Evaluation of OFDM Systems With Virtual Carriers Over V2V Channels

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***Abstract*—Computational complexity and spectral efficiency are key components on the implementation of vehicular communication systems. However, in order to counteract the inter-carrier interference (ICI) in orthogonal frequency division multiplexing (OFDM) systems, it's usual to resort receivers with high computational complexity or reduced spectral efficiency. This paper analyzes the inclusion of virtual carriers (VC) as a mean to reduce the ICI and the computational complexity required by the nonlinear ordered successive interference cancellation (OSIC). From the simulation results, it is demonstrated that using VC provides 90% reduction in the computational cost required for executing data detection, , as well as a gain of 5 dB compared to conventional OFDM system with linear detection. In addition, the system is tested for different rates of channel coding obtaining results that show VC to be a convenient technique for reducing system complexity with low impact on the system throughput.**

***Index Terms*—OFDM, ICI mitigation, Virtual carriers, Time-varying channels, V2V, OSIC.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is used in the new generation communication systems such as vehicle-to-vehicle (V2V) communication [1], because it provides major immunity to fading channel caused by multipath phenomenon. OFDM transforms a frequency selective fading channel into several flat fading channels with a certain coherence bandwidth, by using multiple frequency subcarriers [2]. The subcarriers must be spaced by at least $1/T_s$ to maintain their orthogonality, with T_s being symbol time. However, in highly dispersive channels the subcarriers orthogonality within the OFDM symbol is altered, causing inter-carrier interference (ICI). The ICI degrades the overall system performance in different stages like channel estimation, data detection and error correction for example. The common solution for mitigating this problem is to deliberately sacrifice spectral efficiency of system by increasing the redundancy using lower rates in the forward error correction (FEC) stages or by employing virtual carriers (VC), also known as guard symbols.

The impact of increasing the code rate in FEC on the system performance is analyzed in [3], [4], this change does not imply any reduction in the computational complexity of system, but an increased complexity of the trellis due to a greater number of states. In addition, low code rates increase the system latency which is not practical in vehicular systems.

Several works, e.g., [2], [5]–[8] explore the advantages of using VC in highly time-varying channels. The approaches in [2], [6] use VC as guard intervals for each OFDM symbol, achieving an improvement on the performance in terms of bit error rate (BER) and a reduction in the complexity of channel estimation and data detection. However, analysis in [2] and [6] is limited to linear detector which are not designed for ICI mitigation.

In this paper, VC is applied as data guards in order to combat ICI within the OFDM symbol. The results show the BER achieved by the system with and without VC. The experiments cover simulation and comparison between VC and non-VC systems in the presence of linear and nonlinear detectors. Different rates in the FEC stage are also tested. The results in this work provide insights on the actual gains and trade-offs in terms of computational complexity and system performance.

Notation: Lower- (upper-)case letters refer to vectors (matrices); $[\cdot]^T$, $(\cdot)^H$, $(\cdot)_N$ and $[\cdot]_T$ are the transpose, Hermitian, circular module slipping N and band truncation operators, respectively; $(\cdot)^k$ refers to the k-th OFDM symbol being considered. The subscripts $(\cdot)_p$ and $(\cdot)_d$ are the sampled versions of the vectors in the positions of the pilots and data: and in the case of matrices, the versions sampled in rows and columns in the positions of pilots and data.

II. System model

We consider an OFDM system with a total number of $N = N_d + N_g + 1$ subcarriers, consisting of N_d data subcarriers, N_g guard subcarriers and the DC component. Let $x^k[n]$ the k -th transmitted OFDM symbol excluding cyclic prefix (CP) defined as:

$$x^k[n] = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} s^k[m] e^{j2\pi nm/N}, \quad n = 0, 1, ..., N-1, \tag{1}$$

where N denotes the OFDM symbol length and $s^k[m]$ is the m-th data symbol belonging to a constellation $\mathbf{\Omega}$. Once

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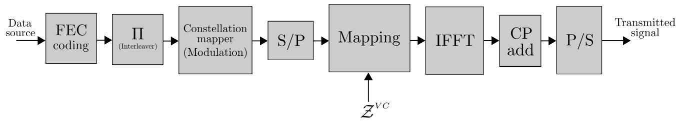

Fig. 1: OFDM transmitter with virtual carriers.

exclusion of CP is done, the received signal for the k-th OFDM symbol in its complex baseband representation can be described by the discrete circular convolution:

$$y^k[n] = \sum_{l=0}^{L-1} h^k[n,l] x^k[\langle n-l \rangle_N] + w^k[n], \qquad (2)$$

where, $n = \{0, 1, ..., N-1\}$, $l = \{0, 1, ..., L-1\}$, L denotes the baseband channel impulse response (CIR) length, $h^k[n,l]$ is CIR for the k-th block in the n-th time instant for an impulse function in the input l samples before, and $w^k[n]$ is the complex additive white Gaussian noise (AWGN), with zero mean and variance $\sigma_w^2 = N_0/2$. The circular convolution (2) between the CIR and $x^k[n]$ can be rewritten in matrix form as:

$$\mathbf{y}^k = \mathbf{H}^k \mathbf{x}^k + \mathbf{w}^k, \qquad (3)$$

where:

$$\mathbf{y}^k = \begin{bmatrix} y^k[0], & y^k[1], & \cdots, & y^k[N-1] \end{bmatrix}^T,$$
$$\mathbf{x}^k = \begin{bmatrix} x^k[0], & x^k[1], & \cdots, & x^k[N-1] \end{bmatrix}^T,$$
$$\mathbf{w}^k = \begin{bmatrix} w^k[0], & w^k[1], & \cdots, & w^k[N-1] \end{bmatrix}^T,$$

and, $\mathbf{H}^k$ is the channel matrix of size $N \times N$ whose elements are formed by the coefficients of the CIR with the following assignment:

$$\left[\mathbf{H}^k\right]_{n,n'} = h^k\left[n, \langle n-n' \rangle_N\right], \qquad (4)$$

where $n, n' = \{0, 1, ..., N-1\}$ and CIR is assumed to be zero for $\langle n-n' \rangle_N > L-1$. The OFDM symbol received in frequency domain (FD) is obtained by multiplying both sides of (3) by the matrix of the normalized discrete Fourier transform (DFT):

$$[\mathbf{F}]_{n,n'} = \frac{1}{\sqrt{N}} e^{(-j2\pi nn'/N)}, \qquad (5)$$

which gives the result:

$$\mathbf{u}^k = \mathbf{F}\mathbf{H}^k\mathbf{x}^k + \mathbf{z}^k, \qquad (6)$$

where $\mathbf{u}^k$ is the OFDM symbol received in the FD and $\mathbf{z}^k$ is the DFT of the noise vector. Since matrix $\mathbf{F}$ is unitary, the equation (6) can be rewritten in the following way:

$$\mathbf{u}^k = \mathbf{G}^k\mathbf{s}^k + \mathbf{z}^k, \qquad (7)$$

where, $\mathbf{s}^k = \mathbf{F}\mathbf{x}^k$ is the DFT of data vector and $\mathbf{G}^k = \mathbf{F}\mathbf{H}^k\mathbf{F}^H$ is the channel frequency matrix (CFM). If the CIR is time varying, it produces $\mathbf{G}^k$ non-diagonal, which provokes ICI.

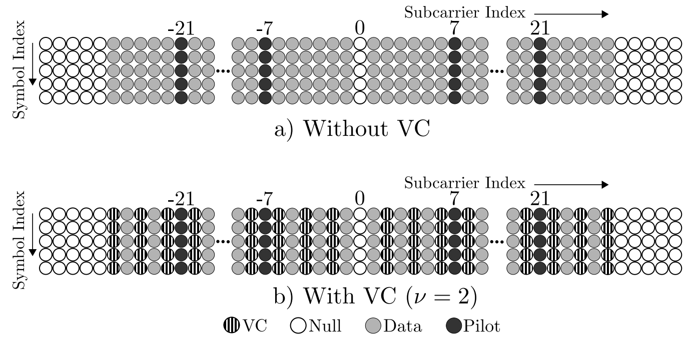

Fig. 2: 802.11p frame without VC and with VC.

A. Virtual carrier insertion

As in [2], an alternative for decreasing the ICI is to insert zero-power guard subcarriers, also known as virtual carriers, which increase the subcarrier spacing. Figure 1 shows proposed OFDM transmitter, based on a conventional OFDM transmitter with a change in the mapping block. The mapping block forms the OFDM symbol, in addition to assigning the vector of zeros $\mathcal{Z}^{VC}$ in their corresponding of VC index within an OFDM symbol. By Including VC in the transmitter leaves $N_{\mathcal{D}} = N_d(1 - 1/\nu)$ active carriers, where $\nu = \lfloor N_d/N_{VC} \rfloor$ is the modulated VC ratio. The active carriers are placed in the subcarrier index belonging to set $\boldsymbol{\psi}$, the elements of $\mathbf{s}^k$ can be expressed as:

$$\mathbf{s}_d^k = \begin{cases} \mathcal{X}, & \text{for} \quad n \in \boldsymbol{\psi}, \\ 0, & \text{for} \quad n \in \overline{\boldsymbol{\psi}}, \end{cases} \qquad (8)$$

where $\mathcal{X}$ denotes a symbol of alphabet of $\boldsymbol{\Omega}$, and $\overline{\boldsymbol{\psi}}$ denotes the complementary set of ψ. On the receiver side, simplification of the detector is made by assuming VCs with negligible energy. The equation (7) can be reduced to following observation model:

$$\mathbf{u}_{\mathcal{D}}^k = \mathbf{G}_{\mathcal{D}}\mathbf{s}_{\mathcal{D}}^k + \mathbf{z}_{\mathcal{D}}^k, \qquad (9)$$

where $\mathbf{u}_{\mathcal{D}}^k, \mathbf{s}_{\mathcal{D}}^k, \mathbf{z}_{\mathcal{D}}^k$, are sampled versions of $\mathbf{u}^k, \mathbf{s}^k$ and $\mathbf{z}^k$ in the $\boldsymbol{\psi}$ index and $\mathbf{G}_{\mathcal{D}}$ is a matrix with rows and columns of $\mathbf{G}$ in the active carrier indexes. Figure 2 shows an example of 802.11p frame without VC and with VC using $\nu = 2$.

III. OSIC DETECTION BASED ON THE QR DECOMPOSITION

First, the QR decomposition [9] of the channel matrix $\mathbf{G}_{\mathcal{D}}$ is computed, we define $\mathbf{G}_{\mathcal{D}} = \mathbf{QR}$, where $\mathbf{Q}$ is a unitary matrix and $\mathbf{R}$ is an upper triangular matrix, both of size $N_{\mathcal{D}} \times N_{\mathcal{D}}$. The basic idea is to obtain a reduces model from (7) using by approximating it in the form:

$$\mathbf{u}_{\mathcal{D}}^k \approx \mathbf{QR}\mathbf{s}_{\mathcal{D}}^k + \mathbf{z}_{\mathcal{D}}^k, \qquad (10)$$
$$\mathbf{Q}^H\mathbf{u}_{\mathcal{D}}^k = \mathbf{R}\mathbf{s}_{\mathcal{D}}^k + \mathbf{Q}^H\mathbf{z}_{\mathcal{D}}^k, \qquad (11)$$
$$\tilde{\mathbf{u}} = \mathbf{R}\mathbf{s}_{\mathcal{D}}^k + \tilde{\mathbf{z}}. \qquad (12)$$

The noise statistics are not altered, since $\mathbf{Q}$ is unitary. The new signal model described in (12) is suitable for the direct application of the ordered successive interference cancellation (OSIC) detection applied to multiple-input multiple-output

TABLE I: Computational complexity in terms of complex products per OFDM symbol required for signal detection.

Detection method	Complexity
Full MLD	$\mathcal{O}(\Omega^N N_d)$
Conventional QR-MLD	$\mathcal{O}(\Omega^N N_d)$
OSIC	$\mathcal{O}(N_d^3)$
LMMSE	$\mathcal{O}(N_d^3)$

(MIMO) systems [9]. Due to the upper triangular structure of matrix $\mathbf{R}$, the j-th element of $\tilde{\mathbf{u}}$ can be obtained by:

$$\tilde{u}_j = r_{jj}s_i + \sum_{i=k+1}^{N_{\mathcal{D}}} r_{ji}s_i + \tilde{z}_j, \tag{13}$$

where r_{ab} denotes the element of matrix $\mathbf{R}$ in the a-th row and in the b-th column. The detection of the j-th received symbol is completed sequentially in the order $j = N_{\mathcal{D}}, N_{\mathcal{D}}-1, \cdots, 1$ using the following expression:

$$\hat{s}_j = \mathcal{Q}\left[\frac{\tilde{u}_j - \sum_{i=j+1}^{N_{\mathcal{D}}} r_{ji}\hat{s}_i}{r_{jj}}\right], \tag{14}$$

where $\mathcal{Q}[\cdot]$ is a decision operator that maps its argument to the closest point in the constellation Ω and $\hat{s}_j$ is the j-th estimated symbol. The contribution of noise $\tilde{\mathbf{z}}$ is not considered due to the fact that its variance was not affected by the $\mathbf{Q}$ matrix' orthonormal property.

A. ICI mitigation in pilots

Because the detection is made taking into account the reduced signal model described in (9), information of the ICI from pilot carriers is not available. As in [10], an alternative to solve this problem is to perform the subtraction of the ICI from pilot carriers, ICI from pilots approximated using a previous OFDM symbol. The approximated ICI is calculated by applying the estimated channel matrix to the pilots from a preceding OFDM symbol in the form:

$$\mathbf{u}^k = \mathbf{u}^{k-1} - \tilde{\mathbf{G}}^{k-1}\mathbf{u}_p^{k-1}, \tag{15}$$

where $\tilde{\mathbf{G}}^{k-1}$ is the estimated channel matrix of previous OFDM symbol with sampled columns on pilot indexes and $\mathbf{u}_p^{k-1}$ is a sampled version of $\mathbf{u}^{k-1}$ in the pilot indexes.

IV. Computational complexity

This section contains a comparison of the most representative detection algorithms used in doubly selective channels. The Table I indicates the order of computational complexity of linear/non-linear detectors. In particular, the use of VC in the communication system reduces the computational cost of the OSIC detector to $\mathcal{O}((N_d/\nu)^3)$. In the case of $\nu = 2$, there is a reduction of 90% of the computational cost required by the OSIC detector compared to the OSIC and LMMSE detectors for an OFDM system without VC.

TABLE II: Simulation parameters.

Parameter	Value
Number of OFDM subcarriers	$N = 64$
Number of data subcarriers	$N_d = 48$
Bandwidth	$BW = 10$ MHz
Samples in the cyclic prefix	$CP = 16$
Sampling time	$T_s = 100ns$
Symbol period	$T_{OFDM} = 8\mu s$
Data modulation	QPSK
Type decoding	Viterbi
Coding rate	$R_c = 1/2, \quad 1/4$
Number of VC (for $R_c = 1/2$)	$N_{VC} = 24$
Number of VC (for $R_c = 1/4$)	$N_{VC} = 0$
Frame length	37 OFDM symbols
Channel model	Exponentially decaying , Rayleigh fading (rms delay spread = 0.4 μs, $f_D = 1$ kHz)
Channel estimation	Perfect channel knowledge

V. Simulations and results

The proposed receiver (see Figure 3) is compared with the performance achieved by an OFDM system without VC but with greater redundancy in FEC encoding/decoding to handle the same spectral efficiency. The experiments were carried out following the specifications of the 802.11p standard [1], replicating a V2V scenario with $v = 100$ km/h [11]. Table II reports the configuration parameters of system.

Figure 4 shows the performance in terms of BER versus SNR achieved by the proposed OFDM system with VC and the OSIC detection. Starting from SNR = 10 dB, the receiver with VC and OSIC detection surpasses by 5 dB the OFDM system without VC and LMMSE detection. Similarly, starting from approximately SNR = 18 dB, the proposed receiver surpasses by 2.5 dB the OFDM system with VC and LMMSE detection, both systems lose half of the spectral efficiency when including VC. However, the OSIC detection obtains a better performance since the LMMSE detection does not perform well on mitigating the ICI. For SNR = 15 dB the presented receiver surpasses by about 3 dB the OFDM system without VC and OSIC detection. The use of $\nu = 2$ in the system means a loss of half the spectral efficiency, however a reduction of 90% is obtained of the computational cost required by the OSIC detector, reducing its complexity order to $\mathcal{O}((N_d/\nu)^3)$ only. In order to provide a fair comparison, the performance of an OFDM system was evaluated with code rate of $R_c = 1/4$ in the FEC coding/decoding to maintain the same spectral efficiency of the system with VC and a FEC of $R_c = 1/2$. The results exhibits and improve on the performance of approximately 1.5 dB starting from SNR = 18 dB, but without reducing the original complexity order of the OSIC detector of $\mathcal{O}(N_d^3)$.

Figure 5 shows the BER-Vs-SNR of OFDM system with OSIC detection without including the stages of FEC coding/decoding, this test emphasizes the improvement on system performance with VC surpassing by 5 dB the system without VC. Again the system with VC obtains a reduction of 90% of the computational cost in the detection, sacrificing half of

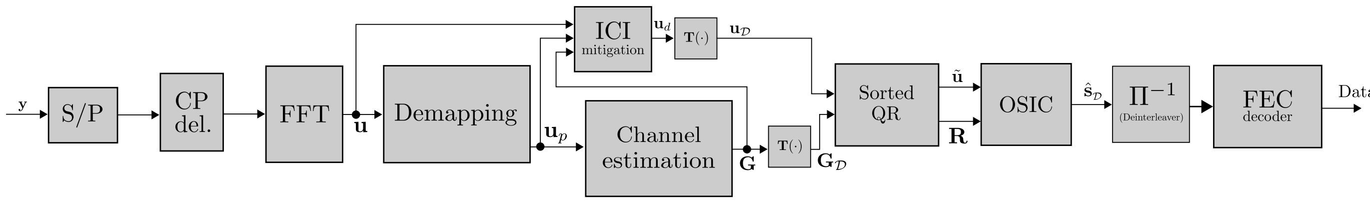

Fig. 3: Proposed OFDM receiver configuration with ICI mitigation and OSIC detection.

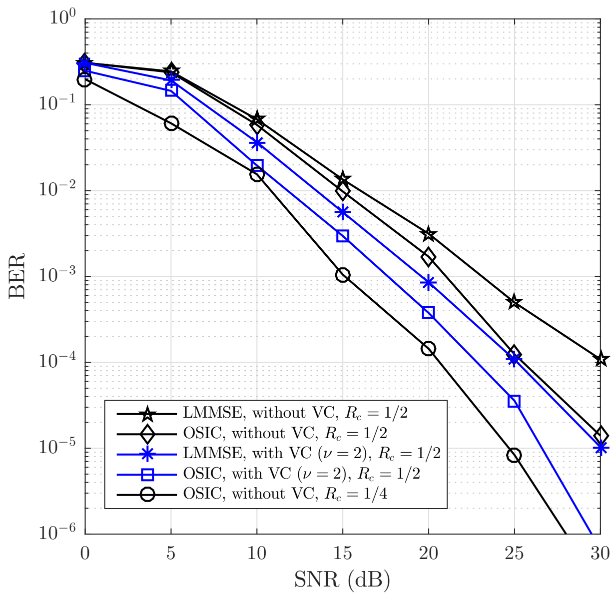

Fig. 4: BER vs SNR for power delay profile exponentially decaying with RMS delay spread of $0.4\mu s$ and frequency Doppler spread of 1 kHz modeling a Rayleigh fading NLOS scenario. The channel model uses a Jake's Doppler profile for each channel tap.

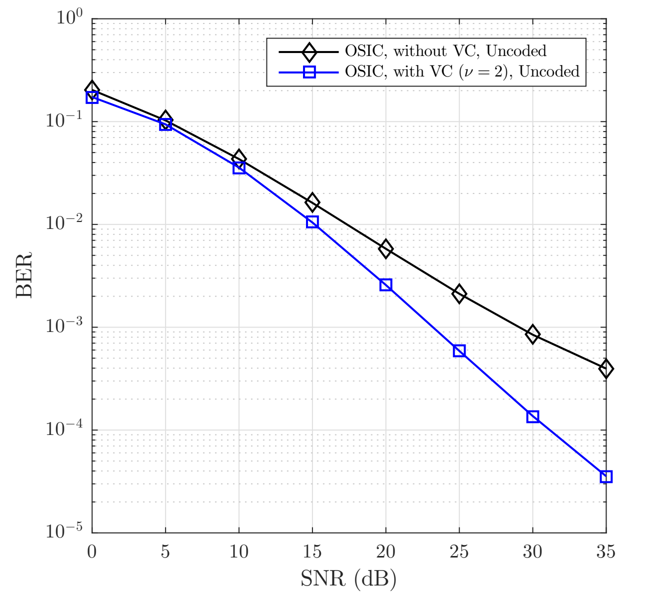

Fig. 5: BER vs SNR comparison of performance of system without FEC coding/decoding with VC and without VC. The channel model uses a Jake's Doppler profile for each channel tap. The power delay profile is exponentially decaying with RMS delay spread of $0.4\mu s$ and frequency Doppler spread of 1 kHz modeling a Rayleigh fading NLOS scenario.

spectral efficiency. It is important to mention that including VC in the transmission improves the system performance and complexity by reducing the ICI on the received signal.

VI. Conclusion

In this paper, the impact of using VC in OFDM systems was analyzed. The results indicate that reduced ICI in systems with VC helps in keeping the receiver complexity low with good performance in terms of BER, surpassing by 5 dB in SNR to system without VC with LMMSE detection. By including VC, a 90% reduction in computational cost was obtained during the detection. Interestingly though, overall VC system throughput with FEC is not reduced impacted when compared with no-VC systems using twice the rate code. Future research lines include exploration of the inclusion of index modulation in OFDM to increase the spectral efficiently in VCs.

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