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A Next-generation down conversion mixer design using Schottky diode to improve performance for WSN

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Abstract: Wireless Sensor Networks (WSNs) are expected to evolve significantly in the future.Wireless sensor networks typically operate at low radio frequencies and include 2.4 GHz, 868 MHz, and 433 MHz. In the future, networks are likely to use larges radio frequencies in mili meter wave because they offer more bandwidth and speed. The high bandwidth and low latency of future generation networks will enable WSNs to transmit large amounts of data quickly and reliably. Mixer applications can help to improve the efficiency and reliability of data transmission in WSNs, especially in situations where there are many nodes transmitting data simultaneously. When the frequency is high, a WSN mixer may have trouble with integration and linearity, and it will need more power.In this research, a down-conversion Gilbert cell mixer that uses a Schottky diode and a BALUN is suggested as a way to enhance the efficiency of mixer in WSN. The input frequency of the mixer is 122.5GHz, and the LO signal frequency is 120.1GHz. This mixer simulation was done with ADS 130 nm RF-CMOS. This mixer changes RF signals from 122.5 GHz to 2.4 GHz using Schottky diodes and baluns to improve RF-LO isolation (70dB), noise figure (11.0dB), and conversion gain (7.9dB). The purposed CMOS mixer possesses a 1-dB compression point in the RF bandwidth of -6.0 dBm and an IF output power of -4.9 dBm.

Keywords: WSN, Mixer, Conversion Gain, Linearity, Compression point, Noise Figure, BALUN, Schottky diode

1. INTRODUCTION

In its most basic form, the Wireless Sensor Network is a self organizing network comprised of a vast number of sensors that is meant to gather, analyse, and send data. The WSN is widely used in a variety of settings, including the military, healthcare, environmental science, industrial monitoring, and more [1].Wireless Sensor Networks (WSNs) at mm-wave represent a new frontier in wireless communications. The possible future frequency range for mm-wave is shown in Figure 1, which is characterised as being between 30GHz and 300 GHz [2].

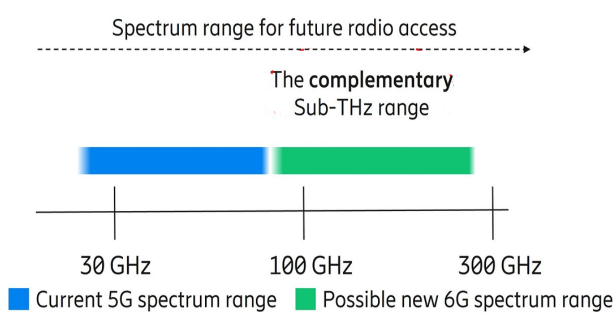

Figure 1. Possible Frequency range for future mm-wave

Wireless sensors can exploit white areas without bothering licence holders. To encourage technology development, unlicensed users can utilise such bands for free. Figure 2 shows ITU-R-defined ISM frequency ranges. At

Range	Center Frequency	Bandwidth
6.765–6.795 MHz	6.78 MHz	30 kHz
13.553–13.567 MHz	13.56 MHz	14 kHz
26.957–27.283 MHz	27.12 MHz	326 kHz
40.66–40.7 MHz	40.68 MHz	40 kHz
433.05–434.79 MHz	433.92 MHz	1.84 MHz
902–928 MHz	915 MHz	26 MHz
2.4–2.5 GHz	2.45 GHz	100 MHz
5.725–5.875 GHz	5.8 GHz	150 MHz
24–24.25 GHz	24.125 GHz	250 MHz
61–61.5 GHz	61.25 GHz	500 MHz
122–123 GHz	122.5 GHz	1 GHz
244–246 GHz	245 GHz	2 GHz

Figure 2. ISM frequency bands that are accessible for use, according to the definition provided by ITU-R. [3]

this frequency, the available bandwidth is much larger than at lower frequencies, which allows for higher data rates and better spectral efficiency. Future developments in wireless sensor networks (WSNs) are anticipated to be

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substantial.Wideband that works at 120 GHz and is made for greater speed wireless internet-of-things applications with short ranges is in trends [4]. WSNs will be a crucial component of the IoT ecosystem. The IoT will enable billions of devices to communicate with each other, and WSNs will play a crucial role in collecting and transmitting data from these devices. WSNs generate massive amounts of data, and machine learning algorithms can help analyze this data to derive useful insights. We can expect to see more intelligent and autonomous WSNs that can make decisions and take actions on their own.The WSN standard frequency specified by the IEEE 802.15.4 standard is 2.4 GHz. The 2.4 GHz frequency band is globally available and is regulated by national regulatory authorities. We need to convert any higher frequency like here RF frequency from 120 GHz to 2.4 GHz. To achieve this we require a down conversion mixer. A mixer is a nonlinear device that combines two or more input signals to produce an output signal that is the sum and difference of the input frequencies. In a down conversion mixer as shown in Figure 1, the local oscillator (LO) frequency is lower than the signal frequency, and the output frequency is the difference between the two. [5]. some key specifications to consider

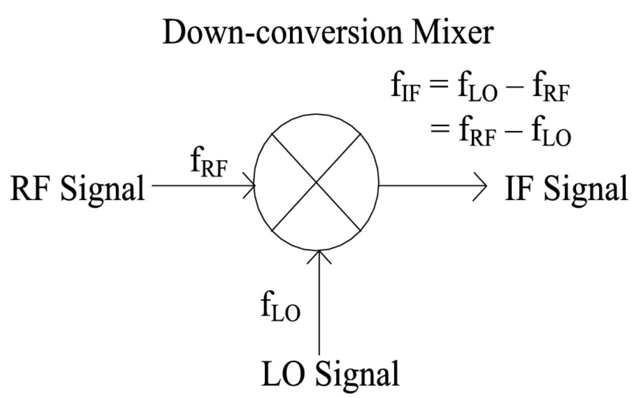

Figure 3. Symbol and operation of mixer [5]

when designing a Gilbert cell mixer for WSN network applications are:

Frequency range: The mixer should be designed to operate within the frequency range specified by the IEEE 802.15.4 standard for WSNs, which is typically 2.4 GHz.

Conversion gain: The conversion gain of the mixer is the ratio of input and output power, expressed in decibels (dB). In WSN applications, the mixer should provide high conversion gain to ensure that the RF signal is effectively downconverted to the desired (IF) range.

Noise figure: Noise figure (NF) of the mixer is a measure of the amount of noise added to the RF signal during the mixing process. In WSN applications, it is important to minimize noise figure to ensure that the signal-to-noise ratio (SNR) remains high, which is critical for reliable communication.

Linearity: The linearity of the mixer refers to its ability to maintain a linear relationship between the output and input signals. In WSN applications, the mixer should have high linearity to minimize distortion and intermodulation products that can degrade signal quality.

Power consumption: The power consumption of the mixer should be low to ensure efficient use of energy in battery-powered WSN nodes.

Isolation: The isolation of the mixer refers to its ability to suppress unwanted signals that may appear at its output. In WSN applications, high isolation is desired to minimize interference from nearby wireless devices.

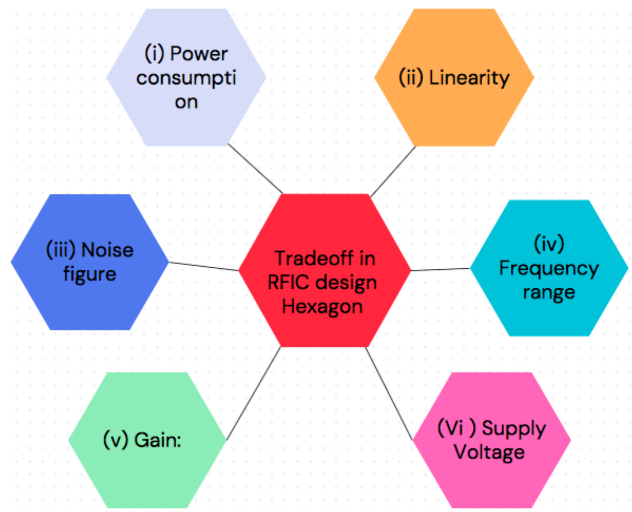

Figure 4. RFIC design Hexagon Trade-offs

The RF design hexagon as shown in figure 2 is a common tool for depicting trade-offs; it's a six-sided figure in which various performance measures are displayed on their respective sides [6]. The ideal design point is then selected based on the needs and limitations of the application. The hexagon is divided into six equal parts, each representing a different performance metric or design requirement, as follows: i) Power consumption: This represents the amount of power the RFIC consumes during operation. Lower power consumption is generally desirable for portable or battery-powered devices, but reducing power consumption can also impact other performance metrics, such as linearity and noise figure. ii) Linearity: This represents the ability of the RFIC to faithfully reproduce the input signal without distortion or non-linearity. Higher linearity is generally desirable to avoid signal distortion and interference. iii) Noise figure: This represents the amount of noise added by the RFIC during signal processing. A lower noise figure is generally desirable to improve the sensitivity and overall signal quality. iv) Frequency range: This represents the frequency range over which the RFIC operates. A wider frequency range is generally desirable for greater flexibility and compatibility with different wireless standards. v) Gain:

This represents the amount of amplification provided by the RFIC. A higher gain is generally desirable to improve the sensitivity and overall signal quality. vi) Supply Voltage : This represents the voltage level provided to the RFIC to operate properly. The supply voltage affects various performance parameters of the RFIC, including power consumption, noise performance, linearity, and output power. Typically, lower supply voltage results in lower power consumption but may also lead to lower output power and degraded noise performance. Higher supply voltage can lead to higher output power, but it also increases power consumption and may degrade linearity and noise performance.

2. METHOD

Wireless Sensor Networks (WSNs) are often used in applications that require low power consumption and low data rates. Down-conversion mixers are a key component in the RF front-end of WSN transceivers, as they are used to convert high-frequency signals to a lower frequency for further processing. Despite their importance, there are several research gaps in the study of down-conversion mixers used in WSNs. Here are some of them: a)Power consumption optimization: Although down-conversion mixers are used in low-power applications, there is still a need for further research to optimize their power consumption. This can involve the design of new circuit topologies, the use of different biasing techniques, or the incorporation of energy harvesting techniques. b)Improved linearity: Down-conversion mixers can suffer from nonlinearity, which can cause distortion in the received signal. Further research is needed to develop new design techniques that can improve the linearity of down-conversion mixers while maintaining their low power consumption. Integration with other RF front-end components: Down-conversion mixers are just one component of the RF front-end of a WSN transceiver. Further research is needed to investigate how down-conversion mixers can be integrated with other components, such as low-noise amplifiers, filters, and oscillators, to optimize the overall performance of the RF front-end. c)Compatibility with different wireless standards: WSNs can use different wireless standards, such as Zigbee, Bluetooth, and Wi-Fi, each with their own requirements for the RF front-end. Further research is needed to investigate how down-conversion mixers can be designed to be compatible with these different standards, while maintaining their low power consumption and high performance. d) Active mixer topologies that make use of the double balanced architecture along with current reuse property have found it difficult to ensure compatibility of the extra components like two BALUNs required to implement the balanced active mixer design. e) Another potential research gap is the optimization of mixer circuit topologies for use with Schottky diode elements in the high GHz range. The performance of a mixer is influenced not only by the properties of the diode element itself, but also by the circuitry surrounding it. There may be opportunities to develop new mixer topologies or optimize existing ones to better exploit the unique characteristics of Schottky diodes at high frequencies. Although some recent research works have attempted to work in this aspect, addressing these research gaps could help to improve RF mixer development and execution for more effective and efficient RF communications. High-performance mixers require balanced transformers, which may limit their frequency band [7], [8], [9]. we can have different mixer design approach for modern RF mixer architectures [10]. For low voltage supply and submicron manufacture, the mixer described in [11], [12] needs almost little DC power but suffers from Conversion losses and requires higher LO power. Depending on power loss, [13], [14] the single balanced design has less input noise but greater LO noise.In [15] showed a fundamental-to-dual-band subharmonic mixer where by adjusting its bias, the mixer may work in either subharmonic or fundamental modes and utilise seven milliwatts of dc power in either situation. This circuit may be suitable for a Milimeter Wave with low power and voltage requirements. Gilbert-cell mixers using 0.13-micrometre CMOS may run at 50 GHz [16], but studies shows that for higher RF frequency we can choose the higher scale CMOS technology.Gilbert cells are suited for low-frequency applications because to their effectiveness and short chip size. Gilbert mixers beyond 100 GHz are also attractive, but they require a corresponding circuit to expand bandwidth. Mixers for millimeter- and microwave waves that are passive balanced and equipped with Marchand baluns are common. Passive balanced mixer baluns are wavelength-proportional and often cover most of the chip. Also, we need a small design that employs passive baluns at a frequency greater than 100 GHz, which is challenging. 180^0-Differential radio Frequency and Local oscillation signals are provided via an integrated balun. that uses transformers [17]. The block diagram of the 122.5 GHz

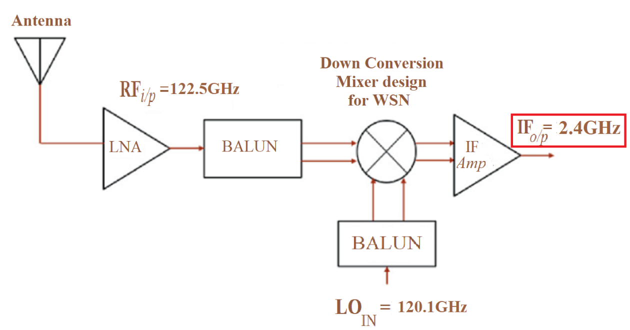

Figure 5. Block diagram of the perposed mixer design for WSN

down-conversion mixer is shown in Figure 5. It consists of double balanced Gilbert cell topology with two baluns, and schottky diodes, all of which are used to convert RF and LO signals to differential 2.4 GHz IF signals. Components with strong linearity mixers for micrometres electronic multiple-input array using alternating rectangle driving are designed by [18]. Although feedback linearization was developed to improve mixer switch linearity, especially at millimetre wave frequencies. But it has limitations that hinder its usage in broadband applications. Transmission-line passive phase shifters [19], [20], and [21] are vector interpolator-based active phase shifters with low uniformity , still there performance metric is crucial since it compares mixers' maximum input power. Power can be input or output. Figure 6 demonstrates how input power and output power define DR(Dynamic range) [22]. Figure 7 depicts

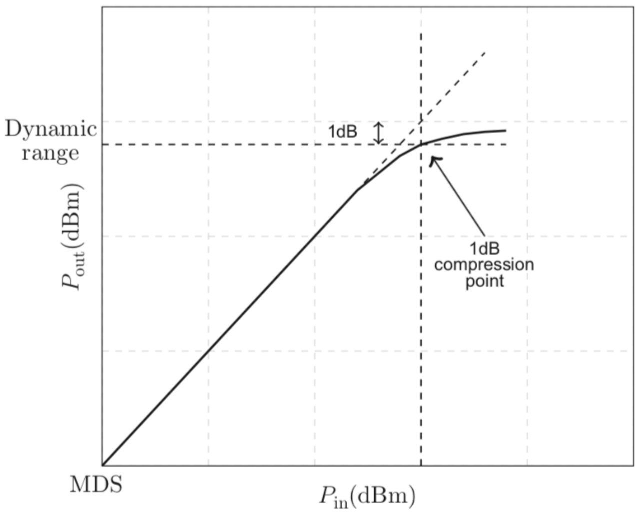

Figure 6. Dynamic range of a mixer [22]

the addition of the two input signals v1 and v2 before they are sent via an appropriate input matching network and onto a nonlinear device, which is here a semiconductor Schottky diode. For the sake of clarity, author have left out of Figure 7 [22], the biassing components like resistor that will be needed to ensure that the mixer is appropriately biassed. Schottky junctions have been characterised along with their inherently nonlinear current/voltage characteristic. This nonlinearity could be employed to downconvert a high-frequency signal to a lower one.

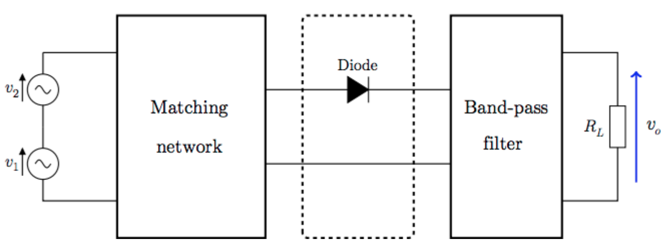

Figure 7. Single balanced Non-linear Schottky diode mixer with out biasing components [22]

Figure 8 shows the double-balanced schottky diode mixer. Four schottky diodes and two "Baluns" make a ring (unbalanced to balanced transformers). Schottky diodes are used in these mixers due due to their high frequency operation and low "on" resistance responsiveness. Balun transformers are vital to mixer design, although they can be hard to acquire the bandwidth and performance needed. Matching the output and input Baluns transformer and transformer legs is crucial to the RF mixer's balance. Balun transformers affect mixer conversion loss and driving level. When discrete transformer Baluns are wrapped on ferromagnetic cores with copper wire their on copper loss, core loss and impedance mismatch all add to the total conversion losses.

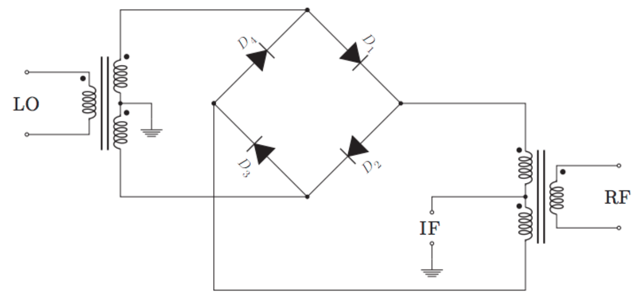

Figure 8. double balanced Non-linear Schottky diode mixer with out biasing components [22]

The balun is a specialised Radiofrequency circuit that facilitates the connection between differential and single-ended Radio-frequency circuits [23].Explanations and illustrations of the current reusable on differential structure make the topology straightforward to grasp and facilitate architectural iteration [24], [25]. To improve the linearity of the mixer, a transformer with passive filter is utilised to provide two separate biases between the switch stage and transconductance stage [26]. A resonant circuit with an inductor can enhance current and minimise pMOS cell linearity degradation [27]. The current leaking circuit is replaced by a current-reused to increase CG, while using the same current [28]. Researchers are studying both dynamic and static current injection ways to enhance current conversion mixer linearity.The paper [29] highlighted key restrictions on important measures to achieve strong linearity. In the paper [30], addressing a number of issues with RF receiver designs and limitations on conventional mixers' topologies and used double-balanced design which employs 2 balanced RF channels and 2 LO balanced frequency signals to reduce LO leakage and improve RF-LO port isolation.While Considering the important suggestion and limitation we purposed a 130nm CMOS down-conversion schottky based mixer with balun to obtain good linearity, CG, low noise figure, and robust port isolation.

3. Purposed Mixer topology for WSN

The purposed mixer for WSN is shown in Figure 9. A Marc-Hand transformer-based 180^0 balun generates Radio Frequency and local oscillation signals.In this configuration, the transistors M1 and M2 receive the RF signal and process it accordingly. Transistors M3 through M6 receive the LO signal. The (M9 and M10) current mirror stage supplies the circuit with the current it requires to function properly.The conversion gain is maintained throughout the design, and even harmonics are eliminated, making it an

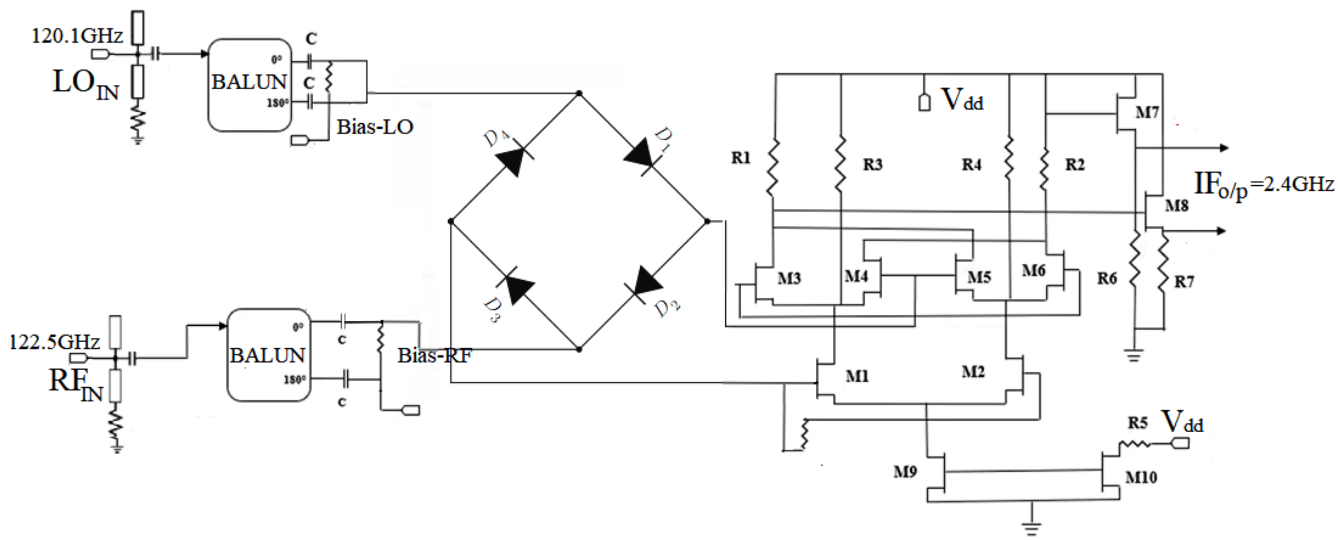

Figure 9. Schematic diagram of purposed mixer for WSN

excellent choice for usage in RF applications. At the very final stage of the circuit, M7 and M8 are added acting as source follower buffers so that baluns may be matched up with the Inter mediate frequency output port. Nevertheless, in order to obtain high conversion gain, big size transistors are necessary, which might lead to an increase in the amount of power used for DC and LO. In order to solve this issue, current bleeding was added to M1 and M2 in the form of resistors R3 and R4 in order to boost the amount of current flowing through the RF stage, which in turn improved CG. In order to reduce the voltage and make sure that M1 and M2 have enough current to operate in the saturation area, load resistors R2 and R1 are utilised. These two resistors are used in conjunction with one another. For the above mixer,

Bias Condition of the Purposed mixer for WSN		
R1,R2,R3,R4	500 ohm	V_{DD}=3Volt
R5,R6,R7	300 ohm	
Transistor	**Transistor Size ratio (W/L)**	**Transistor Function**
M1 –M2	16 µm/0.1 µm	Amplification Stage
M3-M4	16 µm/0.1 µm	Switching Stage
M5-M6	16 µm/0.1 µm	Switching Stage
M7-M8	144 µm/0.1 µm	Source Follower
M9	80µm/0.1 µm	Current Source
M10	16 µm/0.1 µm	Current Source

Figure 10. Biased condition for Schematic diagram of above purposed mixer for WSN

the 130-nanometer CMOS technology has been used, and the biasing condition is shown in Figure 10. These decisions were made in order to keep the conversion gain as high as is practically possible.

4. RESULTS AND DISCUSSION

A demonstration of the simulation results for the down-converter Gilbert cell mixer that was built for WSN can be seen in this section. These findings concern the LO-RF isolation of the mixer as well as the conversion gain, linearity, and noise figure of the system. The aforementioned Figure 9 was analysed with the use of the ADS tool in order to accomplish what was specified in the objective, which was to convert the Input RF frequency of 122.5GHz to the Output IF frequency of 2.4GHz. The LO-RF isolation during a radio frequency range is shown in Figure 11. The measured LO-RF isolation for the chosen RF frequency of 122.5 GHz is 70.1 dB. Figure 12 shows Simulation of the conversion gain (CG), where 7.9db gain was obtained at 122.5GHz Input frequency. Figure 13 shows the linearity of the mixer where the basic signal that would be ideal is shown by the blue color line, whereas the practical signal that is actually obtained is shown by the red line. While the RF input power is low, both lines behave in a linear fashion, but as a specific threshold is crossed, the fundamentals begin to compress. The RF input power point at which the variance among both curves obtained is equal to 1 dBm is -6.0dBm which is referred to as the 1-dB compression point. Figure 14 depicts a simulation of the noise figure at RF frequency range, where we achieved a value of 11.0 dB for the noise figure. In the context of WSN applications, this value is regarded as acceptable. The purposed WSN mixer performance at 122.5GHz RF frequency is compared in Table 1 to that of well-known and widely-published prior research.

5. CONCLUSION

In this research paper , the down converter Gilbert cell mixer was designed for WSN technologies to work at 2.4 GHz frequency where the input RF frequency is close to 122.4GHz as per expected new 6G spectrum range. The

TABLE I. Performance compared to prior research efforts

Re-frence	Tech-nology	Topology	RF Frquency (GHz)	IF Frquency (GHz)	Conver-sion gain (dB)	RF-LO Isola-tion(dB)	Noise Figure (dB)	Linearity(1db compression point IPI(dBm)
This Work*	**130nm CMOS**	**Double balanced Gilbert cell**	**122.5**	**2.4**	**-7.9**	**70.1**	**11.0**	**-6.0**
[31]	65 nm	Current Bleeding	120	-	-11	-30	33.5	-4
[32]	200 GHz f_t BiC-MOS	Double-Balanced Gilbert-Cell	110	-	14.4	-30	19.5	-15
[33]	130nm	SHM mixer	140	13	2.6	45	-	-7.2
[34]	0.13 μm	SHM	-	5	-	-	21	-44
[35]	0.13 μm	122 SiGe passive topology	-	-8	-	8.5	-5	
[36]	90nm CMOS	transconduc-tance stage inductive source	75-85	0.1	1.5	49.2	23.3	-
[37]	55nm CMOS	MGTR	120	52	10.8	57	14	2

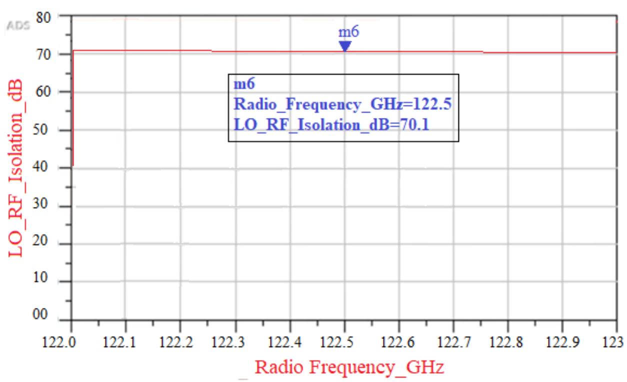

Figure 11. LO-RF Simulation

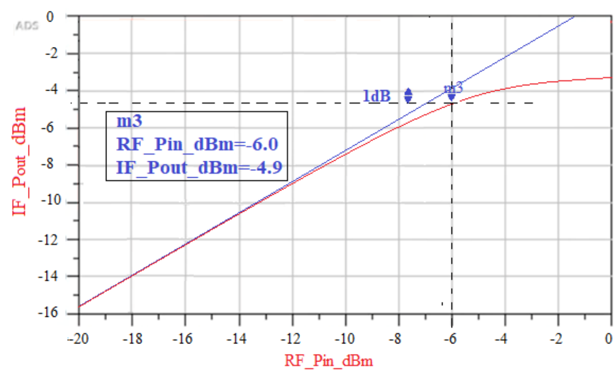

Figure 13. Simulation for Linearity

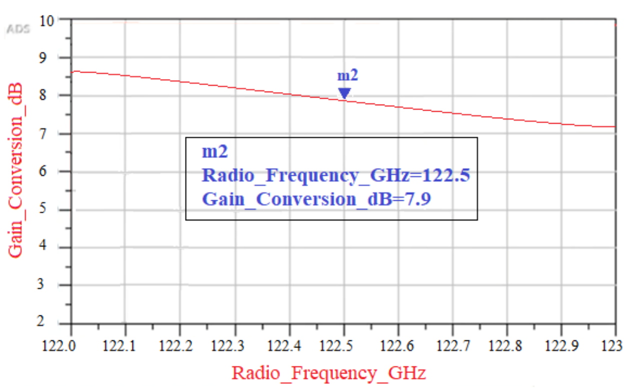

Figure 12. Gain Conversion Simulation

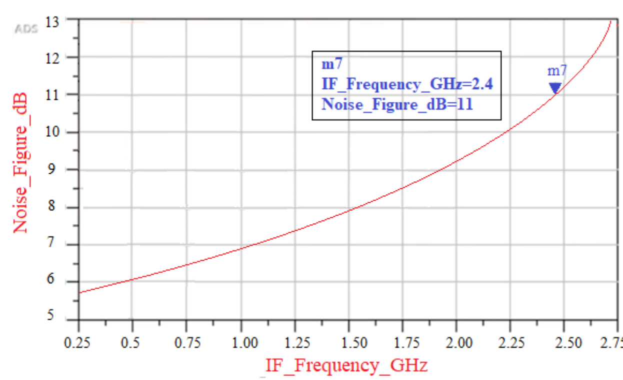

Figure 14. Noise Figure Simulation at 2.4GHz IF output frequency

implementation was performed using the ADS tool at 130 nm CMOS technology. From the WSN requirements, taken from the IEEE 802.15.4 standard, a design parameters for down converter mixer was purposed adopting Gilbert cell mixer due to its better performance in terms of LO/RF/IF ports isolation, suitable gain, adequate linearity and even harmonics cancelation compared to other mixer types. The RF and LO signals are split in half by a balun, and then mixed in a double-balanced mixer set-up with Schottky diodes. In order to achieve symmetrical operation and minimise undesired mixing products, the LO and half of Local oscillator signals are applied to the mixer's inverse inputs. The resultant intermediate frequency (IF) signal is taken from the IF output port. Biasing and impedance matching networks are well considered during design to reduce the noise. To further improve the performance of the designed Gilbert cell, the charge injection technique was utilized because it reduces the voltage in the LO and RF stages while increasing the conversion gain in the RF stage by injecting more current. The design presents good performance and is compatible with other existing designs. The Gilbert cell mixer achieves 7.9 dB of conversion gain, -6.0 dBm of linearity at IF output power of -4.9dBm, 11 dB of noise figure and good LO-RF isolation of 70.1dB. At present, there is no widely accepted standard for WSNs at 122.5 GHz. Standardization efforts will need to be undertaken to ensure interoperability between different systems and to promote the widespread adoption of the technology. Further study and development might make WSN a significant player in the future of wireless communications. It can greatly enhance the capabilities of WSNs for various IOT based applications, including environmental monitoring, healthcare, and smart cities.

6. CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

7. DECLARATIONS

Completing interests: The authors declare no competing interests. Availablity of data and materials: Data will be made available on request.

8. ACKNOWLEDGEMENTS

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