# A Novel Wireless Wake-up Mechanism for Energy-efficient Ubiquitous Networks

Takahiro Takiguchi, Shunsuke Saruwatari, Takashi Morito, Shigemi Ishida,
Masateru Minami, and Hiroyuki Morikawa
Morikawa Laboratory, RCAST, The University of Tokyo, Japan
Email: {takiguchi, saru, morito, ishida, minami, mori}@mlab.t.u-tokyo.ac.jp

***Abstract*—Excessive power consumption is a major problem in wireless communication. This is particularly true in ubiquitous computing environments, since wireless devices consume a considerable amount of energy in idle listening. Wake-up wireless communication technology is a promising candidate for reducing power consumption during idle listening. To realize wake-up wireless communication, this paper proposes a novel ID matching mechanism that uses a Bloom filter. This paper describes the design and implementation of a wireless wake-up module that uses this ID matching mechanism. Simulation results reveal that the wake-up module consumes only 12.4 $\mu$W while idle listening, and that employing this Bloom-filter-based approach eliminates 99.95 % of power consumption in our application scenarios.**

## I. Introduction

Toward realizing ubiquitous computing environments, many wireless communication modules have emerged, including cellular phones, wireless LANs, Bluetooths, and ZigBees. These modules exchange a variety of data with each other. Wireless technology is enhancing the mobility of ubiquitous devices, but this mobility creates a power management problem because mobile devices do not have large power sources. To mitigate this power management problem, it is essential to reduce the power consumption of wireless communication.

The number of ubiquitous devices is increasing dramatically and wireless modules always need to listen for incoming packets from other devices. For example, a laptop PC, which weighs 802.11g, always has to listen for incoming packets from an access point. Consequently, wireless devices consume much power in idle listening. Achieving a low power consumption for idle listening is an important step towards realizing green IT.

Several studies have proposed wake-up wireless communication technologies that drastically reduce power consumption in idle listening [1], [2]. Wake-up wireless communication consists of two wireless modules: a wake-up module and a data communication module.

All wireless modules exchange wake-up packets prior to data communication. A data communication module consumes little power when it is in sleep mode. Wake-up modules can listen for wake-up packets with energy consumptions as low as several tens of microwatts because they are designed to receive only wake-up packets. The wake-up module of a receiver node listens for a wake-up packet at the beginning of a data communication. When the receiver receives a wake-up packet, the wake-up module wakes the data communication module, and the sender node starts transmitting data packets. After the communication has finished, the data communication module returns to sleep mode.

Previous studies of wake-up wireless communication focus on the implementation of a wake-up module [1] or its application to a Voice-Over-IP phone that uses Wi-Fi [2]. Pletcher et al. implemented a wake-up wireless module that consumes 52 $\mu$W when idle listening [1]. Shih et al. implemented a "wake-on-wireless" system for Voice-Over-IP that uses Wi-Fi [2]. They used a low-power wireless module, TR1000, which uses the 915 MHz ISM band and consumes 7 mW when receiving packets. These two studies demonstrate the potential of wake-up wireless communication. In this study, we extend these previous studies by assuming that all Wireless Personal Area Network (WPAN) communication is realized using wake-up wireless communication. Consider 200 Wi-Fi adapters on students' PCs in a classroom, which actively scan every 30 seconds to locate base stations. Wake-up packets for active scanning have to wake multiple unknown access points. If we use a broadcast address to wake the access points, the wake-up packets wake not only the access points but also the Wi-Fi adapters on the other students' PCs, so that the PCs consume energy unnecessarily. We thus require a wake-up module that wakes only specified nodes.

Such a wake-up module needs to rapidly and correctly wake the target nodes, but it is allowed to wake few non-target nodes. The wake-up module should consume little power. This limitation on the power consumption places constraints on hardware resources, such as the number of transistors.

In this paper, we propose a novel ID matching mechanism, which uses a Bloom filter [17], for wake-up wireless communication. We designed and implemented a wake-up communication module that uses the ID matching mechanism and evaluated its performance using a circuit simulator (HSPICE [10]) and a logic simulator (Verilog-XL [12]). The simulation results reveal that the wake-up communication module only consumes 12.4 $\mu$W during idle listening. This paper also proposes an ID space design that uses a Bloom filter for the wake-up protocol. The Bloom filter is a space-efficient probabilistic data structure that permits some false positives but does not permit any false negatives [17]. In the application scenarios that we consider, the Bloom filter based approach was found to reduce power consumption by 99.95 % compared to the power consumption when a Bloom filter is not used.

This paper is organized as follows. We describe the current

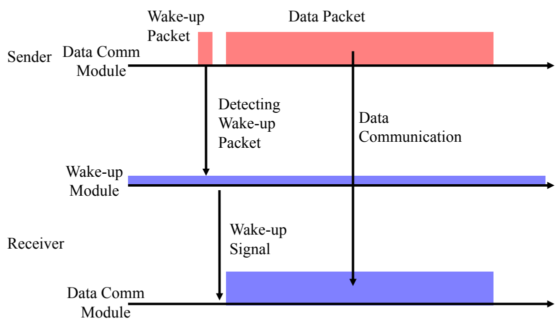


Fig. 1. A wake-up communication scheme

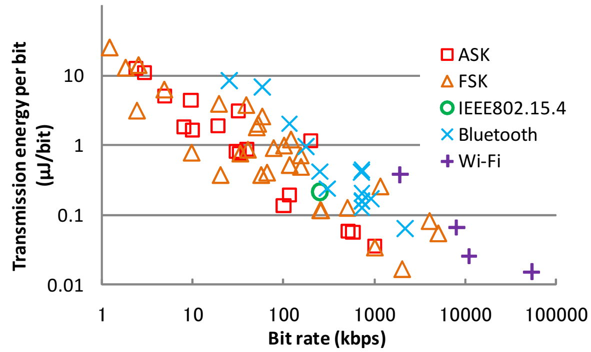


Fig. 2. Bit rate versus transmission energy per bit

state of wake-up wireless communication and the future direction of WPAN technology in Section II. We describe a design for the wake-up module and its ID matching mechanism in Section III and then evaluate them in Section IV. Finally, we summarize the study and present key conclusions in Section V.

## II. Motivation

### A. Wake-up Wireless Communication

Current short-range wireless modules consume most power in idle listening for receiving packets. To reduce the power consumption for energy-constrained applications (e.g., wireless sensor networks) many energy-efficient MAC protocols have been designed to reduce the idle listening time.

On the other hand, [1], [2] demonstrated that wake-up wireless communication can be used as a novel energy-efficient communication scheme. In the wake-up wireless communication paradigm, a wireless module consists of two receiver modules: a wake-up module and a data communication module. Wake-up modules consume little power in idle listening because they are designed to receive only wake-up packets.

Fig. 1 shows a simple overview of the wake-up communication paradigm. The wake-up wireless module expends only several tens of microwatts in idle listening, while the data communication module remains in sleep mode, thereby minimizing its energy consumption. When a sender node intends to send data to a receiver node, it sends a wake-up packet. When the receiver node receives the wake-up packet, the wake-up module on the receiver node wakes the data communication module so that it can receive data packets. Finally, the sender node sends a data packet, and the data communication module on the receiver node starts receiving the data packet. This wake-up wireless communication has different power consumption characteristics compared to those of the currently employed non-wake-up communication scheme, so that a new evaluation criterion is required for estimating energy consumption. Since the wake-up communication scheme consumes more energy in data communication mode than in idle listening, we focus on the power consumption during data communication, and evaluate the energy consumption in terms of the energy consumption per bit. To this end, we collected data from as many commercial wireless modules as possible and used it to determine approximate trends for the energy consumption per bit. The energy consumption of wireless modules may change with future developments in technology, nevertheless the measured trends should provide us with some indications about near-future wireless technology.

### B. Survey of Commercial Wireless Modules

We surveyed 670 commercial wireless modules fabricated by 64 companies and collected their specifications from their data sheets, including frequency, modulation, bit rate, and power consumption (during transmission and receiving). This data is downloadable from [3]. Using the extracted bit rates and power consumptions, we examined two trends: the *transmission energy per bit* and the *receiving energy per bit*.

We excluded modules from this survey that are not for short-range communication, such as wireless modules for satellite communication. In addition, it should be noted that the extracted data are based on published data from the manufacturers, and not on measured data.

Fig. 2 shows the bit rate as a function of the transmission energy per bit. The horizontal and vertical axes have logarithmic scales. When multiple modules have the same modulation and same bit rate, we plot only a single point for the module with the lowest power consumption. A 54 Mbps wireless module for Wi-Fi wireless module has the lowest transmission energy per bit (0.015 $\mu$J/bit). The plot shows that the higher bit rate modules tend to consume less energy per bit. The receiving energy also exhibits the same trend. The lowest receiving energy per bit is 0.014 $\mu$J/bit.

The above results demonstrate that complicated modulation (i.e., high-bit-rate wireless modulation) is advantageous in terms of the energy per bit. The reason for this is as follows. The energy consumption of a front-end circuit in a wireless module is large and does not depend on the bit rate. Baseband circuits are more energy-efficient than front-end circuits, because baseband circuits consist of digital circuits, whereas front-end circuits consist of analog circuit such as RF amplifiers and IF mixers.

From this discussion, higher bit rate wireless modules offer more energy-efficient communication in the wake-up wireless communication paradigm. The result suggests the possibility of integrating high bit rate wireless networks (e.g., Wi-Fi) and energy-efficient wireless networks (e.g., wireless sensor networks).

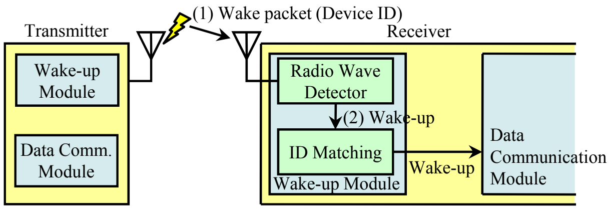


Fig. 3. Two-step wake-up wireless communication

TABLE I
PHYSICAL LAYER PARAMETERS OF WAKE-UP CHANNEL

| | |
|---|---|
| Frequency | 950 MHz |
| Modulation | 90%ASK |
| Baud rate | $\geq$ 40 kBaud |
| Coding | Manchester code |

## III. DESIGN

Our wake-up module realizes a selective wake-up mechanism that reduces the idle listening power.

Fig. 3 shows an overview of the wireless communication wake-up mechanism. The wake-up wireless communication system consists of two RF modules: a wake-up module and a data communication module. The wake-up process consists of two steps: the radio wave detector wakes the ID matching circuit, and the ID matching circuit then wakes the data communication module. This two-step wake-up process reduces the power consumption of idle listening. The radio wave detector listens for an incoming wake-up packet. When a sender node sends a wake-up packet, the radio wave detector wakes the ID matching circuit. The ID matching circuit achieves selective wake-up by extracting the ID from the wake-up packet and comparing that ID with its own ID. If the IDs match, the wake-up module wakes the data communication module. Finally, the sender node transmits data packets, and the data communication module of the receiver node receives the data packets. The data communication module is a general wireless module such as a Wi-Fi.

Details of the wake-up module and the ID matching mechanism are given in the following section.

### A. Wake-up module

*1) Circuit Design:* TABLE I shows the physical layer parameters of the wake-up channel. The wake-up module uses the 950 MHz band because of a communication distance of several meters is required. The UHF band, in which 950 MHz is located, has relatively low loss, enabling longer communication distances than other frequencies for the same power consumption. To reduce power consumption, the wake-up module uses ASK modulation to simplify the demodulation circuit. Since the wake-up channel does not need to send much data, the wake-up module communicates at a baud rate of 40 kBaud (this baud rate is referred to as the 915 MHz band rate in IEEE 802.15.4). The payload of the wake-up packet is coded with Manchester code because the wake-up module can communicate without a high-precision clock generator, which consumes a lot of power.

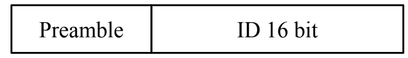


Fig. 4. Frame structure of a wake-up packet

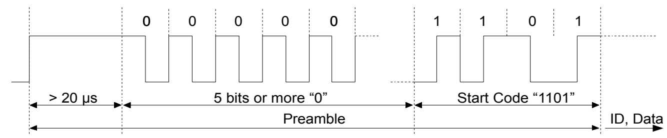


Fig. 5. Details of the preamble

*2) Frame format:* Fig. 4 shows the frame structure of a wake-up packet. The frame is composed of a preamble for bit synchronization and an ID for waking nodes.

Fig. 5 shows the details of the preamble. The top of the preamble is not modulated and is more than 20 $\mu$s long. Not modulating the preamble improves the detection sensitivity, because this allows the radio wave detector to store some energy from the preamble. Following this non-modulated preamble, there are five or more modulated bits of 0 and a start code. The wake-up module uses four modulated bits of 0 for extracting the bit cycle, and uses the last bit for edge synchronization. The bit cycle is derived from the average of the four bits. The start code is the sequence "1101", which indicates the start of a payload frame.

*3) Hardware:* We implemented a wake-up module using the CMOS LSI 0.18 $\mu$m process rule. The supply voltage is 1.8 V, which is the same as the low-voltage technology, TSMC 0.18 $\mu$m. We referred to Refs. [4], [5], [6], [7], [8], [9] for this implementation.

Fig. 6 shows the inside composition of the wake-up module. The wake-up module consists of an analog circuit and a digital circuit. Fig. 7 shows the analog circuit. There are 29 transistors in the analog circuit for the radio wave detector, 20 for the power controller, 19 for the demodulator, 14 for the clock generator, and 5 for the resetter. The digital circuit consists of a bit receiver, a shift register, and an ID matching circuit.

The operation of the wake-up module is as follows. (1) During idle listening, the wake-up module senses a carrier with the radio wave detector, and turns off the data receiver with the power controller. When a sender device sends a wake-up packet, (2) the receiver device detects the carrier and turns

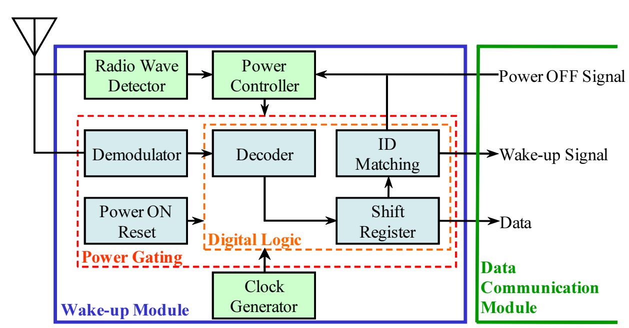


Fig. 6. Hardware organization of the wake-up module

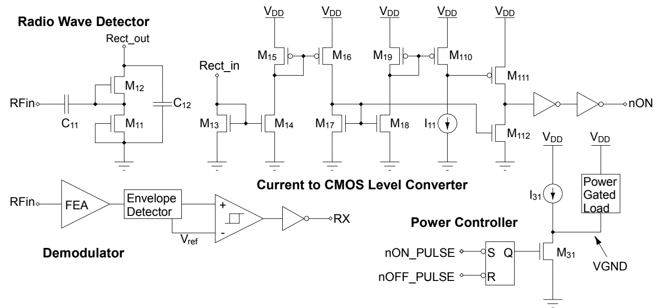


Fig. 7. Analog circuit of the wake-up module

on the demodulator, the bit receiver, the shift register, and the ID matching circuit. (3) The device then demodulates and decodes the wake-up packet, and stores the ID in the shift register. After data reception is complete, (4) the ID matching circuit compares the received ID with the preset ID. If the two IDs match, the circuit wakes up the data communication module with a wake-up signal. After receiving data, (5) the data communication module turns off the demodulator, the bit receiver, the shift register, the ID matching circuit, and itself. (4') If the IDs do not match, the wake-up module turns off the demodulator, the bit receiver, the shift register, and the ID matching circuit.

### B. ID matching mechanism

The ID matching mechanism needs to satisfy the following requirements:

1) have a small circuit size
2) perform selective wake-up
3) reject false negatives
4) accept false positives

A small circuit size is necessary for ensuring a low power consumption since if the ID matching mechanism has a large circuit, it will consume a lot of power. Since we desire the wake-up module have a power consumption of several tens of microwatts, the ID matching mechanism has to be implemented using a simple circuit.

Selective wake-up is necessary for when a sender node needs to wake multiple receiver nodes. Consider 200 Wi-Fi adaptors on students' PCs in a classroom, which actively scan every 30 seconds to locate base stations. Wake-up packets for active scanning have to wake multiple unknown access points. If we use a broadcast address to wake the access points, the wake up packets wake not only the access points but also the Wi-Fi adapters on the other students' PCs, so that the PCs consume energy unnecessarily.

the rejection of false positives and the acceptance of false negatives are necessary to achieve wake-up wireless communication. If the sender node is unable to wake a receiver node (i.e., a false negative), it causes a problem for services since the receiver will be unaware of the sender node if it is not woken up. However, if a sender node wakes a non-receiver node by error (i.e., a false positive), it causes no problems for services, although the non-receiver node does consume a little energy.

TABLE II
SIMULATION ENVIRONMENT

| | | |
|---|---|---|
| Analog | Circuit simulator | HSPICE [10] |
| | MOSFET device model | BPTM 180 nm [11] |
| Digital | Logic simulator | Verilog-XL [12] |
| | Logic synthesis tool | Design Compiler [13] |
| | Standard cell library | GreePDK OSU Library TSMC 0.18 $\mu$m [14] |

To achieve selective wake-up, we propose a novel ID matching mechanism that employs a Bloom filter [17]. The Bloom filter was first proposed by B. H. Bloom and is a space-efficient probabilistic data structure that is used to test whether an element is a member of a set [17]. This testing feature satisfies the requirement of selective wake-up. The ID matching mechanism can also be implemented with a simple circuit with a Bloom filter; the query process only uses an AND circuit. Additionally, a Bloom filter permits some false positives, but does not permit false negatives, thus satisfying the above requirements for the ID matching mechanism.

We assume arbitrary agencies uniquely assign service IDs for devices, services (e.g., base stations for wireless LAN, communication with portable video game consoles), groups such as a synchronized control system, routes on sensor networks, etc. The Bloom filter on the wake-up module has 16 bits (i.e., $m = 16$). When a new service ID is added to the Bloom filter, the service ID is feed to two hash functions to obtain two array positions ($k = 2$). The node sets the bits at all these positions to 1. We assume that each node has less than three service IDs ($n \leq 3$). Therefore, we can calculate the false positive probability $p$ as follows:

$$p = (1 - e^{-kn/m})^k = 0.0138,$$

where $m$ ($= 16$) is the number of bits in the Bloom filter, $n$ ($= 1$) is the number of elements of the Bloom filter, and $k$ ($= 2$) is the number of hash functions [18]. The result of 0.0138 indicates that false positives rarely occur.

## IV. EVALUATION

### A. Wake-up module

We evaluate the wake-up module described in Section III by performing simulations. TABLE II shows the simulation environment. We use HSPICE [10] for the circuit simulator and BPTM 180 nm [11] for the MOSFET device model on the analog circuit. We also use Verilog-XL [12] for the logic simulator, Design Compiler [13] for the logic synthesis tool and GreePDK OSU Library TSMC 0.18 $\mu$m [14] for the standard cell library on the digital circuit.

We determine the idle listening power and maximum transmission range. In idle listening, the data communication module and the digital circuit are turned off. Only the analog circuit consumes 12.4 $\mu$W in idle listening. This is almost the same level as the self-discharge from a 1000 mAh, 1.2 V nickel-metal hydride battery. In idle listening, the wake-up module consumes approximately $1/2300$ the energy of a CC1000, which is a low-power RF transceiver [15]. Thus, the wake-up module consumes very little energy.

TABLE III
POWER CONSUMPTION PER MODULE AND TRAFFIC

| | Wake-up OFF | Wake-up ON | | Traffic |
|---|---|---|---|---|
| | | BF OFF | BF ON | |
| Case 1 | 907.5 mW | 0.013 mW | | 0.780 kbps |
| Case 2 | 907.5 mW | 26.3 mW | 0.016 mW | 0.384 kbps |
| Case 3 | 907.5 mW | 60.5 mW | 0.020 mW | 0.853 kbps |

We evaluate the communication range of the wake-up module at a transmission power of $P_t = 10$ mW. To calculate the propagating radio attenuation, we estimate the power received at a distance $r$ using the Friis equation:

$$P_r = \frac{1}{2}\left(\frac{c}{4\pi f_c r}\right)^2 G_r G_t P_t,$$

where $c$ is the speed of light, $f_c$ is the frequency, $G_r$ is the gain of a receiver antenna, $G_t$ is the gain of a transmitter antenna, and $1/2$ is the radio attenuation in the impedance matching circuit of the receiver. The maximum transmission range is defined as the transmission length at which the receiver acquires the minimum receiving power. We estimate to be $r = 3.9$ m, when $P_r = -36.9$ dBm, $f_c = 950$ MHz, and $G_r = G_t = 0$ dBi. If we apply some circuit techniques such as [7], the maximum transmission range can be extended up to 10 m.

### B. ID matching mechanism

We evaluate how much the ID matching mechanism can reduce the energy consumption. This simulation is based on the wake-up module described in Section III and the simulation results in Section IV-A for a bit rate of 40 kbps, a power consumption in idle listening of 12.4 $\mu$W, an power consumption when receiving the ID of 368.1 $\mu$W. We assume that the data communication module is IEEE802.11g WLRG-RA-DP101 [16], which consumes 907.5 mW when receiving data.

In this simulation, we compare three wireless settings: not using the wake-up mechanism (Wake-up OFF), using the wake-up mechanism without a Bloom filter (Wake-up ON/BF OFF), and using the wake-up mechanism with a Bloom filter (Wake-up ON/BF ON). All wake-up modules sleep again 10 ms after completing data transmission.

We evaluate the settings for the following three cases:

Case1 60 nodes on a sensor network transmit sensor data to the next node every 10 seconds.

Case2 There are 30 portable video game consoles and one mobile router in a train, and all game players search for each other every 10 seconds.

Case3 200 Wi-Fi on students' PCs in a classroom actively scan base stations every 30 seconds.

TABLE III shows the results. In case 1, the wake-up mechanism reduces power consumption by a factor of $1/70000$ compared to not using the wake-up mechanism. There is no difference between the wake-up mechanism with a Bloom filter and the wake-up mechanism without a Bloom filter, because each sensor node has only one destination node. In cases 2 and 3, the wake-up mechanism without a Bloom filter consumes 1600 to 3000 times more energy than the wake-up mechanism with a Bloom filter, because the Bloom filter enables the nodes to wake only the required nodes. All wake-up packet traffic is sufficiently smaller than 40 kbps, which is the bit rate of the wake-up module. These results demonstrate that the ID matching mechanism with a Bloom filter drastically reduces the power consumption compared to when the wake-up mechanism is not used and when the wake-up mechanism is used without a Bloom filter.

## V. CONCLUSION

In this paper, we have proposed a novel ID matching mechanism with a Bloom filter for wake-up wireless communication, which is a mechanism for reducing energy consumption in idle listening. We demonstrate the effectiveness of the proposed mechanism by simulation. The results show that our proposed mechanism reduces power consumption by a factor of $1/70000$ compared to currently used Wi-Fi. The next step is to implement the new wake-up module and to evaluate the wake-up module in actual environments.

## REFERENCES


[1] N. M. Pletcher, S. Gambini and J. M. Rabaey, "A 2GHz 52$\mu$W wake-up receiver with -72dBm sensitivity using uncertain-IF architecture", IEEE International Solid-State Circuits Conference, pp. 524, 525, 633, 2008.

[2] E. Shih, P. Bahl and M. J. Sinclair, "Wake on wireless: an event driven saving strategy for battery operated devices", International Conference on Mobile Computing and Networking, pp. 160-171, 2002.

[3] T. Takiguchi, "A survey on power consumption of wireless modules", http://www.mlab.t.u-tokyo.ac.jp/~takiguchi/public/greencomm09.xls, 2008.

[4] T. Umeda, H. Yoshida, S. Sekine, Y. Fujita, T. Suzuki and S. Otaka, "A 950-MHz rectifier circuit for sensor network tag with 10-m distance", IEEE Journal of Solid-State Circuits, pp. 35-41, 2006.

[5] J. F. Dickson, "On-chip high-voltage generation in mnos integrated circuits using an improved voltage multiplier technique", IEEE Journal of Solid-State Circuits, pp. 347-378, 1976.

[6] T. Umeda and S. Otaka, "ECO chip: energy consumption zeroize chip with a 953MHz high-sensitivity radio wave detector for standby mode applications", IEEE 2007 Custom Integrated Circuits Conference, pp. 663-666, 2007.

[7] N. M. Pletcher, S. Gambini and J. M. Rabaey, "A 65$\mu$W, 1.9GHz RF to digital baseband wakeup receiver for wireless sensor nodes", IEEE 2007 Custom Integrated Circuits Conference, pp. 539-542, 2007.

[8] R. G. Meyer, "Low-power monolithic RF peak detector analysis", IEEE Journal of Solid-State Circuits, pp. 65-67, 2007.

[9] H. W. Chen and W. C. Yen, "A low power and fast wake up circuit", International Symposium on Circuits and Systems, pp. II-293-II-296, 2004.

[10] Synopsys, "HSPICE", http://www.synopsys.co.jp/products/HSPICE/detail.html.

[11] U. Berkeley, "Berkley predictive technology model", http://www.eas.asu.edu/~ptm/.

[12] Cadence, "Verilog HDL simulator: Verilog-XL".

[13] Synopsys, "Design compiler ultra", http://www.synopsys.com/products/logic/dc_ultra_ds.html.

[14] O. S. University, "FreePDK (An open-source variation-aware design kit) OSU library", http://vcag.ecen.okstate.edu/projects/scells/.

[15] Texas Instruments, "Single-chip very low power RF transceiver for 315/433/868/915 MHz SRD band", http://focus.ti.com/docs/prod/folders/print/cc1000.html.

[16] QUATECHC"Airborne 802.11 embedded radio modules"C http://www.dpactech.com/docs/wireless_products/ab_radio.pdf.

[17] B. H. Bloom, "Space/time trade-offs in hash coding with allowable errors", Communications of the ACM, pp. 422-426, 1970.

[18] A. Broder and M. Mitzenmacher, "Network applications of Bloom filters: a survey", Internet Mathematics, Vol. 1, No. 4, pp. 485–509, 2005.