Experimental Investigations on RF Filters in Wake-up Receiver Circuits

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***Abstract*—Wake-up receivers (WuRxs) implementations have emerged as a groundbreaking solution to address the challenges of energy consumption and communication latency in battery-constrained applications. These receivers enable devices to be in continuous receiving mode while minimizing power consumption. WuRxs are subject to out-of-band interferences due to the shared nature of the communication environment. These interferences can degrade the WuRx's overall performance. RF filters serve as a common technique to attenuate unwanted signals from nearby frequency bands hence ensuring the receiver's immunity to interference and enhancing the detection reliability of wake-up signals. In this work, we investigate the impact of integrating off-the-shelf RF filters into WuRxs front-ends, focusing on both laboratory-controlled experiments and real-world scenarios. The findings reveal that although the introduction of RF filters slightly reduces the WuRx sensitivity, it significantly enhances its resilience to interference and reduces random losses. This research highlights the trade-offs involved in filter integration, providing essential insights for optimizing WuRx implementations.**

***Index Terms*—Wake-up receivers, RF filters, Front-end, Selectivity, Sensitivty, Interference, Random packet loss, Missed wake-ups, Trade-off.**

I. INTRODUCTION

Energy efficiency is the major concern when designing battery-powered devices. Wake-up receiver (WuRx) implementations have emerged as a groundbreaking solution to address the challenges of power consumption in on-demand or low-latency applications. These receivers enable devices to be in continuous receiving mode while minimizing power consumption. [1]

Piyare et al. [2] categorized the WuRx implementations into two groups: ASIC-based (application-specific integrated circuit) WuRx and WuRxs implemented using commercial off-the-shelf (COTS) components. ASIC implementations allow for more sensitive and power efficient circuits, however require high production costs for small quantities. Only COTS WuRx allow the implementation in prototypes, because we still found no application-specific integrated circuit (ASIC) implementations commercially available. Our research group concentrates on the COTS-based implementations of WuRx, because of the improved repeatability of results, simpler and more cost-effective implementations. The experiments presented in this article utilize COTS WuRxs. However, the conclusions are applicable to ASIC implementations with wide RF input bandwidth, too.

The transmission of the wake-up packet (WuPt) in the RF range becomes necessary when transmission power consumption and antenna size are restricted by the given application. A low-power LF–RF conversion is needed, because WuPt detection is typically done in the LF range. The simplest and most power-efficient technique of down-conversion is a passive RF envelope detector (RFED). [3]

Fig. 1 shows the typical building blocks of RFED based WuRx. The first building block, the RF band-pass filter is the scope of this article. It limits the bandwidth of the RF input and rejects out-band signals. The RF filter is followed by an optional low-noise amplifier (LNA). The LNA is an RF amplifier, that boosts the RF input signal. The power consumption of such amplifiers are typically high making them unsuitable for an always-on application. Therefore, a duty-cycling approach of the WuRx must be utilized. [4] The key component in this setup is the passive envelope detector, responsible for signal detection and conversion into a LF signal. Subsequently, further amplification of the LF signal can be required to make it suitable for detection by the subsequent analog–digital converter (ADC). The ADC component generates the digital signal. The simplest form is a comparator performing an 1-bit conversion. For added

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functionality, a digital address correlator can also be integrated to enable the WuRx to implement addressing capabilities and prevent false wake-up events. [4]

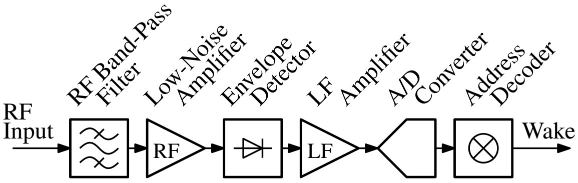

Fig. 1. Typical architecture of a WuRx utilizing an RFED according to [4]

Off-the-shelf WuRxs based on passive envelope detection are commonly used. However, RFEDs have a broad-band and bandpass frequency response in tandem. Other common front-end components like antennas and LNAs have band-pass frequency responses, but they also do not offer a narrow-band response. RF filters become essential to limit the input bandwidth and reject out-of-band interferences. On the other hand, insertion loss (IL) is inevitable. It degrades the the signal-to-noise ratio (SNR), and therefore the receiver noise figure. Therefore, the WuRx's minimum detectable signal (MDS) level increases and the radio coverage decreases.

By integrating different COTS RF filtering technologies into different WuRxs designs, this work highlights the trade-offs involved in filter integration into the front-end of a WuRx circuit and provides essential insights for optimizing WuRx implementations. The remainder of this paper is structured as follows: In Section II, we present an overview of relevant literature on RF filter technologies and WuRx solutions implemented with COTS RF filters. In Section III, we introduce important performance metrics and the measurement setup used. In Section IV, we present the results of our experiments. We summarize and discuss the article in Section V.

II. State of Research

A. Filter Technologies

Surface acoustic wave (SAW) and ceramic filters have emerged as prominent filtering technologies due to their exceptional performance characteristics and suitability for low-power applications. SAW filters are based on the interaction of acoustic waves propagating along the surface of a piezoelectric substrate, offering a compact and highly selective solution for signal filtering. These filters excel in terms of narrow bandwidths, high out-of-band attenuation, and excellent temperature stability. Ceramic filters, on the other hand, leverage the piezoelectric properties of ceramic materials to achieve precise signal filtering. They are known for their compact form factor, not as compact in size as SAW filters though, making them still suitable for integration into space-constrained devices. Ceramic filters also exhibit favorable electrical characteristics, providing good selectivity and attenuation. Their relatively simpler manufacturing process often translates to cost-effective solutions for applications demanding high-performance filtering on a budget. [5]

Other filtering technologies like lumped components or microstrip filters present some major drawbacks not making them the ideal filters for WuRxs. For instance, the availability of lumped components can be challenging as COTS components come in standardized values. In practical manufacturing, it is nearly impossible to create components with exact values as specified in the design. Both inductors and capacitors have tolerances and parasitics associated with their nominal values. These tolerances can affect the accuracy of the filter's cutoff frequency and overall performance. Generally, discrete lumped elements find their conventional usage when operating at lower frequencies. As the operational frequency increases, the parasitic effects alter the filter's performance. As the complexity of the filter increases, requiring more stages or higher-order designs, the number of components also increases. The accuracy of the filter's center frequency Δf_c depends on the accuracy of the component values. This is derived in Eq. 1 for a simple LC filter.

$$f_\mathrm{c} = \frac{1}{2\pi\sqrt{LC}} \quad \Rightarrow \quad \frac{\Delta f_\mathrm{c}}{f_\mathrm{c}} = \frac{1}{2} \cdot \left(\left| \frac{\Delta L}{L} \right| + \left| \frac{\Delta C}{C} \right| \right) \tag{1}$$

Δf_c defines the minimum possible bandwidth to ensure that the desired center frequency always lies in the filter's pass-band. For typical component accuracy of 5% and a center frequency of 868 MHz and minimum possible bandwidth is 43 MHz. Comparing this value to bandwidth capabilities of the SAW filter technology (see Table I), shows a degradation of nearly one order of magnitude.

On the other hand, one of the major limitations of microstrip technology is the physical length. These filters require resonator sections. The more sections needed the more the filter grows in length. Each section requires a minimum path length of $\lambda/4$ [6]. For 868 MHz, $\lambda/4 = 86$ mm. Even with specialized folding techniques, such filters are generally larger than the sensor node's battery making them very unsuitable for the application in the sub-GHz bands. Increasing the center frequency, decreases the filter size. However, this is often not applicable for WuRx applications, because path loss increases and WuRx sensitivity is already limited.

B. Wake-Up Receivers

Doorn et al. [7] proposed a WuRx based on RFED working in the 868 MHz band. In this article, minimizing the risk of false wake-ups due interference was an area of focus while designing the WuRx. In this context, the authors implemented a SAW filter in the WuRx's front-end. Their experiments consisted of observing the receiver's behavior. First, by keeping the receiver run without sending any wake-up signal in a typical RF environment and second by sending a global system for mobile communications (GSM) signal in the wake-up range of the receiver. Based on the result of this experiment, the WuRx was concluded to be immune to interference from GSM band.

Bdiri et al. [8] proposed a WuRx with −90 dBm sensitivity by introducing an LNA in the WuRx's reception path. On one hand, the integration of an RF filter in the WuRx's block diagram was shown. However, no additional details were provided about the filter type or its effect on the WuRx performance. It remains unclear, whether the characterization of the WuRx was performed with or without the SAW filter. For example, the photograph provided by the article shows the node without the SAW filter.

A different design based on RFED and low-frequency pattern matcher (LFPM) is proposed by Bdiri et al. [9]. The integration of a SAW filter in the WuRx front-end was shown in the sensor node's photograph, although it was not included in the WuRx block diagram. No further details were provided about the used filter component, its characteristics and impact on the overall performance.

For our measurements, we will utilize the WuRx design proposed by our research lab in [4]. It reaches a sensitivity of over −80 dBm by introducing an LNA. We introduced a 2.5-dB IL SAW filter to the WuRx. It was mentioned, that filter's IL directly impacts the WuRx's sensitivity. However, a measurement or direct comparison was not performed. In many recent articles like [10]–[14] no RF filter was referenced. To our knowledge, previous literature showed that there is always a trade-off between the power consumption, sensitivity and latency of the WuRx. However, areas like the trade-off between the WuRx sensitivity and the RF filter selectivity or the impact of out-of band interference on the WuRx's radio coverage were not covered. The impact of RF filter integration on the other performance metrics of the WuRx was not investigated and no performance comparisons between WuRxs implementations with and without RF filters were provided.

This publication introduces COTS SAW and ceramic filters into different WuRxs designs and provides an extensive investigation of the implications of their integration on the overall performance of the WuRxs.

III. Measurement Setup

A. Component Selection

To study the impact of integrating an RF filter into a WuRx's front-end, we selected four SAW filters and one ceramic filter based on their characteristics. The center frequency was fixed to 868 MHz because of the selected WuRx designs. Filters with different values of IL and bandwidth (BW) were selected.

Table I shows the characteristics of the chosen COTS filters based on their datasheets.

TABLE I
Parameters of Commercially Available SAW and Ceramic Filters in the 868 MHz Band Based on Datasheets

No.	Type	Part Number	f_c in MHz	IL in dB	BW in MHz[1]
1	SAW	B39871B4377P810	866.5	2.3	14
2	SAW	B39871B2636P810	869	2.7	7
3	SAW	SF2137E	869	2.8	17
4	SAW	SF2137E-2	869	2.3	12
5	Ceramic	DBP.868.U.A.30	868	3	4

[1] −3 dB bandwidth according to the datasheets

These filters were incorporated into different WuRxs designs, that were proposed by our research group in [4], [15]. The LFPM-based WuRx was proposed in [15]. We proposed a WuRx working in the 868 MHz band based on an RFED and LFPM. Because of the excellent signal detection capabilities of the LFPM (138 µV_{PP}) no additional amplifiers are needed to reach an MDS of −62 dBm. The LNA-based WuRx was proposed in [4]. Because the LNAs draw around 6.7 mA, a duty-cycling approach is needed. The WuRx is able to detect the presence of a WuPt within 50 µs, by having a fast LF circuit. Specialized LF amplifiers, comparator circuit, and address coding is proposed.

B. Measurements

Comparing the RF filter together with the RFED was done by probing the RFED's DC output signal. A block diagram of the instruments used in these measurements are shown in Fig. 2.

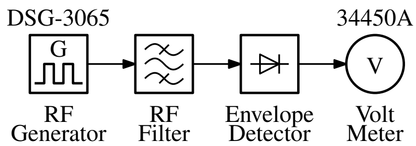

Fig. 2. Setup and utilized instruments for RFED DC output signal measurement

We investigated the impact of out-of-band interference on the WuRx. Due to interference, the trigger event could be overwhelmed or masked which leads to missed wake-ups. Also, the WuRx may unnecessarily activate when it erroneously detects a faulty trigger event. However, measuring false wake-ups falls behind the scope of our work. As other measurements showed, the communication protocol of both WuRx prototypes are extremely reliable and false wake-ups occur seldom [16].

The wake-up range is inversely related to the WuRx's MDS (Friis equation [17]). We measured the MDS, signal-to-interferer ratio (SIR), and wake-up range based on the estimation of the packet error rate (PER).

Fig. 3 shows the building blocks of our measurement setup. The PER measurement unit transmits a fixed number of packets n_{TX}. An RF generator converts this packets to the RF of 868 MHz and connects to the device under test. The PER measurement unit count simultaneously the number of received packets n_{RX} through a digital connection to the WuRx. The PER is estimated according to Eq. 2.

$$\mathrm{PER} = 1 - \frac{n_{RX}}{n_{TX}} \tag{2}$$

Measuring other performance metrics like power consumption and latency are not covered by this article. These metrics are not affected when introducing the passive RF filters due to the nature of the utilized WuRxs.

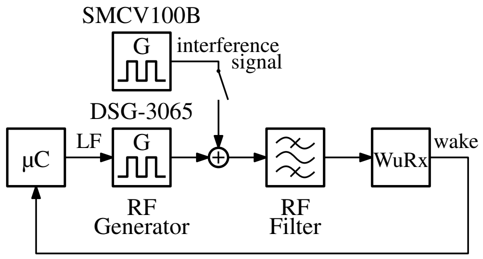

Fig. 3. Block diagram of PER measurement system

IV. Results

In this section, we present a comprehensive analysis of our measurement results. The performed measurements collectively contribute to unraveling the implications on the overall performance of the WuRxs equipped with COTS RF filters. Through this systematic exploration, we endeavor to shed light on the trade-offs involved in filter integration and offer insights for optimizing WuRx implementations.

In the following, we present the results of the S-parameters, RFED output, MDS, interferer and indoor measurements.

A. S-Parameters

Fig. 4 shows the measured $|S_{21}|$ of each one of the filters stated in Table I. All filters showed nearly identical properties to their respective datasheets, especially the SAW filters labeled 1 and 2. In terms of selectivity, SAW filter 1 is the most promising compared to the other filters. In terms of IL, all the filters showed very close values. The ceramic filter shows clearly a lower attenuation in the stop-band.

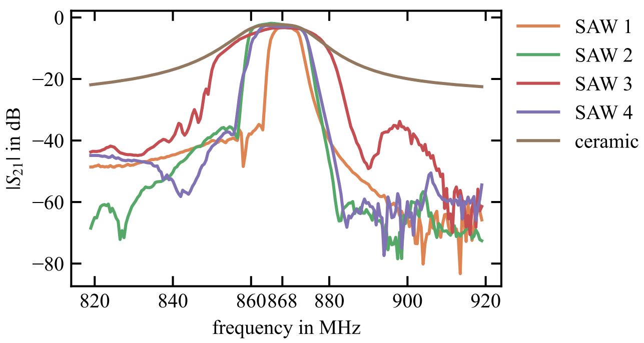

Fig. 4. Magnitude of the S_{21} parameter of all investigated filters

B. Envelope Detector Measurement

The RFED is characterized by a both broad and passband frequency response. After adding the RF filter, the frequency response becomes significantly narrower especially with the SAW filter 1. This can be seen in Fig. 5 The five filters show different output voltage levels in the passband region. This is due to the different IL introduced by each filter. SAW filter 3 introduced the highest IL compared to the other filters. On the lower side, both ceramic and SAW filter 1 have comparable values. SAW filter 1 shows the narrowest frequency response.

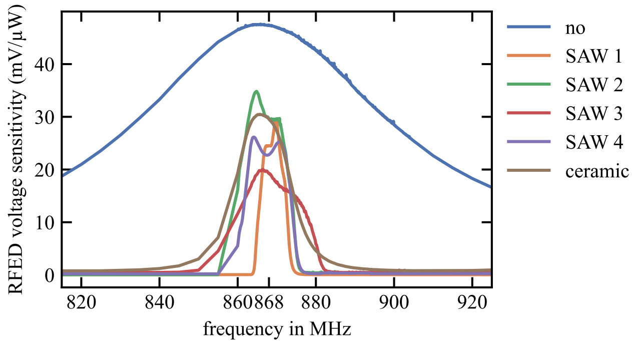

Fig. 5. RFED voltage sensitivity without and with all investigated filters attached

C. Minimum Detectable Signal Measurement

We defined the MDS as the minimum input power, where the WuRx is capable of receiving WuPts with less than 30% PER. [15] We repeated the PER measurement for different input power values and estimated the MDS by regression. Fig. 6 shows the MDS curves of the LFPM-based WuRx equipped with all investigated filters.

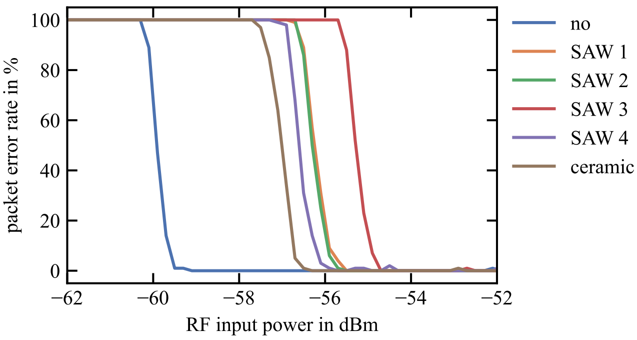

Fig. 6. LFPM-based WuRx MDS curves without and with all investigated filters attached

It was noted that, by adding the RF filters, the WuRx's MDS is degraded. This is due to the additional IL introduced by the filter. SAW filter 3 introduced higher IL compared to the other filters. On the other hand, the ceramic filter added the least IL.

Similarly, adding the RF filter to the duty-cycled WuRx degraded the MDS as shown in Fig. 7. However here, the IL is less significant compared to the LFPM-based WuRxs. Filter 1 degraded the MDS the most compared to the other filters. However, this degradation is only approximately 2 dB.

D. Interference Measurement

In a typical RF environment, the WuRxs are subject to interference from nearby bands. Neighboring GSM and radio-frequency identification device (RFID) utilize strong transmit-

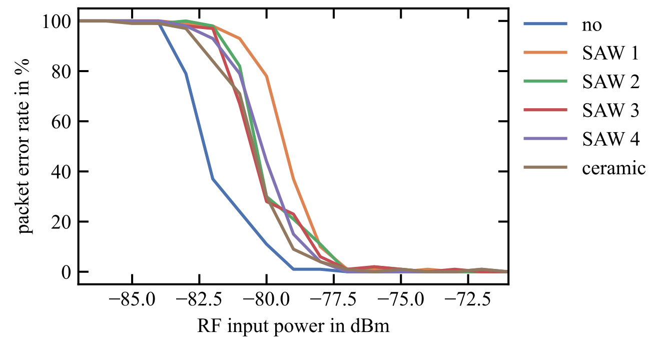

Fig. 7. LNA-based WuRx MDS curves without and with all investigated filters attached

ters, potentially resulting in strong interference sources. Table II summarizes the characteristics of the used interferer signals.

TABLE II
INTERFERER SIGNALS CHARACTERISTICS

Frequency Band	RFID	GSM
Frequency	866 MHz	880 MHz
Modulation	BPSK	
Data rate	100 $\mathrm{kbit\,s^{-1}}$	
Filter	Gauss	
Desired Signal RF power[1]	−45 dBm[2], −70 dBm[3]	

[1] at antenna port, [2] LFPM-based WuRx, [3] LNA-based WuRx

In this measurement the SIR is introduced. SIR quantifies the quality of a received signal necessary to reach a 30% PER. The SIR is calculated as the ratio between the desired signal to interfering signals. A more negative SIR value means stronger interference resilience. Both LFPM-based and LNA-based WuRxs showed significant resilience to interference in GSM band especially with SAW filters 1 and 2. Both receivers resisted stronger interferers due to the integration of these filters compared to the remaining filters. In the RFID sub-band, the improvement was notably less significant than in GSM band due to its proximity to the filter's pass-band. However, there was a visible improvement mainly with the use of SAW filter 1 which has the best selectivity. Table III summarizes the discussed results.

E. Indoor Measurement

In this subsection, we aimed to investigate how the RF filter affects the communication link coverage and the reception quality. To simplify and parallelize the measurements, only SAW filter 1 was used. This is based on the measurements, done in the previous subsections, revealing that SAW filter 1 was found to be more selective and ensured more interference resilience to the WuRx compared to the other four filters. The measurements were carried in a typical RF environment: the corridor of our building at Leipzig University of Applied Sciences. A photograph of our measurements setup placed in the corridor is seen in Fig. 8

TABLE III
SIGNAL INTERFERENCE RATIO MEASUREMENT RESULTS

Interferer	Filter	LFPM	LNA
RFID	no	−9	−12
	SAW 1	−11	−15
	SAW 2	−8	−6
	SAW 3	−10	−11
	SAW 4	−9	−13
	ceramic	−9	−13
GSM	no	−9	−9
	SAW 1	−50	−49
	SAW 2	−53	−47
	SAW 3	−13	−21
	SAW 4	−45	−46
	ceramic	−16	−20

Fig. 8. Place of the indoor measurement: corridor of Leipzig University of Applied Sciences building

For the LFPM-based WuRxs, WuPts were sent at the frequency of 868 MHz and RF level of 14 dBm. The distance between the receivers under test and the transceiver was incremented by 1 m until we reached the corridor's limit at 60 m. The PER measurement was repeated for each step. Fig. 10 shows the results of these measurements.

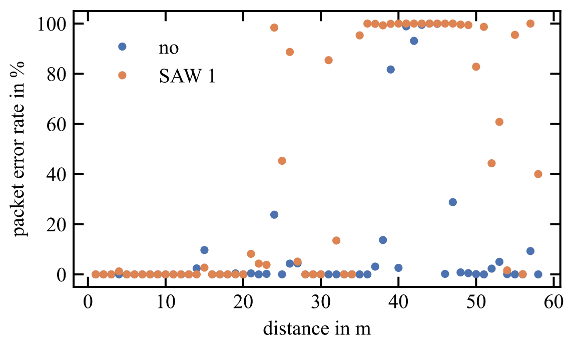

Fig. 9. PER of LFPM-based WuRx with and without SAW filter 1 for each measurement step of indoor measurements

A total of 58000 WuPts were sent during this experiment. The receiver equipped with SAW filter received 31622 WuPts. Whereas the WuRx without filter received 52148 WuPts. In other words, the WuRx without filter received approximately 1.6 times more packets than the receiver with SAW filter.

For the duty-cycled WuRxs, WuPts were sent at the frequency of 868 MHz and RF level of −5 dBm. We reduced the RF power to get decent attenuation over the corridor's length. The measurements were repeated in the same manner. Fig. 10 shows the results of these measurements.

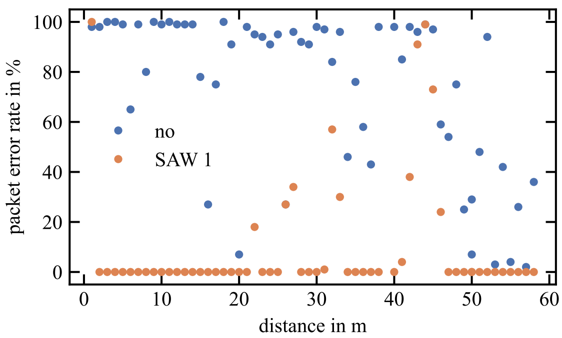

Fig. 10. PER for each measurement step of indoor measurements for LNA-based WuRx with and without SAW filter 1

A total of 5800 WuPts were sent throughout the whole experiment. A total of 5204 WuPts were received by the WuRx incorporating the SAW filter. Whereas the WuRx without filter was only able to receive 1515 WuPts. By adding the SAW filter to the LNA-based WuRx, the latter was able to receive over 3 times more packets during the whole experiment. In the case of the LNA-based WuRx, adding the SAW filter resulted in a significant reduction of random packet loss.

V. Conclusions

This work aimed to investigate the implications of integrating RF filters into WuRxs front-ends. While initially considering the design of custom filters, several reasons made them unsuitable for the intended application. Filters based on lumped components lack precision due to component variations and parasitics. Microstrip filters are typically larger then the node's battery, when working in the sub-GHz bands. This phase resulted in the selection of SAW technology as the most suitable for WuRxs due to its compactness and high selectivity. Controlled laboratory experiments, as well as real-world indoor scenariosrevealed that integrating a SAW filter into the WuRx's front-end led to a degraded MDS, due to the filter's IL. On the positive side, the WuRx's resilience to interference was significantly improved.Another notable outcome was the substantial reduction in random losses. Especially, the LNA-based WuRxs with MDS values below −80 dBm gained in selectivity. With the LFPM-based WuRxs, the signals are stronger, therefore interferers must be stronger to achieve the random packet loss. The interferers in our indoor environment were not strong enough to cause significant packet loss.

Further research and development efforts may focus on the impact of alternating the placement of the RF filter and the LNA on the total noise figure of the receiver [18]. Filtering the amplified signal reduces the additional noise introduced by the LNAs. In our experiments, the filter was always placed between antenna and LNAs.

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