# RF Wakeup Sensor for Wireless Sensor Networks

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***Abstract***

*To break through the energy-latency tradeoff caused by duty cycling in the existing wireless sensor network (WSN), in this paper we propose a new RF wakeup sensor, which is a dedicated small RF module to check potential communications by sensing the presence of a RF signal. With RF wakeup sensor each node no longer requires duty cycling, eliminating both sleep delay and idle listening. The distinctive feature of our RF design from the existing radio sensor studies is that the RF wakeup sensor can provide the same sensitivity as the underlying RF communication module with two orders of magnitude less energy.*

***Keywords:*** *Wireless sensor network, RF wakeup sensor, idle listening, sleep delay*

## 1. Introduction

Idle listening, which is the state of monitoring communication media to check potential traffic, is the dominant source of energy consumption in WSNs. Duty cycling, which makes nodes periodically turn off their RF communication module, can effectively reduce the energy consumption due to idle listening. But it introduces sleep delay due to the sleep state of a receiver. High duty cycle reduces sleep delay but increases energy consumption due to more frequent wakeups while low duty cycle reduces energy consumption but increases sleep delay due to a long sleep state. To deal with this tradeoff between the energy consumption and the sleep delay, the existing WSN studies focuses on MAC protocols to support energy efficient yet high performance communications. To mitigate the impact of sleep delay on packet latency, many MAC protocols exploit dynamic duty cycling [1, 2, 3] or wakeup scheduling [4, 5, 6].

However, these optimizations are not a fundamental solution for eliminating idle listening since they still require duty cycling. A few studies [7, 8] have investigated the design of a radio wave sensor, which is a dedicated RF module to check for potential communications. Since a radio wave sensor doesn't decode an incoming signal, it requires only a subset of components from the RF communication module. Therefore, most of the conventional radio wave sensors are implemented without amplifiers that consume heavy energy. However, it is hard to detect a signal weaker than the minimum signal strength required for passing through a silicon diode. Therefore, Therefore, RF sensing ranges of the existing schemes are much shorter than RF communication ranges [7, 8].

To provide a radio wave sensor with the same sensitivity as the underlying RF communication module, we propose a new design of radio wave sensor called *RF wakeup sensor*. To equalize RF sensing range to communication range, the RF wakeup sensor uses a dedicated amplifier for input signal. Since the RF wakeup sensor does not have to extract information from a received signal, the amplifier in the RF wakeup sensor is indifferent to phase distortion. Therefore, we can simplify conventional amplifier that consist of complex circuits for providing high linearity. Consequently, we are able to design an ultra-low power amplifier with the minimum circuit elements.

The rest of this paper is organized as follows. Section 2 discusses the related works. Section 3 introduces a RF wakeup sensor technique and design. Section 4 analyzes the detailed simulation results for the proposed RF wakeup sensor. Section 5 concludes the paper.

## 2. Related Work

There have been a few studies [7, 8] for a radio wave sensor. However, it is hard to apply the existing radio wave sensors to wireless sensor nodes since the sensors designed so far have shortcomings: additional wakeup channel and insufficient sensitivity. PRFW [8] is one of the pioneering studies that assume an additional wakeup channel. PRFW adds ATA5283 and ATA5276 modules, which use 125kHz frequency. ATA5283 is a signal detector and ATA5276 is a signal generator. However, PRFW requires additional frequency band dedicated for wakeup signal, and the sensing range of ATA5283 is only a few meters.

The High-sensitivity Wakeup Circuit (HWC) [8] is another radio wave sensor design based on CMOS technology. It consists of a rectifier, a switch, and a circuit protector. A rectifier acts as a signal detector, which consists of multiple diodes. However, a signal has to be stronger than -30dBm to pass through a CMOS diode. Therefore, the maximum sensitivity of HWC is -30dBm while CC1000, which is a popular communication module for WSNs, provides -99dBm sensitivity at 38.4K baud rate. Therefore, it is impractical to apply HWC to WSNs since the difference between the sensitivities of HWC and CC1000 is about 69dBm. According to the Friis transmission equation [10], a 69dBm difference in sensitivity implies a range difference of 3000 times. While CC1000 can transmit a packet over 150 meters, the maximum distance of HWC [8] is only 5 cm according to the Friis equation.

## 3. RF Wakeup Sensor

### 3.1. Design Methodology

RF wakeup sensor is dedicated to detect the presence of communication by sensing a carrier signal. In other words, RF wakeup sensor separates a channel monitoring function from a RF communication module. If RF wakeup sensor detects a signal that has higher strength than the predefined threshold, the RF wakeup sensor interrupts a processor to notify the communication occurrence.

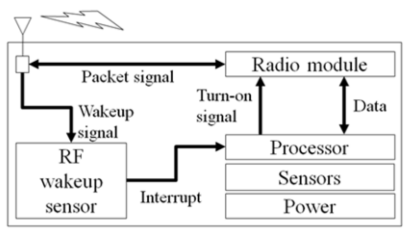


**Figure 1. A Sensor Node with RF Wakeup Sensor**

To design the RF wakeup sensor, we need to understand the mechanism of a general RF communication module. Since carrier signal detection is a part of a general RF module, RF wakeup sensor can be designed by simplifying the RF module. The function of RF wakeup sensor is to sense a RF signal and to interrupt the processor as shown in Figure 1. Since each node can check the presence of a communication by checking RSS of an incoming signal, the signal can be detected at the output terminal of an IF stage. This suggests that RF wakeup sensor needs no components related to demodulation.

A mixer and a VCO are required to shift the frequency of an incoming signal to the intermediate frequency. This frequency shift makes it easy for a communication module to precisely select a channel. To shift an incoming signal to a target frequency, the sensor requires an additional signal from VCO, which is the most dominant energy drain source. In addition, VCO requires a complex circuit to generate a local signal with stable and accurate frequency. To design an ultra-low power RF wakeup sensor, we need to eliminate both mixer and VCO. Fortunately, RF wakeup sensor tolerates inter-symbol interference since it does not have to extract information from the incoming signal. In other words, RF wakeup sensor does not require precise channel selection as the RF module. Therefore, we can eliminate both mixer and VCO by adding a small filter.

In an IF stage, an amplifier reports RSS by using an automatic gain control (AGC). Note that while AGC reports measured RSS values, RF wakeup sensor requires only true or false information about whether the RSS of the incoming signal is higher than the predefined threshold. Therefore, we use a simple signal detector instead of AGC. The signal detector acts as a switch, indicating the presence of a communication. As mentioned above, we require a frequency filter that will substitute a channel selection function of an IF stage. Since the frequency used for a communication is higher than intermediate frequency, RF wakeup sensor requires a precise frequency filter and inductors with high quality factor (Q-factor).

A demodulator is used to recover the information content from the incoming modulated signal. As we explained above, RF wakeup sensor requires no information about on-going communications; it does not need a demodulator. Consequently, RF wakeup sensor consists of a LNA, a frequency filter, and a signal detector.

### 3.2. RF wake-up Module Design

We use Dongbu HiTek's 0.13um RF CMOS technology [11] for the RF wakeup sensor design.

**3.2.1. Detector:** A detector in RF wakeup sensor has two roles: detecting a communication signal and generating an interrupt signal. If the signal strength of incoming signal is higher than the predefined threshold, a detector interrupts the processor. These operations are simply implemented by regarding the incoming signal as the input of a switch for interrupt signal. Therefore, we use a general low-power rectifier to convert an incoming AC signal into a switching DC signal. However, a rectifier using CMOS diodes can convert only AC signal whose strength is higher than -30dbm. Therefore, we need an amplifier, which can compensate for the difference between the sensitivity of a RF communication module and that of the signal detector, in front of the signal detector.

**3.2.2. Amplifier:** An amplifier in RF wakeup sensor has to at least 70dB gain; it makes -99dBm communication signal pass through the signal detector that can detect -30dBm signal. Since an amplifier needs bias current, it consumes energy due to leakage current when there is no RF signal. However, we need to consider the tradeoff between the energy consumption and the gain of an amplifier. We can use a single 70dB amplifier with high energy consumption or multiple low gain amplifiers with low energy consumption.

The energy consumption and the gain of an amplifier depend on bias current. Low bias current reduces both energy consumption and gain. Therefore, we need to find the optimal parameters to maximize gain/power, which depends on transistor size and RF chock.

Intuitively, the highest gain/power leads to an optimal parameter. However, we need a more careful investigation on the parameters, since the analysis assumes ideal elements.

In a RF circuit, impedance matching is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer and to minimize reflections from the load. If we fail to match the impedance, a circuit may lose the incoming signal due to reflections. We need to find optimal parameters both to match the impedance and also to make the amplifier to meet the 50ohm standard for microwave hardware. We can match the impedance of each element by using inductors and capacitors. To reduce signal loss due to the resistance of inductors on a signal path, we need inductors with high Q factor. However, the reasonable Q factor of a CMOS spiral inductor is about 5 ~ 10 while external lumped inductor has about 40 Q factor. Considering the cost of external port and the signal loss due to low Q factor of CMOS inductor, we use only capacitors on a signal path.

**3.2.3. Bandpass Filter:** If the RF wakeup sensor has no frequency filtering, the number of false-positive wakeups due to unrelated signal will be increased. Therefore, we use a frequency filter that requires neither mixer nor oscillator to selectively sense a signal on the predefined frequency band. Since the frequency used for communication is higher than intermediate frequency, RF wakeup sensor requires a precise frequency filter with high quality factor (Q-factor) and inductors for an impedance matching network. Although the proposed filter assumes that they are implemented on the outside of a CMOS chip, the filter can be simply converted into a BAW filter [12] that can be implemented on a CMOS chip.

**3.2.4. RF Wakeup Sensor Design:** Fig. 2 shows the circuit design of RF wakeup sensor that consists of a multistage amplifier, a bandpass filter, and a detector. As shown in this design, all the other devices except amplifiers are passive devices that do not consume energy.

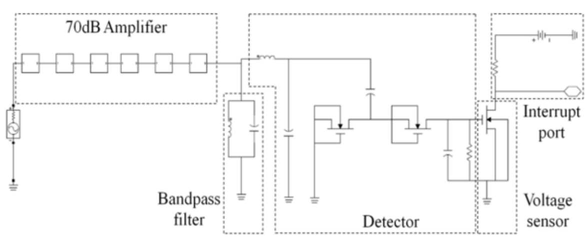


**Figure 2. The Circuit Design of RF Wakeup Sensor**

## 4. Evaluations

We have modeled RF wakeup sensor on Advanced Design System 2009 using Dongbu HiTek's 0.13um RF CMOS technology. An input and output port of the multi-stage amplifier are matched to 50Ω. The multi-stage amplifier has 72dB gain and consumes 228μW.

Figure 3 shows how our RF wakeup sensor generates an interrupt as a function of incoming signal strength. As shown in this figure, the output signal of RF wakeup sensor drops voltage when the strength of input signal is higher than -99dBm. This figure also shows the interrupt generation scenario on the neighbor channel: 913MHz and 917MHz. RF wakeup sensor interrupts the processor when incoming signal strength on the neighbor channels is higher than -50dBm. Theoretically, -50dBm incoming signal comes from a node 1m apart. Therefore, we can ignore the false-positive wakeups due to communications on the neighbor channel.

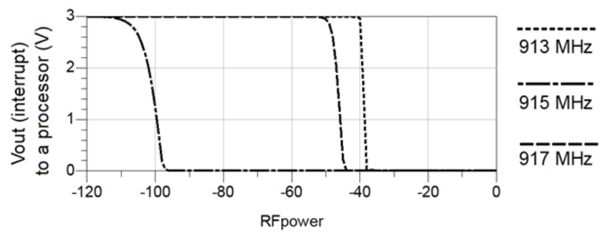


**Figure 3. Interrupt Generation on Neighbor Channels**

## 5. Conclusion

In this paper we propose a new design of RF wakeup sensor to eliminate the energy-delay tradeoff from the existing wireless sensor networking. With the RF wakeup sensor, each node no longer requires duty cycling, eliminating both idle listening and sleep delay. Our RF wakeup sensor design can provide the same sensitivity but two orders of magnitude less energy than the underlying RF communication module by using a low power multistage amplifier and a bandpass filter and also by eliminating demodulator, VCO, and mixer from the RF module. Sensor nodes with RF wakeup sensor can wake up on demand whenever there is traffic, enabling zero sleep delay and zero idle listening for the wireless sensor networks.

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