

A 470 μ W -92.5dBm OOK/FSK Receiver for IEEE 802.11 WiFi LP-WUR

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Abstract—An IEEE 802.11 WiFi LP-WUR receiver in 40nm CMOS technology is presented. The direct down-conversion receiver improves sensitivity by allocating single sidebands above the flicker noise corner for received signals. The receiver demodulates wideband FSK/OOK modulated wake-up messages generated by an 802.11 OFDM WiFi transmitter operating at 5.8GHz. The receiver achieves a sensitivity of -92.5dBm while consuming 470 μ W in OOK demodulation, and sensitivity of -90dBm while consuming 490 μ W in FSK demodulation at a BER of 10^{-3} and data-rate of 62.5kb/s. The radio uses an external clock as external component for baseband demodulation, and frequency calibration.

Keywords—Passive mixer, LC-VCO, 802.11 LP-WUR, WiFi wake-up

I. INTRODUCTION

WiFi (IEEE 802.11 a/g/n/ac/ax) is the most ubiquitous wireless protocol, however legacy 802.11 radios limit the widespread adoption of WiFi in ULP IoT applications because of its excessive active power, and radios usually dominates power consumption of the IoT device. The 802.11 LP-WUR task group has proposed adding wakeup packets to WiFi to reduce the average power without increasing latency [1]. The 802.11 wakeup message uses OOK signaling embedded in an orthogonal frequency division multiplexing (OFDM) WiFi packet, that can be received by an ULP radio [2] while the higher-power WiFi radio remains asleep. This method requires modifying the firmware of legacy WiFi routers, reducing potential impact. As a complimentary wakeup solution, WiFi back-channel communication has been proposed with full backward-compliance with legacy (IEEE 802.11a/g/n) routers [3],[4]. This involves producing FSK or OOK modulated WiFi OFDM packets from legacy WiFi transmitters without firmware/hardware modifications. These prior works, however, have limited range due to its relatively high sensitivity, which is worse than the best sensitivity of commercial 802.11 radios.

In this paper, an ULP 5.8GHz 802.11 wake-up receiver is presented, which supports both 802.11 LP-WUR / back-channel OOK and wideband FSK for improved selectivity, with a sensitivity close to the received signal strength of 802.11 OFDM radio at its lowest link speed (Fig. 1). A mixer-first front-end is used to save power, with a simulated NF of 12dB. The receiver achieves a sensitivity of -92.5dBm at a BER of 10^{-3} and data rate of 62.5kb/s, while operating at 470 μ W.

The rest of the paper is organized as follows. The 802.11 LP-WUR OOK/FSK frequency planning, and its system level (de)modulation will be covered in Section II. Detailed circuit

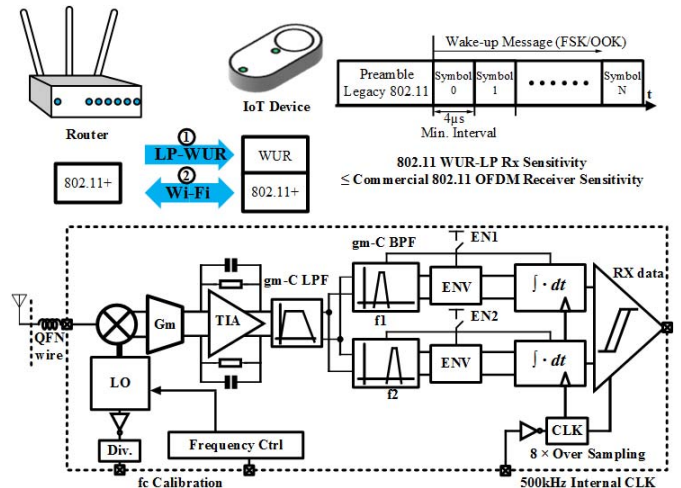


Fig. 1. Block diagram of the receiver, and its system level application.

implementations targeting low-power and low-sensitivity will be covered in Section III. Measured results of the receiver, and a performance comparison will be covered in Section IV. Finally, Section V concludes the paper.

II. 802.11 LP-WUR OOK/FSK (DE)MODULATION

The frequency plan of the 802.11 LP-WUR is shown in Fig. 2. Legacy OFDM WiFi transmitters do not currently support simple modulations such as OOK and FSK, however their wideband DAC-based multi-carrier architectures are capable of producing a wide range of non-OFDM signals [2]. OOK or FSK symbols can be generated by only updating the firmware of an 802.11 OFDM radio to selectively allocate (unequal) power to a subset of the 64 subcarriers [1-2] and disable other unused subcarriers. Notice that OOK and FSK can use more than one subcarrier, and subcarriers are 312.5kHz apart, thus realizing relatively wideband modulation compared to conventional

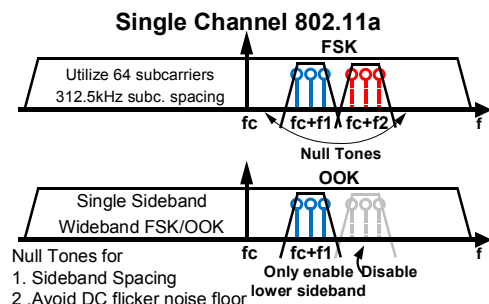


Fig. 2. Frequency plan of 802.11 LP-WUR OOK/FSK, and received waveform

OOK and FSK. In the proposed system, OOK and FSK power allocation is asymmetric with respect to the WiFi channel center frequency to enable single sideband (SSB) modulation as shown in Fig. 2. That is, OOK and FSK signals utilize only one side of the WiFi channel and their center frequencies are also strategically shifted from the center of the WiFi channel to avoid flicker noise in the proposed direct down-conversion architecture. Specifically, the two FSK symbols are placed at 1.575MHz and 2.5MHz off from the WiFi channel center frequency, whereas OOK utilizes only one symbol that is closer (1.575MHz off) to the WiFi channel center frequency. Because the WiFi wake-up message is generated by a WiFi OFDM transmitter, its symbol rate and subcarrier spacing is identical to that of the legacy 802.11 OFDM modulation; 250k sym/s and 312.5kHz, respectively.

III. CIRCUIT IMPLEMENTATIONS

The system architecture, shown in Fig. 1, implements a one-step down-conversion of the WiFi channel to zero-IF, placing the SSB FSK signal at an IF of 1-3MHz. Unlike OFDM receivers, it does not require a highly linear RF front-end, high-bit ADC, and significant digital baseband processing such as an FFT due to its relatively simple demodulation scheme. In addition, the receiver does not require quadrature mixing for in-band image rejection due to its single sideband usage. The wideband nature of the proposed OOK/FSK makes the system relatively insensitive to frequency offset and phase noise (PN) performance of the LO, thus eliminating the need for a high quality PLL. A free running onetime-programmable LC-VCO is implemented for low active power. The 1-3MHz IF helps the receiver avoid flicker noise by placing active subcarriers

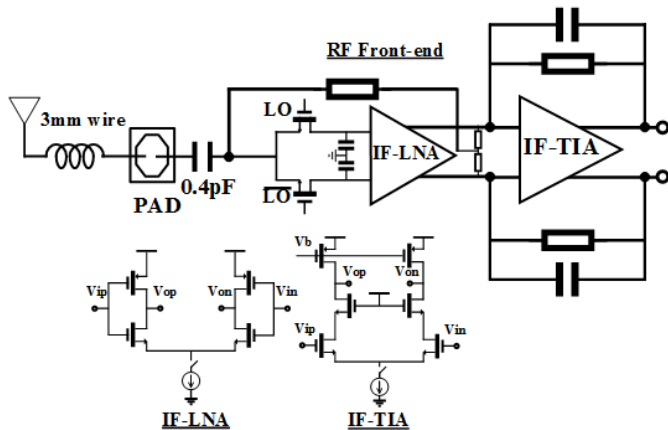


Fig. 3. Circuit Implementations of RF front-end & intermediate gain stages

beyond the noise corner frequency, improving overall noise performance. Programmable band pass filters are implemented for integrating the energy of each sideband. The center frequency of the filter is tunable within the 8MHz single sideband. In addition, the receiver can select the demodulation type between FSK and OOK by en/disabling one path.

A. RF Front-end & Intermediate Frequency Stage

The sensitivity target is set to -93dBm to match the sensitivity of an 802.11 receiver at its slowest link speed. This

sensitivity target translates into a system noise figure (NF) of 12dB. A passive mixer first architecture is chosen for ULP receiver design, however, these typically have a NF (NF) over 20dB [2-3],[6]. This is due to its low conversion gain (insertion loss + passive RF gain) compared to noise introduced from switching resistance [6-7], and NF is also affected by following gain stage. Specially, a zero-IF passive mixer-first architecture has worse NF because the first stage has less gain which is eventually unable to suppress flicker noise of following IF gain stages. NF is improved by increasing the W/L ratio of the passive mixer for switching resistance reduction, and the W/L ratio of following IF gain stage. Direct LO-mixer connection in Fig. 4 enables the receiver to achieve lower NF by only sacrificing a small amount of current from the following IF-LNAs, striking a balanced trade-off between power consumption and NF improvement. Avoiding the flicker noise corner, the receiver achieves a NF of 12.5dB. If necessary, further NF improvement can be achieved with a multi-phase mixer that rejects harmonics and noise at the image frequency, which leads to reduction in switching noise. This, however, requires a significantly large amount of current compared to the

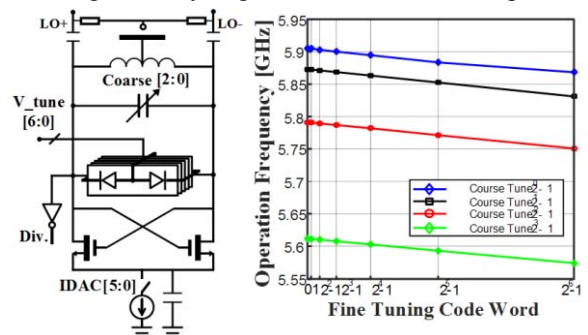


Fig. 4. Circuit detail of LC-VCO, and its tuning steps.

single differential passive mixer [6-7].

To reduce the parasitic loading and on-chip cap from multiple RF front-end paths which affects the Q factor, while maximizing the voltage boost to the load and gain efficiency, a DC-coupled inverter type amplifier is used at baseband instead of AC coupling immediately after RF down-conversion. This requires careful biasing, therefore a self-bias feedback loop is

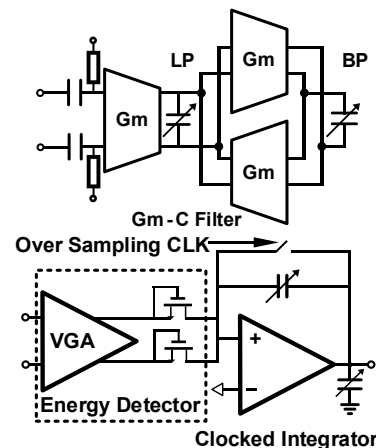


Fig. 5. Baseband circuits. Top figure is a unit cell of Gm-C filters, and bottom figure is an energy detection circuit which is composed of energy detector & clocked integrator.

added around the RF input node reducing the overall parasitic loading from the RF front-end. The IF-LNA is biased with a current controlled DAC to relieve the common mode mismatch. The measured down-converted IF gain from RF to TIA is 42dB. This mixer-first approach saves significant power because the baseband amplifiers require much less active power than 5.8GHz RF gain stages.

B. Local Oscillator

At low RF frequency, an RVCO may be considered as a LO for ULP applications because of its low active power. However, its application is limited by its excessive phase noise. According to the binary FSK demodulation analysis [8], a phase noise of -76dBc/Hz at 1MHz offset is required for FSK demodulation with a frequency deviation of 1MHz. As the total interference rejection of the receiver is limited by the phase noise rather than order of the active filters, using an RVCO at the 5.8GHz carrier leads to higher power consumption than that of the LC-VCO with the same specification.

Thus, the proposed receiver uses a NMOS cross-coupled LC-VCO as the LO. As shown in Fig. 4, the mixers are fed by an LC-VCO directly without LO buffers to further reduce power consumption. The LC-VCO is composed of 3-bit coarse tuning bits and 7-bit fine tuning bits to cover different channels of the IEEE 802.11a standard. The LC-VCO operates at 5.560-5.905GHz with a frequency step of 400kHz, sufficient for the 2MHz LP-WUR FSK frequency deviation. The LC-VCO is free running and one-time calibrated to fix the frequency, however an FLL could be added for better tracking.

C. Baseband Stage

For FSK demodulation, the down-converted IF signal is first low pass filtered and then band pass filtered in two paths with center frequencies of $f_1 = 1.575\text{MHz}$, and $f_2 = 2.5\text{MHz}$ respectively. 2nd-order Gm-C filters were used for each filter design. As shown in Fig. 2, the filtered IF signals are rectified, integrated, and 1-bit compared at a 2x over-sampled frequency of 500kHz to find the accurate symbol boundary. OOK data is retrieved by enabling only one filter path and comparing its output with a fixed DC level at the 1-bit comparator. At a coding rate of $\frac{1}{4}$ (i.e. 4x spreading), symbols are 8X over-sampled, and by post processing the 1-bit comparator output, the wake-up message is retrieved. In FSK mode, the energies from both filter paths are simultaneously compared to determine the received bit.

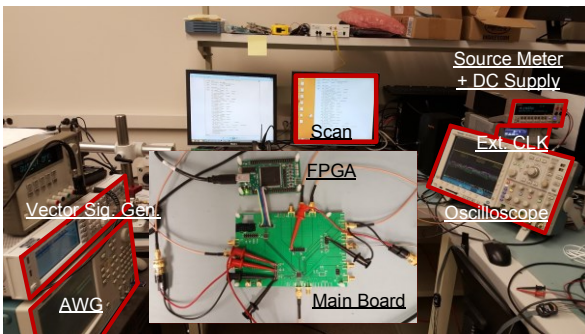


Fig. 6. Test Set-up

IV. MEASURED RESULTS

The receiver was fabricated in a CMOS 40nm technology. The active area is 0.166mm². Fig. 5 shows the measured BER waterfall curve and SIR with the signal bandwidth for each FSK path programmed to 1MHz. The measured sensitivity of receiver for OOK is -92.5dBm at a BER of 10⁻³ and data-rate of 62.5kbps while consuming 470μW. For FSK demodulation, it is -90dBm at a 62.5kbps data rate while consuming 490μW.

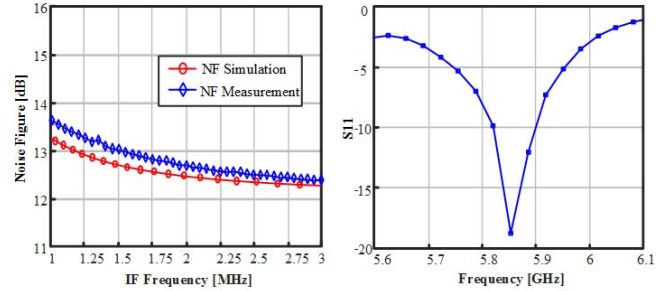


Fig. 7. Noise figure, and S11 of the receiver

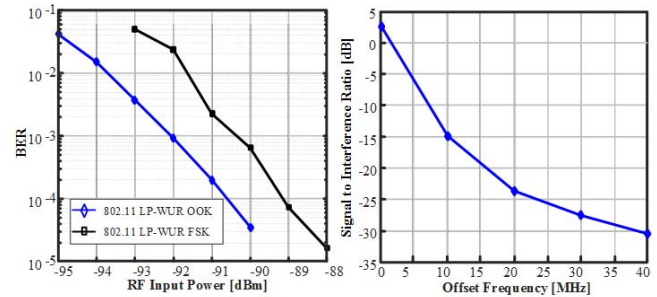


Fig. 8. BER waterfall curve, and SIR of the receiver

Data Rate: 62.5kb/s (Coding Rate: 1/4)
Oversample data to find symbol boundary

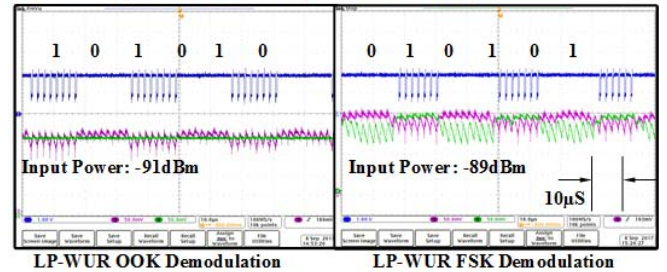


Fig. 9. Demodulated waveform and RX data output at final baseband stages.

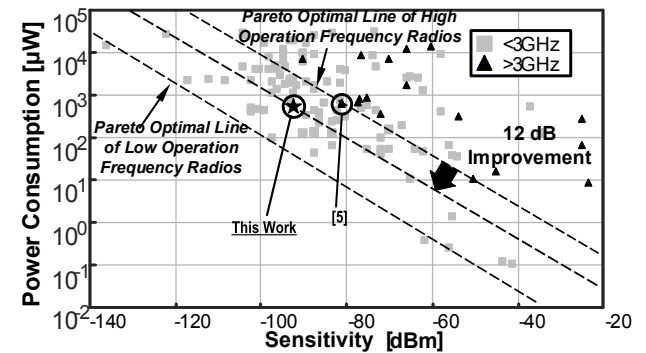


Fig. 10. ULP radio survey from 2005 to present. The data of the radio survey is from top conferences (ISSCC, VLSI, RFIC, CICC) and commercial TRX chips.

TABLE I
COMPARISON WITH STATE-OF-ART ULP RADIOS

	RFIC 2017 [2]	JSSC 2016 [6]	JSSC 2015 [5]	RFIC 2017 [3]	This Work	
CMOS Tech. [nm]	14 FinFET	65	90	65	40	
External Component	32kHz RTC	High-Q inductors External Clock	1MHz External Clock	250kHz External Clock Off-chip RF Filter	500kHz External Clock (Calibration & Demod. CLK)	
Carrier Frequency [GHz]	2.4	2.4	3-5	5.8	5.8	
Voltage [V]	0.95	0.5	1	1	0.95/0.5**	
WiFi WUR	Yes	N.A.	N.A.	N.A.	Yes	
Modulation	OOK	OOK	FM-UWB	FSK	OOK	FSK
Sensitivity [dBm] @ 10^{-3}	-72	-97/-92	-80.5	-72	-92.5	-90
Active Power [μ W]	95	99	580	335	470	490
Noise Figure [dB]	NA.	20***	6.6	25***	12.5	
Data Rate [kb/s]	62.5	10/50	200	31.25	62.5	
LO Generation	Ring with FLL	Unlocked LC-VCO	No LO, RF Env.	Ring with FLL	Unlocked LC-VCO	
SIR*[dB]	-20****	-25/-22	-28	-13	-24	

* Adjacent Channel **0.5V for LC-VCO, 0.95V for Analog Blocks

*** Back calculated from Sensitivity [dB] = $-174 + \text{signal BW} + \text{NF} + \text{SNRout}$. **** ACI rejection measurement

TABLE II
RECEIVER POWER BREAK-DOWN

	LC-VCO	IF-LNA	TIA	Gm-C Filter	VGA	Env. + Int.	Bias Circ.
Power [μ W]	370	40	15	30	10	15	10

Benefiting from the relatively wide channel separation of WiFi, the receiver achieved a signal to interference ratio (SIR) of -24dB and -28dB from adjacent channels 1 and 2 respectively. The measured NF at the down-converted IF was 11.8-13dB, which is <1dB error compared to the simulated NF. Table I summarizes the performance of the receiver with state of art wake-up radios. According to ULP radio survey shown in Fig. 10 [9], this receiver shows a 12dB improvement compared to the next best ULP receiver operating at >3GHz in terms of sensitivity vs. power tradeoff.

V. CONCLUSION

This paper introduced an 802.11 LP-WUR receiver in 40nm CMOS technology. The direct down-conversion receiver improves sensitivity by allocating single sidebands above flicker noise corner. The receiver demodulates wideband FSK/OOK modulated wake-up message which is generated by 802.11 OFDM transmitters. The receiver achieves a sensitivity of -92.5dBm while consuming 470 μ W in OOK demodulation, and a sensitivity of -90dBm while consuming 490 μ W in FSK demodulation at a BER of 10^{-3} and data-rate of 62.5kb/s. In terms of sensitivity versus power consumption, the radio creates new pareto optimal line for >3GHz ULP receivers.

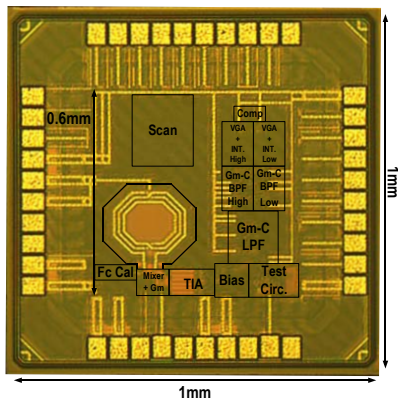


Fig. 11. CMOS 40nm chip photograph.

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