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► **To cite this version:**

Jong-Hoon Won, Diana Fontanella, Matteo Paonni, Bernd Eissfeller, Andrea Emmanuele, et al.. Receiver architecture for multicarrier-based GNSS signals. GSSP 2011, 5th GNSS Signal Workshop on GNSS Signal and Signal Processing, Dec 2011, Toulouse, France. pp xxx. hal-01022488

**HAL Id: hal-01022488**

**<https://enac.hal.science/hal-01022488v1>**

Submitted on 29 Sep 2014

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# Receiver Architecture for Multicarrier-based GNSS Signals

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## 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.

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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

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## 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.

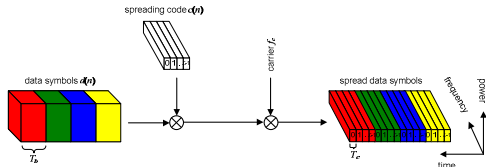
Figure 1 (a) shows the single carrier DS-CDMA signal generation. For signal spreading, pseudorandom noise (PN) code is made up from a number of chips for mixing the data with the code. The size of a chip determines the frequency spreading. Different user information is multiplexed by the use of different 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.

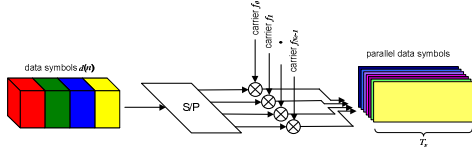
Figure 1 (c) shows the MC-CDMA, also referred as OFDM-CDMA. This is the combination of frequency domain spreading and multicarrier modulation. In this scheme, the multiplexing is carried out by applying different spreading codes in the code domain at the same time for the same bandwidth. The use of multicarrier 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

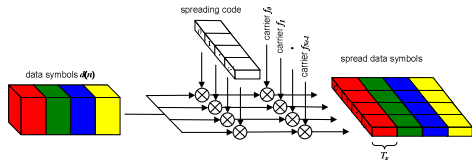
multicarrier modulation signal candidate in this paper, is a type of MC-DS-CDMA incorporated with the SRRC pulses for spreading codes in time domain. There are several different types of MC-DS-CDMA schemes with regard to the direct sequence spreading before or after the multicarrier modulation. The multicarrier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



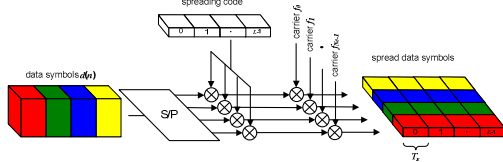
(a) Single carrier DS-CDMA generation



(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  $n = 0, \dots, N_c-1$ , 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]

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

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

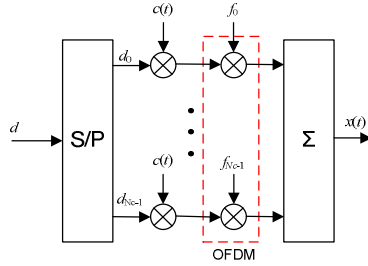
where  $x(t)$  is MC-DS-CDMA signals,  $d_n$  is data symbol at  $n$ ,  $c(t)$  is spreading PRN code,  $f_n$  is sub-carrier frequency of sub-carrier  $n$  [Hz],  $N_c$  is the number of subcarriers,  $T_s$  is symbol time interval [sec],  $T_d$  is data symbol interval [sec], and  $L$  is code length.

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

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

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

OFDM where  $P_{T_c}(t)$  has a rectangular form,  $\alpha$  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

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

where  $d$  is a single data symbol such that  $d = \{d_0, d_1, \dots, d_{N_c-1}\}$  with  $d_0 = d_1 = \dots = d_{N_c-1}$ . 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 rate  $1/NT_c$  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  $1/(N_c T_s)$  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.

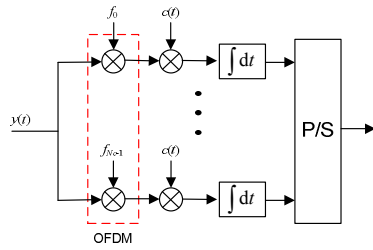
Note that the product of data and code sequence  $d \cdot c(t)$  here is a monomodal signal (not bimodal signal). Even though this, the use of multicarrier with a null power near center frequency makes it possible to have a split of spectrum to left and right, thereby being bimodal signals. Also note 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

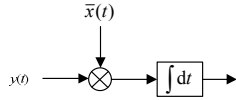
A receiver block diagram based on the OFDM demodulation in Figure 3 (a) is widely used in the MC-DS-CDMA receiver. The receiver gets the received signal  $y(t)$  which includes the channel and noise effect. For the sake of simplicity we assume  $y(t) = x(t)$  in absence of channel and noise effect. First, a multicarrier-demodulator is applied to process the multicarrier-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.

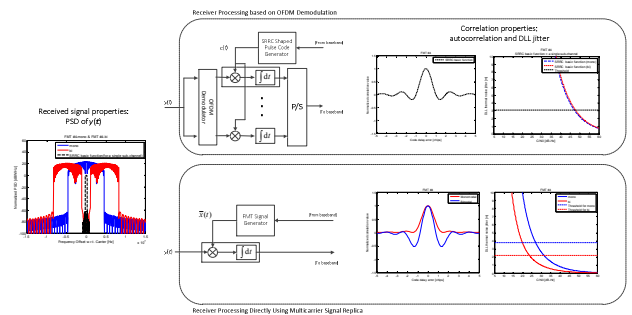


Figure 4 Comparison of receiver signal processing between OFDM-demodulation-based receiver (Type A) and a direct use of multicarrier signal replica receiver (Type B) [4]

## 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].

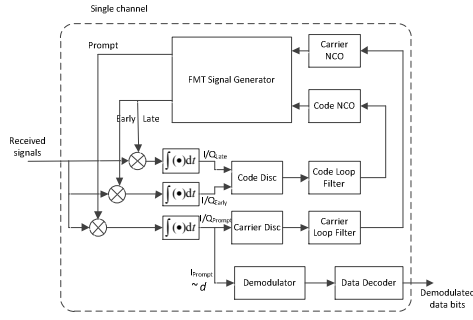
In case of the type B receiver for the method III the three synchronization tasks are carried out in a similar way to the currently widely used BPSK or QPSK receiver except for the use of multicarrier modulated SRRC shaped pulses for the replica signal. However, it does not require the FFT operation 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.

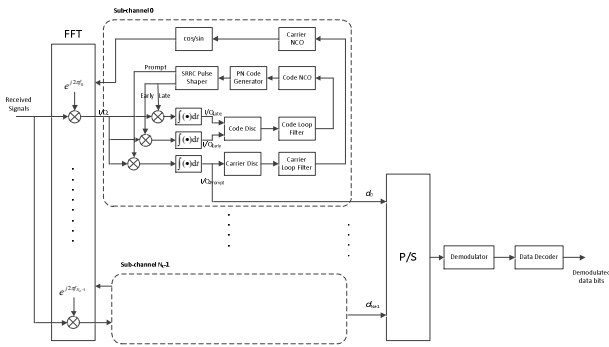
Detailed block diagrams on the signal tracking loop in case of the receiver type B for the methods I and II are shown in Figure 6 for separate tracking loop for individual sub-channels, and in Figure 7 for combined tracking loop. Each individual sub-channel has its own tracking loop with a slower code 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.

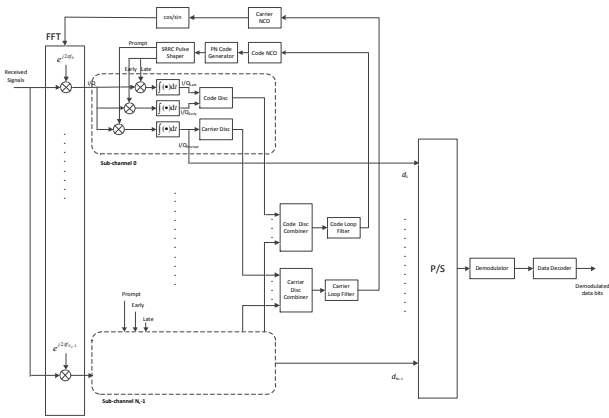




**Figure 5 Detailed view on the signal tracking loop of FMT signal in case of the receiver type B for the method III**



**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:

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

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:

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

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

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

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

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

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.

## ACKNOWLEDGMENTS

This paper is based upon the work done in the framework of the European Space Agency (ESA) funded study ADVISE, Advanced Signal-In-Space Techniques. The content of the present article reflects solely the authors' view and by no means represents the official ESA view or the one from ESA Galileo Project Office.

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