New advances in Multi-Carrier Spread Spectrum techniques for tactical communications.

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ABSTRACT

Spread Spectrum techniques are classically used in tactical communications, in order to mitigate interference due to jamming, while providing a low probability of intercept. This paper addresses a new SS technique, referred to as Multi-Carrier Spread Spectrum (MC-SS). An original MC-SS scheme is proposed using polyphase filtering. As for tactical communications, dramatic performance improvements are achieved, especially for partial-band jammers. Moreover, classical problems of synchronization encountered in Multi-Carrier Modulation systems (MCM) are resolved by the proposed waveform. This provides an extremely good safety level.

The MC-SS technique consists in a combination of standard DS/SS with a MCM scheme. Such a combination is motivated by the advantages of the MCM, which provides robustness in the case of frequency selective channels, as well as an efficient digital implementation in its well known OFDM form (implemented in DAB, DVB, ...).

The paper highlights that this new MC-SS method fits tactical communications constrains. It shows that this new modem proposes an active and reliable method to combat agile jammers. Special attention is paid to synchronization issues. For tactical communications, this leads to a new protection feature.

I INTRODUCTION

A wireless tactical radiowave link may be deployed in any environment. Thus the modem must be able to be used on many types of transmission channels, and especially on frequency selective channels. Moreover, the tactical transmissions have to bear electronic war constraints. As for the waveform, this defines two types of specific features, namely anti-jamming capacities and discrete communication skills.

In this article, we address Multi-Carrier spread spectrum techniques, which provides an efficient way to face those three constraints.

A first justification for the use of Multi-Carrier Modulation is that it is known to be an alternative to channel equalization when used with phase mapped symbols. This can be coupled with a standard spread spectrum mode for a tactical modem. When spread spectrum is employed, a monocarrier modem will require special equalization techniques for frequency selective channel (as RAKE receiver). Such treatment reminds useless, when a multicarrier modem is employed. This equalization feature has already been discussed in many articles, so we shall not focus on it [2].

Another interest of the MC/SS scheme is that it gives a natural observation of the spectrum, which is expressed in the frequency-time domain. This Channel State Information (CSI) is a key knowledge to combat jammers.

However, practical constrains could decrease the performance of the MC/SS modem. For example, MCM are known to be sensible to synchronization defaults. And the application of an MCM modem for discrete communication forces the modem to works with a low input signal load.

In this article, we present a new MC/SS scheme. The general MC/SS scheme is described in section 2. The general architecture of a new MC/SS modem is presented in section 3 and simulation results are proposed, which demonstrate the interest of the solution. In section 4, synchronization issues are developed, to demonstrate the high safety level of the modem.

II THE MC/SS MODULATION

A Waveform Description

Let us first consider the DS/SS modulation scheme presented in Figure 1. Information symbols (either real or complex, at rate $F_s$) are first oversampled by a factor $N$ and multiplied by a sequence, typically a PN one. The chip rate $F_c$ following this operation is $N$ times the symbol rate. This signal is then filtered and send over the channel (as far as only the Base Band signal is addressed). With this technique, all the chips of a symbol are sent together within the symbol duration, on all the band (as we don’t consider any coding).

The MC/SS modulation scheme consist in the association of the multicarrier modulation technique with the DS/SS model. Information symbols are oversampled and multiplied by a sequence derived from a PN one.
This first step of the modulation chain is the same as the spread operation of a DS/SS system. This chip sequence is then distributed on $M$ different sub-carriers.

The way the chips are distributed on each of the sub-carrier, represented by a DEMUX in the figure, is discussed at the end of the section. The multiplying sequence $s_{1,N+m}$ is derived from a PN, and depends on the DEMUX function.

The sub carriers share commonly the same form, but separated from each other by a fix frequency offset. The transmit signal becomes:

$$s(t) = \sum_{m=-\infty}^{+\infty} \sum_{k=0}^{M-1} d^k_m \times g(t - mT) \times e^{j2\pi kAf t}$$

where $d^k_m$ represents the $m^{th}$ chip emitted on the $k^{th}$ sub-carrier.

In this expression, $g(t)$ is for the shaping filter chosen for the sub-carrier. It is well known that with $g(t)$ set to a square impulse response, and with a frequency offset $\Delta f = f_c^{sc}$, the $(\psi^k_m(t))$ base is orthogonal, when sampled at the right instant. This particular case of MCM is known as the Orthogonal Frequency Division Multiplexing (OFDM, [1]). It is of great interest because its implementation involves Inverse DFT at the transmitter and DFT at the receiver, that are well suited to implementation thanks to the FFT algorithm. But the time and frequency synchronization of such a waveform are known to be critical. In the particular case of tactical communication, this problem becomes critical. However, other forms of sub-carrier shaping are possible.

The new DS/SS scheme we propose uses a slightly more sophisticated shaping function for the subcarriers. In the following, it will be referred to as the ‘Filtered OFDM’, to distinguish from the classical OFDM, whose shaping function is not really a filter. In the next sections, it shall be shown that filtered OFDM is of great interest for wireless tactical communications. Indeed, this waveform leads to performance increases in three scopes:

- cancellation of narrow band jammers,
- out-of-band spectrum,
- time and frequency synchronization.

The resulting spectrum of the MC/SS technique is presented in Figure 2. It appears that the bandwidth remains the same as a classical DS/SS technique.

**B Anti-jamming performance**

The scheme presented in Figure 1 offers a very flexible mean to apply time and frequency diversity. Through the MUX operation, the N chips representing a symbol may be distributed on several sub-carriers at several instants. The Figure 3 shows three typical chip distributions for the spread spectrum configuration. Case a) is efficient against frequency selective jammers. Indeed, non jammed chips remains available whatever the jammer frequency position is, even if it is inside the band of the emitted signal, thanks to frequency diversity. Case b) is efficient for frequency time selective jammers, and Case c) is a combination of the two first configurations.

In association with time and frequency diversity, the MC/SS techniques give a description of the time/frequency domain, as every chip is precisely located in the time/frequency domain. Thus, when a jammer is present in a certain part of this domain, only a certain number of chips are disturbed. One can weight very precisely the information whether it is disturbed by a jammer or not [3].
Let us consider three hypothesis:

- the chips are distributed randomly in the area, so that for each symbol a fraction $\rho$ of its chips are disturbed by the jammer,
- the jammer acts as a white gaussian noise of power spectral density (psd) $N_j/\rho$ on the disturbed chips,
- this power density $N_j$ is known (the CSI is perfect).

Then the best recombination of chips is:

$$S_i = \sum_{n=0}^{N-1} \frac{c_{i,N+n}}{\sigma_{i,N+n}}$$

where $c_{i,N+n} = c_{i,N+n} + n_{i,N+n}$ are the received chips for the symbol $S_i$, and $\frac{1}{\sigma_{i,N+n}}$ are CSI factors.

One can check that the optimum choice consist in taking $\sigma_{i,N+n}$ equal to the noise variance if the chip is not jammed, and the (noise+jammer) variance if the chip is jammed. (corresponding performance on Figure 4).

The curves of the Figure 5 illustrate the case when the CSI is approximated by the square of the module of each chip. Reconstructed symbols are:

$$S_i = \sum_{n=0}^{N-1} \frac{c_{i,N+n}}{\|c_{i,N+n}\|^2}$$

One can see that the modem still outperforms blind recombination.

### III THE NEW MC/SS SCHEME

The scheme presented in Figure 6 is a particular case of the MC/SS scheme discussed in the previous section.

The information symbols are first coded. The sequence of coded symbols is distributed on $M$ sub-carriers, in $S_k^n$ sequences, where $k$ indexes the sub-carrier, and $j$ stands for time. The sequences are differential encoded. The spread spectrum functions are inserted on each subcarrier. The $S_k^n$ sequences of differential encoded symbols are oversampled by a factor $L$, and multiplied by a spreading sequence, and become chips sequences $d_{L,j+n}$.

This scheme corresponds to a time diversity chip distribution, according to Figure 3. This aims at allowing chip recombination on a subcarrier. Thus, in the receiver, two different processes are made on each subcarrier: the chips are first recombined, and then they are differential demodulated. It will be discussed in the following.

Frequency diversity is obtain by the use of FEC, before the MUX function. Let $K$ be the expansion factor of the code, and $L$ the expansion factor of the spreading function on the sub-carrier, the global expansion factor of the modem is $N=L*K$.

As for CSI, a trade off is made in the receiver between the quality and the time resolution of the channel estimation. The chips are recombined in subcarriers symbols with no weight factor. The CSI factor is used in the decoder. The weight factor for the symbol $S^k_j$ is $\gamma_j^k$ which is defined by:

$$\frac{1}{\gamma_j^k} = \frac{1}{L} \sum_{m=0}^{L-1} |d_{m,L}^k|^2$$
The information carried on by $j^{k}$ is combined by the information carried on by the module of the recombined symbol $\hat{S}_{j}^{k}$ to determine the nature of the symbol: jammed or non jammed symbol, channel mitigated or well transmitted symbol.

A filtered OFDM is employed. This leads to a better out-of-band contributions cancellation, as one can see in the Figure 2. But this brings others properties: easy synchronization and efficient isolation of jammers. This efficient cancellation of out sub-carrier jammers is illustrated by the Figure 2. For a classical MC/SS systems, if carrier $k$ is disturbed by a jammer, the jammer is only attenuated by 13 dB on its neighbors, whereas the attenuation is 60 dB for a filtered MC/SS scheme.

The synchronization feature are discussed in section 4. Performance of the modem for anti-jamming purposes is shown on Figure 7.

The cost of this filtered OFDM compared to a standard one is negligible. One can show that a classical sampled OFDM signal may be implemented using an inverse DFT in the transmitter, and a straightforward DFT in the receiver. This don’t stand in the case of filtered OFDM. However, the numerical implantation of filtered OFDM remains quite simple, if the frequency offset between the subcarriers is chosen of the right form. This numerical implementation of filtered OFDM is named polyphase FFT. For more details on this polyphase FFT structure recommend [7][8].

\[ E_b/N_0 = 5 \text{ dB} \]

\[ \text{jammer at } E_b/N_j = -5 \text{ dB} \]

**Figure 7: MC/SS modem performance**

The jammer disturbs a fraction $\rho$ of the signal bandwidth, with a psd of $N_0/\rho$. Its power is chosen so that $E_b/N_0=-5$dB.

The chosen MC/SS modem uses a convolutive code with rate $1/2$. Thus, the frequency diversity equals 2, and the MC/SS scheme outperforms a DS/SS one as soon as the jammer uses less than half the signal bandwidth.

**IV SYNCHRONIZATION ISSUES**

One important feature for a wireless tactical modem is its robustness. As explained in the second section, this robustness supposes that the modem is resistant to jammers in terms of BER performance. But to achieve this performance, the demodulator must be able to synchronize with the modulator. That is to say that the algorithm for time and frequency recovery and tracking has to be at least as resistant to jammers as the waveform. This is the reason why specific attention has been paid to synchronization issues along this study.

**A Time synchronization**

As shown in the Figure 2, for an OFDM signal, the spectrum of the sub carriers are not disjoined. This results in the fact that the orthogonality of the different sub-carriers only holds for a precise sampling instant. If the reception is not synchronized with the transmitter, the resulting signal on the sub-carrier $k$ is interfered by the signals of the others carriers. This is shown by the Eye diagram on one sub-carrier presented on Figure 8. The acquisition of time synchronization must take care of that point. Many solutions exist [4],[5],[6].

For example, one can try to limit interference on the subcarrier $k$ by switching off the other carriers during the synchronization phase, or by transmitting it at a higher power (as proposed on DVB). Thus one can proceed to a single carrier synchronization on it. This results in a spectrum transformation during synchronization phases, that is incompatible with tactical constrains: a jammer can detect these phases and affect them specifically. Other solutions overlook the problem. The idea is to process the multicarrier signal as a whole and not at the sub-carrier level.

One can switch off the transceiver from time to time: those interrupts are easy to detect for the receiver and allows a first time synchronization. Such a principle is applied in DAB and is obviously not convenient for tactical applications.

When circular prefix is used, an elegant solution is to take advantage of the redundancy in the multicarrier signal, as shown by [6]. This overpasses the critics of the precedent solution, but the performance of this algorithm is insufficient for a discrete communication scheme.

As shown on the eye diagram of the Figure 8, in the case of filtered MC/SS, the sub-carrier signal remains meaningful even if the modem is poorly time synchronized. The proposed architecture is based on this advantage. Two samples per subcarrier chip are computed. With those two symbols, a single-carrier time synchronization algorithm is implemented. Moreover, as far as all the subcarriers are time synchronized in the transceiver, the synchronization of the receiver can take all subcarrier synchronization into account.

As explained in the introduction, the MC/SS modem design meet discrete communication requirements. That is to say that for a global expansion factor $N$, the energy of each chip may be:

\[ E_c = E_b/N \]
where $E_s$ is the energy for a symbol, in a spreadingless mode. Thus, a first symbol recombination is needed, as used in classical DS/SS schemes. The time synchronization algorithm we propose is based on the computation of:

$$\text{Corr}_k(\tau) = \sum_{l=0}^{W-1} \sum_{m=0}^{L-1} d_{m+l,L} \times s_{m+l,L-\tau} = \sum_{l=0}^{W-1} S_k^l(\tau)$$

where $k$ stands for the $k^{th}$ sub-carrier, $W$ represents the size of the correlation window, $s_{m+l,N}$ is the spreading sequence on the subcarrier, and where $\tau$ takes different values in the supposed range of the time synchronization error. $S_k^l(\tau)$ stands for the supposed recombined sub-carrier symbol at instant $l$ for the subcarrier $k$. This computation is made for even and odd received samples. If the chips of a symbol were sent on different subcarriers, their phase shifts would be different. In that case, the expression given above would not stand, and the phases of the different subcarriers would have to be known before the recombination.

With the new MC/SS scheme, the $L$ chips of a coded symbol are sent on the same carrier, so that they are affected by the same phase shift, and the recombination described above stands.

![Eye diagram on a subcarrier](image)

**Figure 8:** Eye diagram on a subcarrier for non filtered and filtered OFDM.

### B Frequency and phase recovery

For a classical OFDM scheme, frequency recovery is a sensitive point of the modem. Indeed, it has been proved that a frequency offset at the input of the receiver leads to a frequency offset on each subcarrier, and to interference between the subcarriers [2]. As the subcarriers are disjoined in the filtered OFDM case, interference are drastically reduced. Only frequency offsets on the subcarriers remain.

As for the time synchronization, the phase and frequency recovery is made on the recombined sub-carrier symbols. In order to reach the objectives of robustness fixed to the modem by its application, a differential modulation scheme is proposed. In this scheme, the subcarrier symbols are differential encoded and decoded on each subcarrier. This technique is known to be efficient to bear a small frequency offset, and phase noise.

This frequency and phase recovery is sensible to $\Delta fT$, where $\Delta f$ is the real frequency offset, and $T$ is the symbol period of the modulation. With the MC/SS modulation scheme, the symbol rate on each sub-carrier is

$$F_s^{SC} = \frac{N}{M \times L} \times F_s = \frac{K}{M} \times F_s$$

where $N$ is the total redundancy factor, $M$ the number of sub-carrier, $L$ the spreading factor on each sub-carrier, $K$ the coding expansion, and $F_s$ the symbol information rate. Thus $K/M$ must be kept high enough to permit easier frequency recovery. That is to say the symbol rate on each sub-carrier must be convenient with frequency recovery.

### V CONCLUSION

In this paper, we addressed MultiCarrier Spread Spectrum from a pragmatic point of view. Our results confirm that the MC waveform is well suited to tactical radiowave link, as far as performance on selective channels and anti-jamming features is concerned. Moreover, the new scheme we propose is compatible with safety constraints. It is a tradeoff between the MC/SS properties and the military product robustness and discretion constrains. This technique remains applicable to resolve synchronization problems for any multicarrier modem.

At last, the new MC/SS, which is more sophisticated than OFDM-based techniques, is also straightforward to implement, through the polyphase filter structure, which is proposed but not explained in this paper.

### VI REFERENCES


