Article

A Long-Range Directional Wake-Up Radio for Wireless Mobile Networks [†]

Wen-Chan Shih [1,*]**, Raja Jurdak** [2]**, David Abbott** [3]**, Pai H. Chou** [4] **and Wen-Tsuen Chen** [1]

[1] Institute of Information Science, Academia Sinica, 115 Taipei, Taiwan;
E-Mail: teddyshihau@gmail.com; chenwt@iis.sinica.edu.tw

[2] Commonwealth Scientific and Industrial Research Organisation, Pullenvale, 4069 QLD, Australia;
E-Mail: Raja.Jurdak@csiro.au

[3] Commonwealth Scientific and Industrial Research Organisation, Marsfield, 2122 NSW, Australia;
E-Mail: David.A.Abbott@csiro.au

[4] Department of Computer Science, University of California, Irvine, 92697-2625 CA, USA;
E-Mail: phchou@uci.edu

[†] This paper is an extended version of our paper published in Shih, W.C.; Jurdak, R.; Lee, B.-H.;
Abbott, D. Improving the throughput of sensor network wakeup radios using block orthogonal codes.
In Proceedings of the Annual International Conference on Mobile Communications, Networking and
Applications (MobiCONA), Singapore, 2011.

[*] Author to whom correspondence should be addressed; E-Mail: teddyshihau@gmail.com;
Tel.: +886-2-2788-3799; Fax: +886-2-2782-4814.

Academic Editors: Sunil Kumar, Fei Hu and Michael Medley

Abstract: This paper describes a long-range directional wake-up radio (LDWuR) for wireless mobile networks. In contrast to most wake-up radios (WuR) to date, which are short range, ours is applicable to long-range deployments. Existing studies achieve long distance by using modulation and coding schemes or by directional antennas, though the latter require exploring the direction of the transmitter. To address this issue, our LDWuR adopts both static and dynamic antennas, where the static ones are directional, while the dynamic ones are omnidirectional for beamforming. We present our LDWuR prototype and design principle. Simulation results show that our LDWuR and event-driven MAC protocol suppress the idle-listening of Wi-Fi stations in a wireless network, thereby enhancing the Wi-Fi power savings.

1. Introduction

Long-range directional wake-up radios (LDWuR) can be an important technology for reducing the energy consumption of nodes and improving the communication range in wireless mobile networks. For nodes that must keep their radios on for accepting incoming commands or packet relaying, idle listening can dominate the total energy consumption of the sensor nodes. Although low-power listening MAC protocols have been proposed to reduce idle-listening energy by duty cycling the receiver, they incur long wake-up latency, while the energy consumption is still lower-bounded by the duty cycle. WuRs represent a promising solution to completely eliminating the idle listening cost and significantly extending their lifetime.

We illustrate LDWuR through three examples. Clemson's Intelligent River project [1] deploys sensor nodes along the 312-mile Savannah River from the headwaters in North Carolina to the port in Savannah in a large scale. The sensor network provides real-time data on water quality and quantity. The sensor data are important for improving water resources management regarding drinking water and industrial pollutants. The other example is the IBM smart water project [2], which distributes a sensor network along the 315 miles of the Hudson River to collect and analyze data continuously and in real time. Another example is the flying fox tracking project [3], where a resourceful base node needs to communicate with resource-constrained collar nodes on demand with the maximum possible range. These applications exemplify long-range sensor network deployments, which motivate us to take the long communication range into account.

To achieve a long communication range of the WuR, we adopt directional antennas to extend communication distance by increasing the antenna gain. As existing low-power WuRs provide short-range communication, they adopt modulation and coding schemes to improve the distance by reducing the packet error rate (PER). However, they provide a limited improvement on the communication range. A directional antenna represents a promising solution that can bring an order of magnitude improvement to communication distance. A directional antenna focuses the radiation beam in one direction to bring more antenna gain. We take advantage of direction antennas to make long-range communication practical.

The challenge with adopting directional antennas is to search the direction in which the transmitter locates. As the directional antenna focuses the radiation beam in one direction, the transmitter might not lie in the same direction. This incurs the overhead of a motor to rotate the antenna in all directions [4]. To address this, our proposed LDWuR adopts static and dynamic strategies. A static strategy means that the LDWuR uses multiple directional antennas in different directions. A dynamic strategy means that the LDWuR uses multiple omnidirectional antennas that cooperate to form beams in different directions. To evaluate our LDWuR and strategies, we design a MAC protocol and system model to investigate salient characteristics in terms of total power consumption and latency. We design an active LDWuR. Our design is a battery-powered radio. It employs the same battery with the node's data radio. For a long-range communication application in wireless mobile networks, the requirements of WuR are

two-fold. First, we adopt high-gain directional antennas to enhance the communication range with the same power consumption. The characteristic of the directional antenna supports less interferences from other directions, which improves the wake-up signal and noise ratio. From the relationship of the power consumption and packet rate in Figure 7a, our design consumes about 0.0276 W with short data packets at a packet rate of one packet per second. Its power consumption is close to the existing work [5]. Our WuR design still needs to be optimized to reduce its power consumption further to compare with existing WuRs. That will be our future work. Second, our WuR adopts the minimum number of the antenna to explore and point the transmitter. For static antennas, we adopt four directions to cover the entire range. For dynamic antennas, we adopt three omnidirectional antennas that form a beam with about a 90° cover area. That is the minimum cost of extra antennas for a long-range communication application in wireless mobile networks.

Our contributions are as follows. First, we propose adopting directional antennas to enhance the communication range of an LDWuR for long-range applications. Second, we design two strategies to search the transmitter's location for extending the antenna's cover range. Third, we develop the system model and event-driven MAC protocol to evaluate the performance of our design in terms of total power consumption and latency.

The reminder of this paper is organized as follows. Section 2 surveys related literature. In Section 3, we introduce our proposed LDWuR and describe our strategies to explore the transmitter's direction. Then, we carry out a theoretical analysis of our system model and salient characteristics of the MAC protocol for two case studies. Section 4 presents the LDWuR hardware and design principle. Finally, we evaluate our design and event-driven MAC protocol through the case study of Wi-Fi power savings in Section 5.

2. Related Work

This section reviews existing WuRs' communication technologies and design metrics. WuRs have been proposed to improve PER and communication range for IoT and WSN applications. We review modulation, addressing, channel coding and beamforming techniques.

2.1. Modulation and Addressing

Some studies have explored solutions to improve the PER of WuRs through different modulation techniques, such as pulse-width modulation (PWM) [6] and pulse position modulation (PPM) [7], while other studies investigate address-coding schemes [8,9]. However, they achieve limited modulation gain and increase the power consumption by the longer wake-up sequence of 31 to 48 bits to maintain a probability of detection of 90%.

The address-coding scheme from the work [9] maintains the desired probabilities of detection (P_{det}) of 90% by increasing the bits of the wake-up sequence. The wake-up sequence consists of a pseudo-noise (PN) code sequence of length N. The PN code supports low correlation with other sequences, which avoids a false alarm (FA) from other communicating nodes or wake-up signals for neighbor nodes. To maintain a constant P_{det} of 90%, they adjust the correlator threshold and RF input power level. If N is 31 bits, the mean time between FAs is about 10 s at the given RF input power of -56 dBm and a constant

P_{det} of 90%. At the same condition, if N is seven or 15 bits, the mean time between FAs is about 0.1 s. Therefore, increasing the bits of the wake-up sequence reduces FAs in a certain time.

2.2. Channel Coding

Some existing studies propose a variety of channel coding and forward error correction (FEC) methods to improve bit error rate (BER) and PER for wireless and optical communication. Proakis *et al*. [10] proposed the Hadamard codes as a way to improve the probability of bit error over block orthogonal code on a Rayleigh fading channel with a bandwidth constraint. The Hadamard code achieves better performance than the block orthogonal code does at the cost of an increase in decoding complexity. Djordjevic *et al*. [11] proposed two novel classes of optical orthogonal code (OOC) for synchronous and asynchronous incoherent optical CDMA (OCDMA). The proposed OOC scales well with the number of users. Faruque [12] proposed the error control coding using orthogonal codes. From bandwidth efficiency analysis, a specific length of orthogonal codes mentioned by the author provides an error correction scheme without bandwidth expansion by partitioning data into blocks at the expense of complexity. The same author [13] later proposed orthogonal on-off keying (OOOK) for free-space laser communication. A block of data is mapped into a block of bi-orthogonal code, which provides the error correction capability through a correlation process. However, these designs do not consider the sensitivity, power consumption and latency. Pursley *et al*. [14] explored increased interference rejection capability for channels with multiple access or multipath interference. From the results, the 64-ary orthogonal modulation shows better performance than binary phase-shift keying (BPSK) does for the turbo product code at a rate of 0.793 at PER comparison. However, the use of orthogonal modulation and turbo product code increases the implementation complexity. All of the above studies are for wireless communication in general, but are not specific to WuRs. The generality increases implementation complexity and may be impractical for WuRs.

2.3. Beamforming

Several studies have been proposed to optimize beamforming vectors and power configurations [15–18] for improvement of the information and energy transfer. However, they do not take WuRs into account. The most relevant work is by Trösch *et al*. [19]. They take advantage of multiple ultra-wideband impulse radios (UWB-IR) statically mounted on the wall forming a circle that cover all semi-active sensor nodes inside. Multiple UWB-IRs create the beamforming to trigger the wake-up detector of a semi-active sensor node. However, they do not consider the scenario of mobile UWB-IRs and sensor nodes.

2.4. Wi-Fi Power Savings

Hiroyuki Yomo *et al*. [5] designed a WuR mainly to save the power of idle Wi-Fi access points. However, they do not take power savings of the station side into account. Oller *et al*. [20] proposed an IEEE 802.11-enabled device as the WuR transmitter and the low-power WuR receiver. However, the WuR receiver supports the limited sensitivity and communication range. For energy-constrained

station-side and long-range communication, we propose our Wi-Fi MAC protocol and strategies to save power on energy-constrained devices, such as mobile phones, tablets, laptops, *etc*.

This work is an extended work based on our previous design [21] for long-range communication scenario in wireless mobile networks. Previous work adopts an omnidirectional antenna that supports less antenna gain than a directional antenna. Using an omnidirectional antenna, one can receive interferences from all directions. However, previous works cannot support a longer range and less interference for wireless mobile networks.

The main contributions of this paper are three-fold. First, we enhance the communication range of our WuR by directional antennas or beamforming. Second, WuRs collaboratively detect the transmitter's location and receive the wake-up signal sending from the transmitter by static or dynamic strategies without receiving interferences from other directions. Third, we propose the MAC protocol for Wi-Fi power savings. To our knowledge, no research exists addressing WuRs and beamforming for wireless mobile networks.

3. Theoretical Analysis

We first present the system model analysis to determine the block orthogonal code's PER , throughput, power consumption and latency. Second, we analyze two strategies to detect the transmitter's direction for mobile networks in the case study. Third, we propose the MAC protocol based on our LDWuR to enhance Wi-Fi power savings in the other case study.

3.1. System Model

The system is modeled as the transmitter transmitting the input signal *X* of block orthogonal codes through an additive white Gaussian noise (AWGN) channel and the receiver receiving the signal *Y*. One purpose of the model is to find the symbol error probability of the block orthogonal codes. From the symbol error probability, we find the packet error probability of the block orthogonal codes (Section 3.2) and compare it with existing schemes. The received signal *Y* through the AWGN channel is given by:

$$Y(i) = \max\{\beta X(i) \otimes S_{pattern}^{ideal}(\tau - i)\} \tag{1}$$

where β is the attenuation from the AWGN channel with a Gaussian distribution, $S_{pattern}^{ideal}$ is the ideal pattern of the block orthogonal codes' symbols for data bit zero and one , τ is the correlation time period and $\otimes$ is the correlation operation.

The block orthogonal codes use chips per symbol (N_{cps}) and oversampling factor (N_{os}) to suppress noise. The N_{os} reduces the noise variance (noise power) by a factor of $1/N_{os}$. The block orthogonal code can be represented as the *M*-ary block orthogonal codes $O(N_{cps}, k)$ with diversity $L = N_{cps}/M$, where $M = 2^k$, and N_{cps} is the number of chips per symbol.

The average signal-to-noise ratio per chip, SNR_c, is given by:

$$SNR_c = \frac{k}{L}SNR_b N_{os} = \frac{kMN_{os}SNR_b}{N_{cps}} \tag{2}$$

where SNR_b is the signal-to-noise ratio per bit. The symbol (code word) error probability, p_{es}^{orth} for *M*-ary block orthogonal signaling is given by:

$$p_{es}^{orth} = 1 - \sum_{i=0}^{N_{cc}} \binom{N_{cps}}{i} p_{ec}^{ook^i} (1 - p_{ec}^{ook})^{(N_{cps}-i)} \tag{3}$$

where N_{cc} is the number of chips that can be corrected by *M*-ary block orthogonal signaling:

$$N_{cc} = \left\lfloor \frac{d_{min}-1}{2} \right\rfloor = \left\lfloor \frac{N_{cps}}{M} - \frac{1}{2} \right\rfloor \tag{4}$$

The minimum Hamming distance d_{min}, with diversity *L*, is given by:

$$d_{min} = 2L = 2\frac{N_{cps}}{M} \tag{5}$$

the chip error probability of coherent OOK modulation, p_{ec}^{ook}, through a matched filter is given by [22]:

$$p_{ec}^{ook} = Q(\sqrt{\text{SNR}_c}) \tag{6}$$

The value of SNR_c is given by:

$$\text{SNR}_c = \frac{kMN_{os}\text{SNR}B_s}{N_{cps}R} \tag{7}$$

3.2. Symbol Error Rate and Packet Error Rate

To compare the block orthogonal codes with other schemes, we analyze the packet error probability from Equation (3). The packet error probability of the block orthogonal codes, p_{ep}^{orth}, is given by:

$$p_{ep}^{orth} = 1 - (1 - p_{es}^{orth})^{L_{wurp}/k} \tag{8}$$

where L_{wurp} denotes the wake-up packet length in bits. To explore the performance of the varying modulation and encoding schemes, we analyze their symbol error rate (SER) and PER. For PWM modulation, we use the BER in [6]. In terms of other encoding schemes, we apply the system model in [23] to analyze their SER and PER. The relation between the symbol error probability, p_{es}^{ook}, and bit error probability, p_{eb}^{ook}, of binary coherent OOK modulation through a matched filter is given by:

$$p_{es}^{ook} = p_{eb}^{ook} = Q(\sqrt{\text{SNR}_b}) = Q\left(\sqrt{\frac{\text{SNR}B_s}{R}}\right) \tag{9}$$

The packet error probability of OOK modulation with 8B10B coding, p_{ep}^{8B10B}, is given by:

$$p_{ep}^{8B10B} = 1 - (1 - p_{es}^{ook})^{1.25L_{wurp}} \tag{10}$$

The packet error probability of OOK modulation with Hamming $(7,4)$ code, p_{ep}^{h74}, that can detect and correct one error is given by:

$$p_{ep}^{h74} = 1 - ((1 - p_{es}^{ook})^7 + 7p_{es}^{ook}(1 - p_{es}^{ook})^6)^{\frac{L_{wurp}}{4}} \tag{11}$$

3.3. Throughput

For a performance comparison of the block orthogonal codes with other modulation schemes and encodings, we will now analyze the respective throughputs. Reducing PER by channel coding can enhance the throughput of WuR. Lower PER of WuR can receive more successful wake-up packets. This means that WuR has a higher throughput. Therefore, the wake-up time can be shorter. In other words, the WuR can receive more information in a certain time. The PER of WuR is caused by false wake-ups and missed wake-ups.

To clarify the false wake-ups or missed wake-ups, we define true positive, false positive, true negative and false negative for WuR. Positive means the WuR receives the wake-up signal. Negative means the WuR does not receive the wake-up signal. True positive means that the transmitter sends a wake-up signal and the WuR receives a wake-up signal. False positive means that the transmitter does not send a wake-up signal and the WuR receives any other wake-up signal, also called a false alarm or false wake-ups. True negative means that the transmitter does not send a wake-up signal and the WuR does not receive a wake-up signal. False negative means that the transmitter sends a wake-up signal and the WuR does not receive any wake-up signal, also called a miss detection or missed wake-ups. The false wake-ups and missed wake-ups lead to the PER of WuR. They are discussed in cases 1a and 1b of previous work, respectively [24].

We assume the system bandwidth as the noise bandwidth B_s, that the wake-up packet length is L_{wurp} bits, that the transmitter sends L_{packet} wake-up packets and that the packet reception rate (PRR) of the WuR is given by:

$$\text{PRR}_{wur} = 1 - p_{ep} \tag{12}$$

where PRR_{wur} is the WuR's PRR and p_{ep} is the WuR's packet error probability with varying modulation types and encodings. The throughput S_{wur} is given by:

$$S_{wur} = \frac{\text{PRR}_{wur} B_s}{L_{packet} L_{wurp}} \tag{13}$$

3.4. Power Consumption

Our approach to evaluating power consumption for the purpose of comparing WuRs is to analyze how effectively they implement the given wake-up protocol [24] in terms of total power consumption and latency. The wake-up protocol as illustrated in Figure 1 will show that the PER is an important metric. We find the optimal preamble time T_{pre}^{opt} to achieve the minimum power consumption through a single-hop network with neighbors.

We assume the number of WuRs N_{wur} to be the number of neighbor nodes N_n. The optimal preamble time duration, T_{pre}^{opt}, is given by [24]:

$$T_{pre}^{opt} = \sqrt{\frac{P_{wur} T_{wurp} N_{wur}}{((V_{ccd} I_{td}) + \frac{N_{wur} P_{wur}}{2}) \text{PR} E[N_{tx}]}} \tag{14}$$

where T_{pre}^{opt} includes consecutive wake-up packets to the receiver's WuR , P_{wur} is the WuR's power consumption, $V_{ccd} I_{td}$ is the data radio's transmission power, PR is the packet rate, $E[N_{tx}]$ is the expected transmission time and T_{wurp} is the wake-up packet's time duration.
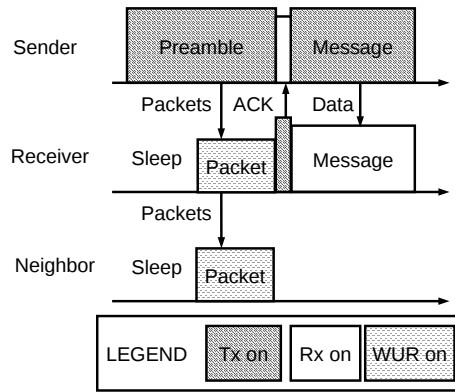
Figure 1. Wake-up protocol.

The total power consumption, P_t, is given by [24]:

$$P_t = (q_1 P_1 + q_2 P_2 + q_3 P_3) E[N_{tx}] + P_{idle} \tag{15}$$

where q_1, q_2, q_3 represent the probabilities of three cases: WuR with packet error, data radio with packet error and WuR and data radio both with all correct packets, respectively. P_1, P_2, P_3 represent the respective power consumption, and P_{idle} is the idle listening power consumption.

Equation (15) shows that the high PER_{wur} will have more expected transmission times $E[N_{tx}]$, then P_t will increase. Higher PER WuRs will increase power consumption significantly, as they have more $E[N_{tx}]$ and wake-up packet retransmissions Re_{tx}^{wur}. Moreover, they wake up the respective higher-power data radios.

3.5. Latency

To compare the latencies of existing WuRs, we implement the given wake-up protocol to determine the total latency instead of the component's propagation delay time in the WuR circuit. Therefore, the latency emphasizes the important metric PER again. Latency is defined as the time duration between transmission and successful reception of the WuR packet. The optimal preamble time period T_{pre}^{opt} for our wake-up protocol [24] is designed to achieve the lowest power dissipation for respective existing WuRs. Moreover, the T_{pre}^{opt} should at least include the eight symbols to represent the wake-up address of 16 bits for addressing 65,536 nodes.

We assume that latencies are the same when the false and successful wake-up signals occur. The WuR's total latency, T_t, is given by [24]:

$$T_t = E[N_{tx}](T_{pre}^{opt} + T_{msg}) \tag{16}$$

where T_{msg} is the message time duration. When the transmitter sends a message to the receiver's data radio, the receiver spends T_{msg} for receiving the message from the transmitter.

For low-power WuRs with a higher PER, they have larger $E[N_{tx}]$, as they require more Re_{tx}^{wur} of wake-up packets. Therefore, they increase the total latency significantly.

3.6. Case Study: Transmitter Localization by LDWuR for a Mobile Network

We propose two strategies to detect the transmitter's direction for mobile networks. One strategy is static antennas. The other strategy is dynamic antennas.

3.6.1. Static Antennas

The receiver adopts the number of LDWuRs in different directions. The receiver polls each LDWuR for each direction in turn to explore the transmitter's direction. The average total power consumption is the same as WuRs Equation (15) with a larger cover range. The average total power consumption, P_t^{sta}, is given by:

$$P_t^{sta} = \frac{\sum_{i=1}^{N_{dir}} P_t T_{scan}}{N_{dir} T_{scan}} = P_t \tag{17}$$

where T_{scan} represents the scan time for each direction and N_{dir} is the number of different directions, which means the number of LDWuRs. For example, the receiver adopts four LDWuRs in different directions, such as east, south, west and north. Equation (17) shows that LDWuRs consume the same power consumption to explore the transmitter's direction. Figure 2 shows that one of four LDWuRs scans the north direction with $90\,°$.
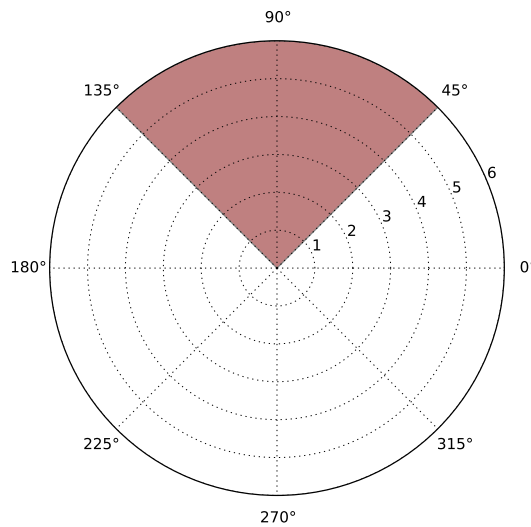

Figure 2. One of four long-range directional wake-up radios' (LDWuRs) scans the north direction.

The total latency is N_{dir} times the total latency of WuRs Equation (16), as the receiver spends more time on the scan of each direction. The total latency is given by:

$$T_t^{sta} = N_{dir} T_t \tag{18}$$

3.6.2. Dynamic Antennas

In this strategy, the receiver adopts multiple LDWuRs. Each LDWuR consists of a WuR built in an omnidirectional antenna. Multiple LDWuRs cooperate to steer a beam in different directions in turn. Therefore, the receiver can use a beam to detect the transmitter's direction.

The average total power consumption is the same as WuRs Equation (15) with a larger cover range. The average total power consumption, P_t^{dyn}, is given by:

$$P_t^{dyn} = \frac{\sum_{i=1}^{N_{dir}^{beam}} N_{ant}^{omn} \frac{1}{N_{ant}^{omn}} P_t T_{scan}^{beam}}{N_{dir}^{beam} T_{scan}^{beam}} = P_t \tag{19}$$

where T_{scan}^{beam} represents the scan time for each direction of beam, N_{ant}^{omn} is the number of omnidirectional antennas and N_{dir}^{beam} is the number of different directions of beams. For example, the receiver adopts three LDWuRs to cooperate to form a beam in different directions with a certain degree of cover range. Equation (19) shows that the receiver adopts N_{ant}^{omn} LDWuRs with N_{ant}^{omn} antennas of $1/N_{ant}^{omn}$ times power consumption to explore the transmitter's direction. Figure 3a shows that three LDWuRs cooperate to steer a beam in the south direction with a normalized spacing of five units, a related phase delay of seven units and beam pattern size of 90 ° at a normalized signal strength of 0.7. Figure 3b shows the beam pattern size and signal strength level of 0.7. Figure 3c shows the 3D beam pattern with the same parameters.
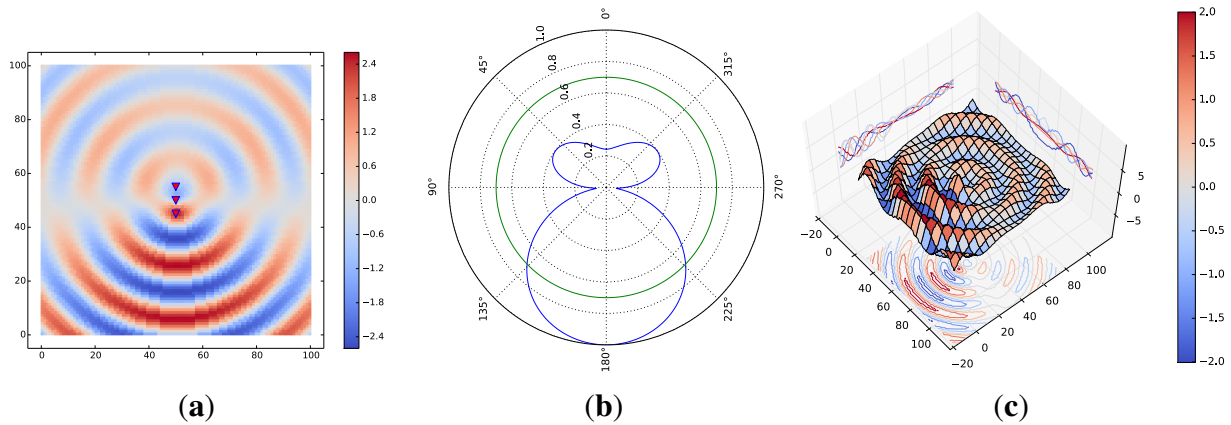

Figure 3. Three LDWuRs cooperate to form the beamforming. (**a**) 2D beam pattern; (**b**) beam pattern size; (**c**) 3D beam pattern.

The total latency is N_{dir}^{beam} times the total latency of WuRs Equation (16), as the receiver spends more time on the scans of each direction. The total latency is given by:

$$T_t^{dyn} = N_{dir}^{beam} T_t \tag{20}$$

3.7. Case Study: Wi-Fi Power Savings by LDWuR

To adopt our LDWuR for Wi-Fi power savings, we take advantage of the event-driven mechanism in the proposed LDWuR protocol. Figure 4 shows a block diagram of the proposed LDWuR for Wi-Fi

power savings. The access point sends a wake-up signal to the station. The station receives the wake-up signal and turns on the high-power Wi-Fi module.

Figure 5a shows a conventional MAC protocol. The station keeps an RF front-end on all of the time to ensure that the station can receive a beacon or data frames on time. This means that it induces a high-power consumption on idle listening for a beacon or data frames. Figure 5b shows the proposed MAC protocol. The station adopts low-power LDWuR to reduce the power consumption on receiving a beacon or data frames. The wake-up signal includes the station ID to wake up the receiver. Neighbors overhear the header of the beacon or data frames to determine whether to turn off the data radio immediately.
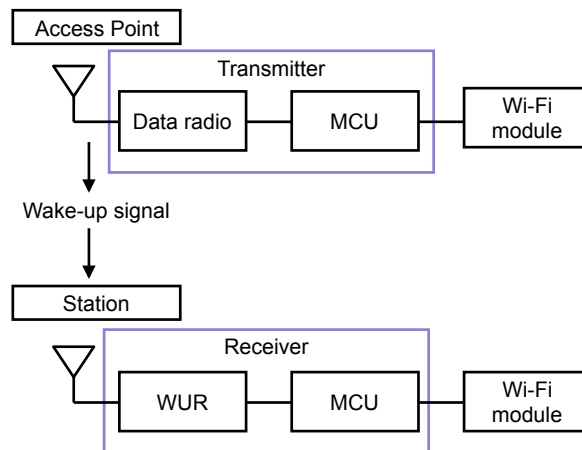

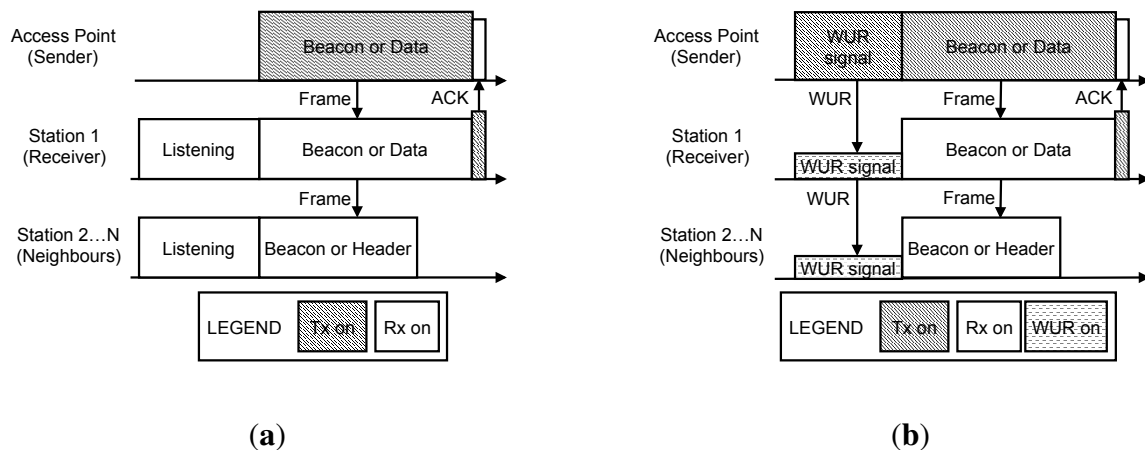**Figure 4.** Overview of LDWuR for Wi-Fi power savings.

(**a**)   (**b**)

Figure 5. Comparison of the proposed MAC protocol with a conventional MAC protocol. (**a**) Conventional MAC protocol; (**b**) proposed MAC protocol.

4. Hardware Design

This section describes the hardware circuit board and the design principle for our proposed LRWuR. To wake up the desired radio, the transmitter sends a wake-up signal in a packet that encodes the 16-bit

wake-up identification (ID) value and 24-bit additional out-of-band data for a total of 40 bits. If the wake-up ID matches the node ID, the wake-up radio sends an interrupt signal to wake up the receiving node's MCU. Then, the transmitter will send a message to the data radio. If the wake-up ID does not match the node ID, the receiving radio ignores the wake-up signal and waits for the next wake-up signal. Thus, the latencies are the same whether a false or successful wake-up signal is received.

Figure 6a shows the block diagram, while Figure 6b shows a photo of the prototype. The sender node consists of a microcontroller unit (MCU) and an IEEE 802.15.4 data radio. The MCU encodes the data with a spreading code and uses the data radio to send an OOK-modulated data sequence to the receiver node. As with previous wake-up radio proposals, we select OOK modulation rather than more complex schemes, since it requires simple hardware and has a low implementation cost. The spreading code scheme consists of 16 chips for each pattern (symbol *A* or symbol *B*). Symbols *A* and *B* represent binary one and zero, respectively. The receiver node employs the wake-up radio to decode the signal using the same spreading code to obtain the wake-up bit sequence.
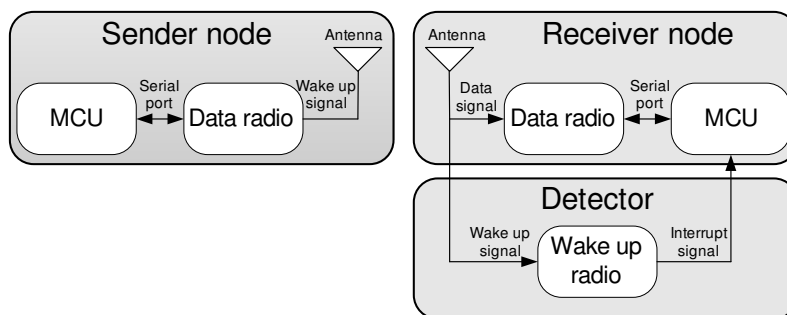
(**a**)
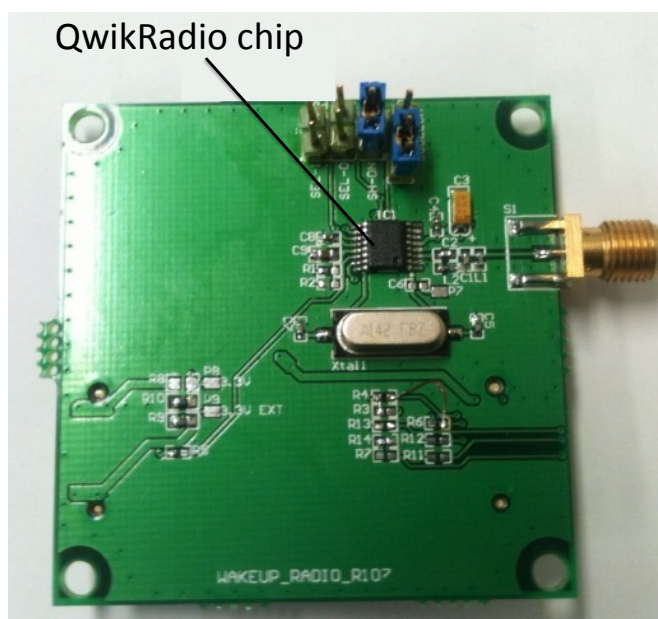
(**b**)

Figure 6. LDWuR prototype. (**a**) Block diagram of LDWuR and nodes; (**b**) circuit board.

We use simple components to implement the proposed LRWuR with proper settings on capacitors and the crystal for the wake-up radio's bandwidth. Our wake-up radio prototype is separate from the sensor node with a built-in main data receiver. It includes a Fleck3b [25] circuit board and an off-the-shelf OOK receiver QwikRadio [26] circuit board. The OOK receiver includes the image-rejection filter, amplifier, AGC (Automatic Gain Control) and OOK demodulation. The OOK receiver circuit board includes impedance matching and a band pass filter for the OOK receiver. The demodulator's bandwidth configuration can be adjusted through jumpers and capacitors on the OOK receiver circuit board. The demodulation bandwidth is set at 6.85 kHz with 22-nF and 1-μF capacitors. The crystal, the reference clock at 14.29983 MHz for all of the OOK receiver's internal circuits, provides the carrier frequency at 916.5 MHz. To improve the sensitivity, our wake-up radio prototype uses a Fleck3b circuit board to process the block orthogonal codes' algorithm.

Other existing wake-up radios [8,27–30] are also applicable if they are tuned to operate at a frequency of 916.5 MHz and a low data rate below 10 kbit/s. The designer can choose a proper OOK receiver to be an alternative solution. In terms of the transmitter, the designer can select any IEEE 802.15.4-compliant data radio to operate at two frequency channels of 916.5 MHz, 916.5 +/− 0.2 MHz and a data rate of about 20 kbit/s to be the other design option.

5. Performance Evaluation

To evaluate our LDWuR and MAC protocol, we exemplify a case study to observe the packet rate and the beacon interval effects on the power consumption and latency. We also compare our LDWuR with existing WuRs [5,20]. The simulation parameters refer to existing studies and datasheets [24,26,31].

5.1. Case Study: Wi-Fi Power Savings by LDWuR

5.1.1. Power Consumption

We observe that the packet rate affects the power consumption at a given beacon interval. Figure 7a shows a relationship between power consumption and packet rate with short data packets (notated as sp) of 34 bytes and long data packets (notated as lp) of 2334 bytes, respectively. The beacon interval is 100 ms. The conventional MAC protocol (notated as 802.11) incurs a higher power consumption than our MAC protocol (notated as WuR), as the conventional MAC protocol has idle-listening on high-power Wi-Fi radio. Our MAC protocol takes advantage of our LDWuR to save listening power. The long data packet induces higher power consumption than the short data packet, as the high-power Wi-Fi radio transmits a longer data packet from the access point to the station. Figure 7b shows a relationship between improvement and packet rate with short data packets and long data packets, respectively. In terms of a short data packet, the improvement percentage decreases slightly when the packet rate increases, as our MAC protocol has more wake-up signal activity before beacons and data packets. In terms of the long data packet, the improvement percentage decreases rapidly when the packet rate increases, as the high-power Wi-Fi radio deals with a long data packet that causes our MAC protocol's power consumption to be closer to the conventional MAC protocol.
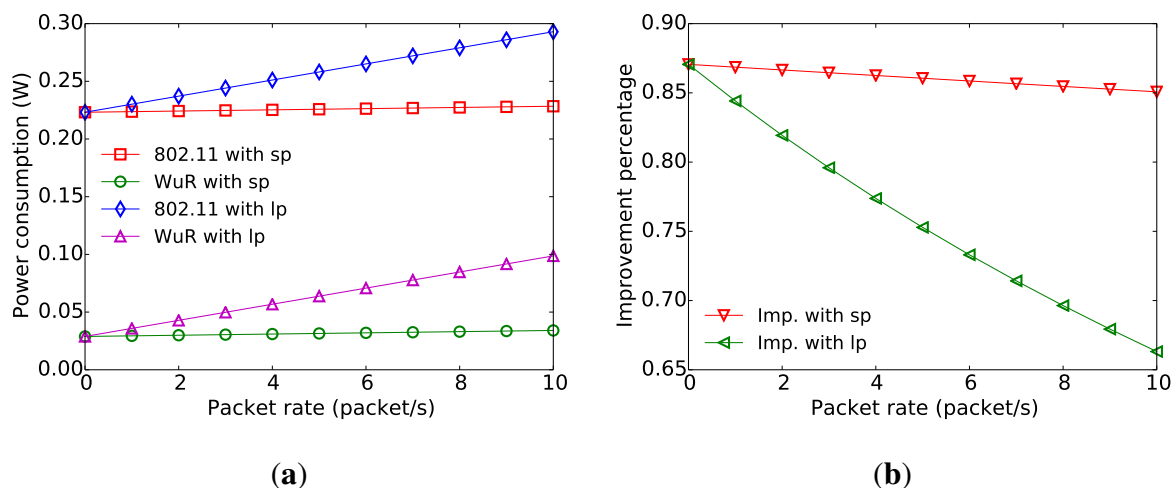
Figure 7. Power consumption is a function of packet rate. (**a**) Power consumption *versus* packet rate; (**b**) improvement on power consumption *versus* packet rate.

We explore the beacon interval impact on power consumption at a given packet rate. The packet rate is 10 packet/s. Figure 8a shows that beacon interval affects power consumption. A small beacon interval has a slightly higher power consumption then a large beacon interval, as a small beacon interval has more beacon activity in a certain time period. Therefore, a small beacon interval has lower improvement in Figure 8b. As the short data packet takes advantage of fewer activities on high-power Wi-Fi radio, it provides higher improvement than the longer data packet.
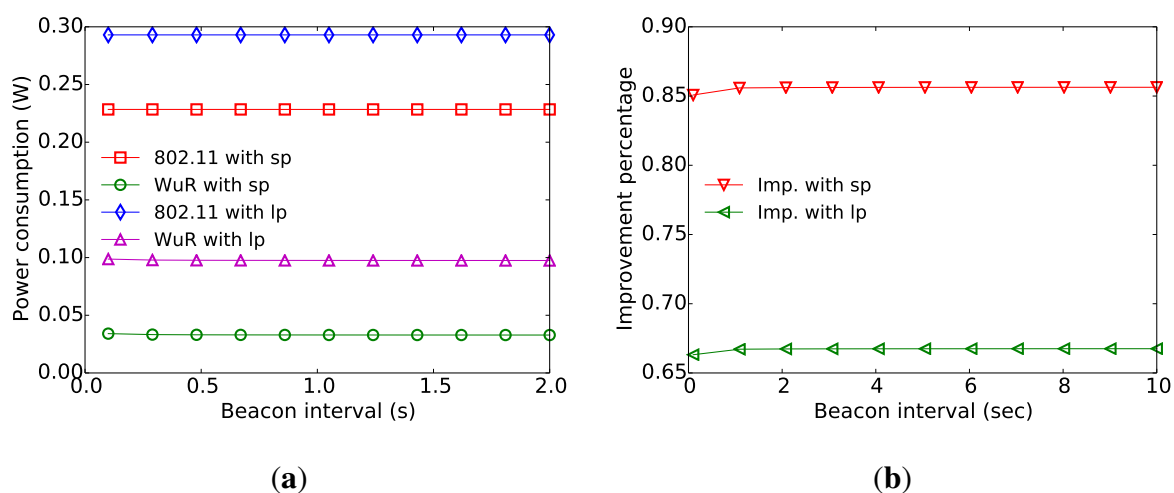

Figure 8. Power consumption is a function of beacon interval. (**a**) Power consumption *versus* beacon interval; (**b**) improvement on power consumption *versus* beacon interval.

5.1.2. Latency

The latency comparison of our WuR with existing WuRs is shown in Figure 9b. Our latencies depend on the expected transmission times of our wake-up radio and IEEE 802.11-compliant data radio that

are computed by their PERs, respectively. In the simulation, we apply the empirical performance of our WuR from previous work [24]. We adopt a receiver sensitivity of -89 dBm with a PER of 8% at 1 Mbps BPSK modulation of the D-Link DI-624 for IEEE 802.11-compliant data radio [32]. Based on those PERs, we calculate their expected transmission times to estimate their latencies. Two radios induce more expected transmission time and increase latency. As our MAC protocol adopts our wake-up radio and IEEE 802.11-compliant data radio, our latency is longer than the conventional MAC protocol. In terms of the hardware performances of our WuR, they are described in previous work [24]. We adopt our WuR as a basic module with directional and omnidirectional antennas for static and dynamic strategies, respectively.
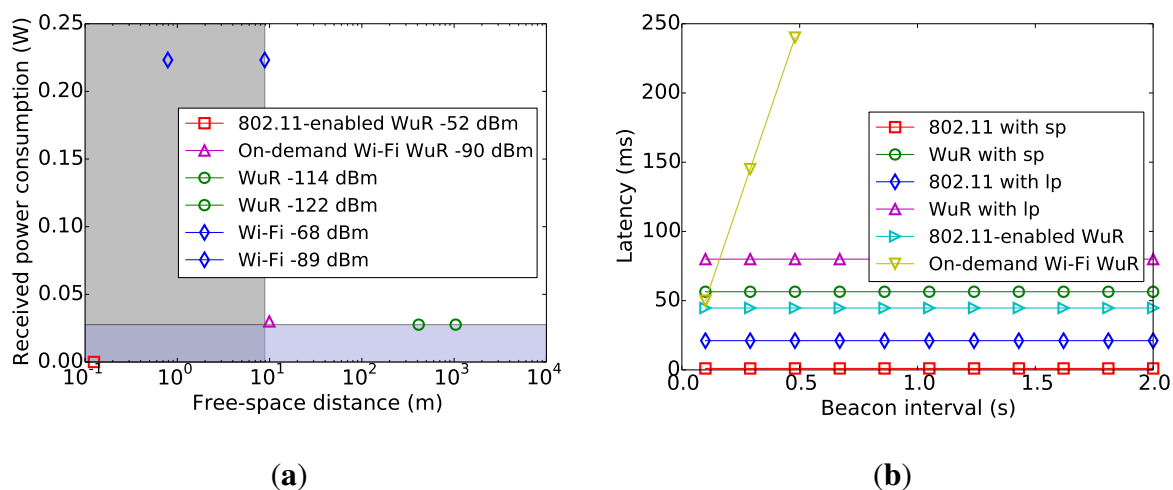

Figure 9. Performance comparison of our LDWuR with existing WuRs. (**a**) Received power consumption *versus* free-space distance; (**b**) latency *versus* beacon interval.

5.1.3. Performance Comparison

Figure 9a shows the comparison of our WuR with existing WuRs [5,20] in terms of received power consumption and free-space distance [33]. To wake up the IEEE 802.11-compliant data radio, WuR is required to have a similar communication range as the IEEE 802.11-compliant radio. To save the IEEE 802.11-compliant radio's power consumption, the required power consumption of WuR is lower than the IEEE 802.11-compliant radio. For the received power consumption, all WuRs' power consumptions support sufficiently low power consumption. For the free-space distance, some WuRs support a sufficient communication range. Especially, our WuR performs with the best communication range among existing WuRs with the proper power consumption. The short-range WuR leads to a high-density deployment. This means that it requires more maintenance cost.

Figure 9b shows the latency comparison with existing WuRs [5,20] with various beacon intervals. Our WuR with sp has a similar latency as existing WuRs. As our design considers PERs and expected transmission times of our WuR and IEEE 802.11-compliant data radio, our WuR's latency increases. However, existing WuRs do not consider the PER and expected transmission time. Thus, they have shorter latency than our WuR. As the latency of the work [5] depends on the backoff time duration, we adopt the average latency of half a beacon interval to estimate it.

We adopt our WuR [24] as a basic module with directional and omnidirectional antennas for static and dynamic strategies, respectively. The power consumption and latency of our basic module are described in the previous work [24]. Our basic module's total power consumption is the same as the average total power consumption of static and dynamic strategies. The latencies are N_{dir} times and N_{dir}^{beam} times our basis module's total latency for static and dynamic strategies, respectively.

In the performance evaluation section, the power consumptions in Figures 7a and 8a include the power consumptions of our WuR. The power consumption of our WuR is 27.6 mW, while the listening power consumption of the IEEE 802.11-compliant radio is 223.2 mW [31,34]. We adopt the average total power consumption of static or dynamic antennas to evaluate performances. The probabilities of our WuR with packet error and the data radio with packet error are considered in Equation (15). The false wake-ups or missed wake-ups are discussed in cases 1a and 1b, respectively [24]. To compare the communication ranges of our WuR and IEEE 802.11-compliant radio, we adopt the sensitivity characteristic of our WuR and IEEE 802.11-compliant radio, as the communication range depends on the environments. Our WuR's sensitivity is -122 dBm, while the IEEE 802.11-compliant radio's sensitivity is -90 dBm for the IEEE 802.11b standard [5]. In free space path loss conditions, our WuR performs a long-range communication of about 1 km, which is better than the IEEE 802.11b-compliant radio.

For the Wi-Fi data communication range of 802.11b (sensitivity level of -90 dBm) [5], our WuR supports -122 dBm [24], which is sufficient to cover the Wi-Fi data communication range. The existing study [20] proposes a WuR with a sensitivity of -52 dBm. However, the sensitivity cannot cover the entire Wi-Fi data communication range, which limits the operational range.

6. Conclusions

We propose two strategies to search the transmitter's direction to concentrate the receiver's resources on the right location. This means that our LDWuR can improve the receiver's cover range and power savings. We design the system model to analyze the power consumption and latency for our LDWuR. We also present our prototype and design concept. From the simulation results, we observe that our LDWuR and event-driven MAC protocol can repress the idle-listening power waste of Wi-Fi stations. Therefore, our design enhances the Wi-Fi power savings in wireless networks.

Author Contributions

The work presented here was carried out in collaboration between all authors.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. White, D.; Esswein, S.; Hallstrom, J.; Ali, F.; Parab, S.; Eidson, G.; Gemmill, J.; Post, C. The Intelligent River: Implementation of Sensor Web Enablement Technologies across Three Tiers of System Architecture: Fabric, Middleware, and Application. In Proceedings of the 2010 International Symposium on Collaborative Technologies and Systems (CTS), Chicago, IL, USA, 17–21 May 2010; pp. 340–348.
2. IBM. Water Management for a Smarter Planet. Available online: http://www.ibm.com/smarterplanet/us/en/water_management/ideas (accessed on 21 July 2015).
3. Jurdak, R.; Sommer, P.; Kusy, B.; Kottege, N.; Crossman, C.; Mckeown, A.; Westcott, D. Camazotz: Multimodal Activity-Based GPS Sampling. In Proceedings of the 12th International Conference on Information Processing in Sensor Networks (IPSN '13), Philadelphia, PA, USA, 08–11 April 2013; pp. 67–78.
4. Bhatti, N.A.; Syed, A.A.; Alizai, M.H. Sensors with Lasers: Building a WSN Power Grid. In Proceedings of the 13th International Symposium on Information Processing in Sensor Networks (IPSN '14), Berlin, Germany, 15–17 April 2014; pp. 261–272.
5. Yomo, H.; Kondo, Y.; Miyamoto, N.; Tang, S.; Iwai, M.; Ito, T. Receiver Design for Realizing On-Demand WiFi Wake-Up Using WLAN Signals. **2012**, *arXiv:1209.6186v1*.
6. Le-Huy, P.; Roy, S. Low-Power Wake-Up Radio for Wireless Sensor Networks. *Mob. Netw. Appl.* **2010**, *15*, 226–236.
7. Drago, S.; Sebastiano, F.; Breems, L.J.; Leenaerts, D.M.W.; Makinwa, K.A.A.; Nauta, B. Impulse Based Scheme for Crystal-Less ULP Radios. *IEEE Trans. Circuits Syst. I Regul. Papers* **2009**, *56*, 1041–1052.
8. Ansari, J.; Pankin, D.; Mähönen, P. Radio-Triggered Wake-ups with Addressing Capabilities for extremely low power sensor network applications. In Proceedings of the IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Cannes, French Riviera, France, 15–18 September 2008; pp. 1–5.
9. Pletcher, N.M.; Gambini, S.; Rabaey, J. A 52 μW Wake-Up Receiver With -72 dBm Sensitivity Using an Uncertain-IF Architecture. *IEEE J. Solid-State Circuits* **2009**, *44*, 269–280.
10. Proakis, J.; Rahman, I. Performance of Concatenated Dual-k Codes on a Rayleigh Fading Channel with a Bandwidth Constraint. *IEEE Trans. Commun.* **1979**, *27*, 801–806.
11. Djordjevic, I.; Vasic, B. Combinatorial constructions of optical orthogonal codes for OCDMA systems. *IEEE Commun. Lett.* **2004**, *8*, 391–393.
12. Faruque, S. Investigation of error control properties of orthogonal codes. In Proceedings of the IEEE Military Communications Conference (MILCOM), Boston, MA, USA, 13–16 October 2003; Volume 2, pp. 791–795.
13. Faruque, S. Free space laser communications based on Orthogonal On-Off Keying (O3K). In Proceedings of the 2011 IEEE International Conference on Electro/Information Technology (EIT), Mankato, MN, USA, 15–17 May 2011; pp. 1–4.
14. Pursley, M.; Royster, T. High-Rate Direct-Sequence Spread Spectrum with Error-Control Coding. *IEEE Trans. Commun.* **2006**, *54*, 1693–1702.

15. Timotheou, S.; Krikidis, I.; Zheng, G.; Ottersten, B. Beamforming for MISO Interference Channels with QoS and RF Energy Transfer. *IEEE Trans. Wirel. Commun.* **2014**, *13*, 2646–2658.

16. Morsi, R.; Michalopoulos, D.S.; Schober, R. Multi-user scheduling schemes for simultaneous wireless information and power transfer. In Proceedings of IEEE International Conference on Communications, ICC 2014, Sydney, Australia, 10–14 June 2014; pp. 4994–4999.

17. Ng, D.W.K.; Schober, R.; Alnuweiri, H.M. Secure layered transmission in multicast systems with wireless information and power transfer. In Proceedings of the IEEE International Conference on Communications, ICC 2014, Sydney, Australia, 10–14 June 2014; pp. 5389–5395.

18. Shih, W.C.; Chou, P.H.; Chen, W.T. Empirical Validation of Energy-Neutral Operation on Wearable Devices by MISO Beamforming of IEEE 802.11ac. In Proceedings of the 2nd International Workshop on Energy Neutral Sensing Systems (ENSsys '14), Memphis, TN, USA, 6 November 2014; pp. 49–54.

19. Trösch, F.; Wittneben, A. A Simple Ultra-Wideband Wake-up Scheme for Semi-Active Sensor Nodes. In Proceedings of the The 2006 IEEE 2006 International Conference on Ultra-Wideband, Waltham, MA, USA, 24–27 September 2006; pp. 663–668.

20. Oller, J.; Garcia, E.; Lopez, E.; Demirkol, I.; Casademont, J.; Paradells, J.; Gamm, U.; Reindl, L. IEEE 802.11-enabled wake-up radio system: Design and performance evaluation. *Electron. Lett.* **2014**, *50*, 1484–1486.

21. Shih, W.C.; Jurdak, R.; Lee, B.H.; Abbott, D. Improving the Throughput of Sensor Network Wake-Up Radios Using Block Orthogonal Codes. In Proceedings the Annual International Conference on Mobile Communications, Networking and Applications (MobiCONA), Singapore, 27–28 June 2011.

22. Couch, L.W. *Digital and Analog Communication Systems*; Prentice Hall PTR: Upper Saddle River, NJ, USA, 1992.

23. Zuniga, M.; Krishnamachari, B. Analyzing the transitional region in low power wireless links. In Proceedings the First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON), Santa Clara, California, 4–7 October 2004; pp. 517–526.

24. Shih, W.C.; Jurdak, R.; Lee, B.H.; Abbott, D. High Sensitivity Wake-Up Radio Using Spreading Codes: Design, Evaluation and Applications. *EURASIP J. Wirel. Commun. Netw. (EURASIP JWCN)* **2011**, doi:10.1186/1687-1499-2011-26.

25. CSIRO. Fleck3B. Available online: http://www.sensornets.csiro.au/content/equipment/fleck3b (accessed on 21 July 2015).

26. Micrel. MICRF221 3.3V, QwikRadio 850MHz to 950MHz Receiver, 2008. Available online: http://www.micrel.com/_PDF/micrf221.pdf (accessed on 21 July 2015).

27. Van der Doorn, B.; Kavelaars, W.; Langendoen, K. A prototype low-cost wakeup radio for the 868 MHz band. *Int. J. Sens. Netw.* **2009**, *5*, 22–32.

28. Atmel. AVR low power 700/800/900 MHz Tranceiver for IEEE 802.15.4-2006, IEEE 802.15.4c-2009, Zigbee, 6LoWPAN, and ISM Applicaitons AT86RF212, 2010. Available online: http://www.atmel.com/images/doc8168.pdf (accessed on 21 July 2015).

29. Shih, E.; Bahl, P.; Sinclair, M.J. Wake on wireless: An event driven energy saving strategy for battery operated devices. In Proceedings of the 8th Annual International Conference on Mobile Computing and Networking, Atlanta, GA, USA, 23–28 September 2002; pp. 160–171.

30. Takiguchi, T.; Saruwatari, S.; Morito, T.; Ishida, S.; Minami, M.; Morikawa, H. A Novel Wireless Wake-Up Mechanism for Energy-Efficient Ubiquitous Networks. In Proceedings the IEEE International Conference on Communications Workshops, Dresden, Germany, 14–18 June 2009; pp. 1–5.

31. Zhang, X.; Shin, K.G. E-MiLi: Energy-Minimizing Idle Listening in Wireless Networks. In Proceedings the 17th Annual International Conference on Mobile Computing and Networking (MobiCom '11), Las Vegas, NV, USA, 19–23 September 2011; pp. 205–216.

32. D-Link. D-Link DI-624 Datasheet, 2005. Available online: http://dlink-manuals.org/dlink-di-624-datasheet/ (accessed on 24 June 2015).

33. Zyren, J.; Petrick, A. Tutorial on Basic Link Budget Analysis. Application Note AN9804, Harris Semiconductor, 1998. Available online: http://www.sss-mag.com/pdf/an9804.pdf (accessed on 21 July 2015).

34. Zhang, X.; Shin, K.G. E-MiLi: Energy-Minimizing Idle Listening in Wireless Networks. *IEEE Trans. Mob. Comput.* **2012**, *11*, 1441–1454.