A SDR ULTRA-WIDEBAND IMPULSE COMMUNICATION SYSTEM FOR LOW AND HIGH DATA RATES

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ABSTRACT

The paper proposes a new way of considering software radio in the specific context of UWB. Due to the extremely wide-band nature of UWB signals, it is shown that a first stage of analog pre-processing is mandatory to make SDR applicable in this context, in other words to obtain flexible or multi-purpose UWB systems. But not any analog front-end is convenient. It must be generic enough in order to fully take benefit from SDR capabilities. The proposed solution is based on two different analog structures for impulse UWB.

One is generic and provides the necessary metrics required for different kinds of digital processing operations: low data-rate communications, synchronization, localization, channel sounding… An original approach permits to relax speed and precision constraints put upon A/D conversion and digital processing. It is then possible to apply SDR techniques in order to target one specific operational system or application.

The second structure is dedicated to very high data rates (up to 600 Mbps) and is based on a non-coherent energy detector with optimum performance. Moreover it also uses the generic structure for synchronization purposes. Physical constraints are so much reduced that low-cost SDR-compatible systems become conceivable, even for high data-rates, with the additional advantage of flexibility.

1. INTRODUCTION

Two of the most promising research areas of future telecommunications definitely are Ultra-Wide Band (UWB) and Software Defined Radio (SDR).

UWB is foreseen as a kind of ultimate communication paradigm, exploiting to its maximum the Shannon theory and redefining the spectrum sharing of the lower frequency bands that had always been reserved for dedicated applications until now. IEEE launched a standardization process on the UWB physical layer (802.15.3) but an agreement still seems to be a long way off as most companies have chosen this topic as a new fighting area beyond IMT-2000. From a different background, the IST project Pulsers [1] could be at the origin of a European UWB standardization proposal and an alternative to IEEE.

As a common agreement, SDR is a key technology for future telecommunication systems [2]. Beside the possibility for operators to offer enhanced services to their customers, it will be of great profit for manufacturers too at both design time and life time. SDR is an enabling technology that can theoretically address any kind of telecommunication system, provided that the related physical constraints (processing speed and power consumption, mainly) are indeed supported by the current technology, and at an acceptable cost. In that respect, analog to digital converters (A/D) and digital processing circuits are decisive factors.

We can easily imagine then that solutions that are able to combine both SDR and UWB could contribute to a major breakthrough in the telecommunication domain. Whereas many issues seem to temper this possibility, we propose here to demonstrate the feasibility of such a combination through the solution devised in our laboratory, at both analytical and hardware feasibility levels.

The paper is organized as follows. First the benefits of combining UWB and SDR are exposed in section 2. It brings up the need for a new way of tackling SDR in that context. We insist in section 3 on the technical challenges UWB imposes on system design, and its consequences on the applicability of SDR. Section 4 then presents an original UWB solution based on two complementary analog RF front-ends, as well as its performance. Finally, some conclusions are drawn.

2. SDR AND UWB

Apart from the potential benefits that can be expected in a general manner by the use of SDR in the design of UWB systems in order to reduce the development cycle and time-to-market, we can already identify concrete points of interest in terms of markets.

2.1. Benefits of SDR for UWB

UWB provides a continuous class of data rates, from several kbps to hundreds of Mbps, easily adapting to the channel propagation conditions whilst it naturally coexists with pre-existing narrow-band systems. Furthermore, the basic UWB waveform is likely to supply environment sensing characteristics (ranging, band selectivity, …). The coupling between communication and accurate channel measurements makes this technology unique. As a consequence UWB is not considered as a communication solution for a particular market, but for a plurality of markets. Among them we can mention: short-range very high data-rate communication systems including home and office environment as well as network-PC world, sensors networks, positioning systems, personal and local area network links… In addition, applications not yet clearly identified are still susceptible to augment the list.

As UWB aims at answering many needs, it may also be implemented in many flavors. Hence it would naturally gain a great benefit in supporting SDR features, for instance to integrate several systems in one, at the condition of having a common global hardware structure for analog and digital processing. The SDR approach may also be a catalyst for new ideas and applications around UWB, thanks to its intrinsic scalability and mutability properties. At least could it permit to provide systems with adaptability features, in terms of data rate or spreading gain adjustment at run-time, depending on the environment's fluctuations (other users or propagation phenomena).

Another issue pushes towards a wide adoption of SDR in the UWB field. It is a consequence of the IEEE-802.15 UWB standardization process that goes towards several solutions regarding the choice of the modulation. DS-CDMA and OFDM are sources of strong oppositions and SDR is foreseen as a solution to accommodate the different proposals [3]. It might not make those different systems compatible, but could at least make them co-exist on the same hardware.

Ad-hoc networking is also considered as one of UWB's great impacts. In this context, UWB systems could be adapted to support some network responsibilities through SDR techniques. Each corresponding configuration could be directly dimensioned depending on the context of ad-hoc networking really needed. This is more flexible than pre-installed general purpose configurations that are either over-dimensioned or too weak.

2.2. Challenges of SDR for UWB

As promising as it may seem, proposals combining UWB and SDR are however not so numerous. The reason for that comes from the a priori incompatible nature of those two technologies. Indeed, SDR aims at generalizing as much as possible the features of a communication system by digitizing the radio signal as close to the antenna as possible. Specialization of the system is consequently done in the digital domain which, thanks to its reconfiguration capabilities, can potentially adapt to any transmission scheme for the physical layer and any protocol behavior for higher layers.

This is not adequate anymore in a UWB context. The fault is that of the large bandwidth which demands very high sampling rates. Even if such conditions can be fulfilled in laboratory conditions, this is completely incompatible with products constraints in terms of performance, power consumption and cost, all the more so for embedded systems powered by capacity-limited batteries.

So high sampling rates are particularly unaffordable regarding the analog to digital converters and the associated digital components required to process signals at such speed.

2.3. Necessity to reorient SDR for UWB

Given those considerations, it seems quite clear that tackling SDR in the usual manner leads to a dead-end. It is technologically impossible to digitize bandwidths of several Gigahertz in a commercial mobile communication system without an unacceptable extra cost. Consequently it is not consistent anymore to move the analog to digital conversion as close to the antenna as possible to make SDR UWB.

On the contrary, it seems mandatory to let the analog front-end do as much of the processing as possible so that a narrower bandwidth digitization becomes possible and sufficient, while preserving all the different potential manners of using the system. This means having some kind of SDR analog front-end.

The first condition is to have an analog front-end that delivers a signal generic enough to be further processed in different ways for the achievement of various kinds of telecommunication purposes.

The second is to realize as much of the processing as possible in a passive low-power manner, without depriving the signal from its general content. We call this analog pre-processing.

The third requirement for the RF front-end is to feed the A/D converters with signals that may be sampled at sufficiently low rates so that technological, cost and power-consumption barriers are removed at a short or medium term.

Fig. 1 illustrates the usual SDR vision with the A/D converter as close to the antenna as possible.

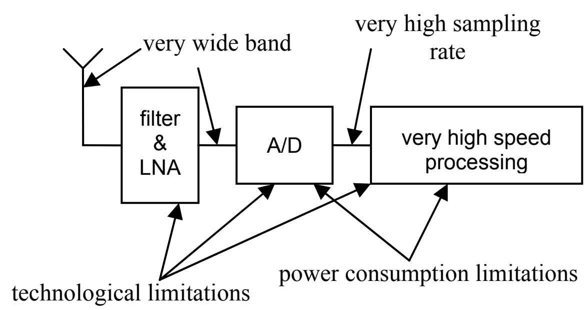

Fig. 1. Usual SDR approach at Rx.

In order for SDR to be viable in a UWB context, it is necessary to add an analog pre-processing stage before conversion so as to reduce the constraints put on the digital part, as shown on Fig. 2.

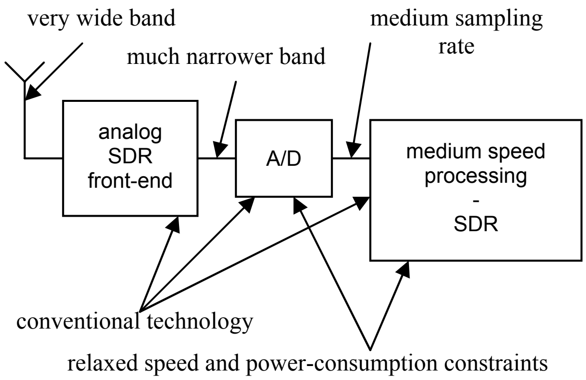

Fig. 2. Convenient SDR approach for UWB.

3. UWB FUNDAMENTALS

As for today, Ultra-Wide Band does not preclude any kind of modulation. The signification of UWB is obvious: use signals with a sufficiently wide band to benefit from the advantages recalled in Tab. 1.

UWB is originally based on Spread Spectrum (SS) techniques and especially Time Hopping (TH) [4]. It is often preferred to other SS techniques as Direct Sequence (DS) because of its lower average power spectral density, and to Frequency Hopping (FH) because this latter is handicapped by the hopping rate. OFDM also generates wide-band signals while combining several sources to make all benefit from the global bandwidth of the generated multiplex [5].

3.1. Origins and advantages

The use of UWB as a communication system dates back to the early Cold War and has known a great popularity in the military sector since that time under its SS category. The reasons that made this kind of transmission method very popular for the military are not so distant from the reasons that make it popular now in the commercial industry. Wide-band signals have some very interesting particularities illustrated in Tab. 1.

If only one feature were to be emphasized, it would concern the ability to reuse the already occupied spectrum. From a commercial point of view, it is like reinventing a 10-GHz band in a spectrum that was considered to be definitively congested. In particular the 0–10 GHz band is very attractive since it considerably reduces technical difficulties in comparison with higher bands, as the 60 GHz band for example.

From a technical point of view, designers rely on the ability of spread-spectrum systems to take multipath as a source of diversity instead of struggling against it. That is the reason why the symbols (called chips) are intentionally chosen short by comparison with the channel's multipath delay spread. On the opposite side, OFDM aims at making the symbols' duration longer than the multipath delay spread to avoid inter-symbol interference. Diversity is obtained through an adequate combination of interleaving and channel coding. Let us note that this capacity of SS, as well as its ability to coexist with other signals in the same band, is directly connected to the spreading factor. The higher, the better discretion and anti-multipath robustness, but the lower information data rate.

	SS	OFDM
low power spectral density	under noise level hardly detectable hardly intercepted (security) does not pollute existing transmissions	
	signal superposition	signal combination
frequency selective channel	some frequency components may be damaged by the channel, but most are preserved	
	diversity techniques against multipath fading (Single Path, RAKE…)	diversity is obtained by a combination of interleaving and channel coding
multiple access capabilities	increased frequency reuse and capacity	
	natural frequency superposition	frequency multiplexing (negotiation or centralization required)
jammers rejection	coexistence with existing in-band transmissions	
	by very nature of SS (fully naturally adaptive)	by bypassing carriers (rigid or adaptive by processing)

Tab. 1. Wide-band signals' particularities.

3.2. Fundamental requirements for commercial UWB

UWB has been foreseen as a promising technology for the implementation of communication systems requiring the following characteristics:

- very high data rate for multimedia,
- spectral coexistence with already existing systems,
- low cost for a mass market,
- low power consumption for battery saving.

UWB systems are supposed to answer new connectivity demand for mobile multimedia devices for a reasonably small fraction of their cost. Let us just mention wireless USB for PC, or PDA digital video and audio services as examples. UWB should also motivate the development of new categories of products in conjunction with the trend to extend large-bandwidth applications within the personal space [6].

In order to be compatible with SDR, constraints become even tougher concerning the cost and power-consumption requirements. Analog to digital bands should not be too wide and processing rates not too high. Computationally intensive structures are simply disqualifying with these features.

3.3. Technological issues

The very large bandwidth required by UWB implies some challenging technological issues, starting from the antenna (small and wide band), the filters (sufficiently flat in the band and sharp at each side) and the amplifiers (low distortion of the frequency response). But this also has repercussions on the system's digital signal processing sub-part that faces much too high sampling rates for demanding algorithms such as RAKE receivers and all the associated synchronization and channel-estimation constraints.

As FCC defined a frequency mask [7] with different frequency steps, and in order to quickly answer the market's demand, the community returned to already existing solutions like OFDM and DS-CDMA with multi-band extension. This permits manufacturers to re-use known transmission schemes, but to the detriment of UWB fundamental requirements concerning low cost and low power consumption, if not feasibility. Above all, this simply bans the possibility of using SDR in such a context.

To the opposite, our reasoning consisted in rethinking the issue of ultra-wide band signaling over a multipath multi-user channel with the postulate of taking as much benefit as possible from an analog passive RF front-end that could deliver a sufficiently informative signal in a narrower bandwidth for multiple applications.

4. UWB SOLUTION

The solution proposed here rests on a generic analog front-end that could be used by any UWB system based on an impulse modulation scheme. An optional complementary analog structure can be appended to it in order to achieve very high data-rate transmissions (up to 600 Mbps).

4.1. Generic analog front-end

The underlying idea to the generic front-end is to transform the signal and make it "shrink" according to the only few necessary degrees of freedom of the channel, while taking into account restrictions in terms of power consumption or implementation complexity. This leads to an original result which consists in sampling the channel in a non-conventional manner. Only the very necessary substance is extracted, unlike the classic oversampling way which integrates lots of superfluous information. The method is based on a coherent integration effect of a time-hopping sequence (TH) in the analog domain, very formally illustrated in Fig 3. Basically, it detects signals and evaluates the channel delay spread.

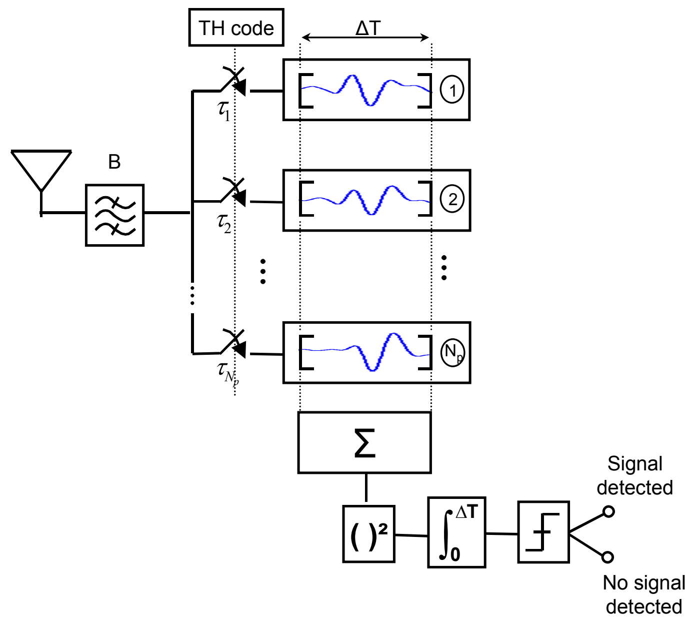

Fig. 3. Coherent integration in the analog domain at Rx.

A first point is that a complexity reduction factor of approximately one order of magnitude is obtained as compared with what would be required in such conditions to process a conventionally oversampled digital signal. More precisely, for pulses spaced every 100 ns at transmission, it is sufficient to integrate the analog signal for a short 2 ns period every 100 ns and then sample only the resulting value, so that the sampling rate is not higher than 10 Mhz. For confidential reasons, this method is only formally depicted now but will be covered in future publications. These orders of magnitude are totally in the scope of digital interfaces for embedded systems, which makes SDR completely feasible. Secondly this structure permits a significant gain on synchronization time compared with classic correlation techniques: with a time-hopping code sequence of 64 chips and pulses of 7 GHz bandwidth, 4 ms only are expected for the receiver to synchronize, whereas a few seconds are usual with correlators.

The common structure is in all cases responsible for synchronization, but the same structure can also deal with low data-rate transmissions, localization and tracking applications. SDR techniques are particularly suitable to manage these different kinds of functional schemes [8], either to differentiate systems at production time, or to adapt them to new behaviors at run-time. The digital signal processing part can be matched to the targeted application in a static way in the first case, or dynamically in the second. Such features require the implementation of adequate hardware and software architectures like those proposed in [9].

4.2. Multi-band for high data rate

Very high data-rate transmission is not in the very nature of UWB, which is more dedicated to low-rate secure applications as explained in paragraph 3.1. That is the reason why another RF front-end has been devised for very high data rates.

An impulse modulation scheme is chosen for transmission with an on/off keying representation of symbols for simplicity purposes. The choice of a non-coherent energy detector at the reception (Fig. 4) definitely gives robustness against the phase distortion provoked by the channel or by the system itself within its filters and amplifiers. This makes the system effective with a simple approximate delay-spread prevision provided by the generic front-end and an optimized energetic threshold adjustment which has been deduced from analytical results.

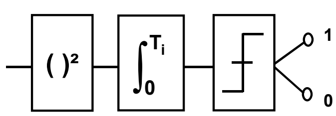

Fig. 4. Non-coherent approach for high data rates.

In the established link mode, the signal does not need to be sampled according to its frequency bandwidth at the antenna, but according to the delay spread after the analog pre-processing front-end. All the metrics necessary to obtain the modulated signal are still available, at the cost of a minor performance reduction which is explained in paragraph 4.3.

A sub-band approach permits to relax even more A/D conversion constraints to a few tens of Megahertz, all the more so as only a small number of digits is necessary. The radio signal may be multiplexed at the transmit side and de-multiplexed at the receive side in the frequency domain in 500 MHz or even 250 MHz bands without diminishing the channel's necessary contribution to diversity. This method permits to dramatically increase the system's throughput on the one hand, while shortening the band to be digitized on each frequency multiplex on the other hand.

A typical value for the sampling frequency after multi-band decomposition is 30 MHz. As for resolution, 4 to 8 bits during the acquisition procedure are sufficient, and this number could go down during the communication phase. A pure analog hard decision is even envisaged, which corresponds to a one bit resolution.

Note that this frequency multiplexing approach does not automatically involve a carrier frequency translation at the transmit side. This can also be obtained by pulse transmission and frequency isolation by filtering with a bank of filters, one per frequency multiplex.

The SDR approach is particularly interesting in this sub-band context: it can provide the system with a means of adapting its processing according to which sub-bands are actually used. Many SDR considerations can be derived from this structure depending on the application's status.

A detailed description of the multi-band analog front-end for high data rates and the corresponding modulation/ demodulation scheme is presented in [10], as well as the technological aspects of its implementation.

4.3. Performance

Tab.2 gives the performance results obtained by analytical studies [11]. These figures have been obtained without channel coding on the IEEE 802.15.3a channel models (CM) for UWB with FCC transmission mask.

Performance are particularly satisfactory since a data rate of 600 Mbps is achievable at 5 m for a bit error rate of 10^{-5}. These performance could still be enhanced with additional channel coding techniques.

R *	**150**	**240**	**600**	*Mbit/s*
d	**15**	**8**	**5**	*m*
B	500	500	250	*MHz*
N_{band}	12	12	24	
T_r	80	50	40	*ns*
CM	4	3	2	
T_i	50	40	30	*ns*
P_e *	10^{-5}	10^{-5}	10^{-5}	

Tab. 2. Analytical performance.

These performance must be compared with those expected of other UWB systems. Due to its non-coherent nature, the system described here needs 3 to 5 more decibels than a coherent receiver to achieve the same performance. On the other hand, since it is able to recover almost 100% of the available energy, it means that a coherent receiver should collect at least 40% of each emitted pulse's energy to yield the same results. With such a spreading channel as the UWB channel is, doing so would require to use a RAKE receiver with lots of fingers running at several tens or even hundreds of Mega-samples per second. This would represent too much processing speed and complexity, as well as too much power consumption, to be a viable solution.

5. CONCLUSIONS

This article proposes a solution to realize a Software-Defined-Radio-based UWB equipment. It rests on a novel UWB design based on the following principle: a digest of the channel extracted from an analog pre-processing stage provides the digital part with signals whose bandwidth is compatible with current digital processing capabilities. Two original analog RF front-end structures have been derived for respectively:

- synchronization, low data-rate transmissions, localization, channel sounding…
- high data-rate transmissions.

Their relaxed technological constraints make it possible to use standard technologies for both the analog front-end and the SDR digital processing part (FPGA or DSP).

The combination of UWB and SDR makes an ideal multi-purpose solution for the UWB market, which doubly benefits from mass market:

- the same generic RF front-end is used by all systems for at least synchronization and low data-rate applications,
- a flexible SDR digital back-end can adapt to each application.

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