Low Power, Short Range transceivers for Sensor Networks applications

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ABSTRACT

Emerging technologies like ZigBee or Ultra Wide Band (UWB) Radio, based on the new standards of the IEEE 802.15 family, will, in a near future, compete with and/or complement Bluetooth technology in the development of Wireless Personal Area Networks (WPAN's), capable to satisfy the increasing demand of high bit rate data transfer links as well as low power and small size constrains. Nowadays coexistence and interconnectivity of Wireless Local Area Networks (WLAN's), WPAN's and mobile phones is just the first step towards the implementation of the so called **Ambient Intelligence**. The main characteristics of this new paradigm are: **ubiquity, transparency,** and **intelligence**. In this context, **sensor networks** are the first front of the communication chain. Thus, most of the wireless data transfers will take place at very short distances and most of the information flow will be performed at very low rates. To implement the RF transceiver devices constituting sensor networks in an Ambient Intelligence environment, several challenges still need to be solved, among them: **packaging** (SoP vs. SoC approaches), **powering** (low power, batteryless systems, energy scavenging) and **system architecture** (new simplified direct conversion approaches). All these matters will be considered in this work.

Keywords: Short Range Communication Systems, Sensor Networks, Ambient Intelligence.

1. INTRODUCTION

There is no doubt that Radio Frequency Communication Systems play an important role in our daily lives. Hand held mobile phones are, probably, the clearest example but they are not the only one. Nowadays, the development of Wireless Local Area Networks (WLAN's), based on the family standards IEEE 802.11[1], allows wireless internet access at home, in the office or in a conference room. Furthermore, the acceptance of Bluetooth technology[2-4] in the short range communications domain (typically between 1m and 10m) is more evident day by day. Data transfer between our desktop or laptop computer and its peripherals, our mobile phone, digital camera, pocket PC and GPS device, etc. are some application examples of this technology. Other emerging technologies like ZigBee[5] or Ultra Wide Band (UWB) Radio[6], based on the new standards of the IEEE 802.15 family[7], will, in a near future, compete with and/or complement Bluetooth technology in the development of Wireless Personal Area Networks (WPAN's), capable to satisfy the increasing demand of high bit rate data transfer links as well as low power and small size constrains.
Coexistence and interconnectivity of WLAN's, WPAN's and mobile phones, which configure our present wireless world, is just the first step towards the implementation of the so called **Ambient Intelligence**[8,9]. The main characteristics of this new paradigm are Ubiquity, Transparency and Intelligence. **Ubiquity**, because anyone of us will be surrounded by a huge amount of interconnected embedded devices of different kind, complexity and functionality. Electronics will be integrated into almost everything, for instance clothing, furniture, construction materials, houses, offices, public places, etc. **Transparency**, because technology disappears into user's surrounding background. **Intelligence**, because technology will be enabled by simple, effortless and seamless interactions, adaptive to the user and autonomously acting, that is an electronic environment aware of and responsive to the presence of people.
To make Ambient Intelligence a reality, many innovations have to be realized, both Hardware and Software related. A crucial issue is the development and further integration of many different and advanced technologies. Such technologies and related process should allow seamless data transfer from their sources/sinks (sensors, actuators and transducers) through interfaces (mixed signal and RF circuits) to the final digital processing units, and back[10]. Most of the wireless

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data transfers are expected to take place at very short distances (typically in the range of few meters) with information flows at very different rates. At the lower end (average data rates in the range of some bits/s) we find sensors and actuators or intelligent labels and cards[10]. At the other end, there will be needs to interface digital video cameras, with data rates around hundreds of Mbits/s, or large HDTV displays with data rates as high as 5 Gbits/s[6,10,11]. Such remarkable differences in bandwidth demands, inevitably leads to strong differences in power requirements[12].
To implement the diversity of devices constituting an Ambient Intelligence environment, several challenges still need to be addressed, among them:

- **Packaging**. Using available technologies it is not possible to implement a whole RF communication system, from the antenna to the first stages of the base band processing, in monolithic form. As a viable alternative to the monolithic RF System on Chip (SoC) approach, there is the RF System in Package (SiP) approach[13]. In essence, several IC's fabrication process and packaging techniques are combined together to get a compact RF system. The key of success is to use the best available technology to perform each part of the system, getting this way the best performance at the lowest prize in the smaller package. In the SiP approach, the role of the carrier substrate is not only to interconnect the different dice attached on it. A variety of passive components, including inductors, transformers, resistors and capacitors, can be embedded in the carrier substrate, diminishing or avoiding this way the use of external discrete components. Actually, RF building blocks as well as transceiver modules have been already implemented using the SiP approach[14-16]. However, to optimize the fabrication process further studies should be carried out in areas such as Chip/Package co-design methodology or mechanical, thermal and electromagnetic characterization of small packages.

- **Powering**. In an Ambient Intelligence environment, depending on the power consumptions three generic classes of devices or network nodes can be defined: microWatt nodes, milliWatt nodes and Watt nodes.

  MicroWatt nodes are the primary nodes attached to the sources/sinks of information (sensors, actuators and transducers). They should be autonomous batteryless devices that extract the required energy from the environment by scavenging ligth, electromagnetic energy, mechanical energy from vibrations or thermal energy from temperature gradients. The usability of these energy sources reduces the power consumption to a maximum of tens of microWatts[17,18]. This limit imposes hard constrains at the circuit level. Very low power design techniques are required to implement such kind of devices.

  MilliWatt nodes are portable devices that use rechargeable batteries with typical autonomous operational times of few hours and standby time of several days. Cellular phones, Personal Digital Assistants (PDA) and Pocket PC are some actual examples of these milliWatt nodes.

  Watt nodes are static devices that in practise have unlimited energy resource. Typical examples are servers, large storage and computer devices or large flat panel displays.

  Examples of these three device classes are already found today, but they are not part of an intelligent interconnected network. It should be noted that from the powering point of view, most of the technological challenges are related to the implementation of microWatt nodes, particularly to the self powering of these devices.

- **System architecture.** Small size as well as low power requirements point out to the reduction of system complexity. This means that both the RF Front-End and digital processing Back-End of the network nodes should be properly designed for the specific application they are devoted to, without unnecessary over dimensions or extra capabilities. In the case of the RF Front-End, direct conversion architectures, or architectures based on new RF building blocks will be the preferred solution[19]. In the case of the Back-End an important concern will be the proper management of sleep and wake up modes of operation. Medium Access Control to avoid collisions will be also a critical issue[20].

From the above discussion, it seems clear that most of the forthcoming research and development work in RF field will be focused on the development of compact, low power transceivers for short range communications. ZigBee and UWB technologies seem to be the best solutions for low and high communications data rates, respectively.

Wireless Sensor Networks[21] is a clear application example of short range-low data rate communication systems. In this context, the present work is devoted to the study of RF Front-End architectures for such application. After reviewing in chapter 2 the general specifications of IEEE 802.15.4 standard for the physical layer, some generalities concerning Phase Shift Keying modulation and demodulation are considered in chapter 3. In chapter 4, a new architecture for the coherent demodulation of BPSK signal, which can overcome some of the problems of PLL based demodulators, is presented. Finally, chapter 5 summarizes the conclusions.

2. Wireless Sensor Networks: IEEE 802.15.4 Physical Layer

Wireless Sensor Networks are intended to handle very low data rates (between some bits per second and some bits per day, in average). Key factors in designing a Wireless Sensor Network are cost and power consumption, which directly affect the choice of the physical layer. Physical layer parameters like: modulation scheme, frequency band of operation, coding, etc, must be compatible with cost and power consumption goals.

In this work we are going to consider the specifications of Physical layer, corresponding to the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs). The main standard specifications are:

- Worldwide unlicensed operation
- Ease of installation and configuration
- Simple and flexible protocol
- Reliable data-transfer
- Short range operation (within a range of 10 m typically)
- Low Power (multiyear operation from a 750 mAh AAA cell)

According to these general constrains, the IEEE 802.15.4 standard specifies a physical layer, which main characteristics are listed in table 1.

Frequency Band (MHz)	**Spreading parameters**		**Data parameters**		
	Chip rate (Kchip/s)	**Modulation**	**Bit Rate (Kb/s)**	**Symbol rate (ksymbol/s)**	**Symbols**
868-868.6	300	BPSK	20	20	Binary
902-928	600	BPSK	40	40	Binary
2400-2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

Table 1. IEEE 802.15.4 standard, main physical layer specifications

A compliant device shall operate in the 868-868.6 MHz and 902-928 MHz frequency bands or in the 2400-2483.5 MHz frequency band. In the first case, 11 channels are allocated (1 channel for the 868-868.6 MHz and 10 channels for the 902-928 MHz band). A total of 16 channels are allocated in the 2400-2483.5 MHz band.

Binary Phase Shift Keying (BPSK) modulation scheme with raised-cosine pulse shaping is used in the lower frequency bands. In the 868-868.6 MHz range data rate (symbol rate) of 20 Kb/s and chip rate of 300 Kchip/s are used, while in the 902-928 MHz range the data rate (symbol rate) is 40 Kb/s and the chip rate is 600 Kchip/s. In both cases, the chip-to-bit (chip-to-symbol) ratio is 15. In the upper frequency band the modulation scheme used is Offset Quadrature Phase Shift Keying (O-QPSK) with half-sine pulse shaping. Every information byte is divided in two 4 bit packets. Each of these packets is then mapped into one of 16 possible symbols. O-QPSK modulation allows the transmission of two bits per transmission period; consequently the resulting symbol rate is 62.5. Each symbol is coded using a 32 chips Pseudo random noise Sequence, and then the resulting chip rate is 2000 Kchip/s.

3. Phase Shift Keying (PSK) Modulation and Demodulation.

The digital phase shift keying of a sinusoidal signal is one of the most efficient and robust modulation techniques, both in terms of noise immunity and required bandwidth. It outperforms other widely used schemes like On Off Keying (OOK), Amplitude Shift Keying (ASK) and Frequency Shift Keying (FSK). Nevertheless, the demodulation of PSK signals use to be more complex than the demodulation of OOK, ASK and FSK alternatives. Both coherent and non-coherent demodulations of PSK signals are possible, however noise immunity is worst in non-coherent demodulation and the bit period has to be known[22].Consequently, interest will be focused on coherent PSK.

3.1 PSK Modulation.

Figure 1 shows the schematic block diagram of a generic PSK modulator. In the case of BPSK signals only the In-phase arm will be present. Figure 2 shows the constellation diagram of a generic M-ary PSK signal. Constant envelope constrains imposes that $A_I^2 + A_Q^2 = K^2$, being K a constant. For M=2 (i.e. BPSK signal) $|A_I| = K$ and $A_Q=0$. For M=4 (i.e. QPSK and O-QPSK) $|A_I| = |A_Q| = K/2^{1/2}$.

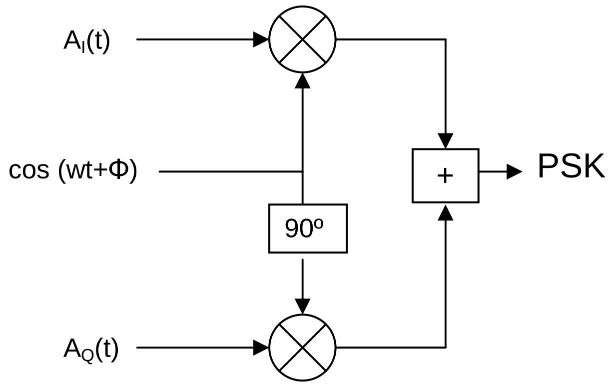

Figure 1: Schematic Block Diagram of a PSK modulator

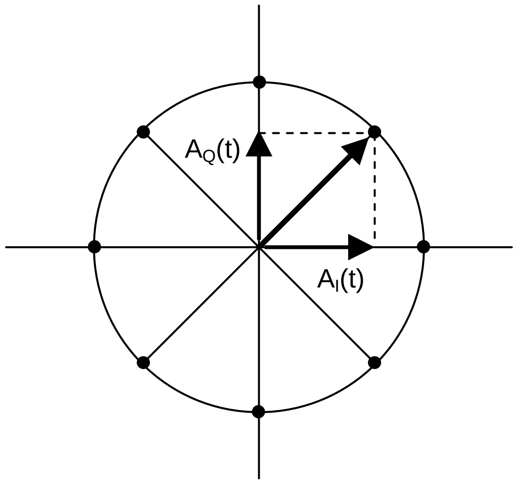

Figure 2: Constellation Diagram for a M-ary PSK signal (M=8)

The only difference between QPSK and O-QPSK signals is the alignment of the base band signals. In the case of QPSK both I and Q arms update simultaneously every two bit periods. This implies that the phase of the output signal can change in 0º (neither I nor Q change), ±90º (I or Q change, but not both) and 180º (I and Q change simultaneously). A phase shift of 180º is bandwidth consuming. To avoid this problem the update of I and Q signals does not take place at the same time in O-QPSK. The update of I and Q arms is delayed one bit period, T, consequently only 0º or ±90º phase shifts can occur. To illustrate this point, figures 3 and 4 show, for the same changes of base band signals, the QPSK and O-QPSK time waveforms, respectively.

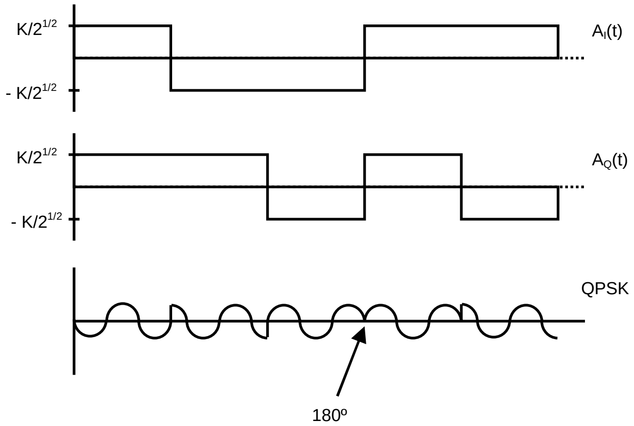

Figure 3: QPSK signal time domain waveforms

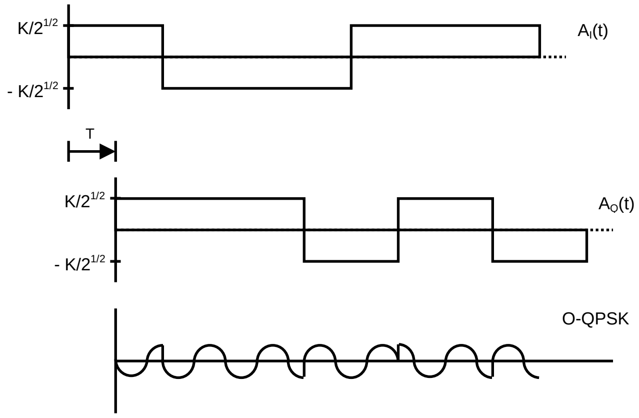

Figure 4: O-QPSK signal time domain waveforms

3.2 PSK Demodulation.

Traditional coherent demodulation of PSK signals requires the availability of a local carrier having the same frequency and phase than the signal we would receive in absence of phase modulation. Frequency and/or phase deviations of the locally generated carrier from the original one degrade the detection process and, consequently, the system performance. Therefore, local carrier synchronization is a critical issue in most digital communication systems. Carrier recovery is usually accomplished by using synchronization loops[23-26]. Figure 5 shows the typical implementation of synchronization loop to recover the carrier from a generic M-ary PSK signal. The incoming signal is first M powered to eliminate modulation information, then it is band pass filtered and used to synchronize a simple PLL. The frequency of the loop output is divided by M, phase compensated and finally used to obtain the I and Q base band signals. In the case of M=2 (BPSK signal) the most widely used carrier recovery system is the Costas loop, which is shown in Figure 6.

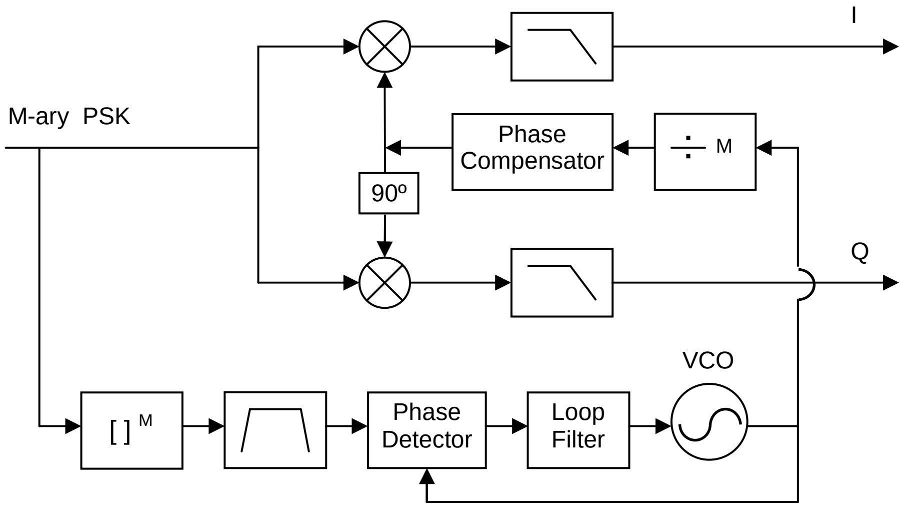

Figure 5: M-ary PSK demodulator with M powering loop carrier recovery system

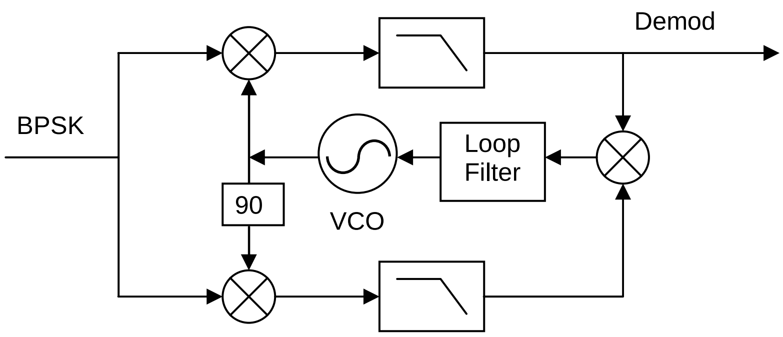

Figure 6: Costas Loop

The main drawback of PSK demodulators based on the use of synchronized loop is the synchronization time, which is usually large, leading to loss of data at the beginning of a communication or malfunctioning in burst mode transmissions. Moreover, Loop Filters are usually external components that complicate the monolithic integration of the whole system. Recently, a new approach for the demodulation of BPSK signals has been proposed[27]. The demodulation procedure is based on the super-harmonic injection of oscillators and interference phenomena. Injection is used to synchronize the oscillator in frequency and phase with the incoming signal and interference phenomena are used to generate an amplitude shift pattern that reproduces the phase change of the injected signal. Next chapter explains in detail this new approach.

4. BPSK demodulation using Injection Locked Oscillators.

Injection is a usual way to synchronize an oscillator with an incident signal. After the pioneering work of Van der Pol[28], the injection locking mechanism has been investigated by several authors[29-31]. When the oscillator is injected with a signal close to the *M* harmonic of its free running frequency, the ensemble is known as superharmonic or M^{th} harmonic Injection Locked Oscillator (ILO). In the locked state, superharmonic ILOs act as frequency dividers, being the dividing factor the nearest harmonic order of the oscillator's free running frequency to the injected signal. For that reason these components are also known as Injection Locked Frequency Dividers (ILFD)[32,33]. The output of a superharmonic ILO or ILFD could be in any of *M* possible phase states (being *M* the harmonic order). This is due to the phase uncertainty related to the frequency division process. For example, in the case of a 2nd harmonic ILO, the output frequency is half the frequency of the injected signal and phase uncertainty is equal to 180º. Figure 7 depicts, schematically, the frequency division process in the phasor plane. The ILO output can be in either of two possible states, identified by labels 0 and 1.

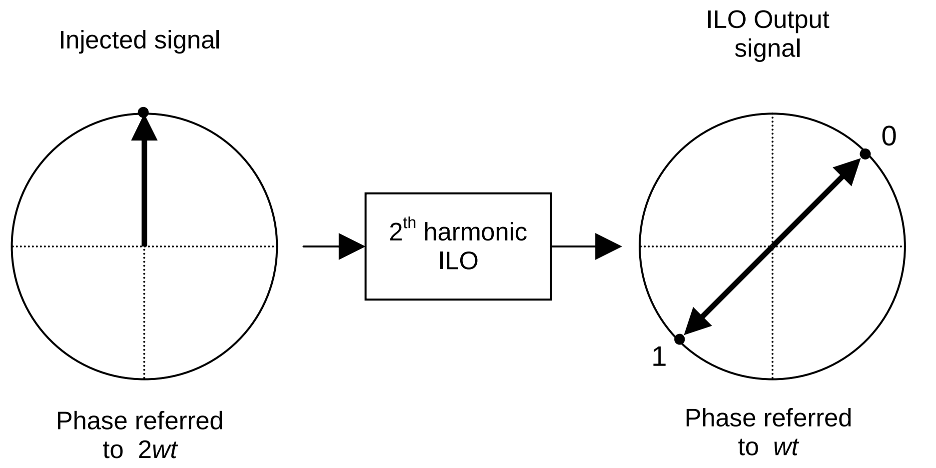

Figure 7: Phasor diagram of a 2nd harmonic ILO

Let's now consider that a 2nd harmonic ILO is in the 0 state and the phase of the injected signal changes in 180º (figure 8). According to the frequency division process, the output of the ILO could be in either of two possible phase states, corresponding to phase changes of +90º and -90º, respectively. A priori there are no arguments to know in which state the ILO output will be after the input phase change.

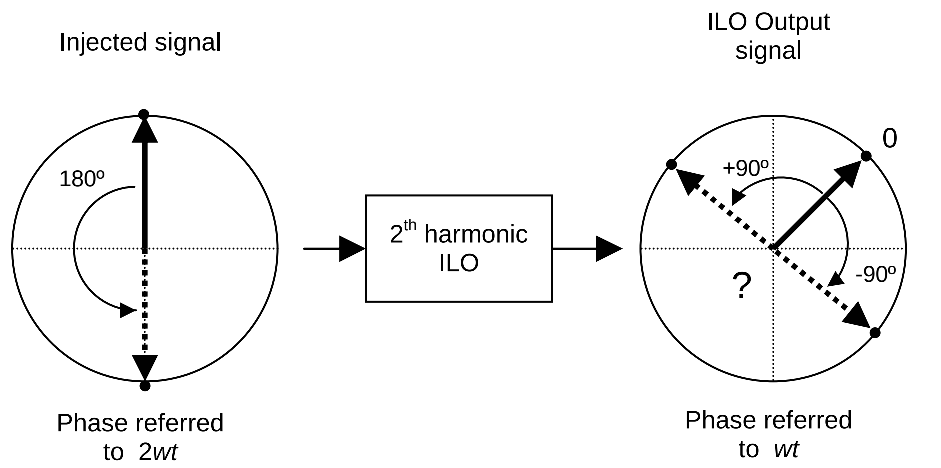

Figure 8: Phasor diagram of a 2nd harmonic ILO injected with a BPSK signal

However, an in depth analysis of the dynamic of ILO systems[15] reveals that the sign of the output phase change depends on the ratio between the injected frequency and the free running frequency of the oscillator prior to the injection. Thus, if this ratio is bigger than 2, the output phase change is equal to -90º, while if it is smaller the output phase change is equal to 90º. Taking this into account let's consider two ILOs injected by the same BPSK signal. One of them has a ratio "*injected frequency/free running frequency*" greater than 2, $ILO_{(-90º)}$, while the other has a ratio smaller than 2, $ILO_{(+90º)}$, as depicted in Figure 9.

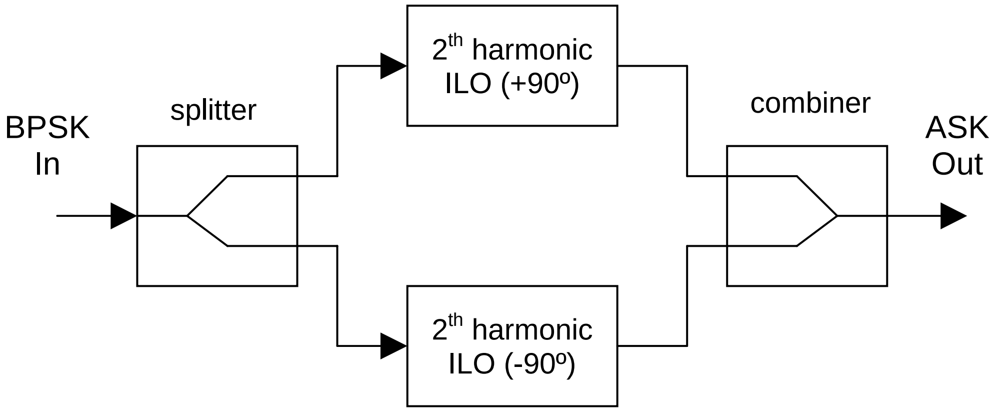

Figure 9: Block diagram of the PSK to ASK converter based on the dynamics of two ILOs.

Let us assume that, in the initial state, both ILOs have the same output phase. This situation is described in figure 10(a). When both outputs are combined, both signals will interfere constructively leading to an amplitude value which ideally is twice the output amplitude of one ILO (assuming both ILOs have identical output amplitudes). Now, if the injected signal changes in 180º, the output phase of $ILO_{(-90º)}$ will changes in -90º whereas $ILO_{(+90º)}$ will change in +90º, as shown in figure 10(b). Thus, by combining both outputs, the signals will interfere destructively; and the amplitude at the output port will ideally be null. Additional changes in 180º degrees of the injected BPSK signal will drive the ILOs to the situations sketched in figure 10(c), (d). Further changes will repeat the amplitude pattern scheme. Therefore, the BPSK signal has been effectively converted to an ASK one (ideally OOK) as shown in figure 11. Note that the frequencies of both ILOs delimit a conversion channel, i.e., only injected BPSK signals will be properly converted if the free running frequencies verify: $2*f_{ILO(+90º)} < f_{inj} < 2*f_{ILO(+90º)}$.
Using this BPSK to ASK converter it is possible to demodulate BPSK signals coherently just adding an envelope detector. The main advantages of this new demodulation procedure are the very short time required to synchronize the oscillators to the injected signal (no external loop is required), the higher degree of integrability in comparison with traditional PLL based schemes (no external filter are required) and simplicity of the proposed architecture, which will be very suitable for low power transceiver design.

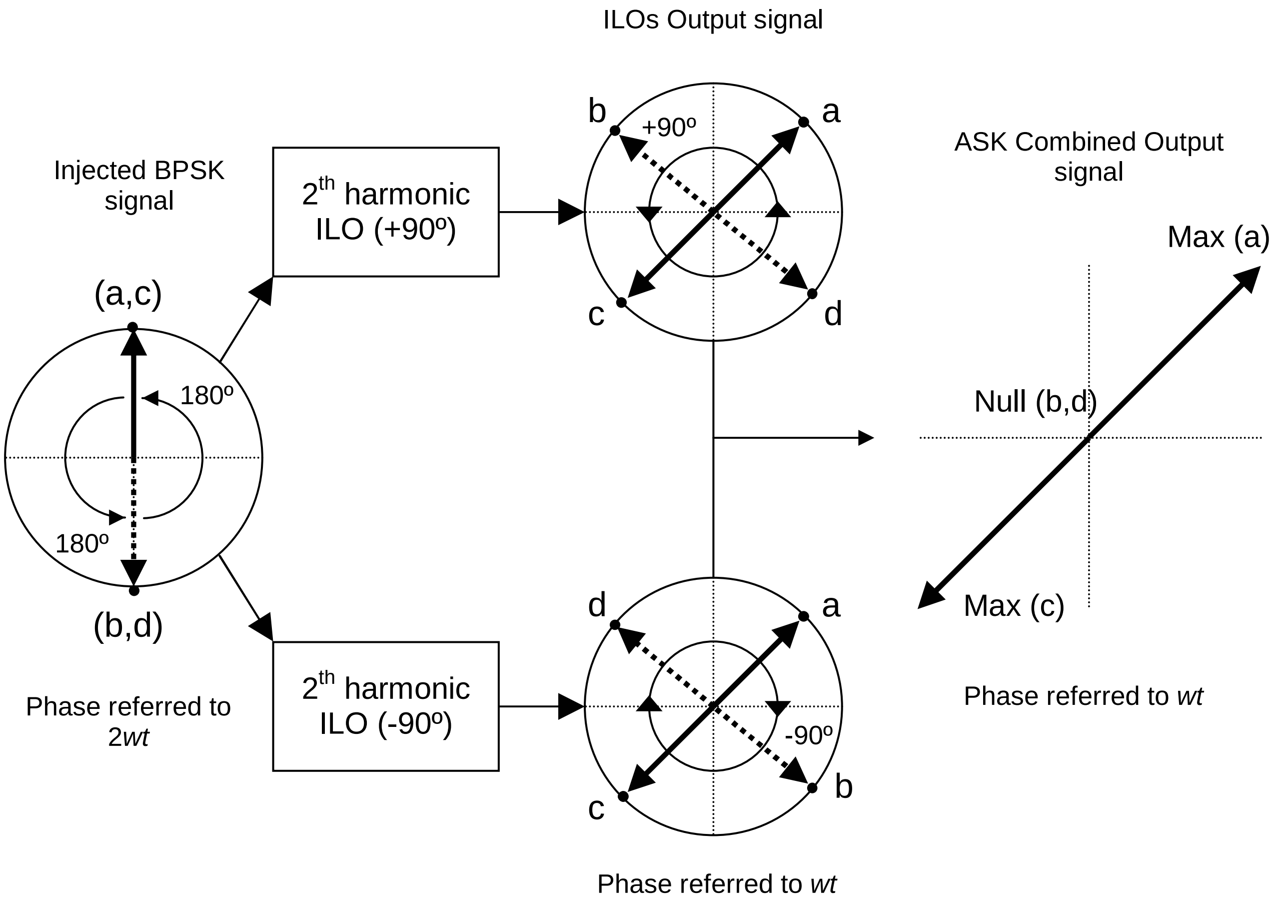

Figure 10: Phasor diagram of the BPSK to ASK conversion

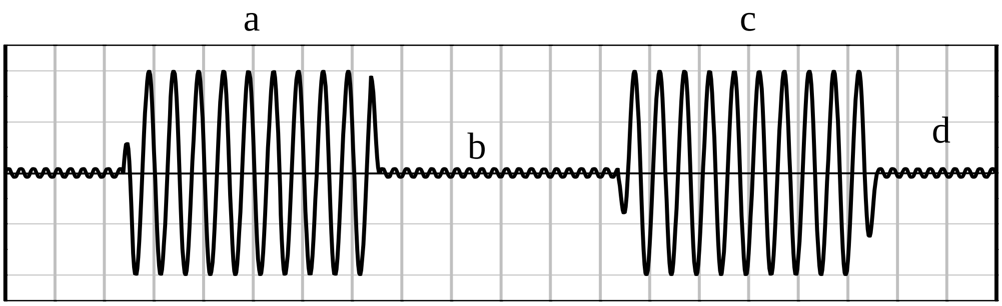

Figure 11: Time domain waveform of the ASK output

5. Conclusions.

This work gives a general overview of short range communications in wireless sensor networks application. After reviewing the state of the art the main specifications of the IEEE.802.15.4 standard related to the physical layer are summarized and discussed. Phase Shift Keying is then analyzed in detail, as the preferred data modulation scheme for wireless sensor network applications. Finally an alternative to the traditional PLL based demodulator is presented and discussed.

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