QUASI-ORTHOGONAL FREQUENCY DIVISION MULTIPLE-ACCESS FOR SERIAL STREAMING TELEMETRY

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ABSTRACT

We propose a spectrally-efficient multiple-access technique that is particularly suitable for aeronautical telemetry applications involving serial streaming of data from multiple test articles to a ground station. Unlike conventional frequency-division multiple access, we assign overlapping frequency bands to different users with a minimum carrier separation corresponding to the symbol rate. We utilize multiuser detection strategies at the ground station to separate the transmissions from different test articles. As shown by the simulation results, the proposed scheme is robust to large frequency offsets due to oscillator offsets and Doppler shifts commonly encountered in aeronautical telemetry applications.
Keywords: FDMA, CDMA, TDMA, OFDMA, SOQPSK, MSK, IRIG, telemetry, serial-streaming, multiple-access, aeronautical.

1 INTRODUCTION

Aeronautical telemetry currently involves serial streaming of data from one or more test articles to a ground station. When multiple test articles transmit simultaneously, each test article is assigned a frequency band such that there is no interference between the signals from different test articles [1]. Whereas using frequency-division multiple-access (FDMA) eliminates multiple-access interference, the undesirable outcome is the use of significant spectrum that is getting scarce as the desired data rates increase from a few hundreds of kilobits per second to several tens of megabits per second. Furthermore, due to the high speeds of test articles, as well as the long distances between the test articles (or users) and ground station, the multiple-access technique should be robust to Doppler shifts, as well as be energy/power efficient.

Conventional multiple-access techniques such as time-division multiple-access (TDMA) require the use of large guard bands due to lack of uplink timing control on a serial streaming link. The use of large guard band (on the order of milliseconds) results in increased latency. Multiple-access techniques based on multicarrier technologies such as orthogonal frequency-division multiple access (OFDMA) and multicarrier code-division multiple-access (MC-CDMA) suffer from problems such as large peak-to-average power ratio, and are susceptible to frequency offsets due to closely spaced subcarriers [2]. Due to the fact that only a few test articles are communicating with the ground station, single-carrier CDMA systems such as direct-sequence CDMA (DS-CDMA) do not have sufficient processing gain to handle timing and frequency offsets.

In order to address the above challenges, we propose FDMA-based multiple-access techniques. Analogous to FDMA, each test article is assigned a different frequency band. However, contrary to FDMA, the frequency bands are overlapping. For example, current telemetry standard prescribes a minimum carrier separation of 5.5 MHz for communicating at a data rate of 5 Mbps using shaped-offset quadrature-shift keying (SOQPSK) [1]. Using QO-FDMA, the test articles will be spaced by 2.5 MHz for a data rate of 5 Mbps using minimum-shift keying (MSK) modulation. Since the minimum separation needed to ensure orthogonality is the symbol rate when there is no pulse-shaping, we refer to this scheme as quasi-orthogonal FDMA (QO-FDMA). Due to a limited number of users transmitting simultaneously, it is possible to utilize multiuser detection techniques to eliminate multiple-access interference due to spectral overlap. Furthermore, the use of modulation schemes such as minimum-shift keying results in a good tradeoff between power efficiency and bandwidth efficiency [3]. Finally, due to the large separation between the carriers of different users, QO-FDMA is as robust to frequency offsets as conventional FDMA.

In this paper, we study the performance degradation of QO-FDMA caused by multiple-access interference, as well as study the impact of frequency offsets on the overall performance. Aeronautical serial streaming multiple-access also suffers from large timing offsets between test articles and multipath channel conditions, and this paper forms the first of the studies to be carried out, and we will focus of frequency offsets due to oscillator offsets and Doppler shifts.

The rest of the paper is organized as follows: In Sec. 2, we present drawbacks of conventional multiple-access techniques when applied to a serial streaming telemetry link. In Sec. 3, we provide an overview of QO-FDMA, followed by a description of the system model for transmitter and receiver in Sec. 4. We study the performance of QO-FDMA in the presence of frequency offsets in Sec. 5. Finally, we provide some concluding remarks and future work in Sec. 6. A note on notation: bold, lower case letters are used to represent column vectors; the superscripts T and H are used to denote matrix transpose, and conjugate transpose, respectively; $[R]_{k,l}$ represents the $(k-l)$-th element of the matrix R; and $\text{diag}(\cdot)$ represents a diagonal matrix generated by the entries.

2 STATE-OF-THE-ART MULTIPLE-ACCESS TECHNOLOGIES

State-of-the-art multiple access techniques include TDMA; DS-CDMA and its multi-carrier variants such as MC-CDMA and variable spreading factor orthogonal frequency code-division multiplexing (VSF-OFCDM); OFDMA; and single-carrier FDMA (SC-FDMA). Of these techniques TDMA requires tight synchronization of signals from different test articles, which is not possible in a serial streaming telemetry scenario, thereby requiring the use of large guard bands to prevent interference. Furthermore, since only one user can transmit at any given instant, the overall peak power constraint results in reduced power efficiency, and the impact is proportional to the number of users. Finally, the bandwidth occupied increases by a factor corresponding to the number of users. DS-CDMA systems rely on the use of long spreading codes in order to separate multiple users. However, current tests involve only a few test articles, which limits the degree of spreading available to separate users, and therefore makes it unsuitable for current telemetry applications.

Multicarrier techniques such as OFDMA, MC-CDMA, VSF-OFCDM and SC-FDMA (SC-FDMA is simply a pre-coded OFDMA, with the pre-coding being a discrete Fourier transform (DFT)) have the following essential characteristics [2]:

- Conversion of a single high-bandwidth signal into multiple low bandwidth signals. These individual low-bandwidth signals are mapped on to different subcarriers that are orthogonal to each other. Such a conversion results in improved spectral efficiency.

- Transmission in blocks or chunks of symbols, with each block containing a guard-band called cyclic prefix to prevent inter-block interference. The use a cyclic prefix allows a receiver to perform frequency-domain equalization for multipath channels using DFT and inverse DFT (IDFT) operations.

- High peak-to-average power ratio (PAPR) relative to single-carrier techniques such as TDMA, FDMA and CDMA due to the combination of several signals on different subcarriers. In case of SC-FDMA, the use of pre-coding reduces the PAPR. In fact, interleaved subcarrier mapping retains the peak-to-average power ratio of the underlying single-carrier signal.

2.1 CHALLENGES ASSOCIATED WITH AERONAUTICAL ENVIRONMENT

The primary challenge to multiple access techniques for unidirectional aeronautical telemetry is the lack of synchronization between signals received from different test articles due to timing and frequency offsets.

- Frequency offsets: Frequency offsets between the received signals from different test articles arise primarily due to two factors: (i) Doppler shifts, and (ii) oscillator offsets. Doppler shift is caused by relative motion between the test articles and the ground station, and oscillator offsets are caused due to the variations in components. For example, a relative velocity between test articles of 300 m/s at 5 GHz can result in a Doppler shift of 10 KHz, and 1ppm oscillator stability will result in a maximum relative frequency offset of around 10 KHz. The impact of frequency offsets on OFDMA-like systems depends on the ratio of frequency offset and the subcarrier spacing. For example, in order to communicate at 5 Mbps using quadrature phase-shift keying (QPSK) with 1024 subcarriers results in a subcarrier spacing of around 14 KHz. Therefore, a frequency offset of 10 KHz results in significant degradation in performance due to loss of orthogonality between subcarriers.

- Timing offsets: Similar to frequency offsets, timing offsets can result in interference between different signals. Lack of synchronized transmission, as well as the difference in transmission delays due to propagation, contributes to the overall timing offset. For example, if we consider a relative distance of 60 Km between two users, then the timing offset between the two transmissions is around 200 us. Since cyclic prefix duration is typically a few microseconds or less, timing offsets of tens of microseconds results in inter-block interference that can be catastrophic to the performance of multi-carrier systems.

- Power efficiency: Often due to long communication link distances, the transmitter power is high (around 10 W), and therefore maximizing power efficiency requires operating close to the saturation point of the power amplifiers. In order to operate the power amplifier close to saturation, it is desirable to use signals with low crest-factor or PAPR, i.e., signals with low variation in their envelope. In order to avoid non-linear distortion of signals with high PAPR, it is necessary to operate the power amplifier with a backoff, resulting in lower average power output, and thereby lower efficiency. Multi-carrier techniques such as MC-CDMA and OFDMA result in high PAPR, with a crest factor of close to 10 dB or more, requiring a large backoff in order to operate the power amplifier linearly. By nature of the design of SC-FDMA, the crest factor is expected to be between that of a pure single-carrier transmission scheme such as CDMA, and a pure multiple-carrier transmission technique such as OFDMA.

The performance impact of frequency and timing offsets on OFDMA, SC-FDMA, and MC-CDMA has been well investigated, and the impact is known to be significant [4, 5, 6]. Our proposed technology of QO-FDMA alleviates the impact of frequency offsets by using single-carrier transmissions and providing sufficient separation between the signals from multiple test articles. Finally, the power efficiency is maximized through the use of constant envelope modulation schemes such as MSK [3].

3 QUASI-ORTHOGONAL FREQUENCY-DIVISION MULTIPLE-ACCESS

The primary difference between FDMA and QO-FDMA is the degree of overlap allowed between the spectra of different users. QO-FDMA allows for a minimum separation of half the bit rate when using MSK modulation, which results in significant spectral overlap. We consider to possible frequency assignments for QO-FDMA: (a) the users are separated by symbol rate (we call this mode *QOFDMA-min*), and (b) the users are divided into groups containing two users each, and users within a group are separated by symbol rate, whereas groups themselves are separated by bit rate (or twice symbol rate) for MSK modulation (we call this mode *QOFDMA-group*). Therefore for four users communicating using QO-FDMA, the overall bandwidth (99% bandwidth) occupied is 13.5 MHz for QOFDMA-min and 15

MHz for QOFDMA-group. In contrast, conventional FDMA operates by assigning users frequency bands that are separated by large guard bands. Signaling using MSK requires a minimum frequency separation corresponding to 1.5 times bit rate to avoid overlapping between different signals. Therefore, the overall bandwidth occupied for four users is around 28.5 MHz (cf. Fig. 1). The spectra for FDMA and QOFDMA are shown in Fig. 1 and Fig. 2, respectively. On the other hand, if we consider communication using OFDMA with 1024 subcarriers and 224 guard band carriers, then the bandwidth occupied to communicate at 5 Mbps using QPSK modulation is between 11.25 MHz and 14.4 MHz (depending on the portion of guard band accounted for in the total bandwidth). Therefore QO-FDMA requires between 48% and 53% lesser bandwidth than orthogonal FDMA, and requires bandwidth similar to spectrally-efficient OFDMA.

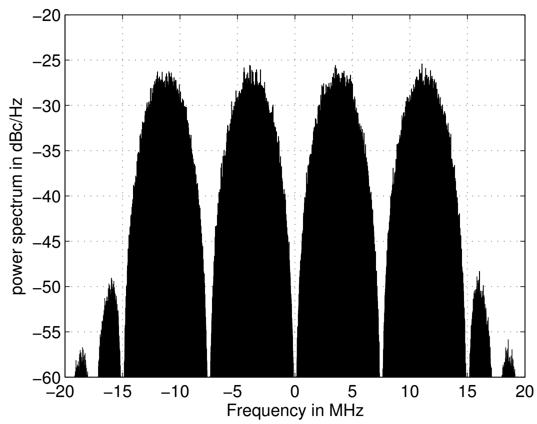
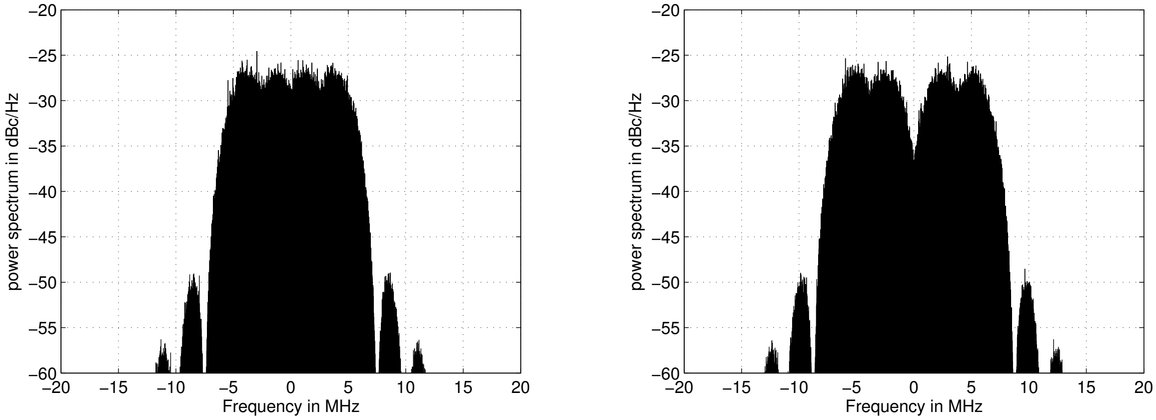


Figure 1: Power spectrum for FDMA at 5 Mbps bit rate. The occupied bandwidth 28.5 MHz.

The minimum carrier spacing to ensure orthogonality between two signals without filtering or pulse shaping is the symbol rate (symbol rate is the signaling rate after coding and modulation), and therefore QO-FDMA uses a carrier separation corresponding to the symbol rate. Although pulse-shaping such as half-sine (which is used for MSK signaling), destroys orthogonality, it is possible to separate the users at the receiver using multiuser detection techniques. Similar to OFDMA, we add cyclic prefix to the end of each frame in order to allow a receiver to perform frequency domain equalization. The length of the cyclic prefix is chosen to be greater than the multipath excess time delay in order to avoid inter-block interference for each user.

4 SYSTEM MODEL

We will formulate the problem for a system using M-ary phase-shift keying (PSK) or quadrature amplitude modulation (QAM), but the analysis can be easily modify to suit modulation schemes such as MSK. Furthermore, the performance should be similar for both QPSK and



(a) QOFDMA with minimum separation

(b) QOFDMA with grouped separation

Figure 2: Power spectra for QOFDMA at 5 Mbps bit rate. The occupied bandwidth 13.5 MHz for QOFDMA with minimum separation, and 15 MHz for grouped separation.

MSK schemes. The complex baseband transmitted signal for the k-th user is given by

$$s_k(t) = \sqrt{E_s} \sum_{n=0}^{\infty} s_k[n] p(t - nT) e^{j2\pi \Delta f_k t}, \tag{1}$$

where E_s denotes the energy per symbol; $b_k[n]$ denotes the M-ary PSK/QAM symbol of unit average energy; $p(\cdot)$ denotes the pulse-shape of unit energy, and we assume has finite support corresponding to symbol duration T; Δf_k denotes the k-th user's frequency assignment, measured relative to the carrier frequency. In order to mimic a performance similar to MSK, we use a pulse-shape that is half a period of a sinusoid, and the symbols $b_k[n]$ are drawn from a QPSK constellation of unit amplitude.

Let $h_k(t) = \sum_{l=0}^{L-1} h_k[l]\delta(t - lT)$ denote the k-th user's channel consisting of L resolvable multipath components. Under symbol synchronous conditions, the complex baseband received signal is then given by

$$y(t) = \sum_{k=1}^{K} \left(s_k(t) e^{j2\pi \tilde{\Delta f}_k t} \right) * h_k(t) + n(t), \tag{2}$$

where we assume there are K users; $\tilde{\Delta f}_k$ is the frequency offset between observed at the receiver due to oscillator offsets and Doppler shift; and $n(\cdot)$ denotes complex additive white Gaussian noise (AWGN) with power spectral density N_0. In order to generate sufficient statistics for each user, the receiver performs digital down-conversion, followed by matched-filtering and sampling, resulting in the following received signal vector during the n-th symbol duration (we omit the details of deriving the received signal vector due to space constraints, but the steps are similar to those involved in generating the received signal vector for DS-CDMA [7]):

$$\mathbf{y}[n] = \Phi[n] R \Phi^H[n] \mathbf{u}[n] + \mathbf{v}[n], \tag{3}$$

where

- $\Phi[n] = \text{diag}\left(e^{-j2\pi n(\epsilon_1+\tilde{\epsilon}_1)}, e^{-j2\pi n(\epsilon_2+\tilde{\epsilon}_2)}, \ldots, e^{-j2\pi n(\epsilon_K+\tilde{\epsilon}_K)}\right)$, $\epsilon_k = \Delta f_k T$, $\tilde{\epsilon}_k = \tilde{\Delta f}_k T$. The matrix $\Phi[n]$ represents the impact of time-variations caused by frequency offsets between the different users. In particular, as proposed, if we consider a carrier separation of a multiple of symbol rate, then the time-variations vanish in the absence of oscillator frequency offsets and relative Doppler shifts.

- R is a $K \times K$ matrix such that $[R]_{k,k'} = \rho_{k,k'} = \int_0^T p^2(t) e^{-j2\pi(\Delta f_k + \tilde{\Delta f}_k - \Delta f_{k'} - \tilde{\Delta f}_{k'})} dt$. The matrix R captures the correlations between different users due to spectral overlapping. Clearly, the correlation depends on the pulse-shaping used, as well as the frequency difference between the various users. In particular, if we consider half-sine pulse-shaping, then the correlation coefficients are either -0.5 or 0, depending on whether the carrier separation is symbol rate, or a multiple of symbol rate greater than 1, respectively.

- $\mathbf{u}[n] = [u_1[n], u_2[n], \ldots, u_K[n]]^T$ with $u_k[n]$ given by $u_k[n] = \sum_{l=0}^{L-1} h_k[l] b_k[n-l]$. The vector $\mathbf{u}[n]$ captures the impact of the multipath channel on the transmitted symbols, and is a convolution between the transmitted symbols and the channel coefficients.

- $\mathbf{v}[n]$ represents the effective noise vector that is complex normal with zero mean and covariance matrix $\Phi[n] R \Phi^H[n]$.

Due to the complexity of maximum-likelihood detector, especially in a multipath environment, we consider a decorrelator to eliminate multiple-access interference, followed by single-user detector [7]. A block diagram of the suboptimal receiver is shown in Fig. 3. The operations performed at the receiver attempt to negate or equalize the effects of time-variations in the form of Φ, multiple-access interference in the form of R, and multipath channel in the form of $\mathbf{u}$. The decorrelator is given by $\Phi[n] R^{-1} \Phi^H[n]$, and the noise enhancement cause by decorrelation is determined by the diagonal values of R^{-1}. The decorrelation operation results in the following signal for the k-th user:

$$z_k[n] = u_k[n] + \tilde{v}_k[n], \tag{4}$$

where $\tilde{v}_k[n]$ represents the effective noise that is also complex normal with zero mean and variance, $\sigma^2_{\tilde{v}_k} = [R^{-1}]_{k,k}$.

The final step in the receiver is to equalize the received signal for multipath effects, and in order to achieve this we transmit signals in blocks of N symbols, with each block appended by a cyclic-prefix. The use to cyclic-prefix of length longer than the excess multipath delay not only eliminates inter-block interference, but also provides the ability to perform frequency domain equalization using discrete Fourier transform.[1]

[1] It is interesting to note that appending a block with zeros also achieves the objective of eliminating inter-block interference. However, equalizing such a channel requires inverting a Toeplitz matrix whose entries are given by the multipath channel coefficients. The beauty of using cyclic prefix lies in the fact that the Toeplitz matrix thus generated is circulant, and the matrices the operation of discrete Fourier transform are actually eigenvectors for any circulant matrix.

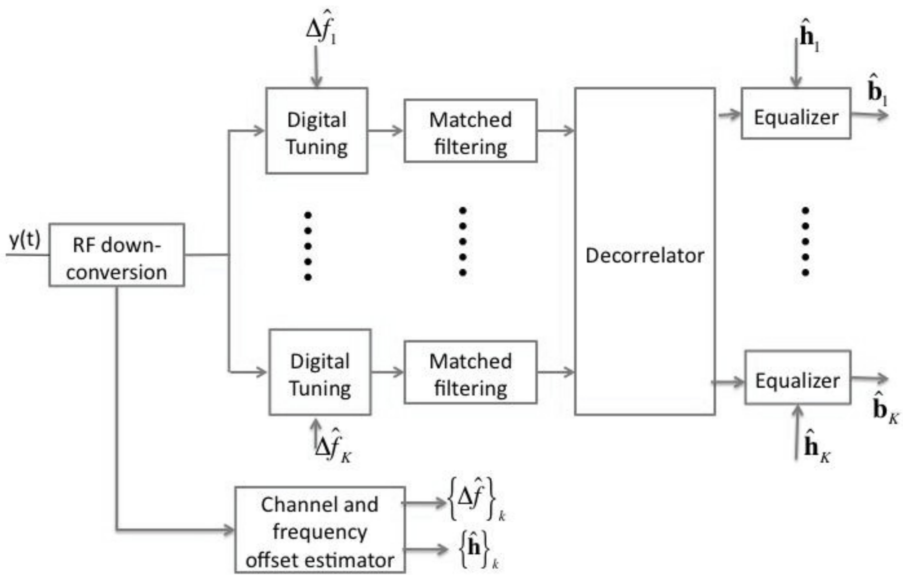


Figure 3: Receiver block diagram.

5 PERFORMANCE RESULTS

In this section we will first study the performance degradation caused due to overlapping spectral assignment for each user in a four-user multiple-access scenario. We will compare the performance of QOFDMA-min and QOFDMA-group with that of conventional, interference-free FDMA under AWGN channel conditions. The performance is depicted in Fig. 4 under symbol-synchronous conditions and no frequency offsets due to oscillator offsets and Doppler shifts. Under AWGN conditions, the performance degradation for QOFDMA is determined by the diagonal values of the inverse of correlation matrix R. The matrix R is given as follows for the two QOFDMA modes:

- QOFDMA-min:

$$R = \begin{bmatrix} 1 & -0.5 & 0 & 0 \\ -0.5 & 1 & -0.5 & 0 \\ 0 & -0.5 & 1 & -0.5 \\ 0 & 0 & -0.5 & 1 \end{bmatrix}; \quad R^{-1} = \begin{bmatrix} 1.6 & 1.2 & 0.8 & 0.4 \\ 1.2 & 2.4 & 1.6 & 0.8 \\ 0.8 & 1.6 & 2.4 & 1.2 \\ 0.4 & 0.8 & 1.2 & 1.6 \end{bmatrix}. \tag{5}$$

- QOFDMA-group:

$$R = \begin{bmatrix} 1 & -0.5 & 0 & 0 \\ -0.5 & 1 & 0 & 0 \\ 0 & 0 & 1 & -0.5 \\ 0 & 0 & -0.5 & 1 \end{bmatrix}; \quad R^{-1} = \begin{bmatrix} 1.33 & 0.67 & 0 & 0 \\ 0.667 & 1.33 & 0 & 0 \\ 0 & 0 & 1.33 & 0.67 \\ 0 & 0 & 0.67 & 1.33 \end{bmatrix}. \tag{6}$$

Based on the inverse of the above matrices, we can easily show that the performance degradation for QOFDMA-min is $10\log_{10}(1.6) = 2$ dB for outer users, and around $10\log_{10}(2.4) =$

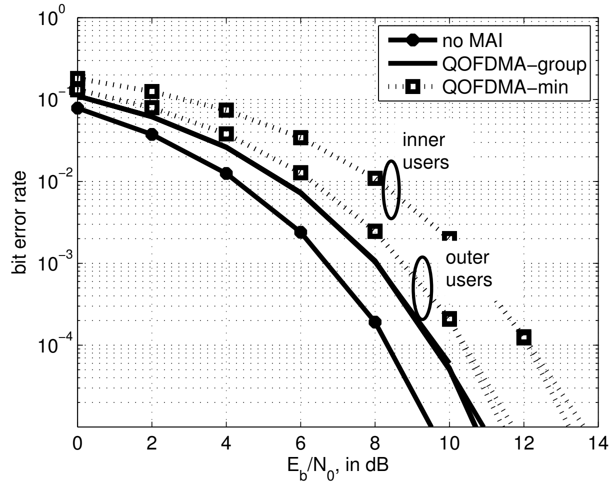


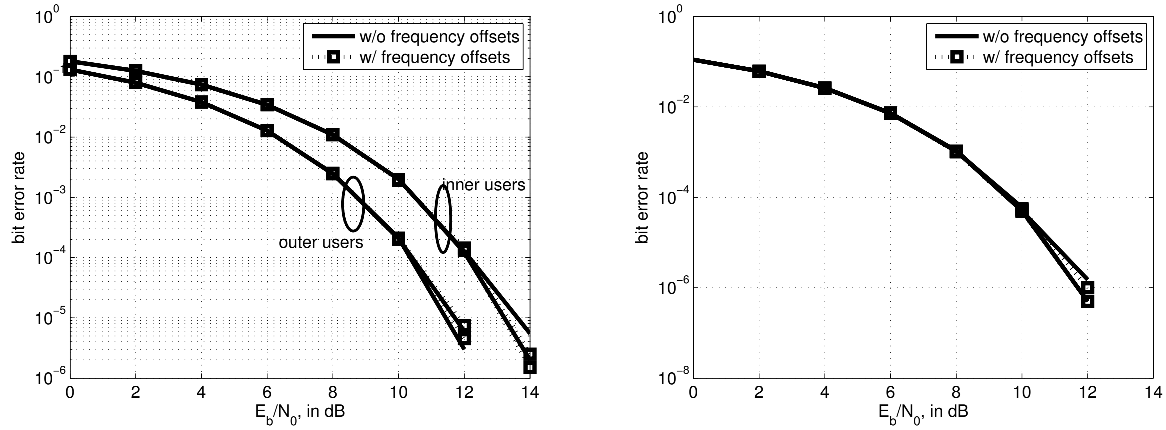
Figure 4: Performance comparison in the absence of frequency offsets due to oscillator and Doppler shifts in AWGN channel conditions.

3.8 dB for inner users (i.e., users assigned carriers between the two outer users). On the other hand, the performance degradation for QOFDMA-group is around $10 \log_{10}(1.33) = 1.25$ dB for all users.

We turn our attention toward the performance impact of frequency offsets due to oscillator offsets and large relative Doppler shifts due high speed articles such as aircraft and missiles. The figure of merit that determines the degree of impact due to frequency offsets is the normalized relative frequency offset, normalized with respect to the carrier separation between the different users. Since we adopt a minimum carrier separation corresponding to the symbol rate, the normalization is done with respect to the symbol rate. For example, if we consider a data rate of 5 Mbps using MSK or QPSK modulation, then the symbol rate is 2.5 Msps. For an article traveling at a speed of around 300 m/s, the maximum Doppler shift observed is around 10 KHz at 5 GHz which results in a normalized frequency offset of 0.004. Furthermore, if we consider an oscillator stability of 1 ppm, then the frequency offset due to oscillator instabilities can be around 10 KHz, resulting in an overall normalized frequency offset of around $0.008 << 1$. Therefore, we expect the impact of frequency offsets to be negligible. The average bit error rate performance, averaged over frequency offsets chosen uniformly between 0 and 7.5 KHz is shown in Fig. 5. We notice that the performance degradation of QO-FDMA due to frequency offsets is negligible. In contrast, the performance degradation under similar frequency offsets for OFDMA and SC-FDMA systems is at least 3-4 dB, with SC-FDMA performing at least 2 dB or more worse than OFDMA [6].

6 CONCLUSIONS AND FUTURE WORK

In this paper we have proposed a novel multiple-access technique based on FDMA that allows overlap between the spectra of different users in order to conserve spectral resources.In



(a) QOFDMA-min (b) QOFDMA-group

Figure 5: Average BER performance comparison averaged over frequency offsets due to oscillator and Doppler shifts in AWGN channel conditions.

addition to a saving of around 48% in spectral occupancy, relative to conventional FDMA, simulation results show that the impact of frequency offsets due to lack of frequency synchronization between users is negligible. In the future, we will study the impact of timing offsets, channel estimation and equalization under multipath fading conditions.

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