Doppler Compensation by Using Dual Antenna for Mobile OFDM Systems

Semih Serbetli and Stan Baggen
Philips Research Laboratories
High Tech Campus 37, 5656 AE
Eindhoven, The Netherlands
Email: {semih.serbetli, stan.baggen}@philips.com

Abstract—The performance of OFDM systems is compromised in mobile environments due to Doppler spreading. In this paper, we investigate how Doppler spread due to the mobility of the receiver can be mitigated by using dual antenna. In this context, we propose two simple antenna combining schemes, namely, simple beamforming (SB) and beamforming with frequency offset correction (BFOC), and investigate the ICI mitigating capability of these methods. We show that by using appropriate antenna spacing, beamforming coefficients and frequency offset correction, the performance of the OFDM systems can be greatly improved in high mobility scenarios.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is an attractive transmission scheme for wireless systems to achieve high data rates [1]. It has been widely adopted in different wireless standards, e.g., DVB-T/H, ISDB-T, IEEE 802.11a/g/n [2], [3], and it is also being considered as the most valuable candidate for future cellular radio systems [4]. With an appropriate guard interval, OFDM provides a spectrally efficient transmission scheme that is robust to the multipath spread of the channel by a simple equalization. Although the robustness against multipath effects and high spectral efficiency are advantages of OFDM systems, the OFDM systems are sensitive to mobility. Since mobility results in Doppler spreading, it leads to the loss of orthogonality among the subcarriers known as intercarrier interference (ICI) [5], [6]. If not compensated, ICI hampers the reception at the mobile terminals.

The ICI problem in mobile OFDM systems is a well known problem that is widely studied [5]–[10]. The proposed solutions so far can be grouped under three categories, i.e., signal processing based ICI cancellation schemes, self ICI cancelling coding schemes, and multiple antenna techniques. Signal processing based ICI cancellation schemes require estimation of the time varying characteristics of the channel to estimate the interference of each subcarrier to its adjacent subcarriers to cancel the ICI [8], [9], whereas self ICI cancelling coding schemes provide robustness to Doppler spread at the expense of reduced spectral efficiency, e.g., [10]. The multiple antenna approaches are based on exploiting antenna diversity and spatial processing to mitigate the ICI [11]–[14].

Recently, spatial diversity has attracted a lot of attention due to its capability to mitigate fading in wireless channels. Especially, using maximum ratio combining (MRC) at the receiver is shown to provide enhanced reception quality in time invariant channels. However, in the presence of high Doppler spread, MRC can not mitigate the ICI e.g., [11], [12]. Thus, there have been several different approaches for mitigating Doppler spread by using multiple receive antennas. The first group of solutions is based on combining the received signals from each antenna considering the ICI power levels, e.g., [11]. The second group of solutions is based on forming virtual stationary antennas by using spatial interpolation to mitigate Doppler spread [14]. These two approaches perform quite well, but they require complex receiver structures. The third group of solutions is based on exploiting the directivity of Doppler spread by using directional antennas. In this context, the ICI power of mobile OFDM systems is investigated in [12], [13] by using ideal sectorized antennas. These schemes provide promising solutions for Doppler compensation with low complexity increase in the baseband. However, they use ideal directional patterns that require a large number of antenna elements. Besides, these antennas may be required to be placed in a small area which results in mutual coupling among the antenna elements that distorts the directivity of the array pattern. In this paper, we focus on beamforming based multiple antenna schemes exploiting the directivity of Doppler spread to mitigate the ICI. We consider the problem in a scenario where we have only two closely spaced antennas to form a directional pattern that would be imperfect due to the few number of antennas and the mutual coupling effect. In this context, we investigate how we can utilize dual antenna for Doppler compensation without increasing the complexity much and considering the effects of mutual coupling.

II. SYSTEM DESCRIPTION

A. Channel Model

We consider a wide sense stationary time varying multipath channel consisting of uncorrelated paths with complex attenuation \( \{ h_i(t) \} \) and delay of \( \{ \tau_i \} \)

\[
h(t, \tau) = \sum_{\tau=0}^{L-1} h_i(t) \delta(\tau - \tau_i). \tag{1}
\]

We assume that the mobile unit is in a rich scattering environment where the scatterers are uniformly distributed around the mobile unit as in Figure 1. Thus, each multipath term \( h_i(t) \) is
composed of multiple independent and identically distributed scattered signals with uniformly distributed angles-of-arrival (AOAs), i.e., \( g(\theta_{l,p}) = \tfrac{1}{2\pi} \) as
\[
h_{l}(t) = \sum_{p=0}^{P-1} h_{l,p} e^{j2\pi f_{c}\cos(\theta_{l,p})},
\]
where \( f_{d} = f_{c} \frac{d}{c} \) with \( v \) as the speed of the mobile unit, \( c = 3 \cdot 10^{8} \text{ m/s} \), and \( f_{c} \) is the carrier frequency. \( \theta_{l,p} \) is the AOA of the \( p \)th scattered component of the \( i \)th multipath. Thus, each path experiences a classical U-shaped Doppler spectrum [15]
\[
S(\nu) = \begin{cases} 
\tfrac{1}{\pi} \sqrt{f_{d}^{2}-\nu^{2}}, & -f_{d} < \nu < f_{d} \\
0, & \text{elsewhere.}
\end{cases}
\]
We assume that the two antenna elements are perfectly aligned with the direction of movement as Figure 1. In an ideal uncoupled case, taking the first antenna as the reference, the second antenna observes a phase shifted version of each scattered component, thus, the channel \( i \)th antenna sees is
\[
h_{u,i}(t, \tau) = \sum_{l=0}^{L-1} h_{u,l,i}(t)\delta(\tau - \tau_{l}),
\]
with \( h_{u,l,1}(t) = h_{l}(t) \); \( h_{u,l,2}(t) = \sum_{p=0}^{P-1} h_{l,p} e^{j2\pi f_{c}\cos(\theta_{l,p})[d\frac{\lambda}{c}]}, \)

where \( d \) and \( \lambda \) are the antenna spacing and the wavelength of the signal, respectively.

### B. Mutual Coupling

When several antenna elements are closely spaced, the electromagnetic field generated by each antenna element affects the distribution of the current and voltage on the others. Thus, the current/voltage at each antenna element does not depend only on the incident electromagnetic field on the antenna itself but also on the field of the other antenna elements. This effect is called mutual coupling effect, and it is widely studied in the context of MIMO systems, e.g., [16]. The coupling effect can be simply modelled by a multi-port network. Following the same approach as in [16], the coupled channels seen by each antenna can be expressed as
\[
\begin{bmatrix} h_{c,1}(t, \tau) \\ h_{c,2}(t, \tau) \end{bmatrix} = C \begin{bmatrix} h_{u,1}(t, \tau) \\ h_{u,2}(t, \tau) \end{bmatrix},
\]
with
\[
C = \begin{bmatrix} \alpha \beta \\ \beta \alpha \end{bmatrix} = (Z_{L} + Z_{s}) \begin{bmatrix} Z_{L} + Z_{s} & Z_{m} \\ Z_{m} & Z_{L} + Z_{s} \end{bmatrix}^{-1},
\]

where \( C \) is the mutual coupling matrix with \( Z_{s}, Z_{L} \) and \( Z_{m} \) as self, loading and mutual impedances, respectively.

### C. OFDM Signal with ICI

We consider a conventional OFDM system where \( N \) symbols, \( s = [s_{1}, s_{2}, ..., s_{N}] \), are modulated onto \( N \) orthogonal subcarriers by using an \( N \)-point IFFT. We assume that a cyclic prefix longer than the length of the channel impulse response is added to the signal to prevent inter-block-interference. In a single antenna case where only the \( i \)th antenna is used, the baseband received signal is
\[
r_{s}(t) = \sum_{n=0}^{N-1} H_{u,i,n}(t)e^{j2\pi f_{s}\nu_{n}t} + \nu_{i}(t),
\]
where \( H_{u,i,n}(t) = \sum_{l} h_{u,l,i}(t)e^{-j2\pi f_{s}\tau_{l}} \), is the channel frequency response of subcarrier \( n \) at the \( i \)th receive antenna and time \( t \) in the ideal uncoupled case. \( f_{s} \) is the subcarrier spacing and \( \nu_{i}(t) \) is the AWGN at the \( i \)th antenna with a variance of \( \sigma_{n}^{2} \). Following the approach in [8], [9], \( H_{u,i,n}(t) \) can be approximated by using Taylor series expansion around \( t_{0} \) up to the first-order term as
\[
H_{u,i,n}(t) \approx H_{u,i,n}(t_{0}) + H'_{u,i,n}(t_{0})(t - t_{0}).
\]
Using (7), the received signal in a single antenna scenario can be expressed as [8], [9]
\[
r_{s}(t) \approx W_{s}(t) + I_{s}(t) + N_{s}(t),
\]
with \( W_{s}(t) = \sum_{n=0}^{N-1} H_{u,i,n}(t_{0})e^{j2\pi f_{s}\nu_{n}t}N_{s}(t) = \nu_{i}(t) \) and
\[
I_{s}(t) = \sum_{n=0}^{N-1} (t - t_{0})H'_{u,i,n}(t_{0})e^{j2\pi f_{s}\nu_{n}t}N_{s}(t),
\]
where \( W_{s}(t) \), \( I_{s}(t) \) and \( N_{s}(t) \) are the wanted part of the signal, ICI generating part of the signal and noise, respectively. Using (5,6,7), the baseband received signal at each antenna in a coupled dual antenna case can be approximated as
\[
\begin{bmatrix} r_{1}(t) \\ r_{2}(t) \end{bmatrix} \approx \sum_{n=0}^{N-1} C \begin{bmatrix} H_{u,1,n}(t_{0}) \\ H_{u,2,n}(t_{0}) \end{bmatrix} e^{j2\pi f_{s}\nu_{n}t}N_{s}(t)
\]
\[
+ \sum_{n=0}^{N-1} C \begin{bmatrix} H'_{u,1,n}(t_{0}) \\ H'_{u,2,n}(t_{0}) \end{bmatrix} (t - t_{0})e^{j2\pi f_{s}\nu_{n}t}N_{s}(t) + \begin{bmatrix} \nu_{1}(t) \\ \nu_{2}(t) \end{bmatrix},
\]
where the second term in the summation represents the ICI generating terms. In the sequel, we use (8,9) to evaluate the performance of the proposed receiver structures.

### III. DOPPLER COMPENSATION USING DUAL ANTENNAS

We consider the mobile reception of OFDM signals in a rich scattering multipath environment. Each multipath term of the channel is a sum of the scattered signals from all around the receiver, and results in Doppler spreading when the receiver is mobile. However, depending on the angle of arrival (AOA), each scattered component of the signal undergoes a different Doppler shift. In this section, we exploit the directivity of the Doppler shifts, and propose simple receiver structures for Doppler compensation.
A. Simple Beamforming (SB)

In [5]–[7], it is shown that the ICI power is proportional to the square of the Doppler frequency shift. In this subsection, we exploit the fact that different Doppler shifts, thus, scattered signals with different angles-of-arrival (AOAs), have different characteristics in terms of generating ICI, i.e., as the AOAs of a scattered signal gets closer to the direction of the movement, it induces more ICI than the scattered signals coming nearly perpendicular to the direction of the mobile unit. In this context, we propose using two closely spaced antennas to form a directional antenna to emphasize the scattered signals with low ICI and suppress the scattered signals that generate high ICI, i.e., forming a beam focusing on the sides of the mobile unit as in Figure 2. Thus, the weights of the beamforming vector should be chosen such that the signals from each antenna should be summed coherently if their AOAs are nearly perpendicular to the direction of movement of the mobile unit. In the uncoupled case, there is no phase difference among the received signals of the antennas for the scattered components with AOAs’ difference among the received signals of the antennas for the mobile unit. In the uncoupled case, there is no phase

\[ \text{gain obtained in the power of the wanted part of the signal using two antennas in the SB mode is} \]

\[ G_{W,SB} = \frac{\mathbb{E}\{|W(t)|^2\}}{\mathbb{E}\{|W_0(t)|^2\}} = |\alpha + \beta|^2(1 + \Re\{\rho_1\}), \quad (12) \]

where

\[ \rho_1 = \mathbb{E}\{H_{u,1,n}(t_0)H_{u,2,n}^*(t_0)/\mathbb{E}\{|H_{u,1,n}(t_0)|^2\}. \]

Similarly, the ICI gain is

\[ G_{I,SB} = \frac{\mathbb{E}\{|I(t)|^2\}}{\mathbb{E}\{|I_0(t)|^2\}} = |\alpha + \beta|^2(1 + \Re\{\rho_2\}), \quad (13) \]

with

\[ \rho_2 = \mathbb{E}\{H'_{u,1,n}(t_0)H'^*_{u,2,n}(t_0)/\mathbb{E}\{|H'_{u,1,n}(t_0)|^2\}. \]

Note that both \( \rho_1 \) and \( \rho_2 \) are dependent on the antenna spacing and the distribution of the AOA. Using (12) and (13), the wanted signal-to-ICI ratio, \( WIR, \) improvement is

\[ G_{WIR,SB} = \frac{G_{W,SB}}{G_{I,SB}} = \frac{1 + \Re\{\rho_1\}}{1 + \Re\{\rho_2\}.} \quad (14) \]

Observe that the coupling among the antennas does not affect the WIR improvement obtained by using the SB approach. It only affects the signal power received by the antenna array. The proposed scheme is expected to provide good ICI cancellation performance in rich scattering environments as shown in Section IV since focusing only on specific AOAs does not degrade the received signal power much.

B. Beamforming with Frequency Offset Correction (BFOC)

In the previous section, we proposed a very simple Doppler compensation mechanism that only requires an adder. It is expected to perform well in rich scattering environments. However, the scheme is sensitive to the channel/scattering environment since it focuses on the scattered signals with certain AOAs. If the environment is not rich enough in terms of scatterers, focusing in certain AOAs, i.e., the sides of the mobile unit, may degrade performance since one may suppress most of the useful signal. In this section, we investigate how we can mitigate the Doppler spread without suppressing any part of the signal by allowing an acceptable level of complexity increase.

Exploiting the directive property of Doppler spread by using directional antennas has attracted a lot of attention [12], [13]. However, in these works, ideal directional patterns are used and mutual coupling among the antenna elements is ignored. Theoretically, if the receiver can form ideal patterns in certain AOAs, it can focus on these AOAs, correct their Doppler shifts via a frequency shift and sum up again to compensate for the Doppler spreading. In this section, we follow a similar
approach. However, we consider the problem in a scenario where we have two coupled antennas where we form two beams focusing on the scattered signals with positive/negative Doppler shifts as in Figure 4. Each beam focuses on different AOAs and apply a different frequency offset correction to correct the Doppler shifts as in Figure 5. Since the scattered signals with AOA 0 and π are the two extreme AOAs that generate the highest ICI levels, we choose to consider these two AOAs to form the beamforming weights. The beamforming weights should be chosen such that the contribution from the other AOA is minimum. Thus, beam looking in front (back) of the mobile unit should null the signal with π (0) AOA. We choose the beamforming weights, \( w_1 \) and \( w_2 \), as [17]

\[
\begin{align*}
\mathbf{w}_1 &= \begin{bmatrix} w_{11}^* \\ w_{12}^* \end{bmatrix} = \frac{\mathbf{w}_1^*}{|\mathbf{w}_1|^2} = C^{-1} \begin{bmatrix} 1 \\ -e^{j2\pi \frac{f_1}{f}} \end{bmatrix}, \\
\mathbf{w}_2 &= \begin{bmatrix} w_{21}^* \\ w_{22}^* \end{bmatrix} = \frac{\mathbf{w}_2^*}{|\mathbf{w}_2|^2} = C^{-1} \begin{bmatrix} 1 \\ -e^{-j2\pi \frac{f_1}{f}} \end{bmatrix}.
\end{align*}
\]

which form beam patterns [17]

\[
p_1(\theta) = \frac{|1 - e^{j2\pi \frac{f_1}{f_0}(1 + \cos(\theta))}|^2}{|\mathbf{w}_1|^2}; \quad p_2(\theta) = \frac{|1 - e^{-j2\pi \frac{f_1}{f_0}(1 + \cos(\theta))}|^2}{|\mathbf{w}_2|^2}.
\]

Observe that \( p_1(\theta) = p_1(-\theta) = p_2(\pi - \theta) = p_2(-\pi + \theta) \). Figure 6 presents some sample array patterns for different antenna spacings. When \( \mathbf{w}_1 \) and \( \mathbf{w}_2 \) are used, the resulting combined signals are

\[
\tilde{r}_1(t) = \mathbf{w}_1^T \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix}; \quad \tilde{r}_2(t) = \mathbf{w}_2^T \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix}.
\]

To correct the Doppler shift of each beam pattern, the combined signals are corrected by a frequency shift of \( f_1 \) and \( f_2 \), for beam pattern 1 and 2, respectively. Considering the uniformly distributed AOAs, \( p_1(\theta) \) and \( p_2(\theta) \), the frequency shifts to be applied are chosen as

\[
f_{1,2} = \int_{-f_0}^{f_0} \frac{p_1(a \cos(f/f_0))}{\pi \sqrt{f^2 - f_0^2}} df \int_0^{2\pi} p_1(\theta) d\theta.
\]

Note that the frequency shifts have the same magnitudes but opposite signs, i.e., \( f_{1,2} = -f_{2,1} \). It is important to note that when ideal sectorized patterns are used, i.e., \( p_1(\theta) = 1/\pi \) for \( \theta \in [-\pi/2, \pi/2] \) and \( p_2(\theta) = 1/\pi \) for \( \theta \in [\pi/2, 3\pi/2] \) and 0 otherwise, the frequency shifts should be chosen as \( f_{1,2} = 2f_0/\pi \) and \( f_{2,2} = -2f_0/\pi \). Thus, these frequency shifts can also be applied to each beam to reduce the complexity of the scheme. After correcting the mean Doppler shifts, the signals from each beam are combined as in Figure 5.

When a frequency shift is applied to an OFDM signal, if \( f_{1,2}/f_0 \) is small, the resulting signal can be approximated as

\[
\tilde{r}_1(t)e^{-j2\pi f_{1,2}t} \simeq \tilde{r}_1(t) e^{-j2\pi f_{1,2}t}(1 - j2\pi f_{1,2}(t - t_0))
\]

Using (15,17) and (19), the resulting signal obtained by the BFOC scheme can be approximated as

\[
\tilde{r}(t) = \begin{bmatrix} \tilde{r}_1(t) \\ \tilde{r}_2(t) \end{bmatrix} \begin{bmatrix} e^{-j2\pi f_{1,2}t} \\ e^{-j2\pi f_{1,2}t} \end{bmatrix}
\]

\[
\tilde{r}(t) = \begin{bmatrix} \tilde{r}_1(t) \\ \tilde{r}_2(t) \end{bmatrix} \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix} + (t - t_0) \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

where

\[
\tilde{w}_1^T \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix} + (t - t_0) \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

Thus, the combined signal can be approximated as

\[
\tilde{r}(t) \approx \tilde{W}(t) + \tilde{I}(t) + \tilde{N}(t)
\]

where

\[
\tilde{W}(t) = \sum_{n=0}^{N-1} \tilde{w}_1^T \begin{bmatrix} H_{u,1,n}(t_0) \\ H_{u,2,n}(t_0) \end{bmatrix} e^{j2\pi f_{1,2}t} s_n
\]

\[
\tilde{I}(t) = \sum_{n=0}^{N-1} (t - t_0) \begin{bmatrix} \tilde{w}_1^T C \\ \tilde{w}_2^T C \end{bmatrix} \begin{bmatrix} H'_{u,1,n}(t_0) \\ H'_{u,2,n}(t_0) \end{bmatrix} e^{j2\pi f_{1,2}t} s_n
\]

\[
\tilde{N}(t) = (\tilde{w}_1^T + (t - t_0) \tilde{w}_2^T) \begin{bmatrix} \tilde{v}_1(t) \\ \tilde{v}_2(t) \end{bmatrix}.
\]

The gains obtained in the power of the wanted and ICI generating part of the signal in the BFOC mode are

\[
G_{W,BFOC} = \frac{E[|\tilde{W}(t)|^2]}{E[|\tilde{I}(t)|^2]} = \tilde{w}_1^T C \tilde{w}_1^T.
\]

\[
G_{I,BFOC} = \frac{E[|\tilde{I}(t)|^2]}{E[|\tilde{I}(t)|^2]} = \tilde{w}_1^T C \tilde{w}_2^T R_2 C \tilde{w}_2^T.
\]
frequency shifts (FBFOC) of the BFOC scheme at different antenna spacings with both received signal since it directly affects the mutual coupling capability of the SB scheme. It only affects the SNR of the factor does not have any effect on the Doppler compensation of the signal. It is important to note that the antenna loading which suppresses most of the ICI generating scattered part power is decreased at $d_{\text{signal}}$ power loss. It is expected that a large portion of the ICI by the SB approach with different antenna loading factors. Using the proposed schemes for different antenna spacings.

In this section, we present numerical results to demonstrate the Doppler compensation performance of the SB and BFOC schemes in a rich scattering environment where the scatterers are uniformly distributed. We assume that the two antennas are simple dipole antennas where the receiver has the information of antenna spacing, carrier frequency and antenna loading which suppresses most of the ICI generating scattered part power is decreased. The ABFOC performs better than the FBFOC since, as the directional pattern of the beams become imperfect, the Doppler compensation performance of the SB and BFOC will be demonstrated in the following section.

### IV. Numerical Results and Conclusions

In this section, we present numerical results to demonstrate the Doppler compensation performance of the SB and BFOC schemes in a rich scattering environment where the scatterers are uniformly distributed. We assume that the two antennas are simple dipole antennas where the receiver has the information of antenna spacing, carrier frequency and antenna loading which suppresses most of the ICI generating scattered part power is decreased at $d_{\text{signal}}$ power loss. It is expected that a large portion of the ICI by the SB approach with different antenna loading factors. Using the proposed schemes for different antenna spacings.

In this paper, we proposed two simple Doppler compensation mechanisms by using two antennas. We show that both schemes provide good WIR improvement over single antenna receivers, thus providing the OFDM receiver some robustness against mobility. They can either be used as a stand-alone ICI cancellation scheme or combined with the other ICI cancellation schemes to improve the robustness to the Doppler spreading further. The proposed schemes can also be extended to utilize more receive antennas to improve the Doppler mitigation capability further.

### References


