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# Remotely UHF-Powered Ultra Wideband RFID for Ubiquitous Wireless Identification and Sensing

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# 1. Introduction

A new term of ubiquitous computing and communication is booming up which will transform our future corporate, community and personal life [1]. Early form of ubiquitous information and communication was happened in the use of mobile phones and nowadays it has become a vital part of everyday life for many million of people even more than internet. Recently, many research and developments are ongoing to bring this phenomenon more into everyday life by embedding smart systems into more objects which can interact to each other and people through a wireless link. It will provide connectivity for anything from anywhere, anyplace and for anyone. These connections create a network between items which lead to Internet of Things (IoT). Several kinds of information can be exchanged through the network such as environment status, and location which make a huge field of novel applications and market. To realize the IoT several technical innovation in different number of fields are essential. In order to have an embedded module in almost everything, first a simple and low cost system is vital. Second, embedding sensor technology into the items allows the system to detect changes in the physical status of things, which allows the system to changes or modifies some parameters of the system. And finally, system miniaturization allows smaller things have the ability of connection. A combination of all of these developments will create the IoT which connect the world's objects intelligently.

Different challenges need to be addressed. Energy issues such as low-power chipset design, energy harvesting, efficient and compact energy storage are some of the key issues. Many research need to be done in this area. Embedding sensor for data collection is another enabler for development of IoT. Low-power processing power and memory are important to process and store the sensor data. Different integration such antenna and passive integration need to be studied. Efficient communication protocol, modulation scheme and transmission speed is required to be studied. New methods for power management at different levels of the network are needed. Itegration of a smart device into the package or into the product is demanded. Different solutions such as system-on-chip and system-on-package should be investigated. Manufacturing challenges must be solved and the implementation cost must be lowered.

Radio frequency Identification (RFID) technology is a promising solution for IoT realization. It has been used mostly in supply chain management and logistic for several years [2].

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However, recently RFID based ubiquitous identification and sensing systems are widely interested [3]. An RFID system identifies items using radio waves. A typical RFID system includes two parts: a transponder or tag which attached to the object to be identified, and an interrogator or a reader which identifies the tags. Active tags incorporate a battery which supplies the power for the operation. They offer long operation range and high performance but they are expensive and usually big size. On the contrary, Passive tags derive the required power from a reader using either inductive coupling or electromagnetic capture and communicate by utilizing load modulation or electromagnetic backscatter. They are more widely used than active tags because of their great advantages such as low cost, small size, and unlimited life time. Inductive coupling tag can offer high data-rate in proximity operation, while backscattering passive tags offer longer operation distance. Therefore they are more widely used. However, the returned signal power scales, unfortunately, as the inverse fourth power of the distance to the tag which makes the identification difficult, especially in a dense multipath and multi user environment. On the other hand, the data rate is limited to few hundreds of kb/s, and positioning accuracy is not better than 70 cm [4]. However, in new applications such as wireless sensing higher data-rate link with more accurate positioning capability is desirable. [2].

Ultra wideband impulse radio (UWB-IR) has been recognized as a promising solution for future wireless sensing and RFID because of its great advantages [5-9]. Information in I-UWB system is typically transmitted using a collection of short pulses with low duty cycle resulting in low power implementation. I-UWB technique has the possibility of achieving Gb/s data rate, several tens of meters operation range, low power consumption, subcentimeter accurate positioning, and low cost implementation [10]. It has been shown that UWB-IR can be a powerful candidate for the next generation of RFID with unique benefits such as longer operation range, fine localization and tracking, reliable tag reading in dense and metallic environment, small size and low cost.

This chapter describes potential applications of UWB-IR in future RFID, its advantages, and its design challenges. A brief introduction of UWB focused on low-power and low-data rate application will be given and possible types of UWB-RFID are presented. A special focus on an UWB/UHF hybrid passive RFID system with asymmetric wireless links is studied as an example. Unlike conventional RFID systems relying on backscattering and narrowband radio, UWB is introduced as the uplink for tag to reader communication. It enables a high network throughput (2000 tag/sec) under the low power and low cost constraint. The hardware implementation issues in silicon level are also considered. A 0.18µm single chip design for proof-of-concept is shown finally.

# 2. Introduction to ultra wideband radio

## 2.1 UWB-IR basics

This technology started 1893 when Heinrich Hertz used a spark discharge to produce electromagnetic waves. However, because of the significant superiority of continuous wave systems , UWB technique has not been used for several years. In 1960 short waves research started again in the impulse radar technology to achieve better imaging and localization capabilities. All UWB research performed prior 1994 were under classified US government programs until 2002 when the FCC (Federal Communications Commission) allowed the use of the 3.1 GHz –10.6 GHz band for unlicensed use with a maximum power emission of - 41dBm/MHz. After some years, the FCC defined the power emission EIRP through out this

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band for different applications [11] such as indoor and outdoor communication, vehicle radar, ground penetrating radar, wall imaging systems, medical imaging systems, surveillance systems and law enforcements. Figure 1 shows the FCC emission mask for indoor and outdoor applications.

Ultra Wide Band has been defined by the FCC as a radio or wireless device where the occupied bandwith is greater than 20% of the center frequency or has a bandwidth higher than 500MHz. Two possible techniques for implementing UWB are Impulse Radio (IR) and multi-carrier UWB. Multi-carrier or multi-band UWB systems use orthogonal frequency division multiplexing (OFDM) techniques to transmit the information on each of the sub-bands. OFDM has several good properties, including high spectral efficiency, robustness to RF interference and to multi-path. It also has been proven in other commercial technologies such as IEEE 802.11a/g. However, it has several drawbacks. Up and down conversion is required and it is very sensitive to frequency, clock, and phase inaccuracy. On the other hand, nonlinear amplification destroys the orthogonality of OFDM. With these drawbacks MB-UWB is not suitable for low-power and low cost application.



Fig. 1. FCC regulation mask for indoor and outdoor communications.

The main advantage of UWB-IR compared with narrowband systems can be described with Shannon's capacity equation (Eq. 1 where "B" is bandwidth, "S" is the signal power and "N" the noise power). The channel capacity is directly proportional to the bandwidth and has a logarithmic relation with the signal power. This means that increasing the Bandwidth higher data rates can be achieved keeping a small signal power.

$$C = B \log_2 \left( 1 + \frac{S}{N} \right) \tag{1}$$

Information in impulse UWB techniques is send by modulating short pulses. In the literature is possible to find many waveforms that fulfill the spectral and power emission regulations stated in different parts of the world. Some of these signals are the Gaussian wave and its derivatives, Hermit pulses, Rayleigh and monocycle waveforms. Figure 2 shows the Gaussian pulses and its fifth derivative and Figure 3 shows the spectrum of them. In UWB-IR a non-carrier wave modulation is employed. The modulation is performed modifying some characteristics of the pulse such as amplitude, phase, and position. There

are several modulation options which depend on application, design specifications and constraints, operation rage, transmission and reception power consumption, quality-of-service, regularity, hardware complexity, and capacity. Some of known modulation options in UWB-IR are ON-OFF Keying (OOK), Pulse Position Modulation (PPM), Pulse Amplitude Modulation (PAM) and Binary Phase Shift Keying (BPSK). In Figure 4, different modulation schemes have been illustrated.



Fig. 2. Gaussian pulse and fifth derivative Gaussian pulse waveforms.



Fig. 3. Spectrums of different derivatives of Gaussian pulse with 500ps width

The transceiver complexity depends on the demodulation coherence. If the system uses OOK, PPM or M-ary PPM, a low complexity non-coherent demodulation scheme such as energy detection can be used. If the system use BPSK or M-ary PAM modulations, a coherent demodulation scheme is required increasing the hardware complexity and cost. Therefore, for low power and low-data-rate applications such as RFID and WSN lower-complexity modulation such as OOK or PPM is desired.



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Fig. 4. Non-Carrier modulation schemes for I-UWB [12].

# 2.2 UWB-IR for RFID and WSN applications

Recently, the interest of the UWB to low-power low-data rate networks with ranging has been growing rapidly, along with the development of the IEEE 802.14.a. Applications such as RFID and wireless sensor network combine low data-rate (50kbps to 1Mbps), ranges 10 m to 100 m with accurate positioning capabilities.

UWB is attractive to RFID and WSN applications, which require low-power and low-cost implementation, due to the high node density of the network. Besides, some of applications need battery-free by energy scavenging. Therefore, an average power consumption on the order of 10 – 100 uW is expected, at the cost of conventional passive tags for identification and tracking. In contrast to conventional RF communication systems, UWB-IR uses very short pulses that are able to propagate without an additional RF mixing stage [13]. The baseband-like architecture with low duty cycle signal guarantees low complexity and low power implementation. Many studies on design of UWB transceiver show that UWB technology is a good candidate to achieve low power and low complexity implementation. Center for wireless communications in University of Oulu demonstrated a tag based UWB wireless sensor system for outdoor sport and lifestyle applications [14]. A VLSI implementation of low power, low data-rate UWB transceiver is designed for such applications. The transceiver based on non-coherent energy detection architecture is implemented in 0.35 µm SiGe BiCMOS technology with 134 mW power consumption at 5 Mbps data rate [8].

Security is a hot topic in RFID and WSN research and development. Noise-like UWB signals guarantee robustness against eavesdropping or jamming. Existing RFIDs using simple coding and modulation schemes are easily to be eavesdropped or jammed. On the other hand, higher level efforts for cryptography results to large area of digital blocks for ciphers, high power consumption and system latency. To address this problem, a research group from Virginia Tech introduced an RFID system replacing cryptography with UWB in high secure application [5]. TH-PPM UWB modulation is applied as their proposed solution. Because UWB signal is inherently with low duty cycle and low-power emission, it is very

difficult to eavesdrop or jam and no extra cryptography block is required. It can simplify the hardware complexity, reduce the power consumption, and upgrade the system throughput. Excellent time resolution is another key benefit of UWB-IR signals for ranging and positioning application. Nanyang Technological University of Singapore developed an UWB-enabled RFID system which works with both active and passive tags to provide ranging and localization capabilities up to centimeter accuracy [15].

# 3. UWB/UHF hybrid system architecture

# 3.1 Design considerations of RFID and WSN systems

RFID and WSN applications hold some notable characteristics that are not shared with other communication systems:

- *System capacity:* A huge number of tags might appear in a reading zone simultaneously. Furthermore, multi-access (anti-collision) algorithm is essential for the system efficiency due to the massive tags environment.
- Asymmetrical traffic loads and resources: Unlike other RF communication systems, the traffic loads of RFID are highly asymmetrical between the uplink and the downlink. Data (e.g. synchronization, command) broadcasted from the reader is very few, but the traffic transmitted by a great number of tags in the field is rather heavy. In hardware perspective, tags have very limited resource such as memory, power supply, and computational ability, but a reader can be a powerful device.
- *Reading speed:* Reading speed in terms of processing delay is an important metric. High processing speed could be achieved by either a high data rate link for tag to reader communication, or an efficient anticollision algorithm.
- Low power and low complexity hardware implementation: Because RFID tags are resource-limited devices, the implementation upon the system specification must be simple and energy-efficient.

# 3.2 Asymmetric UWB-RFID architecture

On the basis of the considerations above, we propose an asymmetric UWB-RFID system architecture illustrated in Figure 5. Due to the nature of the impulse UWB radio, the UWB-IR transmitter integrated on the RFID tag provides a robust, high speed and high security uplink under a low power and low complexity implementation. Instead of the typical full-UWB system, the traditional RF transceiver is applied as the downlink. First, as the discussion in previous section, in full-UWB system, the wide-band RF receiver consumes too much power which makes it impossible for tag to be powered wirelessly in battery-less systems, whereas using battery in tag causes high maintenance cost and big size. Second, unlike other communication systems, RFID and WSN applications are dominated by uplink communication, where the low downlink traffic becomes insignificant for the system efficiency. As a result, the low data-rate narrowband radio is adequate [16, 17].

The reader broadcasts commands to tags using UHF ( $870MHz \sim 960MHz$ ) signal. The modulation is ASK with pulse interval encoding (PIE). The data rate (clock frequency) is adaptive from 40Kbps (KHz) to 160 Kbps (KHz) controlled by the reader. A tag replies information by transmitting UWB signal with adaptive data-rate up to 10Mbps. The UWB pulse rate and data-rate are adapted by reader based on the available power and desired operation distance. In long range operation when the available power to the tag is low, lower pulse rate and data rate is chosen resulting lower power consumption. On the other

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hand, in short range applications, higher pulse rate with high data-rate can be transmitted since the available power is high enough.

In [12], BPSK achieves the best BER performance in the AWGN and Rayleigh fading channels simulations. However the circuit complexity is the highest and the receiver needs a coherent system to demodulate data. Thus, this modulation is not suitable for the RFID implementation. Either OOK or PPM modulation can be used in the tags to modulate the UWB pulses. Although, OOK modulation has less communication performance however, it results in simple and low power implementation. Therefore, in this design OOK modulation is utilized. As can be seen later, UWB pulses are transmitted synchronous with the incoming RF signal, which brings further simplification in synchronization and improves the detection performance in readers.



Fig. 5. Proposed system model of asymmetric UWB-RFID architecture

# 3.3 Data communication protocol

The specification in higher layers is a further issue that determines the energy efficiency as well as the system throughput. Hereby, we devise a specified data communication protocol for the proposed asymmetric UWB-RFID architecture. Multi-access is also considered in the proposed protocol.

# 3.3.1 Operation procedure

Because of the great asymmetric between reader and tags, the system works in a masterslaver communication mode. A reader initiates all the operations, followed by tags' responses. All the calculations are made by the reader and hence the tag implementation is very simple. Five operations are defined in the proposed protocol, namely Wakeup, Request, Write, Modify and Kill. The Wakeup and the Request are basic operations for identifying tags or gathering data. The Wakeup activates and identifies all tags in the reading field while the Request performs the similar function as the Wakeup, but does not affect the identified tags. The Write function is for initialization of the tag and the Modify is used to program a specific tag with access control. The tag can be deleted by using the Kill function. The frame format, also called round, which represents an operation initiated by readers, is composed by four phases: powering, start of frame (SOF), commands, and processing. In the powering phase, the reader radiates a continuous sinusoid wave to power passive tags. A SOF is used for frame synchronization. The sequence consists of ten continuous bit 0s and a bit 1. Afterwards, tags decode the received command and respond the reader.

An acknowledgement mechanism is employed to guarantee the successful receptions and to disable the identified tags. Unlike traditional RFID where data integrity (QoS) is controlled by both readers and tags such as CRC check, in the proposed system, only readers take charge of error handling. As a result, CRC checker can be removed from a tag which reduces the complexity. After each operation, the tag sends its current data and the reader checks the correctness of the operation. Because the uplink speed is high, this approach will not cause the processing delay even transmitting whole data.

Figure 6 shows the state transition diagram of the main state machine for tags.



Fig. 6. The State Transition Diagram of UWB-RFID Tag

- *Powering Up State:* Passive tags capture power by the power scavenging units and store in a relatively big capacitor. This stored energy is used later for transmission.
- *Halt/Detecting State:* This is the initial state of each powered tag. In this state, tags are detecting incoming signals and capturing SOF and Command. After this state, tags enter a new frame to execute the corresponding operation.
- *Transmitting State:* A tag executes three procedures during transmitting state. First step is to load data into the cache and generate a PN code. Secondly, a slot counter in the tag counts down the PN code until it reaches 0. Finally, the tag sends the data and waits for ACK or NAK.
- *Writing State:* A tag programs its memory by receiving data from the reader.
- *Access State:* This state comes before an operation for a specific tag (Modify and Kill Commands). The tag compares its data with the incoming signals bit by bit. This state is interrupted by different bits. Only one tag with the same data completes the state.
- *Kill State*: It sets the Kill Flag to permanently disable the tag.

#### 3.3.2 Anti-collisions

In contrast to conventional wireless system, massive nodes (tags) are deployed in a dynamic environment. Random access method is applied in our work, rather than current medium access control (MAC) protocols for UWB-IR including time division multiple access (TDMA), time hopping, or direct sequence UWB (DS-UWB) [18]. In [19] several versions of the ALOHA algorithm are presented in order to increase its feasibility and efficiency. Among them, the most widely used one in wireless sensor and identification systems is the framed slotted ALOHA algorithm. Time is divided into discrete time intervals, called slots. A frame is a time interval between requests of a reader and consists of a number of slots. A tag randomly selects a slot number in the frame and responds to the reader. A procedure called acknowledgment is required to resolve collisions or failed transmissions. Collided tags retransmit in the next frame [19].

The overall goal of the anti-collision algorithm is to reduce the identification period with simple hardware implementation and low power consumption. To improve network throughput, we propose a more efficient scheme to overcome the anti-collision problem. It is based on the framed slotted ALOHA algorithm by employing following improvements.

• *The pipelined Communication Scheme:* In conventional approaches, a time slot normally contains a tag's data packet and the acknowledgement from the reader. However, because there exist great asymmetry between the downlink and the uplink (UWB data rate is much higher than the narrowband radio data rate), the acknowledgement from the reader to tags becomes a bottleneck that decreases the network throughput. This problem can be solved by using a pipelined method that poses the data packet and its corresponding acknowledgement in two adjacent slots. As can be seen in Figure 7, a tag sends data in the K slot and receives the ACK in the K + 1 slot. Processing gain in slot is calculated in Eq.2.

$$Gain = T_{packet} + T_{ACK} - \max\{T_{packet}, T_{ACK}\}$$
(2)



Reader

Fig. 7. The sketch of the pipelined communication protocol

• *Skipping Idle Slots:* Because the global clock is scalable controlled by the reader, it provides a possibility to skip idle slots. By detecting the incoming signals at the beginning of each slot, the reader can determine if there is any transmission in this time slot. If it is an idle slot (phase B in Figure 8), the reader skips this slot by adjusting the clock frequency and transits into the next cycle (slot) immediately.



Fig. 8. Sketch of Idle Slot Skipping

• *Adaptive Frame Size:* The maximum system efficiency of the framed slotted ALOHA is achieved when the frame size (N) approximately equals to the tag number (n) [20]. Dynamic frame sizes allocation replaces the traditional fixed framed ALOHA. With the tag number estimation algorithm [21], the reader can estimate the number of tags, and optimized the frame size.

Hereby, the system efficiency is defined as the ratio of the successful transmission time to the frame size. Given N slots and n tags, the number of r of tags in one same slot is binomially distributed as Eq.3.

$$B_{n,\frac{1}{N}}(r) = \binom{n}{r} \left(\frac{1}{N}\right) \left(1 - \frac{1}{N}\right)^{n-1}$$
(3)

If the frame size is small but the number of tags is large, too many collisions will occur and the fraction of identified tags will degrade. On the other hand, when the number of tags is much smaller than the number of slots, the wasted slots can occur. As described the dynamic frame size allocation can provide the optimal frame size to achieve the maximum throughput. Moreover, the idle skipping method can eliminate the delay caused by the empty slots. The simulation results of the system performance are shown in Figure 9. It demonstrates that more than 2000 tags/s can be processed. Table 2 presents the comparison result with some standardized RFID protocols.

# 4. Implementation of the remote-powered UWB-RFID tag

A Remote-Powered UWB-RFID tag is designed for proof of concept and implemented in UMC 0.18µm process (Figure 10). The module consists of five parts: an RF demodulator, an impulse UWB transmitter, a power management unit, a clock circuitry, and a digital baseband. The narrowband receiver receives RF signal and demodulates it into digital signal. The power management unit captures the incoming RF signal and rectifies to DC voltage and supplies the whole circuitry of the tag. A low frequency clock is recovered from the received data as the baseband control. Another high frequency clock for the UWB pulse generator is imported by dividing the carrier of the incoming signal. The digital baseband is responsible for control, i.e., decodes commands, programs memory, fetch data, and exports data to the transmitter.



Fig. 9. Simulation Results of System Performance

Standards	Frequencies	Data Speed T→R	Processing Speed	Anti Collision
ISO 18000-3 Mode	HF	106 Kbps	1200 tags/sec	Not Specified
ISO 18000-6 A	UHF	40 Kbps	100 tag/sec	Framed Aloha
ISO 18000-6 B	UHF	40 Kbps	100 tags/sec	Binary Tree Search
EPC Class 0	UHF	Max 80 Kbps	200~800 tags/sec	binary tree search
EPC C1G2	UHF	Max 140 Kbps	1000 tags/sec	Framed Aloha
This Work	Semi-UWB	1Mbps	>2000 tags/sec	Enhanced Framed Aloha

Table 1. Comparison of different standardized protocols



Fig. 10. Block diagram of the UWB-RFID Tag

#### 4.1 Impulse UWB transmitter

Impulse UWB Transmitter generates 5<sup>th</sup> derivatives Gaussian pulses to modulate the baseband information into UWB signals. A tunable impulse UWB transmitter is shown in Figure 11. Duration and amplitude of the output pulse are controlled by two inputs that have capability to compensate the process and temperature variations, interconnection and packaging effects, and frequency response of the antenna. Furthermore, this ability allows the module to control output power and bandwidth in different pulse repetition rates. In short range applications, high repetition rate and low amplitude pulses are transmitted. On the contrary, to transmit data in longer distance, low repetition rate and high amplitude pulses are chosen. In both of two cases, amplitude and duration controls enable the module to transmit a signal comply the FCC regulation [22, 23]. The output impulse of the UWB transmitter and its power spectral density are shown in Figure 12. The power consumption of UWB-Tx at 10 MHz pulse repetition rate is 51  $\mu$ A at 1.8V, and 252  $\mu$ A at 50 MHz pulse repetition rate.







Fig. 12. Output pulse shape of the I-UWB Transmitter and ITS Spectrum

#### 4.2 Power management unit

The power management unit provides power supply for the whole circuitry from incoming electromagnetic wave. Figure 13 shows the principle of operation. During the powering

phase the Power-Switch is open, and thus the power consumption is very low (1uA). The power scavenging unit (PSU) converts the received electromagnetic wave to a dc voltage on an off-chip capacitor. When the voltage across the storage capacitor raises a certain value (e.g. 2.5V), a voltage sensor (Vsen) switches on the Power-Switch and the chip starts to operate. While the chip is working, voltage across the storage capacitor is degraded; therefore a low-dropoutput (LDO) voltage regulator is utilized to provide regulated voltage for the module. If the voltage becomes less than a threshold (e.g. 1.8V), the voltage sensor switches off the chip, and chip starts to gather energy for next run [24].



Fig. 13. Operation principle of power management unit

Figure 14 shows the schematics of different building blocks of the power management unit including of the power scavenging unit, the voltage sensor, and LDO voltage regulator. The minimum input power of 14.1  $\mu$ W is achieved with this technique. It corresponds to 13.9 meters operation range which is great improvement compared with conventional RFID.

# 4.3 RF demodulator

Such as conventional RFID, a simple RF demodulator is utilized. It includes an envelope detector and a discriminator circuit which extract data and clock from the received signal. The envelop detector uses the same CMOS voltage multiplier topology than power scavenging unit, but with smaller capacitors and only 2 stages. The discriminator circuit decides whether a pulse is long or short and extracts data and clock. Extracted clock is used as the global clock for baseband control. Figure 15 depicts the schematic of the RF demodulator including of envelop detector, and clock and data recovery block diagram.

## 4.4 Clock generator

UWB transmitter requires high frequency clock with low skew and jitter. LC oscillators occupy large area and consume high power. On the other hand, ring oscillator show large variation across the process, temperature and voltage as well as huge phase noise [8]. Utilizing the PLLs which are used in communication systems are not applicable in RFID tag because of their high complexity and power consumption. In this work a low power harmonic injection locked (HIL) divide-by-3 is used to down convert the 900MHz carrier frequency [25]. Figure 16 shows the schematic of the divide-by-3 circuit and the output spectrum before and after locking. Simulation result of the harmonic injection locked divider shows total power consumption of 15.3µA. The minimum input voltage for locking is 100mv which is acceptable for this operation range. Phase noise of the output at 10Hz offset is -85dBc/Hz and jitter is 1.47ps.



Fig. 14. Schematics of power management unit



Fig. 16. Schematic of divide-by-3 and output spectrum before and after lock

# 4.5 Digital control logic

Digital control logic is used for baseband processing, medium access control, and power management. Figure 17 illustrates the architecture of the processor. The control unit is formed by several FSMs which generate control signals to each sub module whereas sub modules send status signals to the control unit. The pseudo number generator (PNG) and the slot counter are used to implement the transmission protocol and the anticollision algorithm. The circuit simulation is successful and the design is tested by FPGA prototype. We also map the design in UMC 0.18um process. The area is equivalent to 4000 NAND gates and the power consumption is around 800nW [26]

# 5. Conclusion

In this chapter, a novel system with asymmetric wireless links has been presented for ubiquitous wireless sensing and identification. Such as conventional passive RFID systems, nodes derive the power supply and receive data from the received RF signal transmitted by a reader. However, instead of backscattering, impulse UWB radio technique has been utilized in uplink from the nodes to the readers. It offers several advantages to the system such as high throughput, precise ranging and positioning, more security, long operation range, robustness to multipath, robustness to the narrowband interference and multi user



Fig. 17. Block diagram of baseband logic

interference. A new communication protocol is proposed for the novel system with asymmetric wireless links. It is based on Frame Slotted ALOHA anti-collision algorithm. Dynamic frame size allocation and idle slot skipping methods are investigated and the performance simulation results show a throughput more than 2000 tags per second for the system which great improvement compared to the conventional RFID systems (at most 1000 tags/s). To proof of the concept, a complete module for the tag has been implemented in 0.18  $\mu$ m CMOS process. The measurement results shows the operation distance of 14 meters when 4W EIRP emission is allowed at 900 MHz frequency band. The impulse UWB transmitter consumes 51  $\mu$ A at 10 MHz pulse rate which is low enough to be provided by the power management unit for 1.9 millisecond time. The results proof the validity of the proposed concept and show the great potential of impulse UWB radio for next generation of RFID for ubiquitous wireless sensing.

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The book generously covers a wide range of aspects and issues related to RFID systems, namely the design of RFID antennas, RFID readers and the variety of tags (e.g. UHF tags for sensing applications, surface acoustic wave RFID tags, smart RFID tags), complex RFID systems, security and privacy issues in RFID applications, as well as the selection of encryption algorithms. The book offers new insights, solutions and ideas for the design of efficient RFID architectures and applications. While not pretending to be comprehensive, its wide coverage may be appropriate not only for RFID novices but also for experienced technical professionals and RFID aficionados.

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