Performance Evaluation of GFDM Channel Estimation Using DFT for Tactile Internet Application

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Abstract: In this work, discrete Fourier transform (DFT)-based channel estimation is proposed in generalized frequency division multiplexing (GFDM) system. In the GFDM system, the subcarriers are non-orthogonal; therefore, the pilot symbols cannot be easily observed due to the interference from data symbols and noise. The proposed method can improve the channel estimation of least square (LS) method by eliminating channel impulse response outside the number of actual impulse response. First, the received signal is demodulated using zero forcing demodulator. Then, it is divided with transmitted pilot symbols to obtain channel response. Interpolation in frequency and time domains is conducted to acquire channel response for all GFDM blocks. Finally, the channel estimation algorithm using DFT is performed. The parameters of the system are adjusted so that they are suitable for tactile internet application. The channel model used is NYUSIM, which utilizes mmWave. Three scenarios in NYUSIM such as urban microcell, urban macro cell and rural macro cell are used and power delay profiles generated from NYUSIM simulator are employed in this system. The results show that mean square error (MSE) from DFT-based channel estimation gives substantial improvement for all scenarios. In addition, symbol error rate (SER) of DFT-based channel estimation provides a slight improvement of ~1.5 dB than LS channel estimation.

Keywords: GFDM; DFT-based channel estimation; NYUSIM; tactile internet

1. Introduction

There are many new requirements in the 5th generation (5G) cellular networks. They include high reliability and robustness, ultra-low latency, high data capacity and low out-of-band (OBB) emission [1,2]. The ordinary orthogonal frequency division multiplexing (OFDM) framework has become unable to supply the above requirements. Tactile internet [2–5] is one of several use-cases proposed for 5G networks requires ultra-low latency and high spectral efficiency. Sub-millisecond real-time reaction is the main challenge in tactile internet. If the round-trip delays between the command insertion are too large, then the response of devices will result in poor quality in experience (QoE). This requirement makes the overall frame size limited. It means that the forward error correction (FEC) length should be restricted. In addition, OFDM with one cyclic prefix (CP) per symbol leads to low spectral efficiency. There are some promising candidates to satisfy 5G network requirement. Universal filtered multi-carrier (UFMC) [6] is an OFDM based waveform that employ a short length filter to filter a set of subcarriers. These subcarriers remain orthogonal to each other. In order to combat intersymbol interference (ISI), UFMC does not use CP and employ zero-padding to provide the filter spreading. Hence, UFMC is more sensitive in term of time misalignment which resulting in performance loss. Another OFDM-based waveform is filtered orthogonal division multiplexing (F-OFDM) [7]. In F-OFDM, CP is employed to minimize ISI in multipath channels. F-OFDM is able to compress OOB radiation CP that can be used for synchronization without penalizing performance. Nevertheless, F-OFDM uses one CP per symbol, so reducing spectrum efficiency when short symbols are required.
This constraint does not fit for tactile internet application. In an attempt to answer that challenge, GFDM comes as one of contender that is able to cover the requirements. The GFDM symbol can be compressed to reduce latency [8], while time-windowing and blank time slot [9] can be employed to reduce OOB even further.

Amplitude and phase are varied in wireless channel due to their propagation characteristics. If these two parameters cannot be corrected in receiver, the resulted data cannot be recovered. Therefore, the propagation characteristics are important to be estimated in real time. By inserting pilot symbols at a known period, the restoration of transmitted data can be performed. This method has been proposed for GFDM system in [10]. Two well-known channel estimation methods—least square (LS) and linear minimum mean square error (LMMSE)—have been implemented [11,12]. However, the opportunity to explore the performance of channel estimation using other techniques remains wide-open.

Channel estimation using DFT has been used massively in OFDM and it offers better outcome to estimate the channels, rather than the LS or LMMSE [13,14]. Thus, this motivated us to employ the subject method to GFDM system. A similar method also has been performed in a GFDM system [15]. However, the DFT-based channel estimation method is performed under 2-tap random channel in which this condition is not suitable for 5G scenarios. Moreover, the paper does not discuss about SER performance, which indicates how this method contributes to the enhancement of GFDM performance. The trade-off between data symbol and pilot symbol is not specified in the paper. Hence, in this study, we cover all the drawbacks of the paper and bring realistic case of 5G system as GFDM is one of contender for 5G networks. The only way to evaluate channel estimation using DFT is the length of channel impulse response (CIR) has to be identified correctly in the receiver and the length of channel taps shall be less than CP. Additionally, the recent work of hybrid multiple-input multiple-output (MIMO) GFDM system using millimeter-wave (mmWave) is discussed in [16]: two-step multi user equalization is evaluated in that paper. However, there is no channel estimation process discussed in the system. The work mainly focuses on building MIMO GFDM system by combining the analog–digital receiver structure. Low complexity unit terminals (UTs) present a hardware limitation, where no channel state information (CSI)-based precoder and partial CSI-based precoder are employed in the transmitter side.

1.1. Contributions

In this work, a channel estimation using DFT algorithm is proposed to reduce the mean square error (MSE) floor and enhance the estimation accuracy. This is an extension of our previous work [17]. In the previous work, we discussed channel estimation with DFT by using exponential decay channel taps ranging from 0 to $-8.7$ dB and use only one pattern of pilot symbol. The main objective is to confirm that proposed channel estimation is suitable for GFDM system. The contributions of this manuscript are given below:

- Two different pilot symbols patterns are used in which these pilot symbols are inserted at different subcarriers to evaluate the performance of each pilot symbol pattern.
- The GFDM system is operated for 5G application, where the GFDM parameters used in this work are suitable for tactile internet use-case [4].
- The channel model that we employ is 5G channel, which is introduced in [18,19] as NYUSIM channel. The channel is suitable for millimeter wave wireless communication systems. The channel model operates for wide range carrier frequency (500 MHz to 100 GHz) with bandwidths (0 to 800 MHz). The scenarios provided in the NYUSIM simulator, such as urban microcell, urban macro cell and rural macro cell, are tested in GFDM system using channel estimation with DFT.

This paper is organized as follows: Section 1 is the introduction. Section 2 explains the GFDM system and channel model. Channel estimation using DFT is described by considering pilot symbols insertion. Channel models generated from NYUSIM simulator are also shown and the power delay profile of each scenario is defined. In Section 3, we investigate the impact of different pilot symbol patterns under exponential channel. The
simulation results are presented where channel estimation using LS and DFT in NYUSIM channel are compared.

1.2. Notations

Vector sign \( \vec{X} \) denotes column vector and boldface \( X \) indicates matrices. Time domain representation is denoted by lowercase letter; meanwhile, frequency domain representation is indicated by uppercase letter. The transpose and Hermitian transpose of \( X \) are, respectively, denoted by \( X^T \) and \( X^H \). \( E[\cdot] \) is the expectation operator; \( \sqrt{X} \) is the element-wise absolute square root of matrix \( X \). The indices \( k \) and \( m \) refer to subcarrier and time slot respectively.

2. GFDM Systems and Channel Model

The GFDM system is shown in Figure 1. The GFDM block has a length of \( N = MK \) in which \( M \) sub symbols are transmitted on \( K \) subcarriers. The entries vector \( \vec{d} \in \mathbb{C}^{N \times 1} \) consists of data symbol and pilot symbol which have been multiplexed before modulated by pulse shaping filter. Vector \( \vec{d} \) carries data samples and \( \vec{d} \) includes the pilot samples. Vector \( \vec{d} \) contains zeros at pilot positions, meanwhile vector \( \vec{d} \) has zeros at data positions.

\[
\vec{x}[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} g_{k,m}[n] d_{k,m}, \quad n = 0, \ldots, N - 1
\]  

where \( d_{k,m} \) is the symbol transmitted on subcarrier \( k \) and subsymbol \( m \). In Equation (2), circular filtering is achieved via the modulo operation. Equation (2) can also be represented as

\[
\vec{x} = A \vec{d}
\]
in which \( \vec{d} = \left[ \vec{d}_0^T, \ldots, \vec{d}_{K-1}^T \right]^T \in \mathbb{C}^N \) is vectorized version of \( \vec{D} \) while for each subcarrier \( k \) its corresponding \( \vec{d}_k \) vector is given by \( \vec{d}_k = (d_k[m])_{m=0,\ldots,M-1}^T \). The GFDM transmit matrix \( \vec{A} \) follows:

\[
\vec{A} = \left( \vec{s}_{0,0}, \ldots, \vec{s}_{K-1,0}, \vec{s}_{0,1}, \vec{s}_{1,1}, \ldots, \vec{s}_{K-1,M-1} \right),
\]

with column vector \( \vec{s}_{k,m} = (s_{k,m}[n])_{n=0,1,\ldots,N-1}^T \). The signal \( \vec{x} \) is then protected by a CP against multipath propagation.

Figure 2 illustrates pilot structures in time-frequency grid. Pilot subcarrier spacing is denoted as \( \Delta k \) and the number of pilot symbol used in different time slots is donated as \( M_p \).

As can be seen, the pilot insertion with small \( \Delta k \) reduces the effective data rate by the factor

\[
\eta = \frac{\text{no. of data samples}}{\text{no. of total samples}} = 1 - \frac{M_p}{MK}. \tag{5}
\]

Figure 2. Pilot positions in time-frequency grid: (a). \( \Delta k = 3, M_p = 2 \); (b). \( \Delta k = 6, M_p = 2 \).

The CP is removed at the receiver. Assuming the time and synchronization are perfect, the received signal \( \vec{y} \) becomes

\[
\vec{y} = \vec{x} \otimes \vec{h} + \vec{w}. \tag{6}
\]

The received signal \( \vec{y} \) in time is the circular convolution of transmitted signal \( \vec{x} \) and CIR \( \vec{h} \) as well as AWGN process \( \vec{w} \). In (6), all the channels are assumed to have shorter length \( L \) compared to the CP length. The CIR \( \vec{h} \) is defined as

\[
\vec{h} \triangleq \sqrt{\vec{P}} \vec{s}
\]

where \( \vec{P} \in \mathbb{R}^{N \times N} \) is the diagonal matrix of normalized power delay profile and \( \vec{s} \in \mathbb{C}^{N \times 1} \) is the vector of zero mean complex Gaussian processes with unit variance.

The received signal then goes to GFDM demodulator. There are three demodulator which is provided: matched filter (MF), zero forcing (ZF) and minimum mean square
error (MMSE) [20]. Under the assumption that ZF is employed, the output of GFDM demodulator is

$$\tilde{z} = A^{-1}(\tilde{x}H + \tilde{w}) = A^{-1}(\tilde{A}dH + \tilde{w}) = \tilde{d}H + A^{-1}\tilde{w}$$

(8)

It is important to equalize the channel in order to rectify the transmitted data. However, the first thing needs to be done before equalizing the channel is to estimate the channel. The pilot symbol is an aid to help the receiver in recovering data.

2.1. LS and DFT-Based Channel Estimation

The channel coefficient at pilot symbol can be estimated as follow:

$$\hat{H}_{LS}[k, m] = \frac{Z[k, m]}{\tilde{d} [k, m]}, 0 \leq k \leq K - 1 and 0 \leq m \leq M - 1$$

(9)

in which $Z$ with size $K \times M$ is matrix representation of $\tilde{z}$ with $KM \times 1$ dimension and $\tilde{d} [k, m]$ is pilot symbol position. Note that $\hat{H}_{LS}[k, m]$ is an element matrix of $\hat{H}_{LS}$ which consist of $K$ row and $M$ column where the channel information located only at pilot position. In an attempt to obtain channel response for all $KM$ data, interpolation is applied in time-frequency grid to obtain the estimated channel frequency response. In order to measure the accuracy of this estimation technique, the mean-square error (MSE) of the LS channel shall be estimated. MSE can be written as

$$\text{MSE}_{LS} = E\{ (H - \hat{H}_{LS})^H(H - \hat{H}_{LS}) \}. \quad (10)$$

The performance of LS channel estimation can be enhanced by using channel estimation using DFT technique. This can be obtained by eliminating the effect of interference and noise outside the maximum channel delay since channel information only concentrated in the first $L$ samples. In this case, it is assumed that a priori knowledge of CIR length $L$ is known. The process flow of proposed method is shown in Figure 3.

![Figure 3. DFT-based channel estimation block diagram.](image)

The estimated sample of CIR is written as

$$\hat{h}_{LS}[n] = \text{IDFT}_N\{\tilde{H}_{Mop}[k]\}, 0 \leq n \leq N - 1 = h[n] + i[n] + \tilde{w}[n]$$

(11)
where IDFT\(_N\{\cdot\}\) shows N-point IDFT. Note that an interference \(i[n]\) and noise \(\tilde{w}[n]\) terms emerge in channel frequency response. It causes error floor in the estimated CIR. If the length of \(L\) is known, the Equation (11) can be rewritten as

\[
\hat{h}_{\text{LS}}[n] = \begin{cases} 
  h[n] + i[n] + \tilde{w}[n], & 0 \leq n \leq L - 1 \\
  i[n] + \tilde{w}[n], & \text{otherwise}.
\end{cases}
\]  

(12)

The channel impulse response is contained in the first \(L\) samples. Removing samples outside the \(L\) samples can reject the interference and noise. Expressing this process, we obtain

\[
\hat{h}_{\text{DFT}}[n] = \begin{cases} 
  h[n] + i[n] + b[n] + \tilde{w}[n], & 0 \leq n \leq L - 1 \\
  0, & \text{otherwise}.
\end{cases}
\]  

(13)

From Equation (13), the channel estimation is expressed as

\[
\hat{H}_{\text{DFT}}[k] = \text{DFT}_N\{\hat{h}_{\text{DFT}}[n]\}, \quad 0 \leq k \leq N - 1
\]  

(14)

The accuracy of estimated channel can also be expressed in MSE performance. After obtaining the estimated channel, equalization can be performed. The equalization process is expressed as

\[
\hat{\tilde{d}} = \frac{Z}{\hat{H}} \left( \hat{\tilde{d}} + \tilde{d} \right) + \tilde{w}
\]  

(15)

After equalization process, the recovered data then demultiplexed to separate the data from pilot symbol. The received data \(\hat{\tilde{d}}\) then is processed to demapper to convert it into bits.

2.2. Tactile Internet Application for GFDM

The mission of tactile internet aims for high reliable low-latency services, where the low end-to-end latency must be less than 1 milisecond. This scenario is first introduced in [2]. The requirement for low latency is specified from typical interaction of devices. If the round-trip delays between the command insertion are too large, the response of devices will result in poor QoE. This requirement makes the overall frame size limited. GFDM can satisfy the application by employing a small \(MK\) product.

Table 1 shows the channel and GFDM parameters for tactile internet applications. The GFDM parameters are then used in this paper. In addition, channel parameters are satisfied by using NYUSIM channel model. The detailed channel model is described in the next subsection.

2.3. Channel Model

This section describes the channel model that is used for the experiment. Overall, the channel model is taken from NYUSIM simulator. The channel is suitable for 5G network using mmWave. The simulator is typically used in a wide range of carrier frequencies from 500 MHz to 100 GHz, antenna beamwidths (7° to 45° for elevation and 7° to 360° for azimuth), radio frequency bandwidth up to 800 MHz and other applications (urban microcell, urban macrocell and rural macrocell) [18]. Furthermore, this channel simulator is important for the performance evaluation of communication systems. The power delay profile is obtained by setting the input parameters specified in NYUSIM simulator. Overall, the channel and antenna parameters need to be determined before generating power delay profile.
Table 1. Channel and GFDM parameters for tactile internet application [4].

| Parameters              | Tactile Internet |
|-------------------------|------------------|
| Cell size (km)          | 1                |
| Delay Spread (μs)       | 1                |
| Bc (kHz)                | 200              |
| Doppler shift (Hz)      | 10               |
| Tc (ms)                 | 50               |
| Subcarrier K            | 64 or 128        |
| Subsymbols M            | 5                |
| Receiver Type           | Zero Forcing     |
| TcP (μs)                | 2                |
| Symbol duration (μs)    | ≈5               |
| Modulation order        | 2 or 4           |
| Bw (MHz)                | 100 (fragmented) |

Table 2 provides the parameters that need to be set. Figure 4 shows that the power delay profile for each scenario selecting scenario, such as Umi, Uma and Rma, can be adjusted in its input parameters, as specified in Table 2. Overall, the input parameters for these three scenarios are made to be same in order to satisfy the tactile internet requirements. In addition, the number taps of Umi, Uma and Rma are 23, 39 and 2, respectively.

Table 2. Input Parameters NYUSIM Simulator.

| Channel Parameters                      | Antenna Parameters                          |
|-----------------------------------------|---------------------------------------------|
| Frequency                               | 28 GHz                                      |
| Radio Frequency (RF) Bandwidth [MHz]     | 800                                         |
| Scenario Umi                            | Number of Tx antenna elements: 1            |
| Environment NLOS                        | Number of Rx antenna elements: 1            |
| Lower Bound of T-R distance [m]         | Tx antenna azimuth HPBW: 10°                |
| Upper Bound of T-R distance [m]         | Tx antenna elevation HPBW: 10°              |
| Tx Power [dBm]                          | 30                                           |
| Barometric Pressure [mbar]              | 1013.25                                      |
| Humidity [50%]                          | Rx antenna azimuth HPBW: 10°                |
| Temperature [20 °C]                     | Rx antenna elevation HPBW: 10°              |
| Rain Rate [0 mm/hr]                     |                                             |
| Polarization                            | Co-Pol                                      |
| Foliage Loss                            | No                                          |
|                                        | Rx antenna elevation HPBW: 10°              |

Figure 4. Power delay profile generated from NYUSIM simulator: (a) Umi scenario; (b) Uma scenario; (c) Rma scenario.

3. Experimental Results

Two experimental schemes are defined. The first scheme is to observe the effect of pilot subcarrier spacing under multipath channels using exponential power delay profile. The second scheme is to analyze the influence of NYUSIM model using a power delay profile, as shown in Figure 4. The GFDM properties are adjusted to fulfill the tactile internet system requirements. Table 3 indicates the parameters for those two schemes. The Monte-Carlo method is applied for evaluating SER.

Table 3. Experimental setup parameters.

| First scheme | Second scheme |
|--------------|---------------|
| Parameter    | Value         | Parameter    | Value         |
| Modulation Order [μ] | 2 (QPSK)      | Modulation Order [μ] | 2 (QPSK)      |
| Number of subsymbol [M] | 5            | Number of subsymbol [M] | 5            |
| Number of subcarrier [K] | 128          | Number of subcarrier [K] | 128          |
| Cyclic prefix length [Ncp] | 1/8          | Cyclic prefix length [Ncp] | 1/8          |
| Pilot subcarrier spacing [∆k] | 3, 6        | Pilot subcarrier spacing [∆k] | 3            |
| Pulse shaping filter | Raised Cosine | Pulse shaping filter | Raised Cosine |
| Roll-off factor [α] | 0.1          | Roll-off factor [α] | 0.1          |
| GFDM Demodulator | Zero Forcing | GFDM Demodulator | Zero Forcing |
| Channel taps | 4            | Channel taps | 23, 39, 2     |
| Power delay profile | Exponential | Power delay profile | Umi, Uma, Rma |
| Pilot symbol | Complex      | Pilot symbol | Complex      |

Figure 4. Cont.
3. Experimental Results

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Table 3. Experimental setup parameters.

| Parameter                  | Value                        | Parameter                  | Value                        |
|----------------------------|------------------------------|----------------------------|------------------------------|
| First Scheme               |                              | Second Scheme              |                              |
| Modulation Order (μ)       | 2 (QPSK)                     | Modulation Order (μ)       | 2 (QPSK)                     |
| Number of subsymbol (M)    | 5                            | Number of subsymbol (M)    | 5                            |
| Number of subcarrier (K)   | 128                          | Number of subcarrier (K)   | 128                          |
| Cyclic prefix length (Ncp) | 1/8                          | Cyclic prefix length (Ncp) | 1/8                          |
| Pilot subcarrier spacing (Δk) | 3 and 6                      | Pilot subcarrier spacing (Δk) | 3                            |
| Pulse shaping filter       | Raised Cosine (RC)           | Pulse shaping filter       | Raised Cosine (RC)           |
| Roll-off factor (α)        | 0.1                          | Roll-off factor (α)        | 0.1                          |
| GFDM Demodulator           | Zero Forcing                 | GFDM Demodulator           | Zero Forcing                 |
| Channel taps               | 4                            | Channel taps               | 23, 39, 2                    |
| Power delay profile        | Exponential                  | Power delay profile        | Umi, Uma, Rma                |
| Pilot symbol               | Complex                      | Pilot symbol               | Complex                      |

First, we discuss the first scheme simulation. Figure 5 shows the MSE and SER performance of the first scheme. For the MSE performance, it can be seen that when pilot subcarrier spacing increase, the error occurs due to unclear pilot observations. The interference, as well as noise, can be overcome by increasing the number of pilot symbol in order to acquire better observation. This means that the smaller value of Δk leads to better estimation for both LS and DFT-based estimation methods. Therefore, the error floor grows vertically with the increase of Δk. The effective rate for Δk = 3 and 6 is reduced by η = 86% and 93%, respectively. In addition, DFT-based channel estimation shows better performance than LS channel estimation. By removing the sample outside the maximum channel impulse response, this will reject interference and noise. The gap occurred between DFT-based estimation and LS estimation at MSE $10^{-2}$ is 10 dB for Δk = 3 and 6 dB for Δk = 6.
Figure 5. GFDM performance evaluation in term of (a) MSE and (b) SER with 7% and 14% pilot symbol overhead.

For the SER performance, DFT-based estimation also shows better performance than LS estimation. GFDM perfect compensation is obtained when the CIR is known completely at the receiver. Therefore, when performing equalization in the frequency domain, the channel frequency response can be found by transforming the known CIR.

In other words, the channel estimation does not require pilot symbols. The degradation of DFT-based and LS channel estimation methods from GFDM perfect compensation strongly depends on the number of pilot symbols and the type of receiver. Since the same receiver is employed to these two estimation channel methods, this factor is not considered. Hence, the only factor is the number of pilot symbols. Increasing the number of pilot symbols in the subcarrier and time slot will increase SER performance to the perfect CSI condition. However, the effective data rate \( \eta \) will reduce accordingly.

More observation are acquired at the receiver leads to good MSE reduction and this also leads to better SER performance. The improvement of DFT-based estimation is 1 dB over LS estimation at SER \( 10^{-2} \) for \( \Delta k = 3 \) and 2 dB enhancement for \( \Delta k = 6 \). Next, the constellation of quadrature phase-shift keying (QPSK) is investigated, in order to compare LS and DFT-based channel estimation, as indicated in Figure 6. When channel estimation is not performed, the received signal cannot be recovered and the SER performance is very poor. When the channel estimation method is employed, the channel can be compensated and the data can be recovered. The DFT-based channel estimation method provides better variance than the LS channel estimation, as indicated by the parts that are more highly concentrated near the constellation point. Hence, the proposed method has better SER performance.

Second, we discuss the performance of channel estimation under the NYUSIM channel. In an attempt to satisfy the tactile internet requirements, the parameters of channel dispersion should be calculated. Table 4 summarizes the dispersion parameters for each scenario. By referring to the requirements as given in Table 1, it can be concluded that all parameters meet the requirements for tactile internet application.
Second, we discuss the performance of channel estimation under the NYUSIM channel. In an attempt to satisfy the tactile internet requirements, the parameters of channel dispersion should be calculated. Table 4 summarizes the dispersion parameters for each scenario. By referring to the requirements as given in Table 1, it can be concluded that all parameters meet the requirements for tactile internet application.

Table 4. Dispersion Parameters of NYUSIM channel.

| Scenario | Delay Spread (ns) | Bandwidth Coherence (MHz) | Doppler Frequency (Hz) | Time Coherence (ms) |
|----------|-------------------|---------------------------|------------------------|---------------------|
| Umi      | 9.8               | 20,408                    | 10                     | 0.0423              |
| Uma      | 32.1              | 6230                      | 10                     | 0.0423              |
| Rma      | 0.2               | 1000                      | 10                     | 0.0423              |

The performances of these three scenarios are observed in terms of SER and MSE, as shown in Figure 7. Overall, for all scenarios, the DFT-based estimation method provides a slight improvement of about 1.5 dB, compared to LS estimation methods, in terms of SER.
The deviation of the estimation method from GFDM perfect compensation depends on the number of pilot symbols inserted over the subcarriers and subsymbols.

These three scenarios are classified as frequency selective fading, since the received signal includes multiple versions of the transmitted signal. In the Umi scenario, although the number of channels is smaller than in the Uma scenario, the channel frequency response has a gain that is more varied for different frequency components. This occurs because the gain the power delay profile generated in Umi scenario is larger than in the Uma scenario. Therefore, the channel in the Umi scenario is more distorted than in the Uma scenario. This leads to better SER performance for the Uma scenario. This condition also effects to the Rma scenario, so that SER in this scenario is the best.

In addition, for all scenarios, the MSE performance of the DFT-based estimation algorithm offers better results than the LS estimation algorithm. It can be also proven that the Uma scenario is better than the Uma scenario by observing the MSE performance. The fluctuation of the channel frequency response in the Umi scenario is faster than the Uma scenario.
scenario, so that the channel estimation algorithm cannot follow it. This leads to poor results in estimating the true channel. Furthermore, the Rma scenario provides linear MSE because the channel frequency response tends to be flat for different frequencies. Thus, the pilot symbol observation is more clear than in other scenarios.

4. Conclusions

The DFT-based channel estimation algorithm is proposed for GFDM system. From simulations results, the following points can be obtained:

- The pilot symbol with $\Delta k = 3$ has a better performance in estimating the channel than the pilot symbol with $\Delta k = 6$. However, on the other hand, the efficiency of the information data decreases.
- DFT channel estimation improves channel estimation accuracy with a 9 dB MSE improvement for the Umi scenario, 4 dB in the Uma scenario and 3 dB in the Rma scenario for an MSE value of $10^{-2}$ compared to LS estimation.
- The magnitude of the channel frequency response fluctuations is influenced by the number of tap channels and the magnitude of the gain of the power delay profile. The number of fluctuations decreases the accuracy of channel estimation. Although the number of tap channels in the Uma scenario is more than in the Umi scenario, the gain of each tap in the Umi scenario is greater, so that the estimation accuracy in the Umi scenario is decreased.

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References

1. Wunder, G.; Jung, P.; Kasparick, M.; Wild, T.; Schaich, F.; Chen, Y.; Brink, S.; Gaspar, I.; Michailow, N.; Festag, A.; et al. 5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications. IEEE Commun. Mag. 2014, 52, 97–105. [CrossRef]
2. Fettweis, G. The Tactile Internet: Applications and Challenges. IEEE Veh. Technol. Mag. 2014, 9, 64–70. [CrossRef]
3. NGMN Alliance. NGMN 5G White Paper. 17 February 2015. Available online: https://www.ngmn.org/5g-white-paper/5g-white-paper.html (accessed on 20 March 2018).
4. Ferreira, J.S.; Rodrigues, H.D.; Gonzalez, A.A.; Nimr, A.; Matthe, M.; Zhang, D.; Mendes, L.L.; Fettweis, G. GFDM frame design for 5G application scenarios. J. Commun. Inf. Syst. 2017, 32. [CrossRef]
5. Michailow, N.; Matthé, M.; Gaspar, I.S.; Caldevilla, A.N.; Mendes, L.L.; Festag, A.; Fettweis, G. Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks. IEEE Trans. Commun. 2014, 62, 3045–3061. [CrossRef]
6. Vakilian, V.; Wild, T.; Schaich, F.; Brink, S.; Frigon, J.-F. Universal-filtered multi-carrier technique for wireless systems beyond LTE. In Proceedings of the Globecom 2013 9th International Workshop on Broadband Wireless Access, Atlanta, GA, USA, 9–13 December 2013. [CrossRef]
7. Weitkemper, P.; Bazzi, J.; Kusume, K.; Benjebour, A.; Kishiyama, Y. On regular resource grid for filtered OFDM. IEEE Commun. Lett. 2016, 20, 2486–2489. [CrossRef]
8. Michailow, N.; Mendes, L.; Matthe, M.; Gaspar, I.; Festag, A.; Fettweis, G. Robust WHT-GFDM for the Next Generation of Wireless Networks. IEEE Commun. Lett. 2015, 19, 106–109. [CrossRef]
9. Mendes, L.; Michailow, N.; Matthé, M.; Gaspar, I.; Zhang, D.; Fettweis, G. Opportunities in 5G Networks A Research and Development Perspective; Chapter 13—GFDM: Providing Flexibility for the 5G Physical Layer; CRC Press: Boca Raton, FL, USA, 2016. [CrossRef]
10. Vilaipornsawai, U.; Jia, M. Scattered-pilot channel estimation for GFDM. In Proceedings of the 2014 IEEE Wireless Communications and Networking Conference (WCNC), Istanbul, Turkey, 6–9 April 2014; pp. 1053–1058.
11. Ehsanfar, S.; Matthe, M.; Zhang, D.; Fettweis, G. A study of Pilot-Aided Channel Estimation in MIMO-GFDM Systems. In Proceedings of the WSA 2016; 20th International ITG Workshop on Smart Antennas, Munich, Germany, 9–11 March 2016.
12. Ehsanfar, S.; Matthe, M.; Zhang, D.; Fettweis, G. Theoretical Analysis and CRLB Evaluation for Pilot-aided Channel Estimation in GFDM. In Proceedings of the 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 4–8 December 2016.

13. Kang, Y.; Kim, K.; Park, H. Efficient-DFT based channel estimation for OFDM systems on multipath channels. *IET Commun.* 2007, 1, 197–202. [CrossRef]

14. Cho, Y.S.; Kim, J.; Yang, W.Y.; Kang, C.G. Channel Estimation. In *MIMO OFDM Wireless Communications with Matlab*; John Wiley & Sons: Singapore, 2010; pp. 187–198.

15. Shravan, B.K.; Venkata, K.M.; Drosopoulos, A. Training Based Channel Estimation for Multitaper GFDM System. *Mob. Inf. Syst.* 2017. [CrossRef]

16. Kassam, J.; Miri, M.; Magueta, R.; Castanheira, D.; Pedrosa, P.; Silva, A.; Dinis, R.; Gameiro, A. Two-Step Multiuser Equalization for Hybrid mmWave Massive MIMO GFDM Systems. *Electronics* 2020, 9, 1220. [CrossRef]

17. Permana, A.K.; Hamid, E.Y. DFT-Based Channel Estimation for GFDM on Multipath Channels. In Proceedings of the 2018 10th International Conference on Information Technology and Electrical Engineering (ICITEE), Bali, Indonesia, 24–26 July 2018; pp. 31–35.

18. New York University, NYUSIM. 2016. Available online: [http://wireless.engineering.nyu.edu/5gmillimeter-wave-channel-modeling-software/](http://wireless.engineering.nyu.edu/5gmillimeter-wave-channel-modeling-software/) (accessed on 19 January 2021).

19. Sun, S.; MacCartney, G.R., Jr.; Rappaport, T.S. A novel millimeter-wave channel simulator and applications for 5G wireless communications. In Proceedings of the IEEE International Conference on Communications (ICC), Paris, France, 21–25 May 2017; pp. 1–7.

20. Michailow, N.; Krone, S.; Lentmaier, M.; Fettweis, G. Bit error rate performance of generalized frequency division multiplexing. In Proceedings of the 2012 IEEE Vehicular Technology Conference (VTC Fall), Quebec City, QC, Canada, 3–6 September 2012.