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Synchronization based on Pseudo-Circular Preamble with Generalized Frequency Division Multiplexing in Vehicular Communication

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***Abstract*—This paper introduces the concept of using the first subsymbol in the structure of a GFDM symbol as a pseudo circular preamble. Details about the motivation scenario in vehicular communication and the GFDM modulation are presented together with a prime estimation approach for isolating the preamble information from regular data. The concept aims to allow easy adaptation of state-of-the-art techniques developed for OFDM to estimate time offset at every single GFDM symbol. The performance of single-shot estimation of time offset is evaluated in non line of sight scenarios double dispersive wireless channel.**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a widely deployed multi-carrier modulation scheme that provides spectral efficiency and is robust against distortions in multi-path fading channels. It is well known that OFDM is sensitive to symbol time offset (STO) and carrier frequency offset (CFO). Particularly in vehicular communication scenarios, two effects can cause CFO and significant STO changes: (i) Vehicles driving at high velocity create Doppler shifts of the signal, and (ii) signal reflections at the road surface and buildings cause multi-path propagation. Although the CFO problem can be minimized with initial preamble acquisition or high quality oscilators referenced to GPS (Global Positioning System) clock, the combination of multi-path effects and Doppler (doubly-dispersive channel) make the STO synchronization at the receiver a challenging task and can result in a severe degradation of the communication performance.

For vehicular communication, the IEEE 802.11p standard[1] operating in the 5.9 GHz frequency band has been adopted as part of the protocol stacks [?], [?]. Being based on the 'a' version of IEEE 802.11, the 'p' standard defines a conventional preamble that is used for the estimation of CFO and STO at the beginning of the frame. With fast varying channel conditions, as it is common in vehicular communication scenarios, STO of the strong multipath change along the several symbols in a frame and can considerably blind the correct estimation of the first multipath. The preamble-based synchronization in combination with pilots and cyclic prefix does not allow to easily track this variation during the complete transmission of the frame, which degrade the bit-error rate (BER).

A vast literature for the estimation CFO and STO is available, covering scenarios, such as continues, sporadic and scheduled transmissions [?] [?] [?] [?], for broadcast, random access and cellular networks, respectively. The approaches usually take advantage of special training symbols to achieve faster timing and frequency synchronization and use pilots to keep tracking the varying channel. A specific solution for vehicular communication has been proposed in [?], which requires the complex use of reliable soft decoded data information as pilots. However, the iterative procedure of channel estimation may introduce additional latency. For the target latency in the tens of milliseconds order at the physical layer, this approach is appropriate, but may not be acceptable for even faster timing requirements in the order of milliseconds for PHY frame processing.

This paper presents a synchronization scheme based on a pseudo-circular training sequence that combines training and pilot symbols together with user data symbols into a single block. The proposed scheme aims to efficiently track the first multipath STO changes at every symbol over the complete transmission block and hence alleviates the affects of fast varying channel conditions. The use of a pseudo-circular training sequence is a specific property of the newly proposed waveform termed Generalized Frequency Division Multiplexing (GFDM) [?].

GFDM is a block filtered multi-carrier modulation scheme, in which multiple subsymbols can be transmitted per subcarrier in a block with cyclic prefix (CP). GFDM applies circular pulse shaping of the individual subcarriers. For synchronization, the circularity principle allows GFDM to explore cyclic prefix (CP) and use frequency domain equalization to handle multi-path effects in frequency selective channels. The generalized subsymbol structure of GFDM can be used to combat Doppler effects in time selective channels. GFDM can also resemble the well-known OFDM system, with the choice of a single sub-symbol and a rectangular pulse shape, and the SC-FDE, using a single subcarrier with several subsymbols. This feature suggests that state of the art techniques for synchronization applied for the OFDM and SC-FDE configurations can be adapted for more general configurations of

[1]The p-amendment has been integrated into IEEE 802.11-2012. ITS-G5 is the European variant of IEEE 802.11p.

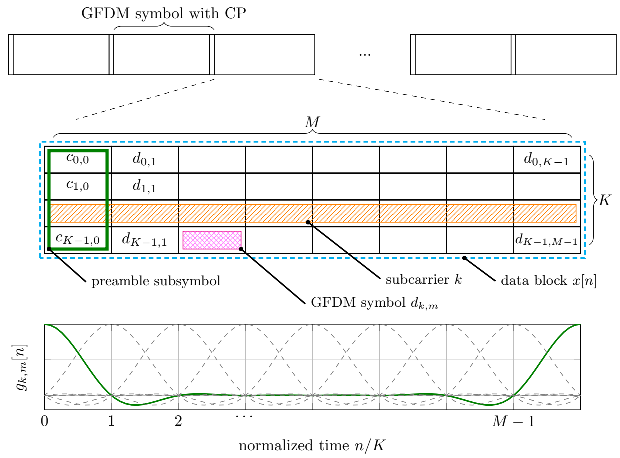

Fig. 1. Sequence of GFDM symbols with CP, terminology structure, preamble subsymbols and pulse shaping

GFDM. A first step using an isolated preamble for one-shot synchronization of sporadically sent data frames has been presented in [**?**], while an accompanying tracking mechanism that examines the GFDM spectrum aspects has been addressed in [**?**].

The paper is organized as follows: Sec. **??** provides details about the vehicular communication scenario. Section **??** contains the system model, Sec. **??** describes the GFDM modem and the relevant information to design a pseudo circular preamble. Sec. V explains the metrics used for one-shot synchronization, followed by performance results in Sec. VI and conclusions in Sec. VII presents the conclusions.

II. Vehicular Communication Scenario

The scenario considered in this paper is based on a system that operates in the 5.9 GHz band allocated for road safety and traffic efficiency applications in North America and Europe, with channel spacing of 10 MHz. Assuming a multi-carrier modulation scheme with 64 subcarriers, the subcarrier separation is $10\,\mathrm{MHz}/64 = 156.25\,\mathrm{kHz}$, which corresponds in a symbol duration of $6.4\mu s$. Assuming a cyclic prefix (CP) of one fourth the symbol duration, $1.6\mu s$, as in the reference case IEEE 802.11p, facilitates that multipath propagation can differ up to $(1.6\mu s) * (3 * 10^8 m/s) \approx 480m$, which is within a maximum intended communication range of about 1 km.

Channel time-variations are characterized by the Doppler spread, and the maximum Doppler frequency is calculated as $f_D = \Delta_v * (5.9 * 10^9)/(3 * 10^8)$, where Δ_v is the relative speed between two vehicles. The term $1/f_D$ roughly estimates the time where the channel significantly changes. For a high-speed scenario with two approaching vehicles and $\Delta_v = 250\,\mathrm{km/h} \approx 70\,\mathrm{m/s}$, $1/f_D$ corresponds to a duration of approximately 90 OFDM symbols in our reference case. But a higher number of symbols is usually required for the transmission of a safety data with a typical size of several hundred bytes, and the proposed frame structure is known to under-perform without complex channel estimation tracking techniques [**?**].

IEEE 802.11p OFDM uses a considerably high amount of resources as guard bands, i.e. 16 subcarriers in frequency and a cyclic prefix extension of a quarter of the symbol duration. Comparatively, GFDM can reuse a single CP for several subsymbols and explore a more granular grid, which better utilizes time and frequency resources. The proposed pseudo circular preamble approach can save overhead for synchronization and potentially enables advanced channel estimation. The payload of an GFDM PHY frame and the GFDM symbol terminology, constituted of K subcarriers carrying M subsymbols, is illustrated in Fig. **??**.

In order to assess the synchronization scheme for GFDM proposed in this paper, we assume a vehicular communication system and protocol stack as it was studied in the cooperative ITS FoTs, including a random medium access procedure as in IEEE 802.11p, ad hoc networking among vehicles and with the roadside infrastructure, facility layer messages, support for security and management, but replace OFDM by GFDM in the PHY layer. Typical application scenarios include vehicle collision avoidance, such as forward collision warning or emergency electronic brake lights, which rely on periodic broadcast of safety messages, called Basic Safety Message (BSM) in the US Wave protocol stack or Cooperative Awareness Message (CAM) in the ETSI ITS protocol stack [**?**]. These messages contain dynamic vehicle information including latitude and longitude, speed and heading, and others.

When a vehicle receives a safety message, it gains information about its vicinity and is able to detect potential safety threats, such as rear end collision; a vehicle driver assistant function can then alert the driver or trigger automatic interventions. From the physical layer perspective, we consider the broadcasted data packets as "single shot burst", opposed to continuous frame transmission as for example in LTE download link, with periodic training sequence and a guard period in addition to the data payload.

The main requirement for STO synchronization in the single shot burst is then to search for the first multipath at every GFDM packet. More specifically this paper will evaluate the performance of the proposed pseudo circular preamble in the line of sight (LOS) and non line of sight (NLOS) scenarios of two vehicles approaching an urban intersection, with other traffic present and buildings and fences present on all corners, and as for NLOS highway, with occluding trucks present between the vehicles, [**?**].

III. System Model

The general system model for the transmitted signal is presented in Fig. **??**. On the transmitter side, the model considers a source of complex data $d[n]$ modulated as a GFDM symbol $x[n]$, see **??**. A guard interval of N_{CP} cyclic prefix samples is added to the transmitted signal $\tilde{x}[n] = [\langle -N_{\mathrm{CP}}\rangle_N \ldots x[0] \ldots x[N-1]]$ to prevent intersymbol interference, where $\langle \bullet \rangle_N$ denotes the remainder modulo N, the sample length of a GFDM symbol.

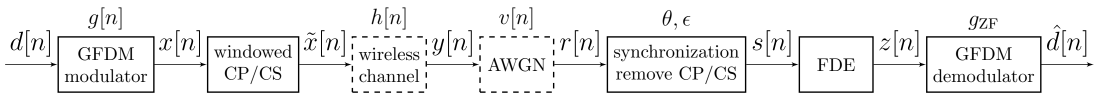

Fig. 2. Transceiver block diagram

The signal passes through a time-varying frequency domain channel impulse response (CIR), $h[n]$, with doubly dispersive behavior [?] described by h_l complex coefficients with τ_l delay and Doppler frequency f_l on each $l = 0, 2, ..., L-1$ multipath tap, leading to

$$y[n] = \sum_{l=0}^{L-1} h[l] e^{j2\pi f_l n} \tilde{x}[n-l], \tag{1}$$

The CIR is considered to be stable within the duration of one symbol, which can be achieved with the proper choice of the symbol length, and is time-variant over a frame composed of several symbols.

On the receiver side, discrete baseband samples are collected with an accurate sampling rate, resulting in

$$r[n] = y[n-\theta] e^{j2\pi\epsilon n} + v[n], \tag{2}$$

where θ is the STO, ϵ is the CFO and $v[n]$ denotes the additive white Gaussian noise (AWGN).

The synchronization task presented in this paper refers to the signal processing carried on the receiver side to estimate ϵ and θ, allowing to remove cyclic prefix and compensate carrier frequency offset and generate the aligned received signal $s[n]$. The properties of the GFDM signal that are relevant for the synchronization approach are explained in the following section.

IV. GFDM Model

In the GFDM modulator the data source $d[n]$ consists of complex QAM values arranged in K subcarriers carrying M subsymbols each, resulting in a total of MK parallel substreams critically upsampled at the rate $N = MK$. Given a prototype filter $g[n]$, each mth subsymbol, $m = 0 \dots M-1$, in a kth subcarrier, $k = 0 \dots K-1$, is shaped by a cyclic time and frequency shifted version of its impulse response. The GFDM modulator expression can be conveniently presented as [?]

$$x[n] = \sum_{m=0}^{M-1} g[\langle n - mK \rangle_N] \delta_m[n], \tag{3}$$

where, the term $\delta_m[\langle n \rangle_K]$ represents K elements, termed here as information coefficient vector, which are repeated M times over the GFDM block. These elements can be seen as the output of M standard OFDM modulators with K subcarriers given by

$$\delta_m[n] = \sum_{k=0}^{K-1} d_{k,m} \exp(j2\pi \tfrac{k}{K} n). \tag{4}$$

Assuming that the a perfect synchronization is achieved and the signal $s[n]$ is available, frequency domain equalization

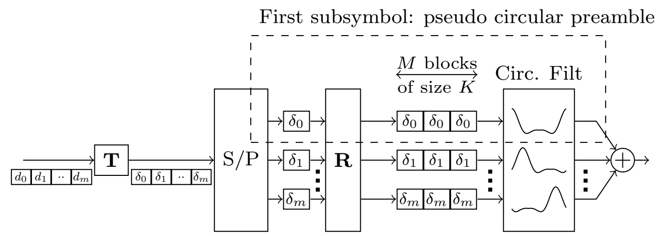

Fig. 3. GFDM modulator and the pseudo circular preamble concept, where $\mathbf{R}$ is a repetition block

(FDE) provides $z[n]$ and the GFDM signal can be demodulated as follows [?]

$$\hat{d}_{k,m} = \sum_{n=0}^{K-1} \hat{\delta}_m[k] \exp(-j2\pi \tfrac{n}{K} k), \tag{5}$$

where

$$\hat{\delta}_m[k] = \sum_{m'=0}^{M-1} \delta'_m[k + m'K], \tag{6}$$

is the received information coefficient vector and

$$\delta'_m[n] = \gamma^*[\langle n - mK \rangle_N] z[n], \tag{7}$$

is a correlation process with $\gamma^*[n]$, which can be a matched filter (MF), or zero-forcing (ZF), or minimum mean square error (MMSE) prototype pulse [?], [?].

V. Pseudo circular preamble

The synchronization approach proposed in this paper considers the transmission of known pilots $c[k]$ allocated in the first subsymbol, i.e. $d_{k,0} = c[k]$,

$$x[n] = p[n] + \sum_{m=1}^{M-1} g[\langle n - mK \rangle_N] \delta_m[\langle n \rangle_K], \tag{8}$$

where

$$p[n] = g[n] \delta_0[n], \tag{9}$$

which corresponds to the pseudo circular preamble shown in Fig. ?? and Fig. ??.

Observe that the preamble energy can be spread along the entire block, but with higher intensity on the edges. In a corner case, choosing $g[n]$ to be a rectangular pulse with the duration of one subsymbol, the proposed system emulates a concatenation of OFDM blocks. Possibly, additional channel tracking information can also be explored at the begging and at the end of the block.

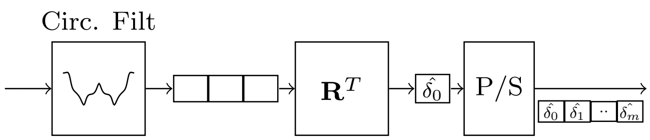

Fig. 4. Proposed circuit to recover the pseudo circular preamble information, where $\mathbf{R}^{\mathrm{H}}$ is a folding block that performs the summation described in Eq. (**??**)

A. Estimation of the information on the Pseudo circular preamble

Depending on the pulse shape design data and training sequence overlaps and causes interference, as suggested in Fig. **??**. Based on (**??**)???, this paper proposes to use the following estimator of the information coefficient vector

$$\hat{\delta}_0[k] = \sum_{m'=0}^{M-1} \delta'_0[k + m'K], \tag{10}$$

with

$$\delta'_0[n] = \gamma^*[n]r[n], \tag{11}$$

as a way to isolate the know information of the training sequence from the data. A corresponding circuit is depicted in the Fig. **??**.

VI. Simple Metric

The CFO estimation problem can be subject mainly to Doppler effects if minimized with the use of stable references, both in transmitter and receiver side. With this consideration, the correlation of the received signal $\hat{\delta}_0$ with the know transmitted information coefficient vector δ_0, given by

$$C[n] = \sum_{k=0}^{K-1} \hat{\delta}_0[n + k]^* \delta_0[k], \tag{12}$$

result in a metric that can reveal the STO of the strongest multipath,

$$\hat{n}_{\text{strong}} = \underset{n}{\text{argmax}} \, |C[n]| \, . \tag{13}$$

In non-line-of-sight the primary echo of the time-variant FSC can be lower than other echoes and the strongest peak at $\hat{n}_{\text{strong}}$ may not represent the correct STO. An additional search before $\hat{n}_{\text{strong}}$ is necessary to verify if there is another yet undetected peak to be considered as the primary one. The metric for uncorrelated sequences can be modeled as a complex Gaussian signal, than a threshold criteria can be used to search other multipaths before $\hat{n}_{\text{strong}}$, with a probability of false alarm p_{FA}, [**?**][**?**]. Considering that the first peak of (**??**) is within the range $(\hat{n}_{\text{o}} - \lambda,\, \hat{n}_{\text{o}}]$, where $\lambda < N_{\text{CP}}$ is an adjustable parameter, the threshold is defined as

$$T_{\text{Th}} = \sqrt{-\frac{4}{\pi}\ln\left(p_{\text{FA}}\right)} \left(\frac{1}{\frac{K}{2} - 2\lambda} \sum_{k=-\frac{K}{2}+\lambda}^{-\lambda} |C[\hat{n}_{\text{strong}} + k]| \right) \tag{14}$$

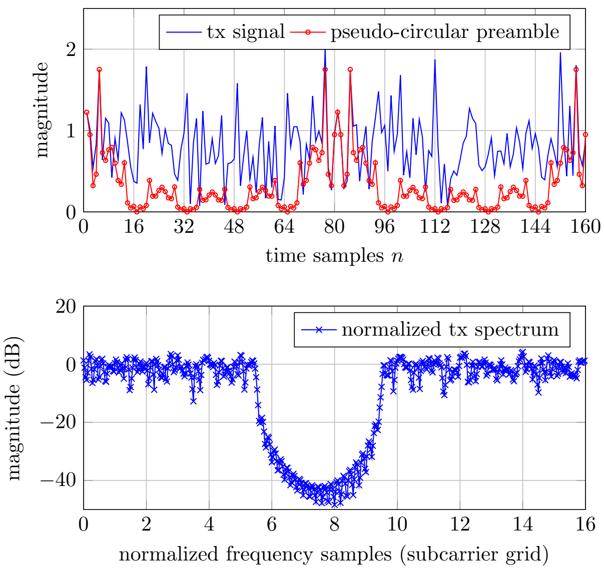

Fig. 5. Tx signal with pseudo-circular preamble in time and frequency domain.

and the fine STO estimation for the first multipath is finally obtained with

$$\hat{n}_{\text{first}} = \underset{\hat{n}_{\text{strong}} - \lambda < n \leq \hat{n}_{\text{strong}}}{\text{argfirst}} \left(|C[n]| > T_{\text{Th}}\right). \tag{15}$$

VII. Performance results

The GFDM signal is configured according to 802.11p, with a BW of 10 MHz and overall symbol duration of $8\mu s$, but here the CP interval is replaced by the pseudo circular preamble. With $K = 16$ subcarriers, $M = 5$ subsymbols and using a Dirichlet pulse shape [**?**], the pseudo circular preamble creates a common guard signal in the boundaries of the GFDM symbol. This particular property allows the smooth concatenation of symbols, reducing drastically the out of band radiation, as shown in Fig. **??**. The system considers that CFO accuracy is achieved by use of stable references, or alternatively by the use of the entire first GFDM symbol in a frame as known information [**?**].

The detection rate and the mean square error of STO estimations have been evaluated for 1000 realizations at each value of SNR and are presented in Fig. **??**. The detection rate is defined as the proportion of STO estimation obtained within the range of the channel impulse response length. The mean squared error of the STO estimation is within tenths of a sample in the channel with LOS. In the NLOS case it is observed that MSE increases considerably, but is still within units of samples. This is not always a issue, once the impact of losing a weak multipath is so severe.

VIII. Conclusions

Motivated by a vehicular communication scenario, this paper has introduced the concept of a pseudo circular preamble using the particular structure of GFDM. The performance of transmitting know information in the first subsymbol and the

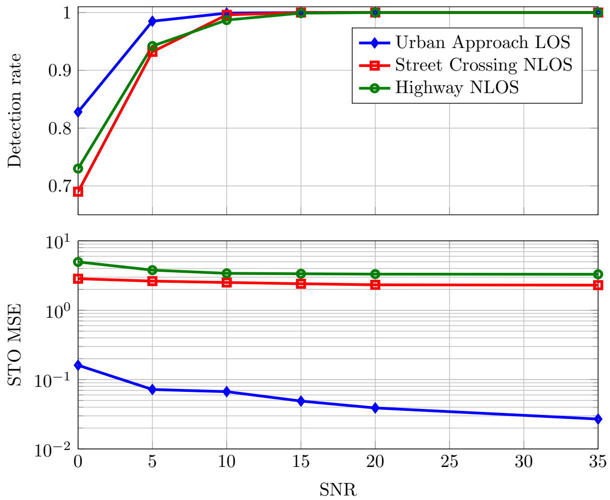

Fig. 6. Detection rate of the STO, within the channel impulse response duration, and corresponding STO MSE.

corresponding estimation of STO was presented in terms of mean square error of the residual errors for two vehicles approaching in line and non-line of sight conditions.

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