section V concludes the paper.

[†] H. Gacanin is the acting Head of the Communication Group at Energy and Communication Department, IPSA Institute, Sarajevo, Bosnia and Herzegovina.

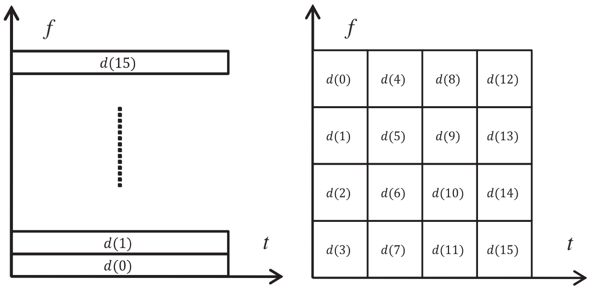


(a) Stage I



(b) Stage II

Figure 1. Network protocol.



(a) Conventional OFDM. (b) OFDM/TDM.

Figure 2. Time and frequency data mapping ($N_c = 16$; $N_m = 4$; $K = 4$).

II. NETWORK MODEL OVERVIEW [10]

We assume that source terminal have a direct line-of-sight communication with an access point (henceforth relay) and destination during the first stage, while the destination is out of the source's coverage area during the second stage. The information is transmitted via two time stages (i.e., TDM orthogonal channels [3]) as shown in Fig. 1. The source transmits the data to the destination, while the relay is listening during the first stage. In the second stage the relay sends the received data after processing to the destination as well, where the two received signals are combined.

The OFDM signaling interval (i.e., OFDM/TDM frame) is divided into K slots as shown in Fig. 2. A data-modulated symbol sequence $\{d(i);\, i = 0 \sim N_c - 1\}$ is divided into K sub-blocks each having N_m $(= N_c/K)$ data-modulated symbols. The kth sub-block $\{d(k,i);\, i = 0 \sim N_m - 1\}$ is transmitted in the kth slot, where $d(k,i) = d(kN_m + i)$ for $k = 0 \sim K - 1$. After insertion of the GI the OFDM/TDM frame, the signal is multiplied with the power coefficient P_s $(= E_s/T_cN_c)$, where E_s denotes data-modulated symbol energy, and then transmitted over a wireless channel.

The OFDM/TDM signal can be expressed using the equivalent low-pass representation as

$$s(t) = \sqrt{P_s} \sum_{i=0}^{N_m - 1} d\left(\left\lfloor \frac{t}{N_m} \right\rfloor, i\right) \exp\left\{ j2\pi t \frac{i}{N_m} \right\} \tag{1}$$

for $t = 0 \sim N_c - 1$. We note here that OFDM/TDM signal with $K = 1$ (i.e., $N_m = N_c$) reduces to the conventional OFDM system with N_c subcarriers, while for $K = N_c$ (i.e., $N_m = 1$) the OFDM/TDM collapses to SC system.

The signal propagates through a wireless channel with a discrete-time channel impulse response $h_{xy}(\tau)$ given by

$$h_{xy}(\tau) = \sum_{l=0}^{L-1} h_{l,xy} \delta(\tau - \tau_l), \tag{2}$$

where $h_{l,xy}$, τ_l and $\delta(\cdot)$ are the path gain between terminals x and y, the time delay of the lth path and the delta function, respectively. $\{h_{l,xy};\, l = 0 \sim L - 1\}$ are zero-mean independent complex variables with $E[\sum_{l=0}^{L-1} |h_{l,xy}|^2] = 1$.

Stage I : As shown in Fig. 1, the transmitted signal arrives via a direct path at the destination. At the destination, an N_c-point FFT is applied over the received OFDM/TDM frame to decompose the received signal into N_c frequency components represented by [10]

$$R_{d,1}(n) = S(n) H_{sd}(n) + N_1(n) \tag{3}$$

for $n = 0 \sim N_c - 1$, where $S(n)$, $H_{sd}(n)$ and $N_1(n)$, respectively, denote the Fourier transforms of the OFDM/TDM signal, the channel impulse response between source and destination and the additive white gaussian noise (AWGN) with the variance $2N_0/T_cN_c$, where N_0 denotes the single-sided power spectrum density.

The signal received at the relay during the first stage can be represented by

$$R_r(n) = S(n) H_{sr}(n) + N_r(n) \tag{4}$$

for $n = 0 \sim N_c - 1$, where $H_{sr}(n)$ and $N_r(n)$ denote, the channel impulse response between source and relay and the AWGN at the relay, respectively.

Stage II : The relay normalizes the received signal by a factor of $\sqrt{P_s/E[|R_r(n)|^2]}$ (so that the average power is unity) and retransmits the signal during the second time stage. We assume that the source and the relay transmit with the half of the total available power.

At the destination, N_c-point FFT is applied over the received OFDM/TDM frames at the first and second stage to decompose the relayed signal into the N_c frequency components represented by $\{R_{d,2}(n);\, n = 0 \sim N_c - 1\}$. Thus the signal received at the destination during the second stage is given by

$$\begin{aligned} R_{d,2}(n) = \sqrt{P_s} S(n) H_{sr}(n) H_{rd}(n) + H_{rd}(n) N_r(n) \\ + N_2(n), \end{aligned} \tag{5}$$

where the first term denotes the desired signal component, while the second and third term denote the AWGN with a slightly increased power.

The joint signal combining and MMSE equalization is done as

$$\hat{R}\left(n\right) = \sum_{m=1}^{2} R_{d,m}\left(n\right)\omega_m\left(n\right), \tag{6}$$

where $\omega_m\left(n\right)$ is the equalization weight during the mth stage $(m = 1, 2)$. The equalization weight at the mth stage is chosen to minimize the mean square error term $E[|\hat{R}_{d,m}\left(n\right) - S\left(n\right)|^2]$ at the nth frequency (note that in OFDM/TDM the term frequency is used instead of subcarriers in conventional OFDM). The MMSE equalization weights for the first and the second stage are given by [10]

$$\begin{cases} \omega_1\left(n\right) = \frac{H_{sd}^*(n)}{\left|H_{sd}(n)\right|^2 + \left(\frac{E_s}{N_0}\right)^{-1}} \\ \\ \omega_2\left(n\right) = \frac{H_{sr}^*(n)H_{rd}^*(n)}{\left|H_{sr}(n)\right|^2\left|H_{rd}(n)\right|^2 + \left(\frac{E_s}{N_0}\right)^{-1}}, \end{cases} \tag{7}$$

where $(\cdot)^*$ denotes the complex conjugate operation. It is evident from (7) that the equalization weight for the second stage includes the channel gain between source and the relay as well.

We note here that in the case of conventional OFDM $(K = 1)$ we apply the equalization weights based on maximum ratio combining (MRC). Hence, only the performance of OFDM/TDM based on joint signal combining and FDE can exploit both the cooperative and frequency diversity gains as presented in the following section.

The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT on $\{\hat{R}\left(n\right); n = 0 \sim N_c - 1\}$ to obtain time-domain signal as

$$\hat{r}\left(t\right) = \sum_{n=0}^{N_c-1} \hat{R}\left(n\right)\exp\left(j2\pi t\frac{n}{N_c}\right) \tag{8}$$

for $t = 0 \sim N_c - 1$. Then, the OFDM demodulation is carried out using N_m-point FFT to obtain decision variables given by

$$\hat{d}\left(k,i\right) = \frac{1}{N_m}\sum_{t=kN_m}^{(k+1)N_m} \hat{r}\left(t\right)\exp\left(-j2\pi i\frac{t}{N_c}\right) \tag{9}$$

for $i = 0 \sim N_m - 1$ and $k = 0 \backsim K - 1$.

III. PERFORMANCE ANALYSIS

In this section, we first derive the decision variable and then, the conditional signal-to-interference plus noise ratio (SINR) expressions for evaluation of the BER are presented.

A. Decision variable

By substituting (3), (5) and (6) into (8) we obtain

$$\begin{aligned} \hat{r}(t) = \textstyle\sum_{n=0}^{N_c-1} \Big[&\sqrt{P_s}S(n)\hat{H}_{sd}(n) + \hat{N}_1(n) + \sqrt{P_s}S(n) \\ &\times\hat{H}_{srd}(n) + \hat{N}_r(n)\hat{H}_{rd}(n) + \hat{N}_2(n)\Big]\exp(j2\pi t\tfrac{n}{N_c}), \end{aligned} \tag{10}$$

where

$$\begin{cases} \hat{H}_{sd}\left(n\right) = H_{sd}\left(n\right)\omega_1\left(n\right) \\ \hat{H}_{srd}\left(n\right) = H_{sr}\left(n\right)H_{rd}\left(n\right)\omega_2\left(n\right) \\ \hat{N}_1(n) = N_1\left(n\right)\omega_1\left(n\right) \\ \hat{N}_2\left(n\right) = N_2\left(n\right)\omega_2\left(n\right) \\ \hat{N}_r\left(n\right) = N_r\left(n\right)\omega_2\left(n\right). \end{cases}$$

Now, by substituting (10) into (9) we obtain

$$\begin{aligned} \hat{d}\left(k,i\right) = &\textstyle\sum_{n=0}^{N_c-1}\left[\sqrt{P_s}S(n)\hat{H}_{sd}(n) + \hat{N}_1(n)\right] \\ &\qquad\times\exp\left\{j\pi\left[\left(2k+1\right)N_m - 1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i) \\ &+\textstyle\sum_{n=0}^{N_c-1}\left[\sqrt{P_s}S(n)\hat{H}_{srd}(n) + \hat{N}_r(n)\hat{H}_{rd}(n) + \hat{N}_2(n)\right] \\ &\qquad\times\exp\left\{j\pi\left[\left(2k+1\right)N_m - 1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i), \end{aligned} \tag{11}$$

where $\Psi(n,i)$ is defined as

$$\Psi(n,i) = \begin{cases} 1, & \text{if } n = Ki \\ \frac{1}{N_m}\frac{\sin(\pi N_m\frac{n-Ki}{N_c})}{\sin(\pi\frac{n-Ki}{N_c})}, & \text{otherwise.} \end{cases} \tag{12}$$

Finally, the decision variable is obtained as [Appendix]

$$\begin{aligned} \hat{d}\left(k,i\right) = &\sqrt{\tfrac{E_s}{T_cN_m}}\tfrac{1}{K}\textstyle\sum_{n=0}^{N_c-1}\left[\hat{H}_{sd}(n) + \hat{H}_{srd}(n)\right]\Psi^2(n,i) \\ &\qquad\times d\left(k,i\right) \\ &+\mu_1^i(k,i) + \mu_1^n(k,i) + \mu_2^i(k,i) + \mu_2^n(k,i), \end{aligned} \tag{13}$$

for $n = 0 \backsim N_c - 1$ and $i = 0 \sim N_m - 1$. The first, second and third term in (13), respectively, denote, the desired OFDM/TDM signal, the residual inter-slot interference (ISI) after joint signal combining and FDE, and the AWGN at the mth stage. $\mu_m^i(k,i)$ and $\mu_m^n(k,i)$ are given by (14) at the top of the next page.

B. SINR

In this section, an analytical expressions of the conditional SINR $\gamma\left[E_s/N_0,\, H_{sr}\left(n\right), H_{sd}\left(n\right), H_{rd}\left(n\right)\right]$ are provided. Joint signal combining and MMSE equalization performed over the entire OFDM/TDM frame is done at the destination terminal before detection. Thus, the conditional SINR $\gamma\left[E_s/N_0,\, \{H_{xy}\left(n\right)\}\right]$, where $H_{xy}\left(n\right) \in \{H_{sr}\left(n\right), H_{sd}\left(n\right), H_{rd}\left(n\right)\}$, for the given set of channel gains $\{H_{xy}\left(n\right); n = 0 \sim N_c - 1\}$ can be written as

$$\gamma\left[\frac{E_s}{N_0}, \{H_{xy}\left(n\right)\}\right] = \sum_{m=1}^{2}\gamma_m\left[\frac{E_s}{N_0}, \{H_{xy}\left(n\right)\}\right], \tag{15}$$

where $\gamma_m\left[E_s/N_0,\, \{H_{xy}\left(n\right)\}\right]$ denotes the conditional SINR at the destination during the mth stage. Assuming that the residual ISI after joint signal combining and FDE, and AWGN at the mth stage given by (14) are complexed-valued random Gaussian variable, and by using (13) we obtain the conditional SINR given by (16) for $m \in \{0, 1\}$.

Next, we present two special cases of OFDM/TDM; the conventional OFDM when $K = 1$ and SC-FDE when $K = N_c$.

$$\begin{cases} \mu_1^i(k,i) = \sqrt{\frac{E_s}{T_c N_m}} \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{sd}(n) \sum_{k'=0,\, k'\neq k}^{K-1} \sum_{i'=0,\, i'\neq i}^{N_m-1} \exp\left\{ j\pi \left[(1-\frac{1}{N_m})(i^{'}-i) - \frac{2n}{K}(k^{'}-k) \right] \right\} \\ \qquad \times \Psi(n,i)\Psi(n,i^{'}) \times d(k^{'},i^{'}) \\ \mu_1^n(k,i) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} \hat{N}_1 \exp\left\{ j\pi \left[(2k+1)\, N_m - 1 \right] \frac{n-Ki}{N_c} \right\} \Psi(n,i) \\ \mu_2^i(k,i) = \sqrt{\frac{E_s}{T_c N_m}} \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{srd}(n) \sum_{k'=0,\, k'\neq k}^{K-1} \sum_{i'=0,\, i'\neq i}^{N_m-1} \exp\left\{ j\pi \left[(1-\frac{1}{N_m})(i^{'}-i) - \frac{2n}{K}(k^{'}-k) \right] \right\} \\ \qquad \times \Psi(n,i)\Psi(n,i^{'}) \times d(k^{'},i^{'}) \\ \mu_2^n(k,i) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} \left[\hat{H}_{rd} \hat{N}_r(n) + \hat{N}_2(n) \right] \exp\left\{ j\pi \left[(2k+1)\, N_m - 1 \right] \frac{n-Ki}{N_c} \right\} \Psi(n,i) \end{cases} \tag{14}$$

$$\begin{cases} \gamma_1^{OFDM/TDM} \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] = \\ \frac{ \left(\frac{E_s}{N_0} \right) \left| \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{sd}(n) \Psi^2(n,i) \right|^2 }{ \left(\frac{E_s}{N_0} \right) \left[\frac{1}{K} \sum_{n=0}^{N_c-1} \left| \hat{H}_{sd}(n) \right|^2 \Psi^2(n,i) \sum_{i'=0}^{N_m-1} \Psi^2(n,i') - \left| \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{sd}(n) \Psi^2(n,i) \right|^2 \right] + \frac{1}{N_c} \left(\sum_{n=0}^{N_c-1} |w_1(n)|^2 \Psi^2(n,i) \right) } \\ \gamma_2^{OFDM/TDM} \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] = \\ \frac{ \left(\frac{E_s}{N_0} \right) \left| \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{srd}(n) \Psi^2(n,i) \right|^2 }{ \left(\frac{E_s}{N_0} \right) \left[\frac{1}{K} \sum_{n=0}^{N_c-1} \left| \hat{H}_{srd}(n) \right|^2 \Psi^2(n,i) \sum_{i'=0}^{N_m-1} \Psi^2(n,i') - \left| \frac{1}{K} \sum_{n=0}^{N_c-1} \hat{H}_{srd}(n) \Psi^2(n,i) \right|^2 \right] + \frac{1}{N_c} \left(\sum_{n=0}^{N_c-1} |w_2(n)|^2 \Psi^2(n,i) \left(1 + |H_{rd}(n)|^2 \right) \right) } \end{cases} \tag{16}$$

1) Special case of conventional OFDM $(K=1)$: When $N_m = N_c$ and $\Psi(n,i) = \delta(i-n)$, the conditional SINR is given by

$$\begin{cases} \gamma_{d,1}^{OFDM} \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] = \frac{E_s}{N_0} \left| H_{sd}(n) \right|^2 \\ \gamma_{d,2}^{OFDM} \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] = \frac{E_s}{N_0} \frac{ |H_{sr}(n)|^2 }{ 1 + \frac{1}{|H_{rd}(n)|^2} }. \end{cases} \tag{17}$$

2) Special case of SC−FDE $(K = N_c)$: When $N_m = 1$ and $\Psi(n,i) = 1$, the conditional SINR is given by (18) at the top of the next page.

C. BER

We assume all "1" transmission without loss of generality with QPSK data-modulation. The conditional BER for the given set of $\{H_{xy}(n) \,;\, n = 0 \sim N_c - 1\}$ can be expressed as [11]

$$\begin{aligned} P_b \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] &= \frac{1}{2} Prob \left[\Re \left[\hat{d}(n) \right] < 0 | \{ H_{xy}(n) \} \right] \\ &\quad + \frac{1}{2} Prob \left[\Im \left[\hat{d}(n) \right] < 0 | \{ H_{xy}(n) \} \right] \\ &= \frac{1}{2} \text{erfc} \left[\sqrt{ \frac{1}{4} \gamma \left(\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right) } \right], \end{aligned} \tag{19}$$

where $\Re[z]$ $(\Im[z])$ and $\text{erfc}[\cdot]$ denote the real (imaginary) part of the complex number z and complementary error function [11], respectively. The average BER at the destination terminal can be numerically evaluated by averaging (19) over $\{H_{xy}(n)\}$ as

$$P_b \left[\frac{E_s}{N_0} \right] = \int \cdots \int P_b \left[\frac{E_s}{N_0}, \{ H_{xy}(n) \} \right] p \left[\{ H_{xy}(n) \} \right] \times \prod dH_{xy}(n) \tag{20}$$

for $n = 0 \sim N_c - 1$, where $p\left[\{H_{xy}(n)\}\right]$ is the joint probability density function of $\{H_{xy}(n)\}$.

Table I. Numerical parameters.

Transmitter	Data modulation	QPSK
	IFFT/FFT size	$N_m = 256/K$
	No. of slots	$K = 1,\ 16$ AND 256
	GI	$N_g = 32$
Channel	L=16-path frequency-selective block Rayleigh fading	
Receiver	FDE	MMSE
	No. of FFT points	$N_c = 256$ $N_m = 256/K$
	Channel estimation	Ideal

The evaluation of the theoretical average BER is done by Monte-Carlo numerical computation method as follows. A set of path gains $\{h_{xy};\, l = 0 \sim L-1\}$ is generated to obtain channel gains $\{H_{xy}(n) \,;\, n = 0 \sim N_c - 1\}$ and then, $\{\omega_m(n) \,;\, n = 0 \sim N_c - 1\}$ is computed for each stage. The conditional BER as a function of the average E_b/N_0 is computed for the given set of channel gains $\{H_{xy}(n)\}$. This is repeated a sufficient number of times to obtain the theoretical average BER given by (19).

IV. NUMERICAL RESULTS AND DISCUSSIONS

Simulation conditions are shown in Table I. In our computer simulation we assume an OFDM/TDM frame size of $N_c = 256$ samples with the GI length of $N_g = 32$ samples, single relay $(M = 1)$, and ideal coherent QPSK data modulation/demodulation. The propagation channel is an $L = 16$ -path block Rayleigh fading channel having uniform power delay profile, where the path gains $\{h_{l,xy};\, l = 0 \sim L-1\}$

$$\begin{cases} \gamma_{d,1}^{SC}\left[\frac{E_s}{N_0},\{H_{xy}(n)\}\right] = \dfrac{\left(\frac{E_s}{N_0}\right)\left|\sum_{n=0}^{N_c-1}\hat{H}_{sd}(n)\right|^2}{\left(\frac{E_s}{N_0}\right)\left[\sum_{n=0}^{N_c-1}\left|\hat{H}_{sd}(n)\right|^2-\left|\sum_{n=0}^{N_c-1}\hat{H}_{sd}(n)\right|^2\right]+\frac{1}{N_c}\sum_{n=0}^{N_c-1}|w_1(n)|^2} \\ \gamma_{d,2}^{SC}\left[\frac{E_s}{N_0},\{H_{xy}(n)\}\right] = \dfrac{\left(\frac{E_s}{N_0}\right)\left|\sum_{n=0}^{N_c-1}\hat{H}_{srd}(n)\right|^2}{\left(\frac{E_s}{N_0}\right)\left[\sum_{n=0}^{N_c-1}\left|\hat{H}_{srd}(n)\right|^2-\left|\sum_{n=0}^{N_c-1}\hat{H}_{srd}(n)\right|^2\right]+\frac{1}{N_c}\sum_{n=0}^{N_c-1}|w_2(n)|^2} \end{cases} \tag{18}$$

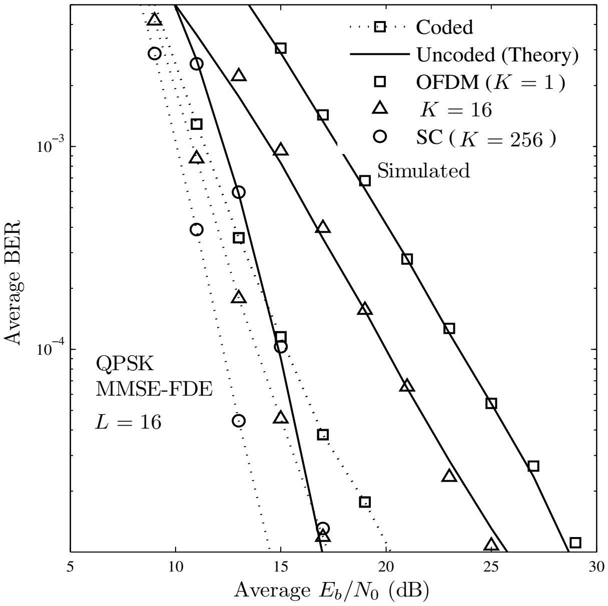


Figure 3. Average BER vs. Average E_b/N_0.

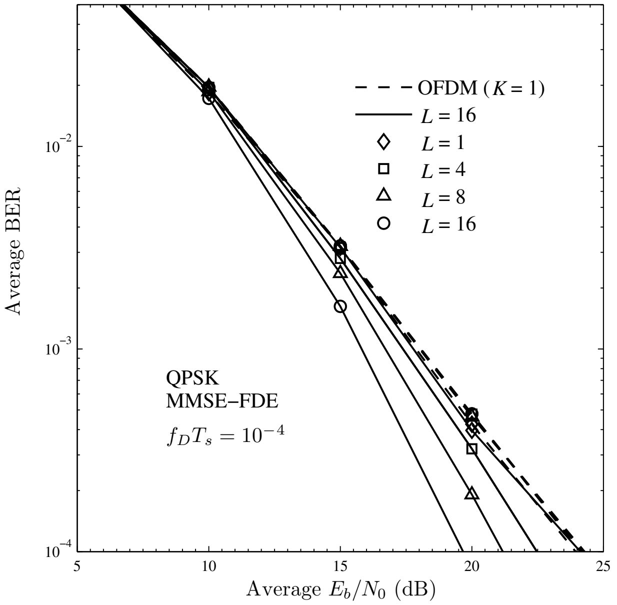


Figure 4. Impact of channel frequency-selectivity.

remain constant over one OFDM/TDM frame length and vary frame-by-frame. The path gains are zero-mean independent complex variables with $E\left[\left|h_{l,xy}\right|^2\right] = 1/L$, where all paths in any channel are independent with each other (we assume the same number of paths in each link). Without loss of generality, we assume $\tau_0 = 0 < \tau_1 < ... < \tau_{L-1}$ and that the lth path time delay is $\tau_l = l\triangle$, where $\triangle\,(\geqslant 1)$ denotes the time delay separation between adjacent paths. The maximum time delay of the channel is less than the GI length (i.e., $L < N_g$). We assume no knowledge of the channel state information at the transmitters, the perfect channel state information at the destination and perfect synchronization. The assumption on synchronization is most critical since synchronization becomes increasingly challenging in larger networks.

The BER performance of cooperative OFDM/TDM network is shown in Fig. 3 with received signal energy per-bit-to-AWGN power spectrum density ratio $E_b/N_0 = 0.5 \times E_s/N_0 \times (1 + N_g/N_c)$, as a parameter. It is evident from Fig. 3 that the cooperative OFDM/TDM using MMSE-FDE with $K = 16$ can be used to improve the BER performance in comparison with the cooperative OFDM because, as K increases, the transmitted symbol energy is distributed over a K times wider bandwidth and MMSE-FDE is used to exploit the channel frequency-selectivity. This is due to the fact that the OFDM/TDM based cooperative network achieves both cooperative and frequency diversity gains leading to the superior performance in terms of the average BER in comparison with cooperative network based on OFDM. As we can see, a fairly good agreement is achieved between the simulated and theoretical results which confirms validity of the analysis presented in this paper.

The impact of channel frequency-selectivity in Fig. 4, with received signal energy per-bit-to-AWGN power spectrum density ratio $E_b/N_0 = 0.5 \times E_s/N_0 \times (1 + N_g/N_c)$, as a parameter. The performance of cooperative OFDM/TDM with MMSE-FDE is largely determined by the channel itself (i.e., the channel frequency-selectivity) and thus, here we investigate the effect of different propagation scenarios. The channel frequency-selectivity is a function of the number of paths L; as L decreases the channel becomes less frequency-selective and when $L = 1$ it becomes a frequency-nonselective channel (i.e., single-path channel).

Figure 4 illustrates the average BER as a function of the average E_b/N_0 with the number of paths L as a parameter. It can be seen that as L decreases (i.e., the channel becomes less frequency-selective) the performance of OFDM/TDM based cooperative network degrades since the channel is becoming less frequency-selective. This is because as L decreases the channel becomes less frequency-selective and lower frequency diversity gain is obtained through MMSE-FDE. In the case of $L = 1$ the performance of cooperative OFDM/TDM and cooperative OFDM is the same since the channel becomes frequency-nonselective.

V. CONCLUSION

In this paper, we presented cooperative network based on OFDM/TDM with MMSE-FDE physical-layer access in a frequency-selective fading channel. The conditional SINR expressions are derived based on the Gaussian approximation of the ISI after MMSE-FDE for the given set of channel gains. The average BER is evaluated by using Monte-Carlo computing method. The results show that cooperative network based on OFDM/TDM achieves a lower BER in comparison with cooperative OFDM since with OFDM/TDM based cooperative network, both cooperative and frequency diversity gains are exploited. The theoretical results were compared with the computer simulation results and a fairly good agreement was observed.

APPENDIX

Here, we present a derivation of the decision variable $\hat{d}(k,i)$.

Starting from (11), we represent decision variable by OFDM/TDM data-modulated symbols as

$$\begin{aligned}\hat{d}\left(k,i\right) = {} & \sqrt{P_s}\sum_{n=0}^{N_c-1}\hat{H}_{sd}(n)\sum_{k'=0}^{K-1}\sum_{i'=0}^{N_m-1}\tfrac{1}{N_c} \\ & \times\sum_{t=k'N_m}^{(k^{'}+1)N_m}\exp(-j2\pi t\tfrac{k^{'}}{K})\exp(j2\pi t\tfrac{i^{'}}{N_m}) \\ & \times d(k^{'},i^{'})\Psi(n,i) \\ & +\tfrac{1}{N_c}\sum_{n=0}^{N_c-1}\hat{N}_1(n) \\ & \times\exp\left\{j\pi\left[\left(2k+1\right)N_m-1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i) \\ & +\sqrt{P_s}\sum_{n=0}^{N_c-1}\hat{H}_{srd}(n)\sum_{k'=0}^{K-1}\sum_{i'=0}^{N_m-1}\tfrac{1}{N_c} \\ & \times\sum_{t=k'N_m}^{(k^{'}+1)N_m}\exp(-j2\pi t\tfrac{k^{'}}{K})\exp(j2\pi t\tfrac{i^{'}}{N_m}) \\ & \times d(k^{'},i^{'})\Psi(n,i) \\ & +\tfrac{1}{N_c}\sum_{n=0}^{N_c-1}\left[\hat{N}_r(n)\hat{H}_{rd}(n)+\hat{N}_1(n)\right] \\ & \times\exp\left\{j\pi\left[\left(2k+1\right)N_m-1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i).\end{aligned} \tag{$A-1$}$$

Now, we extract the ith data-modulated symbol in the kth OFDM/TDM slot from the sum and obtain

$$\begin{aligned}\hat{d}\left(k,i\right) = {} & \tfrac{\sqrt{P_s}}{K}\sum_{n=0}^{N_c-1}\hat{H}_{sd}(n)\Psi^2(n,i)d(k,i) \\ & +\tfrac{\sqrt{P_s}}{K}\sum_{n=0}^{N_c-1}\hat{H}_{sd}(n)\sum_{k'=0,\,k'\neq k}^{K-1}\sum_{i'=0,\,i'\neq i}^{N_m-1} \\ & \times\exp\left\{j\pi\left[(1-\tfrac{1}{N_m})(i^{'}-i)-\tfrac{2n}{K}(k^{'}-k)\right]\right\} \\ & \times\Psi(n,i^{'})\Psi(n,i)d(k^{'},i^{'}) \\ & +\tfrac{1}{N_c}\sum_{n=0}^{N_c-1}\hat{N}_1(n) \\ & \times\exp\left\{j\pi\left[\left(2k+1\right)N_m-1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i) \\ & +\tfrac{\sqrt{P_s}}{K}\sum_{n=0}^{N_c-1}\hat{H}_{srd}(n)\Psi^2(n,i)d(k,i) \\ & +\tfrac{\sqrt{P_s}}{K}\sum_{n=0}^{N_c-1}\hat{H}_{srd}(n)\sum_{k'=0,\,k'\neq k}^{K-1}\sum_{i'=0,\,i'\neq i}^{N_m-1} \\ & \times\exp\left\{j\pi\left[(1-\tfrac{1}{N_m})(i^{'}-i)-\tfrac{2n}{K}(k^{'}-k)\right]\right\} \\ & \times\Psi(n,i^{'})\Psi(n,i)d(k^{'},i^{'}) \\ & +\tfrac{1}{N_c}\sum_{n=0}^{N_c-1}\left[\hat{N}_r(n)\hat{H}_{rd}(n)+\hat{N}_1(n)\right] \\ & \times\exp\left\{j\pi\left[\left(2k+1\right)N_m-1\right]\tfrac{n-Ki}{N_c}\right\}\Psi(n,i).\end{aligned} \tag{$A-2$}$$

From (A-2) we come to (13) in the main text.

ACKNOWLEDGMENT

This work was supported in part by Ministry of Civil Affairs of Bosnia and Herzegovina with “Support grant for preparation of EU FP7-related research projects” and by 2010 KDDI Foundation Research Grant Program.

REFERENCES

[1] E. Meulen, "Three-terminal communication channels," Adv. Appl. Probability, vol. 3, no. 1, pp. 120-154, Spring 1971. [3] T. Cover and A. El-Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inform. Theory*, Vol. 25, No. 5, pp. 572-584, Sep. 1979.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part I, II" *IEEE Trans. Commun*., Vol. 51, No. 11, pp. 1927-1948, Nov. 2003.

[3] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, Vol. 50, No. 11, pp. 3062-3080, Dec. 2004.

[4] R. U. Nabar, H. Bolcskei, and F. W. Kneubiihler, "Fading relay channels: performance limits and space-time signal design," *IEEE J. Select. Areas Commun.,* Vol. 22, No. 6, pp. 1099-1109, Aug. 2004.

[5] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," *IEEE Trans. Wireless Commun.*, Vol. 5, No. 12, pp. 3524-3536, Dec. 2006.

[6] W. Zhang. Y. Li, X. Xia, P. C. Ching and K. B. Letaief, "Distributed Space-frequency coding in broadband ad hoc networks," *2007. ICASSP 2007. IEEE International Conference on Acoustics, Speech and Signal Processing*, 15-20 Apr. 2007, Honolulu, HI, USA.

[7] P. A. Anghel and M. Kaveh, "Relay assisted uplink communication over frequency-selective channels," *The 2003 IEEE Signal processing advances for wireless communications (SPAWC 2003)*, pp. 125-129, 15-18 Jun. 2003, Rome, Italy.

[8] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, Vol. 52, No. 9, pp. 1470-1476, Sep. 2004.

[9] H. Gacanin, S. Takaoka and F. Adachi, "BER performance of OFDM combined with TDM using frequency-domain equalization,"*Journal of Communication and Networking (JCN)*, Vol. 9, No.1, pp. 34-42, Mar. 2007.

[10] H. Gacanin and F. Adachi, "A performance of cooperative relay network based on OFDM/TDM using MMSE-FDE in a wireless channel," *2009 IEEE 70th Vehicular Technology Conference (VTC2009-Fall)*, 20-23 Sep. 2009, Anchorage, Alaska, USA.

[11] J. G. Proakis, Digital communications, 3rd ed., *McGraw-Hill*, 1995.