Abstract—This paper investigates the applicability of gener- alized frequency division multiplexing (GFDM) for an uplink scenario where several users are not perfectly synchronized, as it appears in wireless sensor networks (WSN). We compare the performance in terms of inter-user interference (IUI) caused by time and frequency misalignments between users, where the physical layer is realized with GFDM and OFDM. It is shown that IUI can be significantly reduced when using GFDM. Furthermore, we propose a data-aided phase error estimation and compensation algorithm which is capable of correcting residual phase errors at the receiver.

Index Terms—5G, GFDM, Channel Estimation, Interference

I. INTRODUCTION

With the upcoming 5th generation (5G) of cellular networks, requirements that go beyond increased data rates are stated [1]. The physical layer (PHY) of 5G networks should support low-latency transmissions [2], provide means for an agile and opportunistic spectrum usage [3], [4] and also relax synchronization requirements among nodes [1]. Several waveforms are being researched that address these requirements. One candidate is Filterbank multicarrier (FBMC) [5] due to its advantageous properties of low spectral leakage and robustness against misalignments [6]. However, its long filter tails, which are typically four times the symbol duration, make it spectrally inefficient when transmitting short packets of data, as it appears in machine to machine (M2M) communication [7].

In particular, for WSN, where sensors observe e.g. environmental aspects such as temperature or humidity, data transmission to the access point happens sporadically and with very short packets. Then, synchronization and multiple access (MA) protocols must be of very low complexity and duration to ensure a low energy consumption and signalling overhead. Accordingly, waveforms that are robust against imperfect synchronization are advantageous in these applications, compared to the strictly synchronized orthogonal frequency division multiplexing (OFDM) PHY of the current 4G Long-Term Evolution (LTE) system.

Several efforts are being made in order to obtain robust synchronization for current waveforms. In [8], a time synchronization algorithm based on a time-reversal technique [9] is proposed for OFDM to reduce the impact of the delay profile on timing errors. Another approach selectively chooses Zadoff-Chu sequences to describe a synchronization algorithm that is robust against time and frequency offsets [10]. Selection and maximum ratio combiners are employed in [11] to improve the performance of the timing synchronization in multiple-input multiple-output (MIMO) OFDM. However, the simple devices used in WSN cannot afford the complexity of these synchronization algorithms because of hardware and energy limitations.

In this paper, we investigate the applicability of generalized frequency division multiplexing (GFDM) [12] for the application in WSN. GFDM is a promising waveform for 5G networks, claiming to provide a very low out-of-band (OOF) radiation and means to efficiently transmit packets of small sizes as they appear in the presented scenario. Its time-confined block structure does not exhibit the disadvantage of long filter tails but instead filtering is carried out in a circular manner within the GFDM block, which allows separate processing of each block. In [13], it is claimed that GFDM is robust against time and frequency misalignments, which is an important requirement for the presented scenario, though no evidence was provided. In [14], the authors investigate solely the effect of carrier frequency offsets on a GFDM system, but only the single-user case is presented. The authors in [15] propose a dedicated preamble used for synchronization which is able to estimate timing and frequency misalignments. However, again the multi-user case is ignored. Furthermore, although the synchronization is achieved very accurately with the therein proposed approach, the resulting symbol error rate (SER) diverges from the optimal curve, which is caused by residual offset.

In this paper we examine the inter-user interference (IUI) that occurs between misaligned users in the uplink, when the access point decodes multiple users at the same time. As a baseline, we compare the performance of GFDM with the well known OFDM system, as it is used in e.g. IEEE 802.11a [16]. We show that GFDM significantly outperforms OFDM in terms of IUI. Moreover, we propose a data-aided method to accurately estimate and compensate residual time and frequency misalignments which is applied after coarse synchronization.

The remainder of this paper is organized as follows: In Sec. II, GFDM is introduced and the considered uplink system model is described. Sec. III investigates the influence of time and frequency misalignments of different users onto the system performance. A misalignment estimation and compensation algorithm is described in Sec. IV. Finally, the conclusions are drawn in Sec. V.


II. SYSTEM MODEL

A. GFDM system

GFDM is a filtered multicarrier scheme, where the data is transmitted within blocks which are separated by a cyclic prefix (CP). Within each GFDM block, $M$ subsymbols of $K$ samples each are transmitted per subcarrier. Hence, according to the Nyquist theorem the number of available subcarriers is $K$ and a GFDM block contains $N = KM$ samples. Each subcarrier is filtered with a subcarrier filter $g[n]$ where convolution is carried out circular with period $N$ to confine the transmit signal to the $N$ samples of the block. Usually, a raised cosine (RC) filter is employed as prototype filter [12]. For each user, only the allocated subcarriers are modulated. Hence, the signal $x^{(u)}_{\text{sync}}[n]$ of the $u$th user’s GFDM block is given by

$$x^{(u)}_{\text{sync}}[n] = \sum_{m \in \mathcal{M}} \sum_{k \in K^{(u)}} d_k^{(u)}[m] g_{km}[n] \quad n = 0, \ldots, N - 1,$$

which is assumed to vanish for $n \notin \{0, \ldots, N - 1\}$. There,

$$g_{km}[n] = g[(n - mK) \mod N] \exp(j2\pi \frac{mK}{N})$$

is the prototype filter $g[n]$ circularly shifted to the position of the $k$th subcarrier and $m$th subsymbol. $K^{(u)}$ and $\mathcal{M}$ denote the set of allocated subcarriers and subsymbols of the $u$th user in the GFDM block, respectively. $d_k^{(u)}[n]$ is the complex-valued data symbol to be transmitted in the $k$th subcarrier and $m$th subsymbol of the $u$th user’s GFDM block. Each user successively transmits GFDM blocks one after another, as shown in Fig. 1.

![Fig. 1: Position of the receiver window when User 1 is to be demodulated and other users have different time offsets.](image)

A CP of length of $N_{\text{CP}}$ is added to each GFDM block to combat timing offsets at the receiver and multipath effects in case a multipath channel is considered, resulting in the signal $x^{(u)}_{\text{sync}}[n]$ of length $N + N_{\text{CP}}$. Each user has a time offset of $\tau^{(u)}$ and a frequency offset of $\phi^{(u)}$ samples and hence its transmit signal $x^{(u)}[n]$ is given by

$$x^{(u)}[n] = T_\tau x^{(u)}_{\text{sync}}[n].$$

There,

$$T_\tau x[n] = s[n - \tau] * x[n]$$

and

$$F_\phi x[n] = \exp \left(j2\pi \left( \frac{\phi}{N} + \frac{\tau}{N} \right) \right) \cdot x[n]$$

describe the shift in time and frequency of the user $u$. The application of $s[n] = \sin(\frac{\pi n}{N})$ allows fractional time misalignment and $\phi_0$ models an arbitrary starting phase of the exponential. Note that $s[n - \tau] = \delta[n - \tau]$ when $\tau \in \mathbb{Z}$. Further, let

$$T_\tau^N x[n] = s[n - \tau] \circledast x[n]$$

denote a rotation of $x[n]$ by $\tau$, where $x[n]$ is constraint to $N$ samples. Note that a frequency offset of $\phi^{(u)} = M$ samples equals an offset of one subcarrier. In the present investigation, the signal is sent over a MA additive white Gaussian noise (AWGN) channel. Accordingly, the signals of all users add to the signal $y[n]$ at the receiving antenna of the access point, given by

$$y[n] = \sum_{u \in \mathcal{U}} x^{(u)}[n] + w[n],$$

where $w[n]$ is the AWGN at the receiver and $\mathcal{U}$ is the set of transmitting users.

At the receiver, a coarse synchronization to the user of interest is carried out, leaving a residual time offset $\Delta \tau$ and frequency offset $\Delta \phi$. A receiver window with the length of $N$ samples is used to extract the signal of the user of interest. Based on the coarse synchronization, the window starts roughly in the middle of the CP of this user, combating positive as well as negative timing offsets. Then, the signal within the window is circularly shifted by half of the CP length so that, with perfect synchronization, the original signal of the user is recovered. Without loss of generality, we can assume that user 1 is the user of interest. Further, assume $\tau^{(1)} = 0, \phi^{(1)} = 0$. Then, the signal $y^{(1)}[n]$ sent to the GFDM demodulator is given by

$$y^{(1)}[n] = T_\Delta^N F_{\Delta \phi}(y^{(1)})_{n \in \mathcal{W}} + w[n],$$

where $\mathcal{W} = \{N/2, \ldots, N + N/2 - 1\}$ is the set of samples that are within the receiver window. Eq. (8) can be rewritten to

$$y^{(1)}[n] = T_\Delta^N F_{\Delta \phi} x^{(1)}[n] + I + w[n],$$

where $I$ is the signal in the receiver window coming from other users. Fig. 1 illustrates the signal in the receiver window and the resulting $y^{(1)}[n]$ which is then sent to the GFDM demodulator.

In the GFDM demodulator, the received signal $y^{(u)}[n]$ is first downconverted to the subcarriers of interest, then circularly convolved with a receiver filter $g_{\text{Rx}}[-n]$ and finally downsampled by $K$ to obtain the estimated data values. Afterwards, the subcarrier demapping selects the subcarriers that are allocated for the $u$th user. Accordingly, the GFDM demodulation equation is given by

$$d_k^{(u)}[m] = (g_{\text{Rx}}[-n] \circledast \exp(-j2\pi \frac{mK}{N})) y^{(u)}[n])_{n = mK}, \quad k \in K^{(u)}.$$  

which can be equally described with the scalar product by

$$d_k^{(u)}[m] = \langle g_{\text{Rx}}[m], y^{(u)}[n] \rangle_{\mathcal{C}^{N}},$$  

where $g_{\text{Rx}}[m]$ denotes a time-frequency shift of $g_{\text{Rx}}[n]$ similar to (2). In the present investigation, the receiver filter $g_{\text{Rx}}[n]$ is

*This assumption is without loss of generality since offsets for user 1 are captured in $\Delta \tau$ and $\Delta \phi$. 
a zero-forcing (ZF) filter, i.e. under perfect synchronization and with no noise, the transmitted symbols are perfectly reconstructed at the receiver. This property is due to the bi-orthogonality between transmit and ZF receiver filters [13].

B. Uplink scenario

Consider the following multi-user multicarrier uplink transmission scenario. The available bandwidth is divided into \( K \) subcarriers, where only \( K_{on} \) are actually allocated. These \( K_{on} \) subcarriers are divided into \( B_s \) subchannels, with \( K_s \) subcarriers each and \( K_g \) guard carriers between them. As transmission techniques both GFDM and OFDM are applied. Fig. 2 illustrates the division of the spectrum into several subchannels considering the parameters presented in Tab. I, resembling the subchannel configuration of IEEE 802.11a OFDM, and quantizes the OOB radiation of GFDM and OFDM systems. As visible, GFDM has a significantly lower OOB radiation than OFDM.

We consider an M2M scenario, where devices can select the subchannels for random access transmission of sporadically appearing short bursts of data. The nodes obey a carrier sense multiple access (CSMA) behaviour [17], i.e. they only transmit in a given subchannel if it appears empty. Accordingly, transmissions in different subchannels appear completely asynchronous. Furthermore, due to energy-efficiency, the devices cannot achieve an accurate frequency synchronization with the access point. Hence, frequency misalignments between the users and the access point appear. In the following we analyze the suitability of GFDM in such a scenario and compare its performance with conventional OFDM.

**TABLE I: Parameters for GFDM and OFDM for evaluation.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>GFDM</th>
<th>OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td># subsymbols per block</td>
<td>( M )</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Allocated subsymbols</td>
<td>( M )</td>
<td>{1, \ldots, 13}</td>
<td>{0}</td>
</tr>
<tr>
<td># available subcarriers</td>
<td>( K )</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td># used subcarriers</td>
<td>( K_{on} )</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td># subchannels</td>
<td>( B_s )</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td># subcarriers/subchannel</td>
<td>( K_s )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td># band guard subcarriers</td>
<td>( K_g )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CP duration</td>
<td>( N_{CP} )</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Filter</td>
<td>( g[n] )</td>
<td>RC, ( \alpha = 0.1 )</td>
<td>rect</td>
</tr>
<tr>
<td>Modulation</td>
<td></td>
<td>QPSK</td>
<td>QPSK</td>
</tr>
</tbody>
</table>

Fig. 2: Arrangement of subchannels with GFDM and OFDM modulation. Different subchannels are described by different colors.

**Fig. 3: Overlapping spectra of GFDM and OFDM.** Note that due to the CP, the spectrum of OFDM is not zero at the subcarrier positions.

### III. INTERFERENCE FROM ASYNCHRONOUS USERS

The performance evaluations described in this section consider the parameters presented in Tab. I for both GFDM and OFDM, however only the subchannels 1 and 2 are occupied. User 1 continuously transmits in subchannel 1 and it is perfectly synchronized with the access point i.e. \( \Delta \tau = 0, \Delta \phi = 0 \). The asynchronous case is considered in Sec. IV. Subchannel 2 is allocated by the asynchronous user 2 that has a time and frequency offset according to (3). This scenario is illustrated in Fig. 3. The interference caused by user 2 to user 1 is measured by considering the mean-squared error (MSE) of the constellation points of user 1 after demodulation, given by

\[
\text{MSE}(u^{(1)}) = \frac{1}{|K^{(1)}||M|} \sum_{k \in K^{(1)}} \sum_{m \in M} |d_k^{(1)}(m) - d_k^{(2)}(m)|^2. \quad (12)
\]

Fig. 4 shows the introduced interference of user 2 onto user 1 for both GFDM an OFDM, where Fig. 4a and Fig. 4b describe varying time and frequency offsets, respectively. Since both users are separated by one guard subcarrier, interference at user 1 is caused by spectral leakage from user 2 into the subchannel of user 1. Hence, GFDM with its low OOB radiation significantly outperforms OFDM in this scenario.

With perfect frequency synchronization (\( \phi^{(2)} = 0 \)), OFDM stays orthogonal as long as the timing offset is within the CP length and hence the MSE resides at the noise level. User 2 and user 3 in Fig. 1 show this behaviour. If \( \tau^{(2)} \) grows beyond the guard period and hence the receiver window covers two subsequent data blocks of the interfering user, orthogonality is destroyed and the constellation MSE increases to roughly -16 dB. User 4 in Fig. 1 illustrates this timing situation. When there is a frequency offset (\( \phi^{(2)} \neq 0 \)) in OFDM, the sidelobes of the rectangular OFDM filter reach into the subchannel of user 1 and hence there is significant interference, even within
Fig. 4: Constellation MSE for different offsets of user 2 with a noise level of -40 dB.

In comparison, GFDM shows a different behaviour. With \( \tau^{(2)} \) within the guard period and with \( \phi^{(2)} = 0 \) the GFDM ZF receiver obtains bi-orthogonality and the constellation MSE remains at the noise level. When the time offset increases beyond the guard interval, the same situation as in OFDM appears: (bi-)orthogonality is lost and the spectral leakage of GFDM appears: (bi-)orthogonality is lost and the spectral leakage of GFDM does not interfere with user 1. However, the effect is much lower than that of OFDM because of the significantly smaller sidelobes of GFDM compared to OFDM, which is illustrated in Fig. 3. When a frequency misalignment \( \phi^{(2)} \neq 0 \) occurs, (bi-)orthogonality is again lost. However, the MSE only slightly increases. Note that, in contrast to OFDM, interferences only increase when \( \phi^{(2)} < 0 \), i.e. user 2 gets closer to user 1. If both allocated bandwidths are distancing from each other, the low spectral leakage of GFDM does not introduce visible interference above the noise level. The number of ripples in the interference for varying frequency offset is caused by the shape of the spectrum of the waveforms in Fig. 3 and equals \( M \) for both GFDM and OFDM.

**IV. COMPENSATION OF ASYNCHRONICITY**

In the previous section it was assumed that the access point and the user of interest were perfectly synchronized. Consequently, when no interference occurs, the system is (bi-)orthogonal and the transmitted data symbols can be exactly recovered. In this section, we analyze the effect of asynchronicity between the user and the access point and propose a simple yet effective data-aided synchronization technique to combat these effects.

In this section we assume that only the first subchannel is allocated with user 1 and user 1 has a time misalignment \( \Delta \tau \) and a frequency misalignment \( \Delta \phi \) with respect to the access point. Assuming that \( |\Delta \tau| < \frac{N_{CP}}{2} \), the signal \( y^{(1)}[n] \) sent to the GFDM demodulator is given by

\[
y^{(1)}[n] = T_{\Delta \tau}^N F_{\Delta \phi} x^{(1)}_{\text{sync}}[n] = \text{si}[n - \Delta \tau] \otimes \left( \exp(j2\pi(\frac{\Delta \phi}{\tau} + \phi_0)x^{(1)}_{\text{sync}}[n] \right).
\]  

Hence, the data symbol detected at the \( k \)th subcarrier and \( m \)th subsymbol is given by

\[
d_{km}^{(1)} = \left< g_{km}[n], y^{(1)}[n] \right> = d_{km}^{(1)} \left< g_{km}[n], T_{\Delta \tau}^N F_{\Delta \phi} g_{km}[n] \right> + I_{km},
\]

where

\[
I_{km} = \sum_{k',m'} d_{km,km'}^{(1)} \left< g_{km,n}, T_{\Delta \tau}^N F_{\Delta \phi} g_{km',n'} \right> + w_{\text{Rx}}
\]

is the interference from other symbols plus noise.

First, assume \( \Delta \tau = 0 \), i.e. only a frequency offset occurs between user and access point. Both \( g_{km}[n] \) and \( g_{km}[n] \) are well localized in time, where \( g_{km}[n] \) is concentrated around \( N_{CP} \) (see Fig. 5). According to (5), a frequency shift is described by multiplying the transmit signal with a complex exponential. The phase rotation due to the frequency offset can be considered constant during the main contribution of \( g_{km}[n] \) and hence the phase of the data symbol received at the \( m \)th subsymbol of the GFDM block can be approximated by

\[
\arg d_{km}^{(1)} = \arg d_{km}^{(1)} + 2\pi \left( \frac{\Delta \phi m K}{N} + \phi_0 \right).
\]

Hence, phase error depends on the subsymbol index \( m \). A similar consideration can be carried out in the frequency domain with a timing offset \( \Delta \tau \neq 0 \) and \( \Delta \phi = 0 \). The estimated
data symbol at the $k$th subcarrier and $m$th subsymbol can be expressed in the frequency domain and is given by

$$
\hat{d}^{(1)}_{km} = \mathbb{F}_N^{-1}\{G_{km}[\eta]G_{00}[\eta] \exp(j2\pi \frac{\Delta \tau \eta}{N})\}_{n=mK},
$$

(19)

where $\mathbb{F}_N\{\cdot\}$ denotes $N$-point discrete Fourier transform (DFT) of its argument and $G_{km}[\eta] = \mathbb{F}_N\{g_{km}[n]\}$. Since the transmit filter $G_{00}[\eta]$ concentrates around $\eta = kM$ in the frequency domain (Fig. 5), the phase of the received data symbol can be approximated by

$$
\arg \hat{d}^{(1)}_{km} = \arg d^{(1)}_{km} + 2\pi \frac{\Delta \tau \eta M}{N}.
$$

(20)

Therefore, phase error depends only on the subcarrier index.

A. Estimation of Time and Frequency Misalignment

If both $\Delta \tau \neq 0$ and $\Delta \phi \neq 0$, phase rotation occurs along both subcarriers and subsymbols. Let

$$
\phi_f = 2\pi \frac{\Delta \tau M}{N}, \quad \phi_t = 2\pi \frac{\Delta \phi}{T}, \quad \phi'_0 = 2\pi \phi_0.
$$

(21)

Then, the phase error of the estimated data symbols can be approximated by

$$
\arg \hat{d}^{(1)}_{km} - \arg d^{(1)}_{km} = m\phi_t + k\phi_f + \phi'_0,
$$

(22)

which provides the system model for a data-aided estimation of $\Delta \tau$ and $\Delta \phi$. We introduce a piloting scheme according to Fig. 6 where the $i$th pilot is located at the $\kappa(i)$th subcarrier and $\mu(i)$th subsymbol, where

$$
\kappa(i) = \left\lfloor \frac{i}{2} \right\rfloor
$$

(23)

$$
\mu(i) = 1 + \left( (i + (i \mod 2)) \cdot \frac{M-1}{2} \right) \mod (M-1).
$$

(24)

Notice that this piloting scheme is an initial proposal that has not been submitted to an optimization process. Hence, other piloting schemes with better performance can be available, but finding such optimal scheme is out of the scope of this paper.

We can now state the equation system

$$
\arg \hat{p}_i = \arg p_i + \mu(i)\phi_t + \kappa(i)\phi_f + \phi'_0.
$$

(25)

Note that, depending on the misalignment, $\arg \hat{p}_i$ can become larger than $2\pi$ and hence the phase rotation can become ambiguous (cf Fig. 5). To combat this effect, only the phase difference between pilots is considered by

$$
\hat{\phi}_{ij} = \arg \hat{p}_i - \arg \hat{p}_j = \left[ \mu(i) - \mu(j) \right] \left[ \kappa(i) - \kappa(j) \right] \phi_f.
$$

(26)

Then, $\phi_t$ and $\phi_f$ are estimated as a least squares solution by

$$
\begin{bmatrix}
\hat{\phi}_t \\
\hat{\phi}_f
\end{bmatrix} = \left( V^H V \right)^{-1} V^H \mathbf{p}.
$$

(27)

B. Compensation of Time and Frequency Misalignment

Compensation of the estimated time and frequency misalignment can be carried out in the data or in the signal domain. To compensate in the data domain, the received symbols $\hat{d}^{(1)}_{km}$ are rotated back by the expected phase offset to obtain the compensated symbols $\hat{d}^{(1)}_{km}$, given by

$$
\hat{d}^{(1)}_{km} = \hat{d}^{(1)}_{km} \exp(-j(m\hat{\phi}_t + k\hat{\phi}_f)).
$$

(30)

The constant phase error $\hat{\phi}'_0$ will be removed afterwards, as presented in subsection IV-C. Misalignment compensation in the signal domain is carried out by derotating the signal $y^{(1)}[n]$ to lead to the signal $y^{(1)'}[n]$, given by

$$
\begin{align*}
\hat{y}^{(1)'}[n] &= F_{-\Delta \phi} T_{-\Delta \tau} \hat{y}^{(1)}[n],
\end{align*}
$$

(31)
The performance of the proposed algorithm has been evaluated for a GFDM system with the parameters from Tab. I, but user 1 has received 32 subcarriers. Again, the figure of merit is the constellation MSE after compensation, where the noise floor was set to -40 dB and -10 dB. The results for different time and frequency misalignments are shown in Fig. 7.

Clearly, the compensation in the signal domain outperforms the data domain compensation. The data domain equalization suffers from additional ISI and ICI and hence the MSE increases with the timing and frequency misalignment. One iteration of signal domain compensation already correctly compensates the time misalignment. Frequency misalignment is not correctly estimated and a residual MSE proportional in the log-domain to the frequency misalignment occurs. Three iterations of signal domain compensation also correctly estimate the frequency misalignment and the MSE resides at the noise floor. When the frequency misalignment grows beyond 7% of the subcarrier bandwidth, the compensation in the frequency domain abruptly stops working. According to the pilot structure in Fig. 6, the phase difference between two adjacent pilots on the same subcarrier is given by

\[ \phi_{i,i+1} = 2\pi \frac{\Delta \phi}{M} \]

which approaches \( \pi \) for \( \frac{\Delta \phi}{M} = 0.071 \). In this case, the estimator cannot distinguish between positive or negative misalignment and hence the performance drops. The estimation can be made more robust with a different pilot structure, where pilot distance between sub symbols is smaller. The simulation results also show, that compensation in the signal domain correctly works with higher noise values, such as -10 dB.

Similarly, the phase difference between two adjacent subcarriers introduced by the time misalignment is given by

\[ \theta_{i,i+2} = 2\pi \frac{\Delta \tau}{K} \]

where \( \Delta_k \) is the distance between pilot subcarriers in the resource grid. Assuming the pilot arrangement presented in Fig. 6, we have \( \Delta_k = 1 \). Therefore, the maximum detectable time misalignment is \( \Delta_{\text{max}} = K/2 >> N_{\text{CP}} \). Accordingly, the pilots can be rearranged to increase the distance between subcarriers and decrease the distance between sub symbols in order to achieve a higher performance without increasing the pilot overhead.

V. Conclusion

This paper has investigated the influence of misalignment in time and frequency of several users on the system performance which was measured as the MSE of the detected constellation symbols. It was shown that GFDM significantly outperforms OFDM in terms of IUI because of its dramatically reduced OOB radiation. With GFDM, users on adjacent subchannels virtually do not interfere with each other, when only timing misalignments occur. This finding allows a CSMA-like random access structure of several nodes using different subchannels. When frequency misalignment occurs, GFDM again significantly outperforms OFDM, but a slight performance degradation is visible.

Furthermore, we proposed an algorithm that estimates the resulting phase errors from a residual misalignment with the help of multiplexed pilots. Two different compensation methods were shown and their performances were analyzed. Compensation in the signal domain offered a better performance, at the cost of increased complexity. To achieve a higher performance without increasing the pilot overhead, the pilots can be rearranged to increase the distance between subcarriers and decrease the distance between sub symbols in order to achieve a higher performance without increasing the pilot overhead.
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REFERENCES


