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Wake-Up Radio Architecture Utilizing Passive Down Conversion Mixing

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Abstract: This letter describes a low energy wake-up radio that is based on passive down conversion. The receiver activates when it receives two closely located frequencies that are down converted in the passive mixer. The down converted signal is applied to a low frequency wake-up IC that provides an identification code and wakes up an active radio for further communication. This letter derives an expression for the voltage sensitivity of the mixer and verifies the concept experimentally at 2.45 GHz. The wake-up radio consumes 6.8 μA at 3 V.

Key Words: Detectors, mixers, transponders, wake-up radios, wireless sensors.

1. Introduction

Future ubiquitous sensing, computing, and manufacturing systems necessitate wireless sensor networks [1]. Such networks are proposed, e.g. for health [2] and environmental monitoring [3]. Traditionally sensor nodes are equipped with a battery while an emerging solution is to use devices capable of harvesting ambient energy [4]. In both cases, the supply power is scarce.

Radio transceiver consumes often the most power in a wireless sensor node. To save power, wireless sensor nodes communicate during predefined time slots, e.g., in Zigbee and Bluetooth Low Energy (BT LE) [5]. Numerous low-power radios are proposed for sensor nodes [6]-[8], but they are not commercially available.

In this letter we present a novel wake-up radio receiver that is based on passive mixing, which has been recently used in intermodulation sensors [9] and millimeter wave RFID [10], as well as wake-up circuits at 900 MHz [11]. A comparison of low energy radios in Table 1 illustrates the very low power consumption of the suggested wake-up concept.

In addition to the 900 MHz solution in [9], we provide PER analysis and an equally sensitive application for 2.45 GHz. We also derive an analytical expression for the low-frequency wake-up signal. The expression can be used to optimize the radio front-end and to derive the wake-up distance.

The base station transmits both RF (radio frequency) and LO (local oscillator) signals in air, which are then passively mixed in the wake-up receiver to generate the base-band signal. Saving need for a local oscillator in the wake-up receiver, the approach reduces reception current consumption dramatically. The receiver can be on all the time, still achieving lower current consumption than the scheduled active radio. In addition to this, the phase noise in RF and LO correlates and cancels out, which provides higher signal-to-noise ratio.

The first radios, in fact, also transmitted the LO signal wirelessly [12]. The modern heterodyne architecture enables a good spectral efficiency, but may not be ideal for power limited systems, such as wireless sensors. Further, the base station can generate two sinusoids for wake-up signal by the full AM modulation. Hence, the same transmitter can be used for wake-up signal generation and active radio communication.

2. Theory

The RF electrical equivalent circuit of the wake-up radio receiver is presented in Figure 1. It consists of an antenna, matching components, and a mixing element supplying the base-band signal to the wake-up IC, which is modeled as a parallel RC-circuit. A Schottky diode is used for mixing.

To calculate the down-conversion efficiency, let us consider a Schottky diode under a DC bias and small signal conditions. The AC diode current is given as

$$I_j(V_j) = I_s\left(e^{\alpha(V_j+V_{dc})} - 1\right) \approx \frac{V_j}{R_j} + \frac{\alpha V_j^2}{2R_j}, \tag{1}$$

where I_s is the saturation current, V_j is the AC voltage across the junction, α the diode parameter, and $R_j = (\alpha I_s e^{\alpha Vdc})^{-1}$ is the dynamic junction resistance. The junction capacitance under DC bias is given as

$$C_j(V_{dc}) = C_{j0}\left(1 - \frac{V_{dc}}{\varphi}\right)^{-\gamma}, \tag{2}$$

where γ is the profile parameter and φ is the junction potential. We neglect the voltage-dependent capacitance in the mixing process, because the resistive term dominates at the low mixing frequencies that are considered in this paper.

The antenna receives two sinusoids from the transmitter and generates a voltage of

$$V_g = \hat{V}_g\left[\sin(\omega_1 t) + \sin(\omega_2 t)\right], \tag{3}$$

where $\hat{V}_g = 2\sqrt{2P_{in}R_g}$, P_{in} is a received power at one frequency, R_g is the antenna resistance, ω_1 and ω_2 are angular frequencies. Assuming that the frequency difference $\omega_\Delta = \omega_2 - \omega_1$ is small compared to the bandwidth of the matching circuit, the voltage generated across the diode junction is given as

$$V_g = S_{jg}(\omega_{RF})\hat{V}_g\left[\sin(\omega_1 t) + \sin(\omega_2 t)\right], \tag{4}$$

where $\omega_1 \approx \omega_2 \approx \omega_{RF}$, and $S_{jg}(\omega_{RF})$ is the voltage transfer function of the matching circuit. Now the current of an equivalent Norton current source in parallel with the junction at the difference frequency ω_Δ can be calculated by inserting (4) in (1), and assuming the voltage across the load at the difference frequency is roughly equal to the junction voltage

$$V_L(\omega_\Delta) \approx V_j(\omega_\Delta) = \frac{\alpha}{2R_j} Z_N(\omega_\Delta) S_{jg}^2(\omega_{RF}) \hat{V}_g^{\,2} \cos(\omega_\Delta t), \qquad (5)$$

where $Z_N(\omega_\Delta)$ is the impedance of the equivalent Norton current source in Figure 1.

3. Experiments

A photograph of the wake-up radio prototype at 2.45 GHz ISM band is presented in Figure 2. The main components include a low-frequency wake-up IC (Austriamicrosystems AS3930) that provides an 8-bit identification code, a passive down conversion mixer based on a Schottky diode (Avago HSMS-286) with lumped element matching, and a ceramic antenna.

A. Down-conversion efficiency

To measure the performance of the down-conversion mixer, the antenna is replaced with a 50-Ω coaxial cable. Two sinusoids from signal generators (Agilent E8257C and 8362B) are fed through a power combiner (Mini-Circuits ZAPDQ-4) to the antenna port. The voltage at the difference frequency is measured with a high-impedance probe (Tektronix P6243) and a spectrum analyzer (Hewlett-Packard 8562E). The measurement results are compared to theoretical curves, which are calculated using the parameter values in Table 2.

The voltage at the difference frequency $V_j(\omega_\Delta)$ is presented as a function of the carrier frequency f_{RF} and as a function of the difference frequency f_Δ in Figs. 3 and 4, respectively. The input power is –30 dBm at one frequency in both figures. A distinct sensitivity improvement of 6 dB due to biasing is seen in both figures.

The calculated curves correspond to the measured ones at zero-bias, but there is some difference under forward bias. We assume that the discrepancies occur, because the junction capacitance does not precisely follow the model in (2), and because the small signal approximation does not hold at high power levels.

The voltage $V_j(\omega_\Delta)$ as a function of the input power is shown in Figure 5. The specified voltage sensitivity of the wake-up circuit is 100 µV. This voltage is achieved when the input power is greater than -44 dBm for an unbiased receiver and -50 dBm for a biased one. The small-signal approximation is seen to be valid when $V_j(\omega_\Delta)$ is below 10 mV.

The achieved unbiased sensitivity is 8 dB lower than that of the radio presented in [9] at 900 MHz. This is because the down-conversion efficiency of the unbiased Schottky diode decreases with an increasing frequency due to the RC cut-off. Above the cutoff, the voltage over the junction is defined by capacitance only, leading to a ω^{-1} decay. Taking into account the square-dependence of output voltage to the input voltage (Equation 5), we can calculate a theoretical sensitivity decrease as $(900\ \text{MHz}/2.45\ \text{GHz})^2 \sim -8.5$ dB. Hence the sensitivities in this work and in [9] are equivalent.

Biasing of the receiver helps to reduce the diode resistance, and thus drive the RC-cutoff to higher frequencies. With sufficiently high bias current, the sensitivity is independent of frequency. However, we have limited the bias current to 1 µA to save a battery, and hence the biased sensitivity is not exactly as high as at 900 MHz.

B. Packet error rate and range

The packet error rate (PER) for an AGWN (additive Gaussian white noise) channel is [12]

$$PER = 1 - \left(1 - \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_{bit}}{N}}\right)\right)^n, \qquad (6)$$

where E_{bit} is the energy per bit, $N/2$ is the receiver noise power spectral density and n is the number bits in the wake-up packet. Because the conversion loss in the passive mixer is strongly dependent on incoming power, we have to calculate E_{bit} and N at wake-up IC input, leading to expression

$$\sqrt{\frac{E_{bit}}{N}} = \frac{\beta P_{rf}}{V_0} \sqrt{\frac{BW}{2 f_{bit}}}, \tag{7}$$

where β is the measured mixer voltage sensitivity from Figure 5, P_{rf} is the input RF power that can be calculated from Friis equation, V_0, BW, f_{bit} are the wake-up IC sensitivity, bandwidth and bit rate, respectively. Theoretical PER vs. range can be calculated using Eqs. (6) and (7) and system parameters in Table 3.

In Figure 6, the calculated PER as a function of range is presented with the measured values. The measurement was carried out in an empty seminar room. A range of about 7 m (PER < 0.5 %) is achieved with a transmit power of 5.6 $\mathrm{mW_{ERP}}$. Radio regulations allow more than 100-fold transmit power, leading in theory to over ten-fold range. Again, the result is in line with the work in [9], when taking into account the difference in frequency.

The measured current consumption of the wake-up radio is 6.8 μA, of which 5.8 μA is delivered to the AS3930 and 1 μA to Schottky diode bias.

4. Conclusion

We have presented a low-power wake-up radio that is based on passive down-conversion. The mixer receives two frequencies located close to each other and generates a signal at the difference frequency, which is then applied to wake-up IC that provides an identification code. We demonstrated the concept at 2.45 GHz, and achieved a range of 7 m (PER < 0.5 %) with a transmit power of 5.6 $\mathrm{mW_{ERP}}$. The current consumption of the receiver is 6.8 μA.

Acknowledgment

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Figure 1 Electrical equivalent circuit of the wake-up receiver.

Figure 2 Photograph of the prototype.

Figure 3 Measured (markers) and calculated (lines) voltages at the difference frequency for a zero-biased and forward-biased diode as a function of the carrier frequency. $f_{\Delta} = 100$ kHz.

Figure 4 Measured (markers) and calculated (lines) voltages at the difference frequency for a zero-biased and forward-biased diode as a function of the difference frequency. $f_{RF} = 2.45$ GHz.

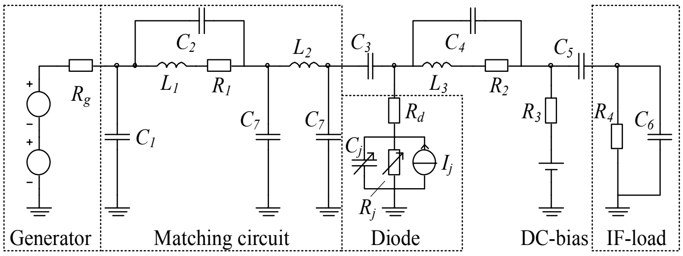
Figure 5 Measured (markers) and calculated (lines) voltages at the difference frequency as a function of the input power. $f_{RF} = 2.45$ GHz and $f_{\Delta} = 100$ kHz. Sensitivity of the wake-up receiver is the input power, at which output voltage is 100 µV, i.e. -44 dBm unbiased and -50 dBm for biased receiver (extrapolated).

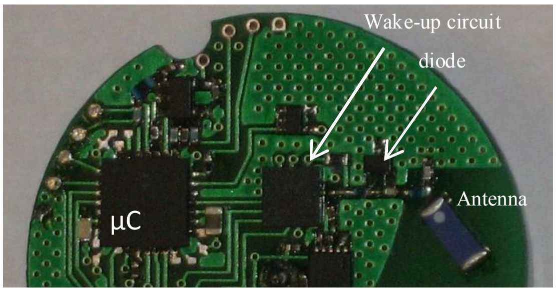
Figure 6 Measured (markers) and calculated (line) PER of the wake-up radio.

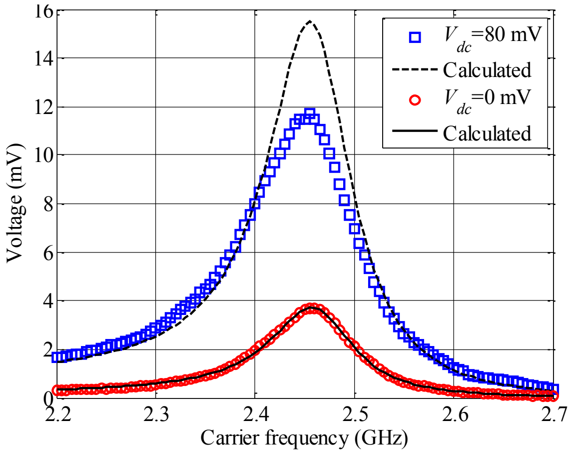
Table 1 Low energy radio comparison at 2.45 GHz.

Table 2 Mixer parameters.

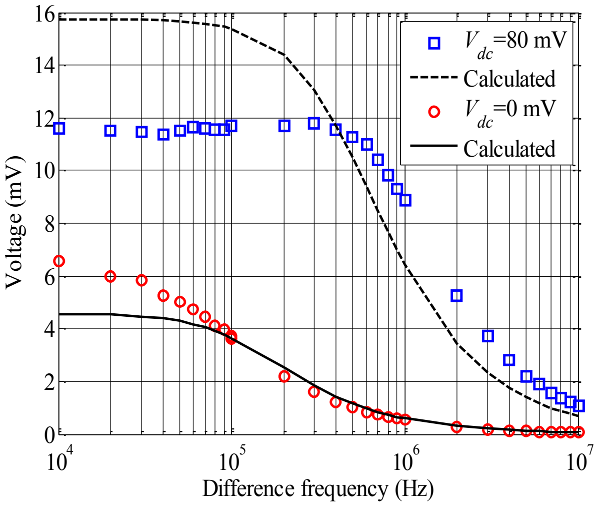
Table 3 System parameters.

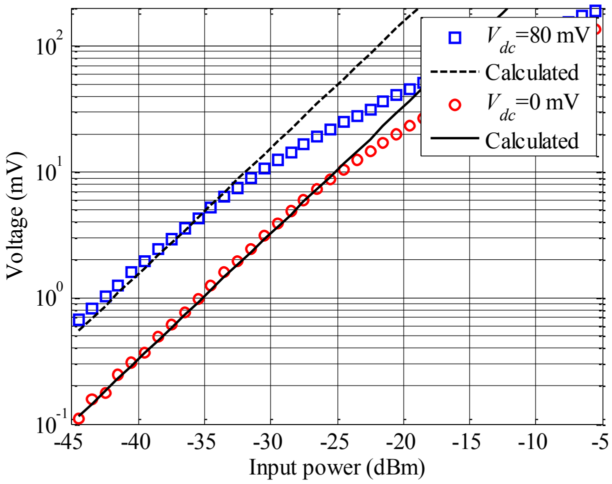

+
−
+
−
R_g
C_1
C_2
L_1
R_1
C_7
L_2
C_7
C_3
C_4
L_3
R_2
C_5
R_d
C_j
R_j
I_j
R_3
R_4
C_6
Generator
Matching circuit
Diode
DC-bias
IF-load

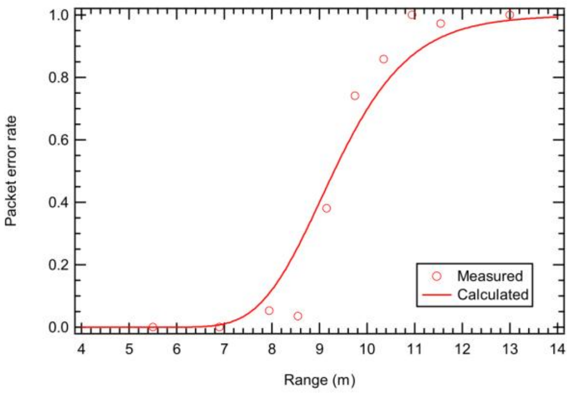

Wake-up circuit
diode
Antenna
μC



Voltage (mV)
Carrier frequency (GHz)
0
2
4
6
8
10
12
14
16
2.2
2.3
2.4
2.5
2.6
2.7
V_{dc}=80 mV
Calculated
V_{dc}=0 mV
Calculated


16
14
12
10
8
6
4
2
0
Voltage (mV)
10^4
10^5
10^6
10^7
Difference frequency (Hz)
V_{dc}=80 mV
Calculated
V_{dc}=0 mV
Calculated


V_{dc}=80 mV
Calculated
V_{dc}=0 mV
Calculated
Voltage (mV)
Input power (dBm)
10^{2}
10^{1}
10^{0}
10^{-1}
-45
-40
-35
-30
-25
-20
-15
-10
-5


Packet error rate
1.0
0.8
0.6
0.4
0.2
0.0
4
5
6
7
8
9
10
11
12
13
14
Range (m)
Measured
Calculated

	[5]	[6]	[7][2]	[8]	[9][3]	This work
Sensitivity (dBm)	-87	-95	-100	-72	-52	-50
Supply current	13.5 µA/ 11.1mA[1]	500 – 1875µA	400 µA	104 µA	2.78 µA	6.8 µA
Supply voltage	1.9 – 3.6V	0.4 V	1 V	0.5 V	3V	3 V
Latency	1 s	70 µs[4]	4ms[4]	200 µs[4]	13 ms	13 ms
Architecture	BT LE, heterodyne	resistive mixing	super-regen.	uncertain IF[2]	passive mixing	passive mixing

[1] Average with the latency mentioned / receiver on state.

[2] Carrier frequency 1.9 GHz.

[3] Carrier frequency 900 MHz.

[4] Estimated time for a 20-bit transmission based on data rate.

Generator resistance	$R_g = 50\ \Omega$
Series resistance of L_1	$R_1 = 0.082\ \Omega$
Series resistance of L_3	$R_1 = 0.35\ \Omega$
DC bias resistor	$R_3 = 1\ \mathrm{M}\Omega$
Parallel resistance of load	$R_4 = 1\ \mathrm{M}\Omega$
Series resistance of the diode	$R_d = 6\ \Omega$
Matching inductor	$L_1 = 6.8$ nH
Matching inductor	$L_2 = 4.8$ nH
RF-block inductor	$L_3 = 56$ nH
Matching capacitor	$C_1 = 1.5$ pF
Parallel capacitance of L_1	$C_2 = 0.1$ pF
Junction capacitance at zero bias	$C_{j0} = 0.18$ pF
Low frequency block capacitor	$C_3 = 2.2$ pF
Parallel capacitance of L_3	$C_4 = 78.5$ pF
DC-block capacitor	$C_5 = 1$ nF
Parallel capacitance of load	$C_6 = 1$ pF
Matching capacitor	$C_7 = 2$ pF
Parameter for the depletion capacitance	$\gamma = 0.5$
Junction potential	$\varphi = 1$ V
Saturation current	$I_s = 18$ nA
Diode parameter	$\alpha = 31\ \mathrm{V}^{-1}$

Transmit power	$P_{tx} = 5.6$ mW
Transmit antenna gain	$G_{tx} = 2.0$ dBi
Receive antenna gain	$G_{rx} = -2.0$ dBi
Carrier frequency	$f_{RF} = 2.45$ GHz
Bit rate	$f_{bit} = 2730$ Hz
Wake-up Bandwidth	$BW = 40\ 000$ kHz
Wake-up sensitivity	$V_0 = 100\ \mu V_{rms}$
Receiver sensitivity	$\beta = 7943$ V/W
Number of bits in packet	$n = 22$