Uplink One-tone Filtered Multitone Modulation Transmission for Machine Type Communications

Guanping Lu∗, Jinsong Wu†, Jun Wang‡

∗Department of Electronic Engineering, Shanghai Jiao tong University, Shanghai, China
† Department of Electrical Engineering, Universidad de Chile, Santiago, Chile
‡ Tsinghua National Lab information Sci. and Tec., Tsinghua University, Beijing, China

Email: ∗ lugp@sjtu.edu.cn, † wujie@ieee.org, ‡ wjun@tsinghua.edu.cn

Abstract—To accommodate current machine type communications (MTC), an uplink waveform is proposed where MTC nodes use one carrier to transmit signal, and central nodes demodulate different nodes’ signal jointly. Furthermore, the carrier bandwidth is variable to fit for the channels of nodes. This waveform may reduce the hardware complexity of low cost MTC nodes, and loose the time and frequency domain synchronization requirements of the entire system. This paper also provides the interference analysis and complexity comparisons of proposed scheme and orthogonal frequency division multiplexing (OFDM).

I. INTRODUCTION

Machine type communications (MTC) and Internet of things (IoT) are important user scenarios for next generation networks [1]. The main challenge for MTC is the scalability problem with thousands of MTC nodes in a cell under the premise of low cost and long lifetime.

In system viewpoint, the MTC trafﬁc has the property of sporadic low data rate and low synchronization quality. The current 4-th generation system based on orthogonal frequency division multiplexing multiple access (OFDMA) is not ﬁt fully for MTC due to high complexity, ﬁxed subcarrier bandwidth, high sidelobe and critical synchronization requirement.

The channel conditions of MTC sensor are heterogenous for different transmission scenarios. Some sensors are installed in vehicle with high Doppler frequency shift, some are at long distance from central nodes. In frequency division systems, the subcarrier bandwidth is correlated with symbol length, and determines the system ability to combat inter carrier interference (ICI) and inter symbol interference (ISI) introduced by synchronization errors and channel fadings. In some classical OFDM-based standards, such as digital video broadcasting terrestrial (DVB-T) [2] and digital video broadcasting for return channel terrestrial (DVB-RCT) [3], the systems could select different subcarrier bandwidths to support different scenarios. In these systems, subcarrier bandwidths are variables in different spectrum bands, which increases the complexity of system realizations and applications.

On the other hand, ﬁlterbank multicarrier modulation (FBMC) [4] has been extensively studied for the recent decades. Unlike OFDMA systems, the subcarriers in FBMC systems are more independent due to low sidelobes and the avoidances of cyclic prefix, which brings the potential ﬂexibility in emerging cognitive networks and heterogenous networks [7]. The typical examples of FBMC waveform include FBMC/OQAM (offset quadrature amplitude modulation), ﬁltered multitone transmission (FMT), generalized frequency division modulation (GFDM) [5], and Universal Filtered multicarrier (UFMC)[1].

In this paper, we consider an uplink transmission scheme based on FMT, which is intended for application in uplink transmission system where MTC nodes can select their bandwidths based on the channel conditions. The transmission signals are with single carrier quadrature amplitude modulation (QAM) and conventional shaping ﬁlter. Each node could select its carrier bandwidth based on frequency selective fades, propagation delays, carrier frequency offset and doppler shift due to moving. In central nodes, the received signals are demodulated in the ways of frequency division multiple access (FDMA). There are a number of advantages for this proposed approach: i) reduced sensitivity to narrowband interferers, ii) higher ﬂexibility to allocate groups of subchannels to different users, iii) mitigation of ICI on severely time-frequency selective wireless channels, iv) pulse shaping and subcarrier spacing can be selected to improve spectral efﬁciency, v) absence of any cyclic preﬁx extension.

This paper is organized as follows. In Section II, we present the conventional FMT frequency domain reception scheme. In Section III, we introduce the basic idea of one-tone FMT, which is described in time domain. In Section IV, we provide the joint receiver for one-tone FMT, and the ICI and ISI analysis of one-tone FMT is provided. In section V, We discuss the simulation results and performance comparisons of different bandwidths under different channel conditions as well as the complexity analysis. paper is concluded in V.

II. CONVENTIONAL FMT SCHEME

The proposed one-tone FMT system is based on FMT, where subcarriers are orthogonal with each other. Each subcarrier is shaped by pulse filter which is across a length of several symbols [5]. We assume in an FMT system, the sampling rate is \(f_s\), the sample period is \(T_s = 1/f_s\). It has \(M_f\) subcarriers and \(M_0\) samples per symbol, and the filter length is \(M_3 = LM_0\), where \(L\) is the pulse filter order. The baseband waveform of FMT could be written as

\[
x(i) = \sum_{l=\lfloor i/M_f\rfloor-L+1}^{\lfloor i/M_f\rfloor} \sum_{k \in \Omega} a(l,k)g(i - M_0k)e^{2\pi ik/M_3}
\]

(1)
where \( x(i) \) is the time domain modulated sequence, \( i \) is the time domain sample index, \( l \) is the time domain symbol index, \( a(l, k) \) is the data symbol transmitted on the subcarrier \( k \) of the \( l \)th FMT symbol, \( g(n) \) is the real prototype filter with unit energy, \( \Omega \) is the subcarrier set which means \( \Omega \in \{0, \ldots, M_1 - 1\} \). For FMT systems the frequency spacing between adjacent subcarriers is given by \( 2\pi/M_1 \).

In FMT, in order to satisfy the "perfect reconstruction" constraints so that the transmission may be free of intersymbol interference (ISI), a cascaded Nyquist filter could be chosen as the prototype filter, which implies that the combination of filters in transmitter and receiver may have the Nyquist property. Here we choose the truncated root-raised-cosine pulse \[ \text{[6]} \] . Truncation gives rise to sidelobes and non-perfect raised cosine autocorrelation but the sidelobe are relatively small.

The filter has a parameter as \( M_0, M_1, M_3 \) which has been defined in \( (1) \). In our discussion, the mainlobe of the subcarriers are not overlapped with each other. The roll-off factor could be calculated as \( \rho = M_1/M_0 - 1 \). The element filter has the subcarrier bandwidth of \( f_0 = 1/(M_1 T_s) \) , the filter order is \( L \), the pulse length is \( T_3 = M_2 T_s \). Denote the time domain filter as \( g(n) \), then the frequency domain representation \( \tilde{G}(f) \) has a basic expression as

\[
|\tilde{G}(f)| = \begin{cases} 
\frac{1}{\sqrt{L}} \sqrt{1 - \sin\left(\frac{\pi f}{2 f_0}\right)} & |f| \leq (1 - \rho)/2T_0 \\
\frac{1 + \rho}{2T_0} & \text{otherwise} 
\end{cases}
\]

(2)

Tonello[6] designed a framework of frequency domain implemented modulator for filtered multicarrier transmission which may be compatible to OFDM structure and simplify the transmitter. The expression in \[ (6) \] is the frequency domain representation of \( (1) \). It could be derived using the DFT format of \( g(n) \) as

\[
x(i, k) = \sum_{k=0}^{K-1} \sum_{|i/M_0| = 0}^{M_0-1} a(l, k)g(i - M_0 l) e^{j2\pi (kL_1 + N_1)/M_1} \]

\[
= \sum_{|i/M_0| = 0}^{M_0-1} \sum_{n=0}^{N_1-1} B^1(l, n) e^{j2\pi \eta_1 m} \]

where \( B^1(l, n) = e^{j2\pi \eta_1 m} B(l, n) \) is the frequency domain representation of the prototype filter. Note that the additional complexity of the rotation parameter in \( B^1(l, n) \) may be avoided. In this paper we simplify it as \( B^1(l, n) = a(l, k)G(n - (kL_1 + N_1)) \).

III. ONE-TONE FMT SYSTEM

As demonstrated in Fig. 1, in a one-tone FMT system, each user uses only one subcarrier, and the subcarrier bandwidth is variable, determined by the channel condition and synchronization quality. For the \( u \)-th user, denote \( M_{0,u}, M_{1,u}, M_{3,u} \) as the number of samples per symbol, the number of subcarriers, and the number of samples per pulse filter. Thus the symbol rate is \( T_{0,u} = M_{0,u}T_s \), and the subcarrier bandwidth is \( f_u = 1/(M_{1,u} T_s) \). The users are frequency multiplexed through the assignment of a carrier from the \( M \) available tones. The carrier transmitted by user \( u \) can be written as follows

\[
x^u(i) = \sum_{n \in Z} g^u(l) a(i - lM_{0,u}) e^{j2\pi f_{u,i}} \]

(4)

where \( i \in Z \) are the data sample, \( a^u(l) \) belong to the M-QAM signal set and is the sequence of data symbols transmitted, \( g_u(n) \) is the \( n \)-th pulse of the prototype pulse of the FMT modulator for the \( u \)-th user, \( L = M_{3,u}/M_{0,u} \) is the filter order, \( f_u = f_s/M_{1,u} \) is the subcarrier bandwidth and \( k_u = f_s/(M_{1,u} T_s) \) is the frequency sample number in one subcarrier. The modulation process expressed in \( (5) \) is shown in Fig. 1.

![Fig. 1. The one-tone FMT time domain realization scheme](image)

We denote the longest filter as element filter. Denote \( M_{0,e}, M_{1,e}, M_{3,e} \) as the number of samples per symbol. Prototype pulses used in \( (4) \) are changed according to the bandwidths of users. For the \( u \)-th user with sub-carrier bandwidth of \( f_u \), the prototype pulse is constructed by

\[
g_u(n) = g_e(\eta_1 n) \]

(5)

where \( g_u(n) \) is the decimation of \( g_e(n) \), and \( 0 \leq n \leq M_3/\eta_1 \). And if the decimation would not lead to band aliasing, \( g_u(n) \) is the prototype impulse as long as \( M_{3,u} = M_{3,e}/\eta_1 \) due to the decimation. The filter bandwidth will be \( \eta_1 f_e \), and the symbol length is \( M_{0,u} = M_{0,e}/\eta_1 \). Using this filter, the available subcarrier bandwidth FMT would be realized by one element filter.

Decimation leads to frequency domain overlapping. If the sequence is decimated by \( 2 \) and no aliasing appears, the decimation results are the summation of the two sequences generated by split the frequency spectrum of \( g_e(n) \) from central. This implies that frequency width is two times wider, while the pulse length is reduced to half. Furthermore, if the synthesis filter \( g_e(n) \) is decimated by \( \eta_0 \), the filter bandwidth will be \( \eta_0 f_e \), \( L_1,u = L_1, e \eta_0 \), the filter length will be \( M_{0,u} = M_{0,e}/\eta_0 \). If decimation does not lead to band aliasing, the filter is just stretched and most properties will remain unchanged.
After analog-digital (AD) conversion, the signal is modeled as
\[ y(i) = \sum_{n=-\infty}^{\infty} c^n(i-n)z^n(n) + w(i) \]  
where \( y(i) \) is the \( i \)th sample of received signal, \( w(i) \) is complex additive white Gaussian noises (AWGN). We model the baseband channel of user \( u \) with a discrete-time time variable filter as \( c^n(u) = \sum_{p \in P} \alpha(p)\delta(n-p) \) where \( \delta(n) \) is the Kronecker delta function.

In receiver, \( y(n) \) is passed through an analysis filterbank with ideal prototype matched filter \( h^{eq}_u(n) \), which fulfills the effect of the channel and matched filter. The sampled outputs in rate \( 1/(M_0T_s) \) is
\[ z^u(l) = \sum_{n \in \mathbb{Z}} y(n)h^{eq}_u (lM_0u - i)e^{-j2\pi f_u i} \]  
where \( z^u(l) \) is the recovered information by receiver, \( h^{eq}_u(n) \) is the equivalent matched filter in theoretical, which could equalize the channel and shaping filter. In frequency domain, the match filter could be written as \( H^{eq}_u = \text{FFT}(h^{eq}_u(i), M_3, e) \). \( H^{eq}_u(n) \) is the combination of channel and SRC filter.

**IV. JOINT DEMODULATION AT RECEIVER**

In the basic one-tone FMT design as in (7), carriers from different users are demodulated separately, the scheme is complicated especially when there is large amount of nodes. In future heterogeneous networks, there will be various waveforms from different users. The subcarriers with different bandwidths must share most of demodulation procedure to simplify the system design. So the frequency domain joint modulation and demodulation is necessary.

As described earlier, the pulse length is variable determined by the frequency bandwidth of each subcarrier. Owing to the orthogonal property, subcarrier groups could be distinguished in frequency domain. So the received signal is
\[ z^n(l) = \sum_{n=N_e + k-1}^{M_3-1} Y(n, l)H^{eq}_e (n - N_e) \]  
where \( Y(n, l) = \sum_{n=0}^{M_3-1} y(lM_0 + i)e^{-j2\pi in/M_3, e} \). \( H^{eq}_e(n) \) is the frequency domain representation of \( h^{eq}_e(n) \), \( k_e \) is the frequency domain sample number of one subcarrier. It has the same principle and structure as one-tap equalization of OFDM. To get \( H^{eq}_e(n - N_e) \), system must get the channel information by channel estimation, which is not the focus of this work.

For the \( u \)-th user, the \( (lp_u + s) \)-th data symbol is
\[ z^n(l) = \sum_{n=0}^{M_3-1} y(lM_3 + i)h^{eq}_e (n - N_u) + \sum_{n=N_u \pm L_1, u}^{M_3-1} Y(n)H^{eq}_e (n - N_u) \]
\[ = \sum_{n=N_u \pm L_1, u}^{M_3-1} Y(n)H^{eq}_e (n - N_u) \]
where \( h^{eq}_e(u, n) = \text{FFT}([0, \ldots, 0; h^{eq}_e(u, i), 0, \ldots, 0]) \)
and this time domain filter correspond to frequency domain filter of \( H^{eq}_e(u, n) = \text{FFT}(h^{eq}_e(u, n), M_3, e), N_u \) is the start frequency sample of \( u \)-th user.

The demodulator is illustrated in Fig. 3, where, after joint FFT operation, the data symbols in all subcarrier groups are equalized. Then the equalized data symbols in different subcarrier groups are match-filtered simultaneously. Finally, data symbols in one subcarrier are detected as in Fig. 3. Using (9), we would construct the frequency domain demodulator.

To analyze the ICI and ISI [7], the equivalent impulse response between the input channel \( k \) and output subchannel \( k \) is defined as
\[ h^{eq}_e(k,l) = e^{j2\pi (f_u mM_0 u - f_s lM_0 u)} \sum_{i=0}^{\infty} h(u, lM_0 u - i) \]
\[ \times \sum_{p} \alpha_p(i)\delta(l, i - p - mM_0 u) \]  
where \( e^{j2\pi (f_u mM_0 u - f_s lM_0 u)} \) is the frequency error of transmitter and receiver, and the later is equivalent channel considering the matched filter. In fading channel, one-tap equalization as (9) is equivalent as that of time domain representation in (7). Its ICI and ISI is written as
\[ z(u,l) = a(u,l)g(u,l)h^{eq}_e (lM_0 u, mM_0 u) \]
\[ + \sum_{m=-\infty}^{\infty} a(u, m)h^{eq}_e (lM_0 u, mM_0 u) \]
\[ + \sum_{u'} \sum_{m=-\infty}^{\infty} a(u', m)h^{eq}_e (lM_0 u, mM_0 u) \]
As in (11), the ratio between channel delay and symbol length determines the ISI. If users choose a wider subcarrier, the ISI would be large for the short symbol time, but the ICI will be small. So one-tone FMT systems are able to combat the fading channels by changing the subcarrier bandwidth. For example, a MTC node chooses its own carrier in both the bandwidth and spectrum position determined by its special channel condition, just like (4) and Fig. 1, and use (9) or Fig. 2 to get the recovered data jointly. By this method, the system could flexibly support MTC nodes under different mobile speeds, spectrum bands and channel conditions.

![Fig. 2: Joint receiver for one-tone FMT system](image-url)
through changing the subcarrier bandwidths.

It is understandable that the performances for the two cases are similar. From the simulation results, we could conclude that the one-tone FMT could support different Doppler spreads while maintaining a comparable BER. The transmitter of this scheme is single carrier modulation with linear complexity. The receiver of one-tone FMT designed in Fig. 2 has the similar structure to OFDMA one, but they require oversampling, thus the FFT scale is larger than OFDMA. FTT has a complexity of $O(n \log_2 n)$. OFDMA is with the unified complexity $\alpha(M_3 \log_2 M_4)(M_1 + N_{CP})$, where $\alpha$ is a constant, while the one-tone FMT has a FFT complexity of $O(M_3 \log_2 M_4)(M_0 \cdot c)$. The other additional operations, such as frequency domain matched filtering and summations, are the complexity of $O(n)$. The number of those operations is $M_3 x k / M_0 \cdot c$. Thus, the receiver complexity of one-tone FMT is approximately $L$ times larger than that of OFDMA, but one-tone FMT obtain a number of advantages mentioned in this paper.

VI. CONCLUSION

An one-tone FMT system has been proposed in this paper, which includes both waveforms and implementation structures to support MTC. Furthermore, the proposed implementation framework in this paper could be compatible with conventional OFDM systems. A recommended receiver structure has also been provided for the proposed approach. Finally, simulation results have shown that the system could support various transmission scenarios by changing the subcarrier bandwidths.

VII. ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China under Grant No. 61401274.

REFERENCES

[1] G. Wunder, P. Jung, M. Kasparick, et al., “5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications,” IEEE Commun. Mag., vol. 52, no. 2, pp. 97-104, Feb. 2014.
[2] ETSI, “Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television,” 2006.
[3] ETSI ETS 301 958, “Digital Video Broadcasting (DVB); Interaction Channel for Digital Terrestrial Television (RCT) Incorporating Multiple Access OFDM,” ETSI ETS 301 958, Mar. 2002.
[4] B. Farhang-Boroujeny, “OFDM versus filter bank multicarrier,” IEEE Signal Process. Mag., vol. 28, no. 3, pp. 92-112, May 2011.
[5] G. Fettweis, M. Krondorf, and S. Butten, “GFDM - Generalized Frequency Division Multiplexing,” Proc. IEEE 69th VTC Spring, Barcelona, Spain, Apr. 2009, pp. 1-4.
[6] A. Tonello, “Time domain and frequency domain implementations of FMT modulation architectures,” in Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2006), Toulouse, vol. 4, pp. 625-628, Mar. 2006.
[7] A. M. Tonello, “Analytical Results About the Robustness of FMT Modulation with Several Prototype Pulses in Time-Frequency Selective Fading Channels,”IEEE Trans. Wireless Commun., vol. 7, no. 5, pp. 1634-1645, May 2008.