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Jong-Hoon Won, Diana Fontanella, Matteo Paonni, Bernd Eissfeller, Andrea
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Jong-Hoon Won, Diana Fontanella, Matteo Paonni, Bernd Eissfeller
The Institute of Space Technology and Space Application, University FAF Munich, Germany

Andrea Emmanuele, Marco Luise
Department of Information Engineering, University of Pisa, Italy

Axel Garcia-Peña, Olivier Julien, Christophe Macabiau
ENAC, France

Francesca Zanier, Gustavo Lopez-Risueno
European Space Agency/ESTEC, The Netherlands

BIOGRAPHIES

Jong-Hoon Won studied control engineering at Ajou University, S. Korea (PhD). In 2004 he worked with Korea Aerospace Research Institute (KARI) on the high accuracy nationwide DGPS in Korea. Since August 2005 he has worked with the Institute of Space Technology and Space Applications (former the Institute of Geodesy and Navigation), University FAF Munich, Germany. He was nominated as Head of GNSS Laboratory in 2011 at the same institute, and involved in lectures on advanced receiver technology at Technical University of Munich since 2009. He has worked as a project engineer in many industrial/governmental funded research projects since 1995, and published many technical papers in the fields of GNSS signal, receiver, navigation, and target tracking systems.

Diana Fontanella received her M.Sc. in Telecommunications Engineering from Politecnico di Milano, Italy (2009). She is research associate at the Institute of Space Technology and Space Applications (former Institute of Geodesy and Navigation) at the University of the Federal Armed Forces (UFAF) Munich. She is currently involved in ESA and EC/GSA projects with focus on GNSS signal design, GNSS radio frequency compatibility, and GNSS performance assessment.

Matteo Paonni is research associate at the Institute of Space Technology and Space Applications (former the Institute of Geodesy and Navigation) at the University of the Federal Armed Forces Munich. He received his M.S. in Electrical Engineering from the University of Perugia, Italy, and is PhD candidate at the Faculty of Aerospace Engineering of the University FAF Munich. He is actually involved in several European projects with focus on GNSS as project engineer as well as project manager. His main topics of interest are GNSS signal structure, GNSS compatibility and interoperability and GNSS performance assessment. He is involved in the Galileo program, in which he actively supports the European Commission through the Compatibility, Signal and Interoperability Working Group (CSI WG), formerly Galileo Signal Task Force.

Bernd Eissfeller is Full Professor of Navigation and Director of the Institute of Space Technology and Space Applications (former the Institute of Geodesy and Navigation) at the University FAF Munich. He is responsible for teaching and research in navigation and signal processing. Till the end of 1993 he worked in industry as a project manager on the development of GPS/INS navigation systems. He received the Habilitation (venia legendi) in Navigation and Physical Geodesy in 1996 and from 1994-2000 he was head of the GNSS Laboratory of the Institute of Geodesy and Navigation.

Andrea Emmanuele received the B.E. and the M.E. degrees (cum laude) in Telecommunications Engineering from the University of Pisa, Pisa, Italy, in 2006 and 2008, respectively. He is currently working toward the Ph.D. degree in information engineering at the same university. He is currently involved in ESA projects with focus on GNSS signal design, GNSS radio frequency compatibility and GNSS performance assessment. His current research activities are mainly focused on satellite positioning systems, focusing on time delay estimation for satellite positioning systems and wireless communications.

Marco Luise is a Full Professor of Telecommunications at the University of Pisa, Italy. After receiving his M.E. and Ph.D. degrees in electronic engineering from the University of Pisa, he was a Research Fellow of the European Space Agency (ESA) at ESTEC Noordwijk, The Netherlands, and a Researcher of the Italian National Research Council (CNR), at the CSMDR Pisa. Prof. Luise is a Senior Member of the IEEE and served as an Editor for Synchronization of the IEEE Transactions on Communications, and as an Editor for Communications Theory of the European Trans. on Telecommunications. He is the co-Editor-in-Chief of the recently founded International Journal of Navigation and Observation, and acts as the General Secretary of the Italian Association

GTTI, Gruppo Telecomunicazioni Teoria dell'Inform-
azione. His main research interests lie in the area of
wireless communications, with particular emphasis on
CDMA/multicarrier signals and satellite communications
and positioning.

Axel Garcia is a researcher/lecturer at the signal
processing laboratory of ENAC (Ecole Nationale de
l'Aviation Civile – French Civil Aviation University),
Toulouse, France. His research interests are GNSS
navigation message demodulation, optimization and
design, GNSS receiver design and GNSS satellite payload.
He received his double engineer degree in 2006 in digital
communications from SUPAERO and ETSETB-UPC,
and his PhD in 2010 from the Department of Mathematics,
Computer Science and Telecommunications of the INPT
(Polytechnic National Institute of Toulouse), France.

Olivier Julien is a researcher/lecturer at the signal
processing laboratory of ENAC (Ecole Nationale de
l'Aviation Civile – French Civil Aviation University),
Toulouse, France. His research interests are GNSS
receiver design, GNSS multipath and interference
mitigation and GNSS interoperability. He received his
engineer degree in 2001 in digital communications from
ENAC and his PhD in 2005 from the Department of
Geomatics Engineering of the University of Calgary,
Canada.

Christophe Macabiau graduated as an electronics engineer
in 1992 from the ENAC in Toulouse, France. Since 1994,
he has been working on the application of satellite
navigation techniques to civil aviation. He received his
Ph.D. in 1997 and has been in charge of the signal
processing lab of the ENAC since 2000. His research now
also applies to vehicular, pedestrian and space
applications, and includes advanced GNSS signal
processing techniques for acquisition, tracking,
interference and multipath mitigation, GNSS integrity, as
well as integrated GNSS inertial systems and indoor
GNSS techniques.

Francesca Zanier received the M.E. (cum laude) in
telecommunications engineering and the PhD degree in
information engineering from the University of Pisa
(Italy), in 2004 and 2009, respectively. During her PhD
studies, she cooperated with the Radio Navigation
working group at the European Space Research and
Technology Center (ESTEC) of the European Space
Agency (ESA), concerning aspects on signal design for
future GNSS. Since 2009, she has been with the
Radionavigation section at ESA/ESTEC, Noordwijk. Her
research activities are mainly focused on digital
communication theory, signal processing and satellite
positioning systems, with special emphasis on time delay
estimation and signal design for satellite positioning
systems.

Gustavo Lopez-Risueno has received the M. Sc. and the
Ph.D. in telecommunications engineering from the
Universidad Politécnica de Madrid, Spain. He has held
several positions in academia, ESA and NC3A (NATO).
Currently, he is a Radionavigation systems engineer at
ESA/ESTEC, Noordwijk working mainly on signal
processing for GNSS receivers and monitoring.

ABSTRACT

This paper presents the receiver architecture analysis on
FMT signals for navigation purposes, which are a
multicarrier signaling technique based on OFDM for
CDMA signals with SRRC pulses for the spectral
efficiency. A new type of FMT signal processing scheme
making use of the complex FMT replica to have a narrow
correlation peak and thus to achieve precise ranging
without performing the IFFT operation is proposed. The
distinctive features of the proposed receiver architecture
are discussed and preliminary considerations on the signal
processing schemes, e.g. acquisition and tracking, for
FMT signals are described.

INTRODUCTION

Current Signals-In-Space (SIS) of Global Navigation
Satellite Systems (GNSSs) has been designed mainly
based on rectangular chip pulses. Such a choice has
indeed many advantages in terms of simplicity of the
generation scheme and the receiver architecture; however
these signals are characterized by high out-of-band (OOB)
emissions which may interfere with other services in
neighbor bands. Therefore, bandwidth efficient
modulation schemes by shaping of pulses or waveforms
should be taken into account for the design of next
generation GNSS signals [1].

GNSSs are very complex systems and a considerable
trade-off is necessary to fulfill the various requirements,
such as maximizing the synchronization performance,
providing the required data delivery rate, minimizing the
overall signal acquisition time and so on. In particular the
design of a navigation system has to take into account for
communications and ranging aspects at the same time.
The Code Division Multiple Access (CDMA) is a
technique widely used in GNSS since it perfectly meets
the needs of these two aspects, i.e. an easy multiple
accessibility and data delivery for different users and an
optimal ranging capability due to the wide spectral
occupancy of the signals which corresponds to a high
time resolution. Another good property of CDMA is its
intrinsic robustness to interference and jamming.

The multicarrier (MC) modulation scheme widely used in
the communication community could be another
interesting technique. The principle of classical
multicarrier transmission is to convert a serial high-rate
data stream onto multiple parallel low-rate sub-streams;
thus each sub-stream is modulated on another sub-carrier,
i.e. MC modulation transmits the data across multiple
narrow band channels by dividing the bandwidth into
many small orthogonal frequencies, effectively achievable
using the FFT, where the multiple narrow band channel

suffers only from flat fading. As a consequence, the symbol rate on each sub-carrier is much less than the initial serial data symbol rate and the distortions introduced by the channel are attenuated; Inter-Symbol-Interference (ISI) is significantly decreased in MC signals with the effect of reducing the required complexity of the equalizer. Another good property of MC modulation is indeed the spectral efficiency which reflects in low OOB emissions. Furthermore, the MC transmission is a low-complex technique to efficiently modulate multiple sub-carriers by using digital signal processing based on IFFT operation. For all these reasons, MC techniques have been adopted in digital broadcast television and radio, and accepted as the next generation standard for wireless LAN systems [2].

The MC modulation however has also some drawbacks such as difficulty in subcarrier synchronization and sensitivity to frequency offset. Another disadvantage is represented by its non-constant envelope nature, which results from the fact that the composed signal is obtained as the sum of several subcarriers with overlapping power spectra; as a consequence the transmitter amplifier is forced to work in the nonlinear region [2].

Despite these drawbacks, the multicarrier CDMA seems to be a promising technology and is expected to play a role in GNSS scenarios near future. In particular it is of interest in this paper the filtered multi-tone (FMT), which is a MC technique based on Orthogonal Frequency Division Multiplexing (OFDM) for CDMA signals with Square-Root-Raised-Cosine (SRRC) pulses [3,4].

In this paper the results of the receiver analysis on FMT signals conducted in the framework of ESA funded research project, so called Advanced Signal-In-Space Techniques (ADVISE), are presented. First the general aspects of multicarrier signaling techniques are reviewed. And two different types of FMT signal processing schemes, a conventional MC demodulation-based receiver and a receiver scheme making use of the complex FMT replica, are presented. In particular this second scheme is of interest since it operates on the complex signal to provide accurate ranging information without performing the IFFT operation. Finally, the distinctive features of the proposed receiver architectures will be discussed and some preliminary considerations on the signal processing schemes, e.g., acquisition and tracking, for FMT signals will be given.

REVIEW ON MULTICARRIER SIGNALS

Multicarrier Signaling

In fact there are so many different configurations of OFDM technology that should be dealt in different ways. In this section we review the MC signaling technique, e.g. OFDM, with a special attention on navigational purposes.

The navigation system is a combination of communication system and ranging system. For this, a CDMA technology is widely used due to its benefits stated before. Therefore, the core technology expected

near future in this field is multicarrier CDMA. Originally, the multicarrier CDMA was proposed by Yee et al. for indoor wireless radio networks [5], where they used a little bit different definition on multicarrier CDMA technology from that widely used in nowadays. An overview on different forms of multicarrier CDMA technologies was well summarized in [6-9] including its relationship with OFDM, a comparison of its performance with direct sequence CDMA, and some specific implementation problems.

Figure 1 is three distinctive multicarrier modulations with four sub-channels $N_c = 4$ in comparison with a single carrier direct-sequence (DS) CDMA signal redrawn from [2]. Note that the three-dimensional time/frequency/power density representation is used to illustrate the principle of various schemes. Also note that for the sake of simplicity we do not consider the signal pulse shaping effect in this figure but this will be taken into account later for FMT signals.
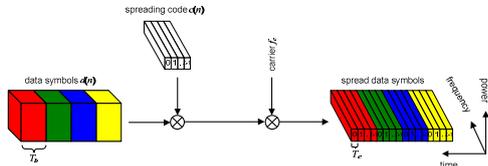
Figure 1 (a) shows the single carrier DS-CDMA signal generation. For signal spreading, pseudorandom noise (PN) code is made up from a number of chips for mixing the data with the code. The size of a chip determines the frequency spreading. Different user information is multiplexed by the use of different PN codes. The drawback is that synchronization becomes more difficult and requires a time consuming search technique or a pilot signals for aided acquisition.

Figure 1 (b) shows the multicarrier modulation with $N_c = 4$ sub-channels based on the OFDM without the use of DS codes. The channel can be considered as time-invariant during one OFDM symbol and fading per sub-channel can be considered as flat. This lead to the fact that the OFDM symbol duration should be smaller than the coherent time of the channel and the sub-carrier spacing should be smaller than the coherent bandwidth of the channel.

Figure 1 (c) shows the MC-CDMA, also referred as OFDM-CDMA. This is the combination of frequency domain spreading and multicarrier modulation. In this scheme, the multiplexing is carried out by applying different spreading codes in the code domain at the same time for the same bandwidth. The use of multicarrier leads to the decrease of the occupied bandwidth. The MC-CDMA transmits a data symbol of a satellite simultaneously on several narrow sub-channels by mapping the chips of a spread data symbol in frequency direction over several parallel sub-channels.

Figure 1 (d) shows the MC-DS-CDMA that is the multicarrier modulation with a number of sub-channels based on the OFDM for the DS codes. Apart from the MC-CDMA, this method maps the chips of a spread data symbol in the time direction over several multicarrier symbols. First, a serial-to-parallel converter is applied to convert the high-rate data symbols into parallel low-rate sub-streams before spreading the data symbols on each sub-channel with a satellite specific spreading code in time direction. This corresponds to direct sequence spreading on each sub-channel. Note that FMT, the

multicarrier modulation signal candidate in this paper, is a type of MC-DS-CDMA incorporated with the SRRC pulses for spreading codes in time domain. There are several different types of MC-DS-CDMA schemes with regard to the direct sequence spreading before or after the multicarrier modulation. The multicarrier signaling can be realized by using the low-complex OFDM operation by using an efficient FFT operation [2].
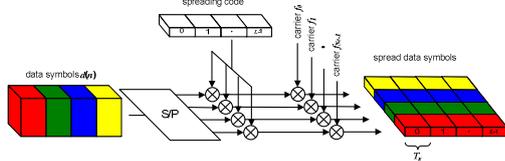

(a) Single carrier DS-CDMA generation
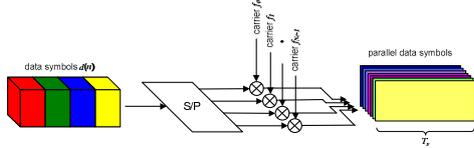
(b) Multicarrier signal generation with N_c = 4 sub-channels
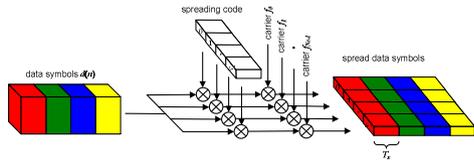
(c) MC-CDMA signal generation with N_c = 4 sub-channels

(d) MC-DS-CDMA signal generation with N_c = 4 sub-channels

Figure 1 Various multicarrier modulation techniques in comparison with a single carrier modulation for CDMA signals; redrawn from [2]

In comparison with the single carrier DS-CDMA (Figure 1 (a)), both multicarrier systems, such as MC-CDMA (Figure 1 (c)) and MC-DS-CDMA (Figure 1 (d)), have another degree of freedom in the number of bits involved in the serial-to-parallel conversion, which determines both the symbol duration and chip duration. This also determines the total number of subcarriers within the bandwidth. Moreover, the MC-DS-CDMA is known to provide additional degrees of freedom, such as the chip duration in time domain that is used in spreading the symbol in time domain, and the number of bits involved in the serial-to-parallel conversion that determines the symbol duration. These additional ones determine the spreading factor of each subcarrier signal and the frequency spacing between two adjacent subcarriers [8]. However, the use of these degrees of freedom should be limited in designing a navigation signal because of the trade-off in navigation signal between the data rate for a better data delivery capacity and the code rate for a better ranging performance.

MC-DS-CDMA System

As mentioned before, the MC-DS-CDMA signal is generated by:

1) converting high-rate data symbols into low-rate data symbols, i.e., N_c sub-streams by using a serial-to-parallel converter,

2) applying DS-CDMA on each individual sub-stream,

3) and finally applying N_c sub-carriers to the corresponding DS-CDMA signals in each individual sub-channel.

Thus, in MC-DS-CDMA, each data symbol is spread in bandwidth within its sub-channel, but in contrast to MC-CDMA or DS-CDMA, not over the whole transmission bandwidth for $N_c > 1$. Note that an MC-DS-CDMA system with one sub-carrier is equivalent to a single-carrier DS-CDMA system [2].

Figure 2 shows a brief schematic view on a general architecture of MC-DS-CDMA transmitter. The data symbol d has a $1/T_d$ of data symbol rate. A sequence of N_c complex-valued data symbol d_n for $n = 0,…,N_c$-1, is serial-to-parallel converted onto N_c sub-streams, thereby becoming a $1/(N_c T_d)$ data symbol rate on each sub-stream. In a single sub-stream, a data symbol is spread with the satellite-specific spreading PN code of length L. With multicarrier direct sequence spread spectrum, each data symbol is spread over L multicarrier symbols, each of duration T_s. Therefore, the data symbols are transmitted simultaneously on N_c parallel subcarriers, each occupying a small fraction $1/N_c$ of the total available bandwidth. The complex-valued sequence obtained after spreading is given by [2]

$$x(t) = \sum_{n=0}^{N_c-1} d_n c(t) e^{j2\pi f_n t} , \ 0 \le t < LT_s \qquad (1)$$

$$\text{with} \quad T_c = T_s = \frac{N_c T_d}{L} \ \text{and} \ f_n = \frac{(1+\alpha)n}{T_s} \qquad (2)$$

where $x(t)$ is MC-DS-CDMA signals, d_n is data symbol at n, $c(t)$ is spreading PRN code, f_n is sub-carrier frequency of sub-carrier n [Hz], N_c is the number of subcarriers, T_s is symbol time interval [sec], T_d is data symbol interval [sec], and L is code length.

The satellite-specific spreading PN code of length L is given by

$$c(t) = \sum_{l=0}^{L-1} c_l P_{T_c}(t - lT_s) \qquad (3)$$

where $P_{T_c}(t)$ is the pulse shape of the chips (i.e., the SRRC pulses in this paper), and the choice of α depends on the selected pulse shaping form $P_{T_c}(t)$. In case of

OFDM where $P_{T_c}(t)$ has a rectangular form, α is equal to 0 while we used 0.2 for FMT. Therefore, the MC-DS-CDMA system with broadband sub-channels can be regarded to be N_c classical broadband DS-CDMA systems, and multiple access detection techniques known for DS-CDMA systems can be applied in each data stream.
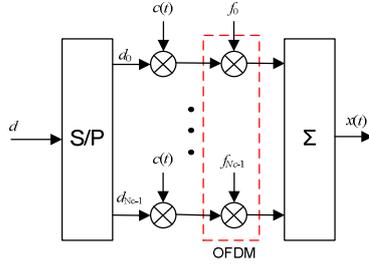

Figure 2 Schematic view on the architecture of MC-DS-CDMA transmitter

Assumption on Navigational Purposes

In this paper we suppose to transmit the same data for all the N subcarriers. Under this assumption, the complex-valued sequence for a single data symbol can be modified from (1) as

$$x(t) = d \sum_{n=0}^{N_c-1} c(t) e^{j2\pi f_n t}, \, 0 \le t < LT_s \tag{4}$$

where d is a single data symbol such that $d = \{d_0, d_1, \dots, d_{Nc-1}\}$ with $d_0 = d_1 = \dots = d_{Nc-1}$. This type of multicarrier signal can be regarded as the signal in N parallel streams of data×chips with each one modulating a different subcarrier, i.e., the spreading (the multiplication of data to chips) were performed before the multicarrier modulation. The input spread symbols with the given ranging code chip rate $1/T_c$ are split into N parallel stream with the lower late $1/NT_c$ using the serial-to-parallel converter, where $T_s = NT_c$ is the symbol interval. At the output of the serial-to-parallel converter the spread symbols are partitioned into groups of size N and each of them is modulated on the N equal-spaced subcarriers, after being filtered by the filter-bank for the pulse shaping. In this case we can have the higher tracking performance by directly using the multicarrier code signal replica compared to the case before but with the loss of the available high data-rate that is limited by the spreading factor.

RECEIVER ARCHITECTURES FOR FMT

The incoming signals, which include the noise effect throughout the channel, are demodulated and despread by multiplying the sub-carrier and the replica code pulses at each sub-channel followed by an integrator for the correlation. The low-rate output of each channel is converted to the high-rate data symbols by a parallel-to-serial converter.

As mentioned before FMT in this paper is a special case of MC-DS-CDMA systems when the subcarrier spacing is equal to $1/(N_cT_s)$ by the efficient use of SRRC pulses for pulse shaping of codes. This kind of MC-DS-CDMA system is also referred as multi-tone CDMA (MT-CDMA).

As seen in Figure 2 the data d is serial-to-parallel converted and spread by a (shaped pulse) code sequence; in alternate way, the code sequence is applied first and then the resulting code and data product is converted by a serial-to-parallel converter. After then, the N-parallel signals are modulated by using OFDM (i.e., N-multicarriers) and summed up to transmit the consequent multicarrier-modulated spread signal $x(t)$. By allocating the multicarrier frequency f_i for the i-th channel, we can control the type of signal (i.e., monomodal or bimodal), power level, and frequency band separation [4]. As well known the multicarrier modulation as indicated in dotted box can be done effectively by using IFFT operation.

Note that the product of data and code sequence $d \cdot c(t)$ here is a monomodal signal (not bimodal signal). Even though this, the use of multicarrier with a null power near center frequency makes it possible to have a split of spectrum to left and right, thereby being bimodal signals. Also note that the parallel N sub-channels carry the same data symbol. This is a special case of MC-DS-CDMA signals to provide a high accurate tracking result for the navigation purpose even though the loss in the data symbol rate. For this there can be two types of receiver processing scheme as follows.

**1) Type A – OFDM demodulation-based receiver**

A receiver block diagram based on the OFDM demodulation in Figure 3 (a) is widely used in the MC-DS-CDMA receiver. The receiver gets the received signal $y(t)$ which includes the channel and noise effect. For the sake of simplicity we assume $y(t) = x(t)$ in absence of channel and noise effect. First, a multicarrier-demodulator is applied to process the multiacrrier-modulated spread signal $x(t)$ as indicated in dotted box. Second, the despreading process is performed by multiplying the code sequence $c(t)$. Note that a SRRC shaped pulse code generator with a given roll-off-factor in the FMT should be employed. Finally, we use a parallel-to-serial converter. The input to sub-channels should be controlled in a proper way (e.g. acquisition/tracking).

2) Type B – direct use of FMT replica signal for correlation

An alternative way of receiver processing can be implemented especially for correlation function of FMT signals (Figure 3 (b)). A relevant replica shaped pulse code sequence $\bar{x}(t)$ generated by the signal generation method same as in Figure 2 except for the use of data bits was used in the correlation. Under the assumption on the same data symbol for all sub-channels, the correlation output of this produces the data symbols.
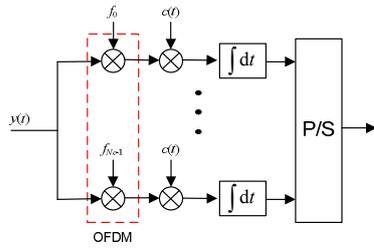
(a) type A - OFDM demodulation-based receiver
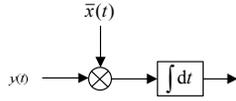
(b) type B – direct use of FMT replica signal

Figure 3 Schematic view on the architectures of MC-DS-CDMA receiver

Figure 4 shows a comparison of these two receiver architectures in terms of received signal and correlation output properties. This is an example for an option for FMT with a special care to achieve a lower peak of secondary lobes of the correlation function for each component but with decreasing of performance in terms of Gabor bandwidth and Spectral Separation Coefficient (SSC) [4]. The figure in left shows the PSDs of incoming FMT signals at the end of antenna with a spectrum split into monomodal and bimodal components where the actual signal power is not taken into account here. Even though the PSD of incoming signal is spread over wideband, the signal of each sub-carrier component at each sub-channel is a narrowband SRRC signal as depicted in black dotted line. The bandwidth of SRRC basic function equals the original code rate divided by the total number of subcarriers that was used in multicarrier modulation. Therefore, the consequent code rate of each sub-carrier should be divided by the total number of sub-carriers.

The receiver receives the signal occupying the intended signal band, where the PSD of the received signal can be split depending on the configuration of the monomodal and bimodal signal components. The direct use of FMT replica signal correlates the incoming signals with the local replica FMT signals that were generated by the FMT signal generator, i.e., the OFDM modulation to the SRRC pulse code sequence with assuming $d = 1$ as in Figure 2. This is the type B receiver. Each signal components, such as monomodal and bimodal FMT signals, can be generated and processed separately.

Compared to this, in the OFDM demodulation-based method, the OFDM demodulated signals (i.e., a parallel signal) are correlated with the replica SRRC shaped pulse codes in a bank of sub-channel correlators (type A receiver). The frequency offset of each sub-channel of multicarrier signal components is wipe-off by the OFDM demodulator by using FFT operation with a proper frequency offset. The resulting output of the OFDM demodulator at each sub-channel should be same to the

SRRC shaped pulse spread spectrum code sequence with a narrow bandwidth, depending on the number of subcarriers used in a given FMT option. Consequently, the correlation function of each sub-channel should be same to that of SRRC signals if it is expressed in chips. Note that we have M sub-channels for M sub-carriers. Thus, we have M correlation functions with the same shape and bandwidth at different frequency offsets. It is obvious that the DLL noise jitter at each sub-channel for this case is worse than the previous one because of the multiple narrower bandwidth sub-channels. One of the easy ways to reduce the DLL noise jitter in case of multiple sub-channels is to combine the output of all sub-channels to produce a mean value of tracking errors but the consequent noise jitter is worse than the wideband single carrier case.

In addition, as well known, the performance of multicarrier synchronization tracking loops depends strongly on the RF oscillator phase noise characteristics. The combination of multicarrier modulation and CDMA in this way is seen as a very promising technique for the development of high-capacity wireless communications. However, this scheme is very sensitive to the signal distortion generated by the imperfect frequency down-conversion at the receiver due to the local oscillator phase noise and frequency offset. Moreover, the signal dynamics caused by the movement of a receiver will introduce the Doppler frequency shift that will pose additional probability to impair the reference oscillator performance. The vibration induced oscillator jitter caused by the vibration of receiver mounted on the navigational body will cause a worse environment than the normal communication system working in static mode. Therefore, the impact of both the carrier frequency offset and the phase noise on the system performance should be severe. Note that the navigation receiver does not only require the data delivery but also the precise ranging information that is highly affected by the performance of both code and carrier trackings. The performance loss of an MC-DS-CDMA system is mainly due to the presence of nonlinear RF power amplifier, phase noise, and frequency offset of the RF oscillator, chip synchronization timing errors, and fading. Each impairment produces loss of orthogonality between subcarriers, thereby increasing the ICI.
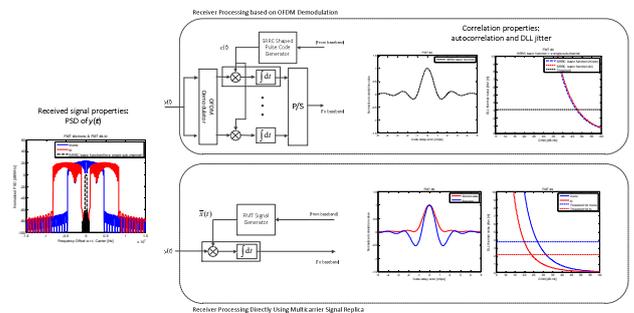

Figure 4 Comparison of receiver signal processing between OFDM-demodulation-based receiver (Type A) and a direct use of multicarrier signal replica receiver (Type B) [4]

IMPLEMENTATION ISSUES

Receiver Block Diagrams

So far we have at least two methods of MC-DS-CDMA schemes in communication field [10].

- Method I – the serial data stream is first spread by a PN sequence, and then converted into N parallel chip sequences with each one modulating a different carrier; the number of carrier required is N, which equals to the number of chips per data symbol; this type of system offers both the robustness of orthogonal modulation and the flexibility of the DS-CDMA scheme.
- Method II – the serial data stream is first converted into M parallel data sub-streams, and each sub-stream is then spread by a PN sequence and transmitted over one of M sub-channels as narrow-band DS waveforms; the number of carriers required is M, which is usually much less than N; while maintaining the overall data rate unchanged, this scheme lowers the chip rate in each sub-channel so that a longer chip time makes it easier to quasi-synchronize the transmissions; the multiple access interference can be effectively reduced in this type of system by applying orthogonal spreading sequences.

In this paper we supposed to transmit the same data for all the N subcarriers, for $L=M/N$ symbol times. Therefore, we defined an additional type of MC-DS-CDMA scheme.

- Method III - the serial data stream is first spread by a PN sequence, and then converted into N parallel streams of data×chips with each one modulating a different subcarrier; if M is the spreading factor, we suppose to use $M=L×N$ chips of the PN sequence to transmit a single data; in this way the spreading is on frequency (N subcarriers) and in time (M/N symbol times); in this study we assumed M is greater than N.

On another hand, there are mainly three synchronization tasks in the signal processing of a receiver. They are 1) timing recovery, 2) carrier frequency recovery, and 3) carrier phase recovery.

In case of type A receiver, in particular for the OFDM-based signals, the received signal should be processed first by means of the FFT operation at the beginning of digital signal processing to wipe-off the sub-carriers. Large numbers of FFT points resulting in long OFDM symbol durations make the system more sensitivity to the time variance of the channel, e.g. Doppler effect, and more vulnerable to the oscillator phase noise. On the other hand, a large symbol duration increases the spectral efficiency due to decrease of the guard interval loss. For any OFDM realization a trade-off between the number of FFT points, the sensitivity to the Doppler and phase noise effects, and the loss due to the guard interval has to be found. This is different from the normal single carrier CDMA signal. The time-positioning of the FFT window including the adjustment of the sampling rate is important. The time-positioning of the FFT window determines the start point of parallel-to-serial converted symbol sequence,

leading to a correct order of data symbol sequence. For this in case of an OFDM receiver realization, a coarse symbol timing estimator and/or a path time delay estimator can be employed in a FFT window controller [8].

In case of the type B receiver for the method III the three synchronization tasks are carried out in a similar way to the currently widely used BPSK or QPSK receiver except for the use of multicarrier modulated SRRC shaped pulses for the replica signal. However, it does not require the FFT operation at the beginning of digital signal processing. Therefore, there is no need to estimate the time-positioning of the FFT window. The start point of symbols (or data bits) is acquired after the code and carrier locks by testing logics based on a priori information on the bits (i.e. preamble, available frame identifiers, fixed reserved bits, parity check, etc.) as similar to the bit synchronization process of current receivers. Also a normal acquisition process can be employed. Thus, we consider in this paper that the MC-DS-CDMA technology was used only for the spectrum efficiency not for the fully use of OFDM technology for the data transmission.

Figure 5 shows a detailed block diagram of the signal tracking loop of the receiver type B for the method III. The received signals are directly correlated with the replica FMT signals that were locally created by the method similar to Figure 2 (a) with $d_n = 1$ for all sub-channels. The output of the FMT signal generator at prompt and early/late arms includes not only the SRRC shaped pulse code sequence but also the multicarrier modulation function block, multiplexed into a serial sequence.

Detailed block diagrams on the signal tracking loop in case of the receiver type B for the methods I and II are shown in Figure 6 for separate tracking loop for individual sub-channels, and in Figure 7 for combined tracking loop. Each individual sub-channel has its own tracking loop with a slower code rate (i.e., narrower bandwidth), and the carrier tracking can be performed for each sub-carrier. In case of combined tracking, the code and carrier discriminator outputs of each sub-channel are combined to create a common code and carrier tracking error, and then applied to code and carrier loop closure. In particular for the carrier tracking, the estimated carrier Doppler is applied to FFT block where the estimated Doppler is used to create the reference carrier signal in each sub-channel with relevant offsets. The output in inphase prompt arm is used to demodulate the data bits after the P/S converter.

The signal in Method III can be processed by using either the receiver types A or B whereas only the receiver type A can be applied to the methods I and II.
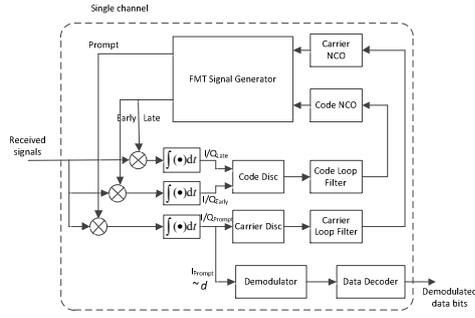
Figure 5 Detailed view on the signal tracking loop of FMT signal in case of the receiver type B for the method III
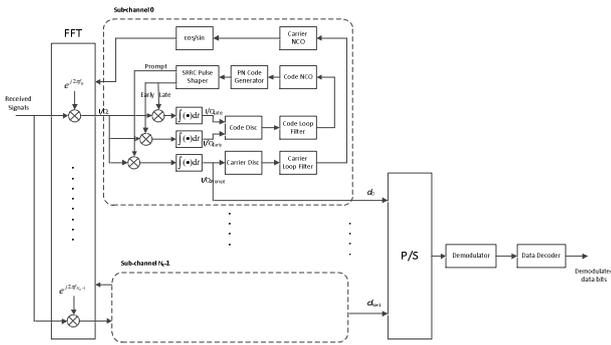

Figure 6 Detailed view on the signal tracking loop of FMT signal in case of the receiver type A for the method I and II (separate tracking)
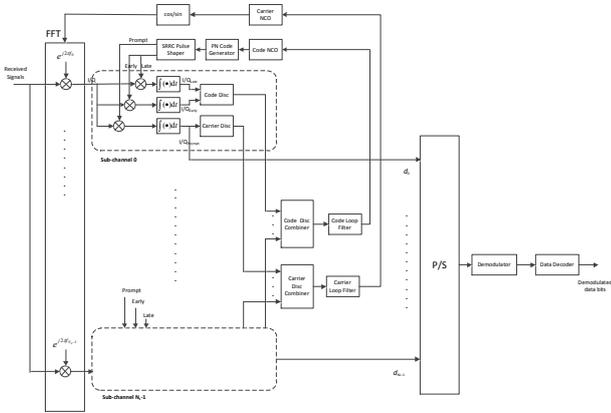

Figure 7 Detailed view on the signal tracking loop of FMT signal in case of the receiver type A for the method I and II (combined tracking)

Local Replica and Integration Time

The generation of the local replica will vary depending on the type of receiver and on the chosen MC-DS-CDMA method. For the sake of simplicity, only the local replica of method II is described in this paper for both types of receivers, A and B. Besides, the local replica generation process of method II can be extrapolated to the local replica generation process of method III for the B type of receivers. In this paper, the local replica does not include the cosine and sine terms generated at the receiver which are responsible of transporting the received signal from its

central carrier frequency to the intermediate or baseband frequency.

The main difference between the local replicas of receivers A and B is the removal of the frequency components of the subcarriers. This means that whereas for the type A receivers the local replica is simply the shaped PRN code, for the type B receivers the local replica also contains the frequency carrier of each subcarrier.

The mathematical expression of the local replica, $c_{lA}(t)$, of all the subcarriers of the type A receiver is:

$$c_{lA}(t) = c(t) = \sum_{l=0}^{L-1} c_l P_{T_c}(t - lT_s) \tag{5}$$

where $c(t)$ is the shaped PRN code of the signal. The mathematical expression of the local replica of each individual subcarrier n, $c_{lBn}(t)$, of the type B receiver is:

$$c_{lBn}(t) = c(t) \cdot e^{j2\pi f_n t} \tag{6}$$

The total local replica, $c_{lB}(t)$, of type B receiver is,:

$$c_{lBn}(t) = \sum_{n=0}^{N-1} c_{lBn}(t) = \sum_{n=0}^{N-1} c(t) \cdot e^{j2\pi f_n t} \tag{7}$$

The most important part of previous expression is that the code delay affects equally the shaped PRN code and the subcarrier frequency component.

$$c_{lBn}(t - \tau) = \sum_{n=0}^{N-1} c(t - \tau) \cdot e^{j2\pi f_n(t - \tau)} \tag{8}$$

If this condition is not fulfilled, the receiver does not obtain the correlation function of Figure 4. Another important characteristic is that the local replica of the type B receiver is generated independently from the generation (and estimation) of the received FMT signal central carrier frequency. This means that values of the f_n frequency components of the generated local replica are the values of the equivalent baseband FMT signal.

The integration time of the receiver's correlator block is another parameter to be defined for the proposed FMT signals. In fact, due to the SRRC shaping of the PRN code chips, each SRRC shaped PRN code sequence transported by each different subcarrier has a larger duration than the PRN code period. This means that successive integrations are overlapped if the correlator block integrates the entire length of a received SRRC shaped PRN code sequence. However, this overlapping increases the complexity of the receiver. Therefore, this paper proposes to limit the integration time to the exact duration of the PRN code period since the gain obtained by integrating the entire length of the received SRRC shaped PRN code sequence is negligible as is preliminary presented.

The limitation of the integration time to the PRN code duration raises the question about the truncation of the generated local replica. Two options are considered:

1. The local replica is truncated at the PRN code period: the tails of the SRRC shaped chips which are located

at the beginning and at the end of the PRN code are eliminated.
2. The tails of the SRRC shaped chips which are located at the beginning and at the end of the PRN code and which are outside the PRN code sequence duration are folded inside the main body of the current PRN local replica.

The second solution is ideal for a pilot component due to its periodicity. This means that since the values of the transmitted symbols are the same, the tails of the SRRC shaped bits of the previous and posteriori shaped PRN code sequences appear with the same sign inside the main body of the current PRN local replica. Therefore, the generated local replica is equal to the received signal and the equivalent effect of a matched filter is found (best SNR).

The situation for a data component is different. In this case, the tail bits of the previous and posteriori shaped PRN code sequences do not have to have the same sign as the current shaped PRN code sequence. Therefore, the second solution could degrade the final correlation result with respect to first solution depending on the values of the received symbol (d_n). In any case, the degradation introduced by the limitation of the integration time and the truncation of the local replica with respect to the ideal case of a matched filter is negligible. For example, assuming a PRN code of 1023 chips, a SRRC shaping with a duration limited to 60 times T_c (chip time) and a data transmission of -1,+1, -1 (worst scenario), the SNR degradations of options 1 and 2 with respect to the matched filter are 0.0006 and 0.0017 dB respectively.

CONCLUSIONS

In this paper the distinctive features of several receiver architectures of the FMT technology for GNSS uses have been evaluated. The proposed receiver architecture was for a new type of FMT signal processing scheme which is based on the assumption on the same data for all the N subcarriers for L symbol times. The proposed receiver architecture directly uses locally generated complex FMT signals in correlation. Thus, it has a narrow correlation peak and achieves precise ranging without performing the IFFT operation. This fact means the FMT technology in this paper was used in the transmitter to suppress OOB emission power. Also high level block diagram of three types of receiver implementation was described.

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