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CMOS LNA for BLE Applications

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Abstract—Bluetooth Low Energy (BLE) is an advanced technology that has been designed as complementary technology to classic Bluetooth and also it is the lowest possible power wireless technology that can be designed and built. This paper provides an overview of bluetooth low energy technology and utilization of CMOS Low Noise Amplifier (LNA) for BLE applications. The aim of this paper is review and comparison of different parameters such as power dissipation, power consumption, noise figure, etc of the CMOS LNA for Bluetooth low energy applications.

Keywords—Bluetooth(BT); Bluetooth Low Energy(BLE); CMOS;Low Noise Amplifier (LNA) ; Common gate(CG); Common Source(CS); Noise Figure (NF).

I. INTRODUCTION

Nowadays, tremendous growth and increasing demand for the Bluetooth low energy(BLE) and Internet of things(IoT) has become standard solution for wireless devices. In the fourth release of Bluetooth wireless technology standard, it introduces innovative operative mode i.e., Bluetooth Low Energy (BLE) [1]. BLE also works in the samefrequency band i.e., 2.4 GHz ISM band, as classic Bluetooth. However, it ismodified to obtain ultra-low power devices which can be constrained by coin-cellbatteries, like wearable devices, wireless payment tags, and wireless sensor networks (WSN) for indoorlocalization. For these applications, the performance parameters can be sacrificed little bit in order to achieve anextended battery-life acquired by reducing the overall powerconsumption of the radio. The performance parameters of BLE compliant receiver are a target sensitivity of 70 dBm,a noise figure (NF) value around 30 dB, image rejection value 21 dB as well as IIP3 greater than30 dBm[2]. These specifications for BLE-basedtransceivers are ideal for minimizing power consumption as well as cost;for short-range communication devices.

Furthermore, LNA is the primary component inthe transceiver section of a communication system. A major function of the LNA is amplification of weak signals that are coming from the antenna withaddition of as little noise as possible. The design specificationsforthe LNA are noise figure, third order intercept point (IIP3), S parameters, gain, 1dB compression point, and power consumption.The overall performance of receiver system issignificantly affected by noise figure. However, there is a tradeoff between various parameters such asnoise figure andother design specifications i.e., third order input intercept point (IIP3), second order input intercept point (IIP2), gain, power consumption, etc [3][4].

The most commonly used standard for short range communication systems is Bluetooth. The necessary requirements for a Bluetooth transceiver are low cost, low power consumption as well as full-integration because of its application environment [5]. Inside the receiver section of the bluetooth low energy (BLE) transceiver, the low noise amplifier (LNA) plays a dominant role for the system performances like receiver sensitivity and power consumption. Hence, the implementation of the LNA with specifications of low power consumption, low noise and circuit robustness represents a crucial challenge for design of a bluetooth low energy transceiver[6].This paper is organized as follows: an introduction to BLE and IOT is given in Section II, LNA is explained in section III, CMOS LNA for BLE applications is explained and reviewed in section IV;finally, the conclusion is given in section IV.

II. BLE AND IOT

With the increasing demand for the Internet of things (IoT) in daily life, Bluetooth has become a widespread technology for mobile devices [7]. It is basically used in cellular phones,medical sensors, and various other consumer electronics. As compared to other wireless technologies, Bluetooth technology is the best suitable for IoT after introduction of energy saving feature i.e., BLE.

A. Key Featuresof BLE:

The key features that allow BLE to have the lowest cost possible are usage in industrial,science, and medical (ISM) radio band; low power; and IP license [8]. The benefits of using the ISM radio band are that an authorization or fee is not necessary;however it must follow aspecific power requirement for transmission of data. Themaximum power which is fed into the antenna must be lower than 30 dBm i.e., equivalent to 1W [8]. The Bluetooth special interestgroup (SIG) distributes a sensible price for an Intellectual Property(IP) license, which is comparativelylesser thanother competitors [8]. With the increasing number of customers and users who are supporting BLE devices, that’s why the cost of the license can be reduced.

The main requirement for mobile devices is low power since consumers are expected to utilize thedevices for extensive periods without charging or changing the power source. Production of an endurable device needs low power consumption and more energy storage.However, the storage of energy in the sustainable device requires additional space. The manufacturing costs of large size devices werehigher,as a resultescalating the energy storagewas not efficient solution for longer-period usage. Consequently, lowering the power of thedevice not only minimizes themanufacturing cost but also enhances battery usage. In view of the fact that morepower is required for the device, further space is maintained for the power source or battery. Although low power is appropriate for the device, sometimes the device needs to workat high speeds for several applications. For that reason, bluetooth version 4.0 wasestablished tomerge the needs of different usage modes, which shows the solution thatpermitted for bluetooth to have three operation modes [9].

B. Operation Modes of Bluetooth:

After Bluetooth had evolved to version 4.0, the classification of modes of Bluetooth (BT) was divided into three different modes which are classic BT, BLE,and dual mode [10]. The Bluetooth Smart Ready mark represents the dualmode,the Bluetooth mark represents the classic BT mode, and the Bluetooth Smart markrepresents BLE mode [11].Classic BT was originally designed to connect two devices at a short range distance fortransfer of datafrom one device to another, like linking mobile phones to computers. Additionally, theapplication was enhanced to not only transferring data but also to stream audio and video.This advancement provided a vigorous wireless connection among devices which are ranging fromsmartphone and car audio devices to industrial controllers as well as medical sensors. On the other hand,BLE has key feature i.e., more power efficient and cost effective solution for several of theseapplications.

Comparing between the BLE and classic BT, the major difference between these two is power dissipation. TheBLE devices manage to work for extended periods of time. This advantage is beneficialin machine to machine (M2M) communication because it can last for years withoutchanging the power source once the BLE device is placed in the machine. On the other hand, toobtain this goal, the data transmission rate must be lower in exchange for low powerdissipation[12].

The pros and cons of BLE and BT are discussed herewith. Firstly, BLE devices slow down the data transmission rate from one device to other,although theyalso effectively reduce thepower consumption. Unlike classic BT devices, BLE devices do not require to be at themaximum speed possible. An example of application utilizing BLE can be using the smartphone to switch on the airconditioner and adjust the room temperature.These applications do not have significantdata to transfer. The considered application requires sending the package which consist of “power on” as well as “increase/decrease temperature” from the transmitter to the receiver. Whereas in case of bluetooth, we can consider an example: when auser uses a smartphone to stream television by a BT connection.Here, it is not asimple package containing a single command; instead, it can be a high definition (HD)video or high quality (HQ) music file that must be smoothly played on television.The structure of BLE isslightly different from the structure of BT because of the low energy requirements in case of BLE. TheISM

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band, IP license, and low power are key elements that allow BLE to have the lowestcost possible[9].

III. LOW NOISE AMPLIFIER

In a representative radio transceiver, the low-noise amplifier (LNA) is one of the major components, as it tends to dominate thereceiver sensitivity. The LNA design includes various tradeoffs among noise figure (NF), gain, linearity, impedance matching, and power dissipation [13]. Generally, the main goal of LNA design is to achieve simultaneous noise and input matching (SNIM) at any given amount of power dissipation. A number of LNA design techniques have been reported to satisfy these goals. To name a few representative techniques; the classical noise matching (CNM) technique [14], SNIM technique [15], power-constrained noise optimization (PCNO) technique [16], and power-constrained simultaneous noise and input matching (PCSNIM) technique [17].

A. *Design overview of LNA*

LNA architecture consists of three main sections: (i) input matching network; (ii) main amplifier section; and (iii) output matching network. The main function of the input matching network is to reduce the input return loss (S11) without introducing additional noise. The network between the LNA and the antennainvolves a fascinating issue that divides analog designers and microwave engineers. Considering the LNA as a voltage amplifier, we may expect that the ideal value of its input impedance is infinite. From the noise point of view, we may require a transformation network to precede the LNA so as to obtain minimum NF. From signal power point of view, we may utilize conjugate matching between the antenna and the LNA. While each of these choices has certain merits and drawbacks, the last one is dominant in today's systems, i.e., the LNA is designed to have a 50Ω resistive input impedance. Amplifier section ensures a high gain, high linearity, low noise factor and low power consumption and at the same time it provides input impedance that can be conducive to the realization of broadband matching. The output buffer guarantees that the output impedance is 50 Ω in order to test[18]. The design of matching network circuitry is called the topology of LNA.

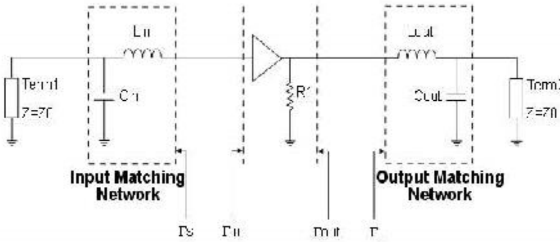

Fig.1: Structure of LNA [19]

We present in a tabular form, the characteristics for an ideal LNA.

TABLE I :CHARACTERSTICS OF LNA [20]

Noise figure	2 dB
IIP3	-10dBm
Gain	15dB
Input and output impedance	50Ω
Input and output return loss	-15dB
Reverse isolation	20dB
Stability factor	>1

B)Design Specifications for LNA

We describe henceforth the design specifications for an LNA.(i)Input matching: The distance between the LNA and the antenna is usually of the same order ofmagnitude as the signal wavelength, which means that the propagation effects require that connections are made using standard impedance transmission lines [20][21]. To maximize power transfer, the LNA and the antenna should be impedance matched.Although, from an analog point of view, an LNA is a voltage amplifier and its ideal input impedancewould be infinity; it is designed to have 50 Ω resistive input impedance. This is because there is a need for input matching.The LNA is typically connected to an antenna and the distance between these circuits is of the order of carrier wavelength, which means that the propagating effects require that the connections are made using standard impedance transmission lines. So, there is the need for input matching, in order to maximize power transfer. The 50 Ω is a standard termination impedance value that goes back to the development of coaxial cables, where 50 Ω represents a compromise between power handling and low loss [22].

(ii)Low noise:Friis' Law shows that the first block of an amplifying chain has a greater contribution to the overall cascade noise factor, which means that the LNA noise contributionshould be as low as possible to prevent the degradation of the SNR.

(iii)Feedback isolation: the LNA should have a good feedback isolation to prevent instability andsignal leakage from the subsequent blocks that might be reradiated by the antenna [23].

(iv)Output matching: the LNA output impedance does not have to be impedance matchedbecause the mixer is also integrated and the interconnection can be made short.

(v)Power efficiency: LNAs are usually used in portable receivers and therefore they mustbe efficient in terms of power use.

(vi)S parameters:In microwave theory and concepts, we deal mostly with power quantities rather than voltage or current quantities. As we know, there are many distinct ways to exemplify the behavior of a two port network. In a linear electrical network at low frequency; Y, Z, H, T and ABCD parameters are commonly used to calculate the relation between voltage and current quantities. In these networks, open and short circuit conditions are used to characterize a network. Furthermore, these parameters are quite complex to realize at high frequencies. Due to the radio frequency range (high frequencies), scattering parameters (S-parameters) are normally employed. This is basically for matching load termination; and also the measurements depend on incident and reflected waves[30].

(vii)Bandwidth: System bandwidth is defined as the range of input signal frequencies for which the gain is not more than 3 dB under its passing band value. It is also defined as the range of input signal frequencies for which the following conditions are met: (i) gain is no more than 3 dB lower than its passing band value; (ii) noise figure value is below 3 dB; and (iii) S_{11} value is below -10 dB.

IV CMOS LNA FOR BLE

B. Circuit Topologies for BLE

(i) Cascode Topology: Chin-To Hsiao [24] proposed a design for a 2.4 GHz CMOS LNA for bluetooth low energy applications using 45 nm technology. He has considered three predominant LNA topologies i.e., common gate (CG),cascode and common source (CS). Advantage of cascode amplifier isthat it provides the highest gain and broad bandwidth but there is a slight scarifice in NF as well as design complexity. The cascode topology isthe most prominent topology for LNA. Basically, the architecture of a cascode amplifier consists of a CS stage with CG stage. Firstly, CS stage gives the greatest stability which has surpassing sensitivity to process, temperature variation immunity, power supply, and component variations.That’s why a cascode amplifier is implemented in the LNA design of the BLE front-end receiver. The structure of cascode LNA with different blocks is shown in figure 2 below.

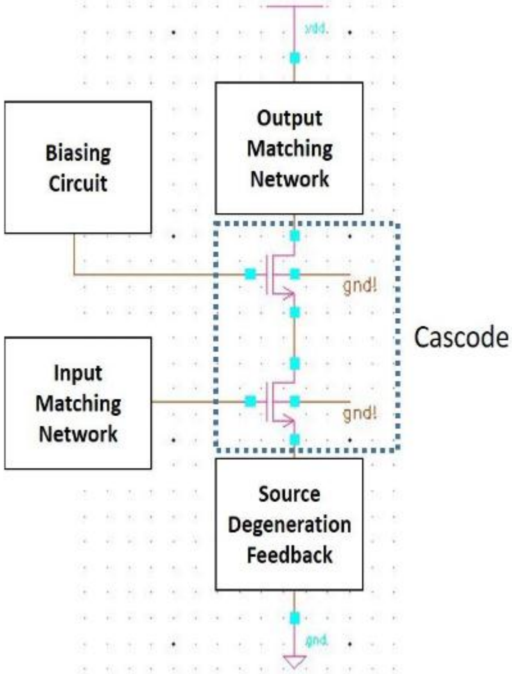

Fig 2: Structure of Cascode LNA with different blocks[24]

The schematic of LNA is presented [24] in which four blocks are to be configured in cascode amplifier i.e., source degeneration feedback, input matching network, biasing circuit and output matching network. These four blocks are combined together to complete the LNA design. Four factors have been used to measure the performance of LNA i.e., power consumption, gain, linearity, and noise figure. The specifications of LNA for BLE front end receiver,as measured [24] are, noise figure nearly 0.98 dB, power consumption of 1.01 mWand gain of 14.53dB.Here [24], the LNA has been designed in such a manner that the power consumptionhas been minimized up to1.01mW;a major aim of reducing power has been achieved.

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Ayari Nadia et.al [25] have proposed a CMOS LNA which has been fabricated with 0.13um CMOS technology. Theamplifier has beenoptimized forBluetooth applicationsworking in the 2.4 - 2.5 GHz band. The main aim of this work was to enhance the performance parameters of LNA.The importance of this study was to minimize the powerconsumption of the CMOS LNA although still havingsuitable noise performance, good input/ outputmatch, enough linearity, and a high dynamic range.The authors have usedcascode amplifier topology with inductivedegeneration at the source. The LNAprovided, output return loss of -44.69dB, NF of 1.98dB and input return loss of-11dB, input ICP1 of-10 dBm and IIP3of 5dBm and power consumptionof 7.33 mW[25].

Laichun Yang et. Al [26] proposed a fully integrated low noise amplifier implemented in 0.18 μm RF CMOS process for Wireless Local Area Network (WLAN) and Bluetooth band. Using cascode configuration, it providedacceptable power consumption along with higher voltage and power gain. In this work, target specification was having a good trade-off between noise, gain, and stability. The authors haveused inductive source degeneration LNA topology to obtain good input matching for a narrow bandwidth. The LNA offerspower gain of 22.1 dB, noise figure of 1.47 dB and power consumption of 11 mW from a single 1.8 V power supply**.**

(ii) Common gate topology:

Lei Liaoet.al [27] presented a low Power LNA for application in bluetooth lowenergy (BLE) receiver front-end in UMC 130-nm CMOS technology. The authorsreported a capacitor cross-coupled common-gate LNA. The pros and cons of common-gate LNA are sufficient linearity although exhibitingmoderately high value of noise figures greater than 3 dB.In case of BLE standard ,the sensitivity requirement is not so high i.e., -70dBm so that noise figure provided from common-gate LNA topologyis appropriate for bluetooth receiver front-end circuitry. In this work,capacitive cross coupling technique is used to improve the performance of noise figure of common gate LNA although maintaining the benefits of CG amplifier.This techniquehas been practiced to a low power LNA as shownin Fig. 3 for the bluetooth low energy receiver front-end.In order to minimize the power consumption of LNAcircuitry, the current flows i.e. I_1,I_2 of both common-gate stages asgiven in Fig. 3have been reduced.Insidethe circuit of LNA, the currents which are flowing through both thetransistors$M1$ and $M2$, are put to 480 μA. Due to this, the total currentconsumption of LNA is lower(1 mA).Finally, the capacitive cross-coupled common-gate technique for LNA gives a voltage gain of 23 dB with NF of 2.98 dB at2.44 GHz in no-load condition [27].

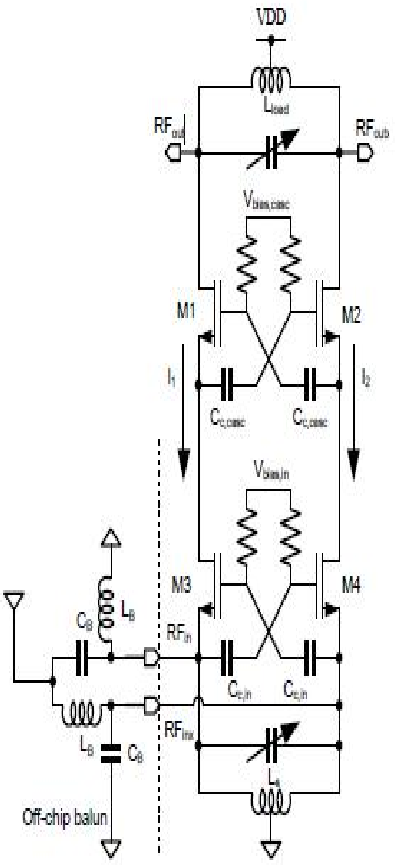

Fig.3: Cross coupled common gate LNA[27]

3)Common source - common gate topology

GholamrezaKarimi [28] reports the design of an ultra low voltage and ultra low power RF CMOS LNA using a two-stage common source-common gate topology with source inductive degeneration. The proposed architecture minimizes the voltage supply as well as power consumption. Taking into consideration the complexity of the analysis, it is needed to simulate a neural model including high

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speed and accuracy. The proposed LNA in the paper is precisely modeled using ANN and ANFIS. The model accuracy of LNA is obtained for all the input–output parameters in the Bluetooth frequency range. A model of low voltage and low power LNA using ANN for Bluetooth applications is developed.

In this schematic of LNA, the NMOS transistors are still in weak inversion region at low supply voltage 0.36V, which can lead to increased noise figure (NF). A solution to the threshold voltage problem is the forward body bias technology.

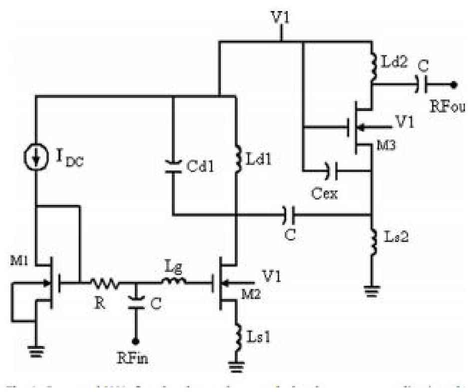

Fig. 4:Ultra low power and low voltage LNA [28]

The given architecture is simulated with ADS simulation tool in TSMC 0.18 µm CMOS process with RF MOSFET model BSIM3. The circuit is designed for 2.45 GHz ISM frequency band. The proposed LNA has 2.27 dB NF at operation frequency. The results showed a power gain of 19.36 dB and input return loss S11 of −105.971 dB at 2.45 GHz for the proposed LNA.

Anith Selvakumar et.al [29] report the design of the low noise amplifier which accomplishesthe quadrature on tRF signal path. The architecture of receiver front end in which single RC network behaves, simaltaneously, as a low-pass filter for the common-gate stage (CG) is realized with M0I, as well as a high-pass filter for common source stage (CS) implemented by M0Q.It generates a 90-degree shift among the two outputs currents.A wideband quadrature is guaranteed by choosing C0 larger than gate-source capacitances of M0I/M0Q, while amplitude matching is obtained only around the filter cut-off frequency $1/R_0C_0$. Despite that, since the BLE standard range of frequencies is of only between the 83.5 MHz around 2.44175 GHz, in which they obtained good amplitude matching and image rejection over the entire range of frequencies without re-centering the w_0 for each channel. The topology used in this paper was a single RC network, to implement both, allowing a simple calibration. To assure sufficient amplitude matching, a single calibration is needed to center the filter cut off frequency in ISM radio band. This can be implemented through use of a transistor working in triode region in series with the resistor R. The I/Q quadrature relationship is also independent of the matching network preceding the LNA, guaranteeing robustness with respect to external components variations.

TABLE I. COMPARISON OF DIFFERENT PARAMETERS FOR BLE TECHNOLOGY

References	[26]	[27]	[25]	[24]	[28]
Operating frequency	2.4GHz	2.4-2.483 GHz	2.4-2.5 GHz	2.44GHz	2.4GHz
Power gain	22.1dB	-		14.53dB	
Noise figure (dB)	1.47	3.2	1.98	0.98	2.27
IIP3	8.1dBm	-	5dBm	-10.67	
Technology	0.18 µm	130 nm	130 nm	45 nm	180 nm
Power supply voltage	1.8V	1.2V	1.2 V	1V	0.36V
Power consumption	11.1 mW	1.2mW	7.33 mW	1.01 mW	2.57 dB
Application	Blue tooth	Blue tooth low energy	Blue tooth	Bluetooth low energy	Blue tooth

IV. CONCLUSION

This paper provides an overview of the Bluetooth Technology, key features of BLE and their operation modes. The paper also includes an introduction of LNA and its design parameters. The main aim of this paperis search for a design with low power consumption that can be employed for BLE devices. The circuitry of LNA provides unexpectedly low energy consumption as well as noise figure. Comparison of different parameters such as noise figure, power consumption, etc of BLE front end circuitry has been done.

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