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Research article

A Review on design of low noise amplifiers for global navigational satellite system

Ch Priyanka, D Venkata Ratnam* and Sai Krishna Santosh G

Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Andhra Pradesh, India

* **Correspondence:** Email: ratnam2002v@gmail.com.

Abstract: Low noise amplifier (LNA) is a ubiquitous Radio Frequency (RF) component employed in the global navigation satellite system (GNSS) front end receiver to amplify the degraded RF signals captured by the antenna to the desired level. GNSS LNA boosts the desired signal power by adding minimal noise and distortion to mitigate the impact of noise added by subsequential components of the RF receiver chain thereby improving the overall signal-to-noise ratio (SNR) and the overall performance of the system. This paper explores the various GNSS LNA topologies that improve the system's overall performance with minimum power consumption, low noise figure (NF), high gain, good input-output matching, stability, and linearity. The outcome of this research work would help to design a successful LNA for enhancing the performance of the GNSS receiver.

Keywords: GNSS; GPS; low noise amplifier (LNA); noise figure (NF)

1. Introduction

Global Navigation Satellite System (GNSS) is a worldwide position and time determination system with one or more satellite constellations accessible by millions of military and civilian users simultaneously. Currently, civil applications of GNSS include navigation-aviation applications, maritime applications, Rail applications and road applications, surveying and mapping, geographical information systems, disaster prevention management system, etc [1]. , United States of America (USA)'s Global Positioning System(GPS), Europe's GALILEO, Russia's GLONASS, China's Bei Dou, and regional GNSS systems like India's Indian Regional Navigational Satellite System

(IRNSS)/Navigation with Indian Constellation (NAVIC) and Japan's Quasi-Zenith Satellite System (QZSS) are the operational satellite navigation systems for navigation and timing users.

GNSS receivers determine the PVT (Position, Velocity, Time) information by processing the signals transmitted by the satellites [2]. First, the generalized RF front end GNSS receiver interfaces through an antenna to the satellite system to receive the incoming satellite signals. Next, the received digitized signal is fed to the baseband processing block. The baseband processing consists of independent channels that track the signal from each satellite and extract the demodulated navigation data, code ranges, carrier phase measurements, Doppler frequency, and carrier to noise ratio [3].

Designing a good performance LNA is of significant concern as the received signals are weak. LNA design with minimum Noise Figure (NF) is the primary constraint, as the receiver's initial stage contributes to the receiver's overall NF according to Frii's formula. Furthermore, high gain, impedance matching, low power consumption, linearity, and stability are significant performance parameters to consider when designing an LNA. Low NF (<1 dB) can be achieved by designing an LNA using Complementary metal–oxide–semiconductor (CMOS) technology, but it requires additional circuitry to protect against high input power, such as RF protection limiting and Electro Static Discharge (ESD) circuits. However, ESD protection circuits contribute additional noise to the circuit and degrade the performance of LNA. The drawback of the ESD circuit can be resolved by employing High Electron Mobility Transistors (HEMT) instead of CMOS in designing an LNA.

In this paper, Section 2 presents the various Global navigation satellite systems and their signal characteristics. Section 3 discusses various LNA topologies using CMOS and HEMT for wireless communication and GNSS applications.

2. Global navigation satellite systems and their signal characteristics

In this section, various satellite constellations and their signal characteristics are discussed as follows.

2.1. Global positioning system (GPS)

GPS is a multi-use Code Division Multiple Access (CDMA) based satellite navigation system developed by the US DOD (Department of Defense) and operated by the United States Air Force (USAF) [4]. It provides precise position accuracy within meters in real-time all over the worldwide 24/7. GPS is considered the most predominant GNSS system among all other satellite constellations because of its distinct features, adequate satellite constellation with real-time navigation with high dynamic range, worldwide operation, tolerance to any interference.

GPS uses two main links - L1 operating at 1575.42 MHz and L2 operating at 1227.60 MHz respectively to continuously broadcast the signals. Newer GPS satellites also use L5 frequency operating at 1176.45 MHz. On each link, one or more codes can be transmitted, which are known as Pseudo Random Number (PRN) codes. The two predominant PRN codes are C/A and P codes, are chosen based on their correlation properties. Newer GPS satellites transmit codes such as M(Military-encrypted), L1C(Civilian-open) signals [5]. In addition, each satellite broadcasts an unrestricted signal at L1. The unrestricted L1 signal is BiPhase modulated by 50 bps navigation data stream and C/A code, consisting of 1023 chips repeating every millisecond and having a chipping rate of 1.023 Mcps. Similarly, the L2 signal is also Biphase modulated by the same 50 bps navigation data and P(Y) code, which is much longer and has a chipping rate of 10.23 Mcps, i.e., 10 times faster than C/A code, thereby providing a precise time delay and range measurements. Hence overall, there are three signals: C/A code at L1 for Standard Point Service (SPS) users and P(Y) code at L1 and L2 for Precise Point Service (PPS) users [6].

GPS modernization incorporated new civil and military signals to enhance the performance of the GPS by providing high accurate PNT (Positioning, Navigation and Timing) services. The advantages of modernized GPS include dual-frequency ionosphere correction capability, multipath mitigation capability, signal redundancy, signal availability, and system integrity. The modernized M-code is used for military purposes, replacing P(Y) code which can be transmitted on both L1 and L2, with an improved jamming resistance and thus enables transmission of signal at much higher power without any interference. The new L1C (Civil signal) is supported by the Block III GPS satellites, which uses different modulation techniques Multiplexed Binary Offset Carrier (MBOC) and provides easier interoperability between GPS and Galileo navigation systems. The GPS L5 is used for civilian aviation and safety of life applications. It uses a BPSK modulation technique. Further information on GPS modernized signals is reported in [7].

The Power Spectral Density (PSD) of various GPS satellite constellations are shown in Figure 1.

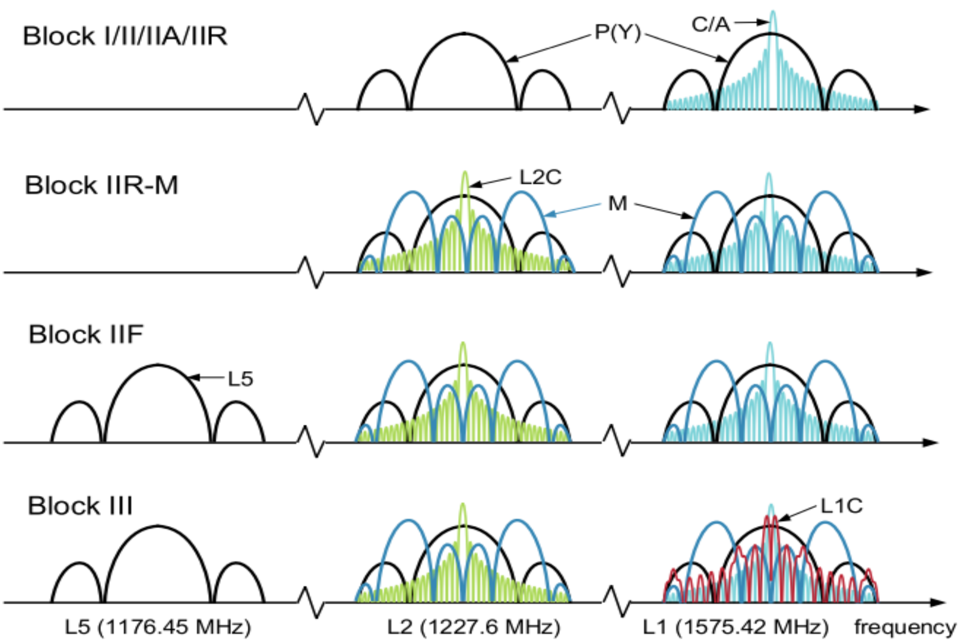

Figure 1. PSD of various GPS generations with modernized signals, Ref [8].

2.2. Globalnaya navigazionnaya sputnikovaya sistema (GLONASS)

GLONASS is a FDMA (Frequency Division Multiple Access) space-based navigation system developed by the Soviet Union in 1976. It is the second most global navigation satellite system that provides accurate Position Navigation Timing (PNT) services alternative to GPS. Furthermore, the GLONASS system improves positioning in high latitudes, an added feature compared to GPS.

“Cyclone” was the first soviet navigation spacecraft launched in 1967. The beginning of the first low orbit navigation system called “Cicada”, placed in circular orbits 1,000 Km high with an inclination angle of 83^{o} concerning the equator. The Cicada system of four satellites was commissioned in 1979. The Cicada and Cicada-M (“Modernization”) were designed for military users. In 2008, the operation of the Cicada systems was halted, and the first-generation GLONASS was initiated as the low orbit systems could not meet a considerable number of users requirements [9]. Thus, in 2010, GLONASS achieved full coverage of Russia's territory. In 2011 GLONASS achieved fully global coverage, enabling 24 satellites in three orbital planes with an inclination angle of 64.80 to the equator, an orbital altitude of 19,000 km, and an orbital period of 11 hours 15 minutes 44 seconds [10].

Like GPS, GLONASS also uses L-band for broadcasting the signals. However, in GLONASS, the carrier frequencies are represented with G instead of L for better differentiation from GPS carrier signals. GLONASS provides two essential services: Standard positioning services for civil users using open standard accuracy signal (C/A code) having a chipping rate of 0.511 MHz on G1/L1 (1598.062–1602.00 MHz) and G2/L2 (1242.937–1246.000 MHz) nominal frequencies and precise positioning service for military users using high accuracy signal (P-code) having a chipping rate of 5.11 MHz on G2/L2 carrier frequency using Direct Sequence Spread Spectrum (DSSS) technique. The navigation message is modulated upon the signals at 50 bps [11].

GLONASS-K is the first of third-generation satellites launched in 2011 with an increased life span of 10 years and contains more navigation signals by improving the system accuracy. It uses both CDMA and FDMA signals for broadcasting. GLONASS-K uses new GLONASS modernization signals designed to provide high accuracy, multipath resistance, and greater interoperability between the GNSS systems. In addition, it uses a new CDMA civil signal G3/L3 operating in between 1202–1204 MHz. Furthermore, the signal uses DSSS modulation like G1/L1 and G2/L2 signals, providing a high chipping rate of 4 MHz. GLONASS-K2 is the next-generation satellite developed by Reshetnev Information Satellite Systems (Reshetnev ISS), expected to launch in 2022. GLONASS-K2 uses four additional Code-Division Multiple-Access (CDMA) signals and Frequency-Division Multiple-Access (FDMA) signals for civil and military users. The PSD of various GLONASS generations is shown in Figure 2. The GLONASS ICD (Interface control document) provides the complete information regarding GLONASS unrestricted signals used to design a GLONASS receiver [12].

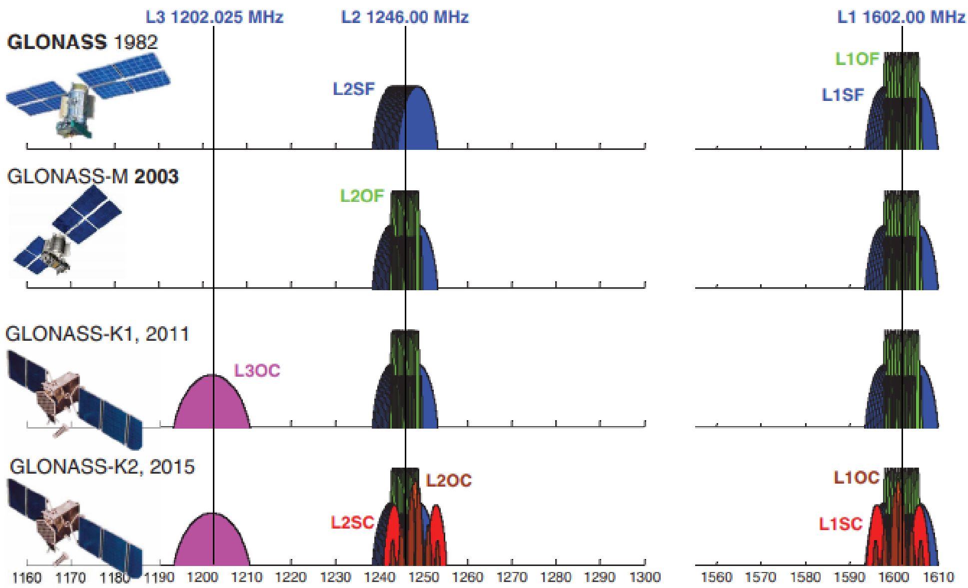

Figure 2. PSD of GLONASS Signals, Ref [11].

2.3. Galileo

Galileo is a CDMA-based European global navigation satellite system operated by the European Union Space Agency for the Space Programme, providing better positioning services at high latitudes compared to other GNSS systems. Galileo's constellation consists of 30 satellites arranged circularly in three Medium Earth Orbit (MEO) orbital planes at 23,229 km altitude above the earth. GIOVE-A is the first Galileo satellite launched in 2005 and reached full operational capability in 2019 [13]. The system offers four distinct services referred as Open Service (OS), Commercial Service (CS), Safety of Life service (SOL), Public Regulated Service (PRS) [14].

The Galileo system uses four frequency bands for broadcasting the signals, which are referred to as E1 (1575.420 MHz, like GPS L1), E5a (1176.450 MHz, similar to GPS L5), E5b (1207.140 MHz), and E6 (1278.750 MHz), among which the spectrum E6 is utilized for radio navigation satellite services (RNSS) and E1, E5a, E5b spectrum bands are used for Aeronautical radio navigation services (ARNS). All the frequency bands use the CDMA technique. The E1 signal is further categorized into E1A: An encrypted cosine phased Binary Offset Carrier (BOC) (15, 2.5) signal used for PRS. E1B and E1C: The signals are data and pilot components of MBOC signal, which uses 125 bps navigation data and 4092 length PRN code having a chipping rate of 1.023 MHz. It provides OS, CS and SOL services. E5 signals contain two components E5a and E5b: The signals are data and pilot components of DSSS signal used for high precision applications. E5a signal contains 25 bps navigation data, and E5b contains 125 bps navigation data with 10230 length PRN code. The E6 contains E6A: BOC (10, 5) signal used for PRS, E6B and E6C: DSSS signal used for CS containing 500 bps navigation data with PRN code having 5.115 MHz chipping rate. Figure 3 shows the PSD of various Galileo signals.

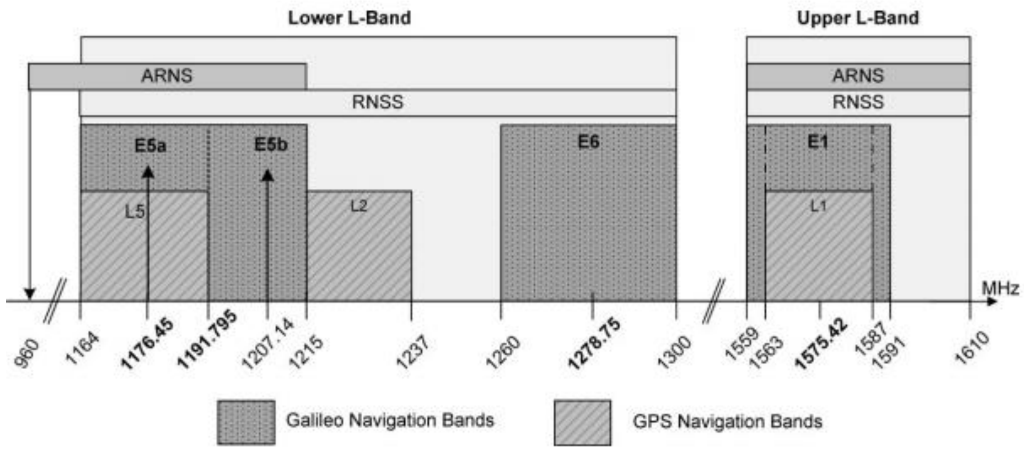

Figure 3. PSD of Galileo signals, Ref [2].

2.4. BeiDou

The BeiDou is a Chinese navigation satellite system composed of a three-stage development strategy. The name BeiDou means "Northern Dipper". BeiDou-1 is the first-generation satellite launched in 2000, also known as BeiDou satellite navigation experimental system that offered regional PNT services only for users in China and neighbouring regions. It consists of 5 satellites (2 in IGSO+ 3 in MEO orbit). BeiDou-2, also known as a compass, is the second-generation navigation satellite system comprising 19 satellites (18 in MEO and 1 GEO orbit) in orbit, thereby offering services to the Asia Pacific region by 2012. Finally, in 2015 the first third generation BeiDou-3 navigation satellite was launched, providing global services to users worldwide. It consists of 30 satellites (3 in GEO, 3 in IGSO, and 24 in MEO orbit) with new frequency signals [15]. The BDS-3 constellation deployment was carried out by June 23, 2020 [16].

BDS-3 uses four carrier links B1C/B1I/B1A (1575.42 MHz), B2a/B2b (1191.795 MHz), B3I/B3Q/B3A (1268.52 MHz) and Bs test frequency (2492.028 MHz) for broadcasting the signals. Open signals broadcast on carrier signals B1I, B3I, B1C, B2a, B2b, and authorized services on carrier frequencies B1A, B3A, B3Q. Using Alternative Binary Offset Carrier AltBOC (15, 10), the B2 carrier is modulated similar to Galileo E5A/E5B but with different data rates. The lower side lobe of B2 is referred to as B2a, which uses 25bps navigation data, and the upper sidelobe as B2b, which uses 50 bps navigation data for the life and safety service channel.

2.5. Quasi-Zenith satellite system (QZSS)

The QZSS is a CDMA-based regional navigation satellite system developed by Japan, providing stable and high precision PVT services covering mountain environments and urban canyons in East Asia and Oceania. The QZSS transmits eight signals in four frequency bands. They are L1, L2, L5 (like GPS L1, L2, L5), and E6 (similar to Galileo E6 [17].

2.6. Indian regional navigation satellite system (IRNSS)

The IRNSS is a CDMA-based independent regional navigation satellite system developed by India Space Research Organization (ISRO). IRNSS provides accurate position information to IRNSS users and the region extending up to 1500 km from its boundary [18]. In 2016, The IRNSS was renamed NAVIC (Navigation with Indian Constellation), India’s Prime Minister. The IRNSS constellation consists of 8 satellites, among which the first satellite, IRNSS-1A, was launched in 2013. It uses L5 (1164.45–1188.45 MHz) with centre frequency 1176.45 MHz (similar to GPS L5) and S-band (2483.5–2500 MHz) for broadcasting the signals. NAVIC system provides two essential services: Standard Positioning Service (SPS), an unencrypted service to users. The navigation message with a data rate of 50 sps added to the C/A code with a chipping rate of 1.023 Mcps is modulated on both L5 and S bands using BPSK for SPS users [19]. Restricted /Authorized Service (RA), an encrypted service provided only to authorized users. It employs Binary offset carrier modulation BOC (5, 2) on both L5 and S bands to improve RA users’ acquisition and performance [20]. It is planned to use NavIC tracers in all consumer vehicles and mobile phones in India by 2021. In 2020, IRNSS was identified as IMO’s worldwide Navigation system, which facilitates merchant vessels to use IRNSS for position information. The summarized frequency band of all the satellite constellations is shown in Figure 4. Table 1 represents a brief overview of global and regional navigation satellite systems.

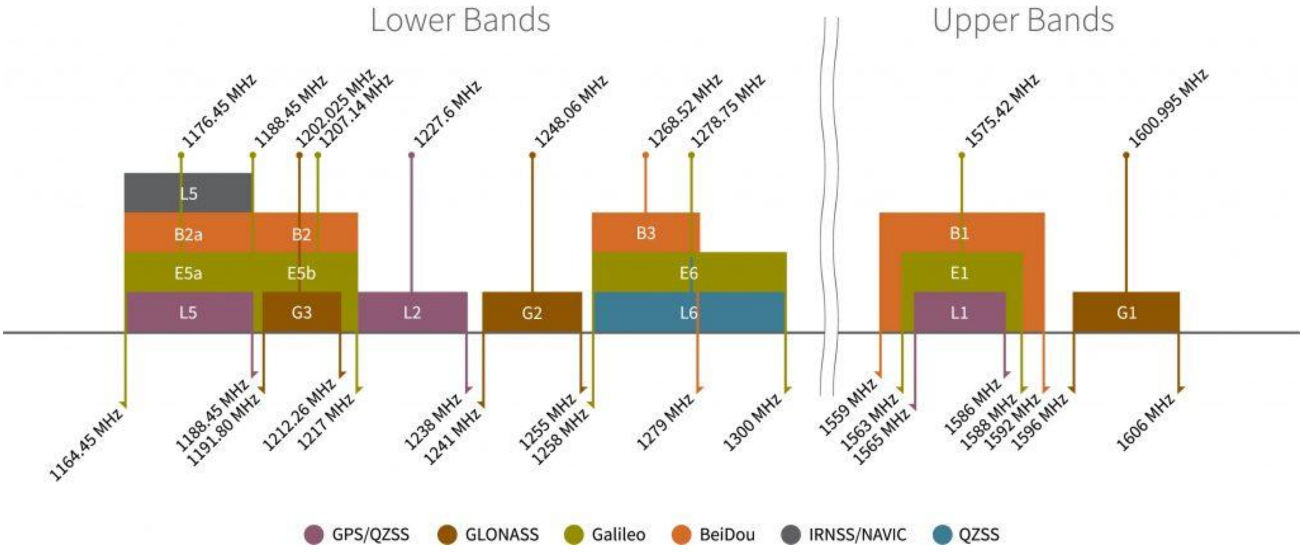

Figure 4. Frequency band limits of GNSS system.

Table 1. Summary of the various GNSS system.

S.NO	GNSS System	Country	Coverage	Number of Satellites operational	Coding	Frequency (MHz)
1	GPS	US	Global	31	CDMA	L1-1575.42 L2-1227.60 L5-1176.45
2	GLONASS	Russia	Global	24	FDMA & CDMA	L1-1598.06 to 1602.00 L2-1242.93 to 1243.00 L3-1204.00
3	Galileo	Europe	Global	24	CDMA	E1-1575.42 E5a-1176.45 E5b-1207.14 E6-1278.75
4	BeiDou	China	Global	30	CDMA	B1-1575.42 B2-1191.795 B3-1268.52
5	IRNSS/NavIC	India	Regional	8	CDMA	L5-1176.45 S band- (2483.5-2500 MHz)
6	QZSS	Japan	Regional	4	CDMA	L1-1575.42 L2-1227.6 L5-1176.45 L6/TEX-1278.75

3. Literature survey on low noise amplifier topologies for GNSS

GNSS system broadcasts the signals, which acts as an interface between the system and the receiver. GNSS receiver is an electronic device comprising of antenna and processing unit. The antenna receives the signals from more than one satellite constellation and is processed digitally through a processing unit, thus offering accurate PNT information.

Low noise amplifier (LNA) is the first stage of GNSS RF front-end receiver used to amplify the received weak RF signal from the antenna and is further down-converted by the mixers to a low-frequency signal. In designing a high-performance LNA circuit, several requirements need to be fulfilled: low power consumption, low noise figure, high gain, stability, linearity, and proper matching at input and output terminals. However, the design includes an inevitable trade-off in achieving the required circuit specifications.

LNA design parameters include bandwidth, noise figure, impedance matching, nonlinearity, stability, power consumption, device selection, DC bias network. The selection of transistors plays a vital role in designing an LNA for a required frequency range. BJT, CMOS, HEMT, Heterojunction Bipolar Transistor (HBT) are various types of transistor technologies used in LNA design. DC bias network offers a selection of appropriate constant Q-point over variations in transistor parameters with temperature changes. NF Measures the quality of the amplifier by calculating the SNR of the signal traversed in the receiver front end. NF having less than 2-3 dB is the desirable specification for a better GNSS LNA design.

For maximum power gain with minimum loss, designing an LNA with proper impedance matching network of 50 Ω is significant. Linearity of the circuit can be achieved for high values of IIP2 (Second- order input intercept point) and IIP3 (Third-order input intercept point). S-parameter measurements determine the stability analysis of the amplifier. However, there exists a trade-off in achieving high gain and low power consumption. Common source, common gate, and cascade are the most conventional LNA topologies. Common source topology offers less NF with moderate gain, and less stability at high frequencies also requires an input impedance matching network. With compromising design complexity, the cascode amplifier is the most versatile among the three topologies providing more stable gain over a wide range of frequencies. The cascode implementation minimizes the miller’s effect, provides input-output matching with improved reverse isolation.

In this section, the implementation of LNA topologies using various techniques and technologies operating within an L-band for GNSS systems are discussed as follows:

R. Benton et al., [1992] designed, tested, and fabricated an GaAs Monolithic microwave integrated circuit (MMIC) consisting of LNA and RF-IF downconverter for the GPS front end receiver. In this paper, an LNA with two L-bands as input and output is designed for military applications [21]. Figure 5 shows the block diagram of LNA.

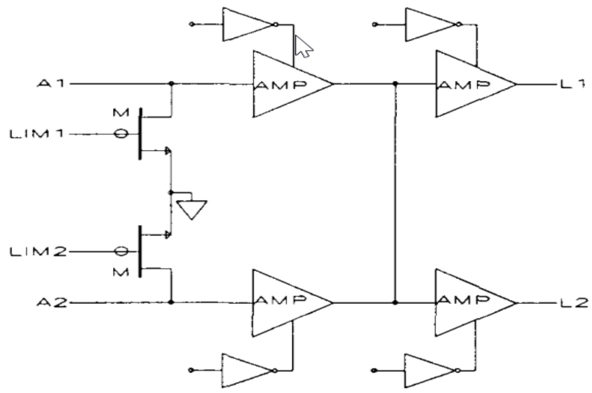

Figure 5. Block diagram of LNA, Ref [21].

And circuit schematic of GPS LNA is shown in Figure 6. The design uses resistive feedback for proper input matching. The impact of noise on the device can be controlled by choosing a feedback resistor value high. The autotransformer in the design provides a high voltage gain of 28 dB with a noise figure of 2.7 dB [21].

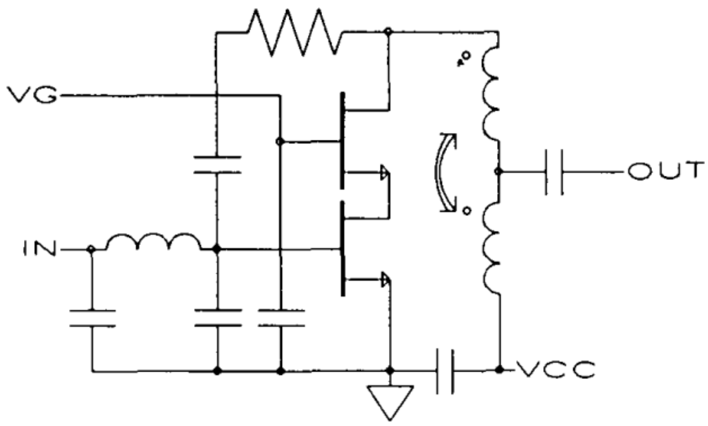

Figure 6. Circuit schematic of FET LNA, Ref [21].

Fred Bonn., [1995] modelled and tested a low current high-performance LNA for GPS receiver applications using enhancement-mode GaAs FET. Figure 7 shows the circuit schematic of the two-stage LNA using the current sharing technique [22].

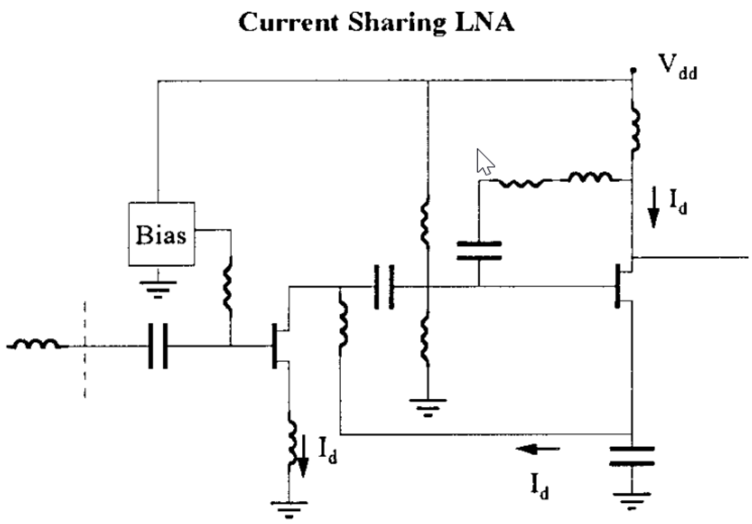

Figure 7. Circuit schematic of LNA using GaAs FET, Ref [22].

The source inductors in the first stage enhance the noise parameters. The parallel feedback in the second stage improves stability, broad amplifier response, and reduced component sensitivity. The designed LNA operates in between 2–5 V producing a gain of 18.4 dB at 5 V and 1dB NF at 1575 MHz.

Derek K. Shaeffer et al., [1997] implemented a 1.5 GHz LNA using 0.6 µm CMOS process for GPS receiver. The implementation of an RF front-end receiver using CMOS is attractive because of the integration of the complete system on a single chip [23]. Figure 8 shows the CMOS implementation of a two-stage cascode LNA amplifier. The amplifier yields a gain of 22 dB with an NF of 3.5 dB, having 30 mW power consumption from 1.5 V supply voltage. However, the noise figure of the circuit exceeds the theoretical NF value (<=3 dB) due to the induced gate noise.

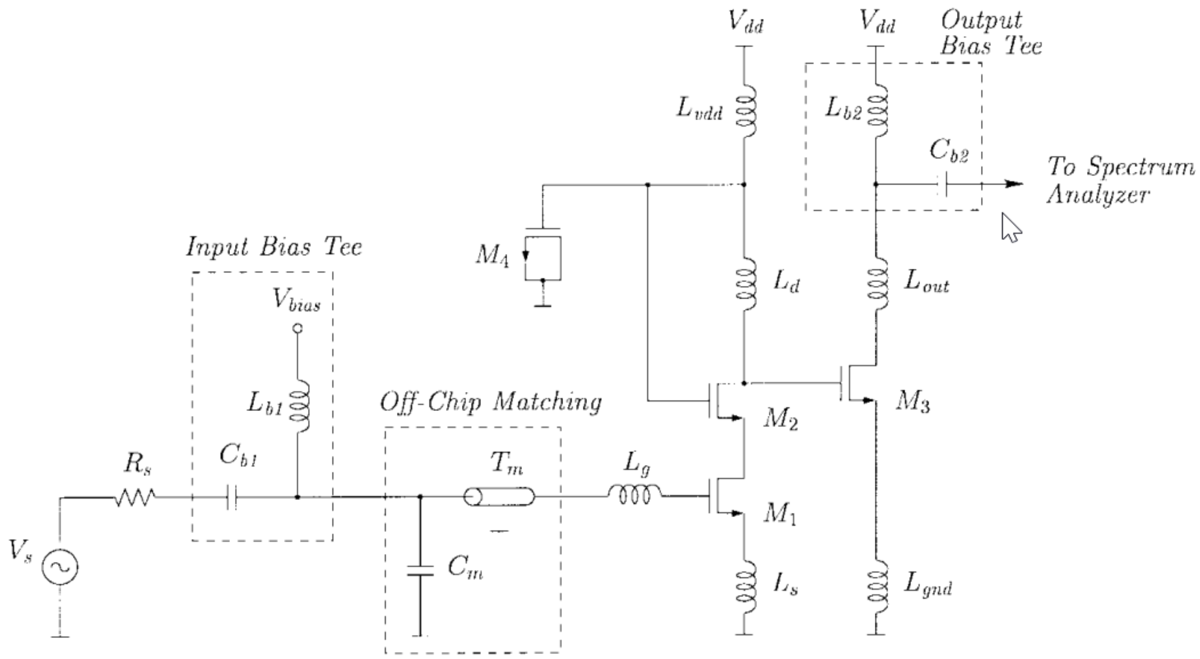

Figure 8. Circuit schematic of CMOS LNA, Ref [23].

Zhangfa Liu et al. [2003] proposed a 1.5 GHz LNA for GPS applications using inductors which offers very less NF of 0.2 dB. The designed circuit yields a gain of 28.7 dB with 1 V supply. Figure 9 shows the circuit schematic of LNA, which is simulated using the cadence spectra RF tool [24].

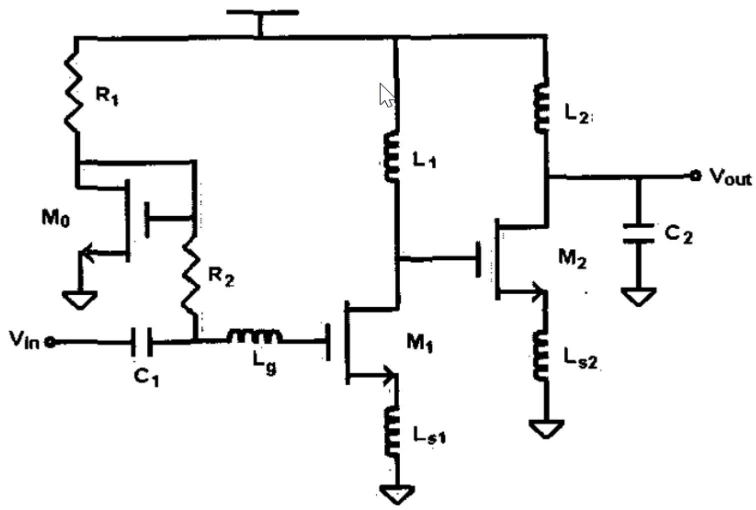

Figure 9. Circuit schematic of LNA using Inductors, Ref [24].

Sarang Thombre et al., [2010] implemented and simulated a LNA which operates over the whole range of GNSS 1164 MHz–1615.5 MHz. The LNA design mainly works for three constellations GPS, GLONASS, and Galileo [25].

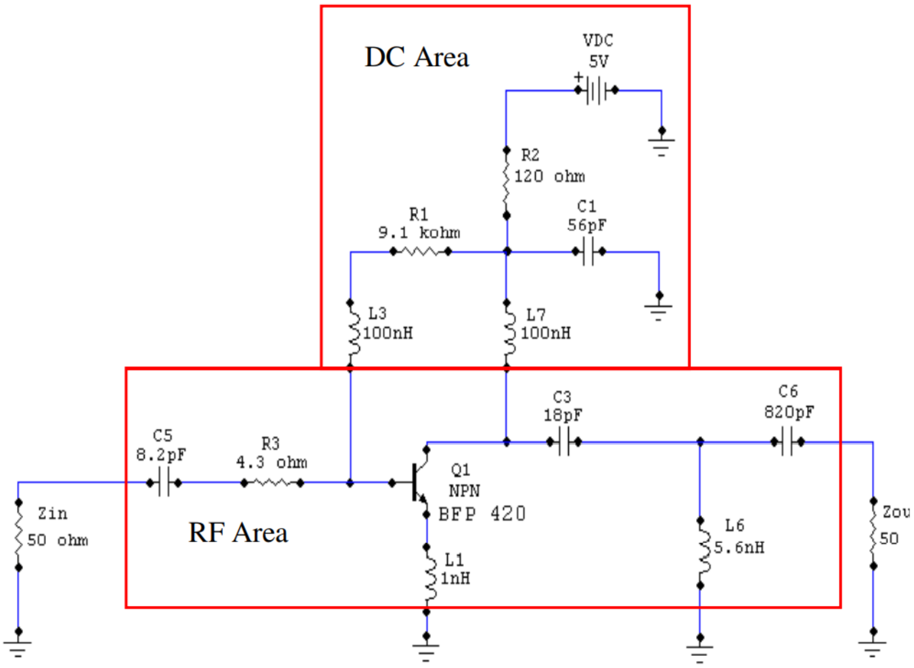

Figure 10. Circuit schematic of LNA using BJT, Ref [25].

Figure 10 shows the circuit schematic of LNA. The biasing network provides a standardized DC operating voltage of 5 V and a current 20 mA for the transistor, The simultaneous conjugate matching technique is used to match the LNA for maximum gain. Resistors R_1 and R_2 are the biasing resistors. The series resistor R_3 is used for input matching and makes the amplifier stable at low frequencies but contributes low noise to the overall NF. Capacitor C_1 and inductors L_3 and L_7 are RF chokes to block unwanted energy entering the DC biasing circuit. C_6 and L_6 are used for output matching C_3 is the output DC blocking capacitor. Z_{in} and Z_{out} are dummy source and load impedance. The designed circuit with a 5 V supply voltage provides a gain of 18.2 dB and NF of 2.18 dB.

Jun Wu et al., [2010] presented the design and implementation of a 1.2 GHz/1.57 GHz dual-band reconfigurable LNA for multiband GNSS receivers using 0.18 μm CMOS technology. Figure 11 shows the inductively degenerated common-source topology with built-in single-ended to differential conversion. An ESD protection circuit is incorporated at the input pad for the reliable operation of the circuit. The single-ended to differential conversion is attained by the tail current source M_0. LM and CM are used for impedance matching. The designed LNA achieves a gain of 25 dB and 22 dB and NF of 2.1 dB and 2.3 dB at frequency bands of 1.2 GHz and 1.57 GHz, respectively. An in-band IIP3 of -5.7 dBm and -3.3 dBm is achieved at 1.2 GHz and 1.57 GHz [26].

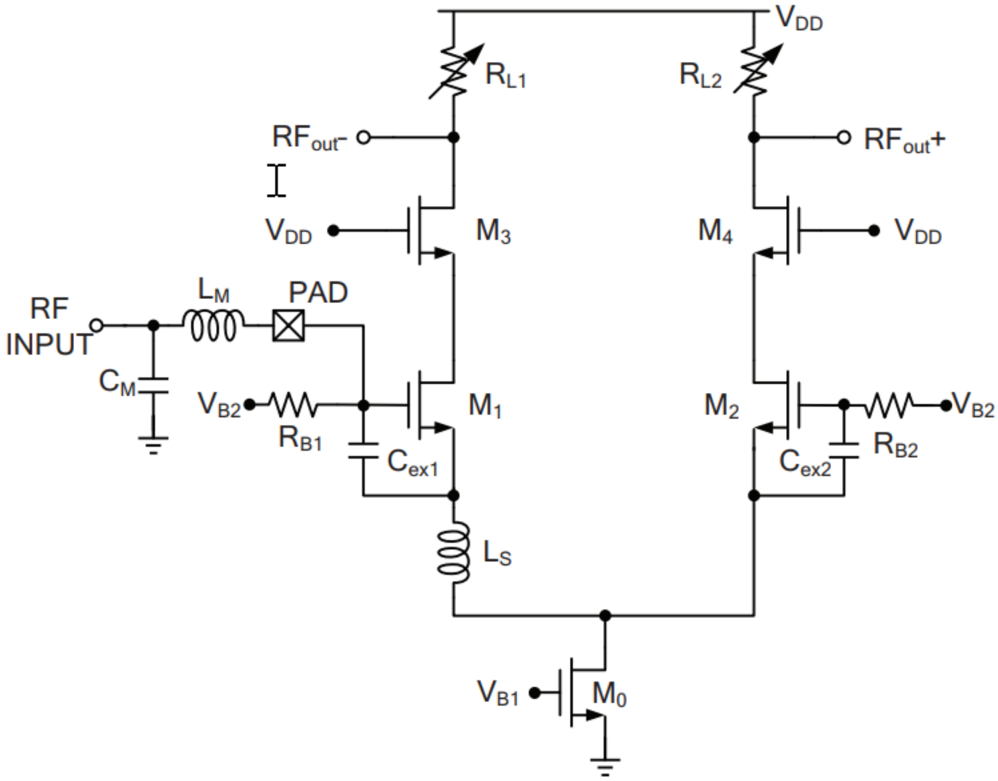

Figure 11. LNA Schematic with in-built single ended to differential conversion [26].

G. Rivela et al., [2011] presented a low-power RF front-end receiver for L1/E1 GPS/Galileo and GLONASS [27]. The design is implemented using 65 nm CMOS technology. Figure 12 shows the single-ended cascode LNA configuration. The configuration is chosen because of its better isolation characteristics and low power consumption. The design includes external input and output matching for a better trade-off between gain and NF. The designed LNA attains a gain of 18.5 dB (GPS/Galileo) and 18 dB (GLONASS) with an NF of 1.7 dB (GPS/Galileo) and 2.4 dB (GLONASS).

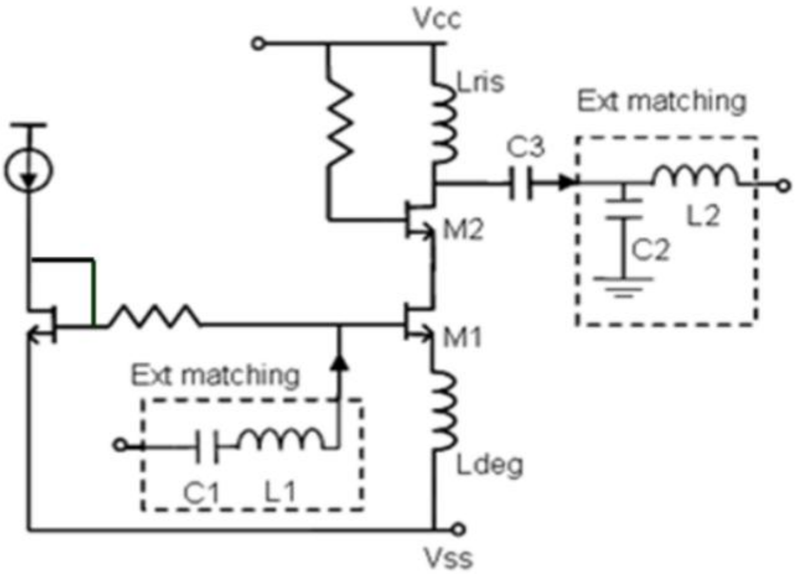

Figure 12. Circuit schematic of LNA [27].

Fei Song et al, [2014] implemented an ESD-protected GNSS LNA using 0.18 µm SOI CMOS technology [28]. Figure 13 shows the detailed LNA schematic comprising of ESD protection circuit, constant g_m biasing, and LNA core. The LNA core circuit is implemented using floating body FETs because of its Kink effect and less impact on NF over body contacted FETs and bulk MOSFETS. Furthermore, GNSS LNA circuit employs inductively degenerated common-source topology with an LC network.

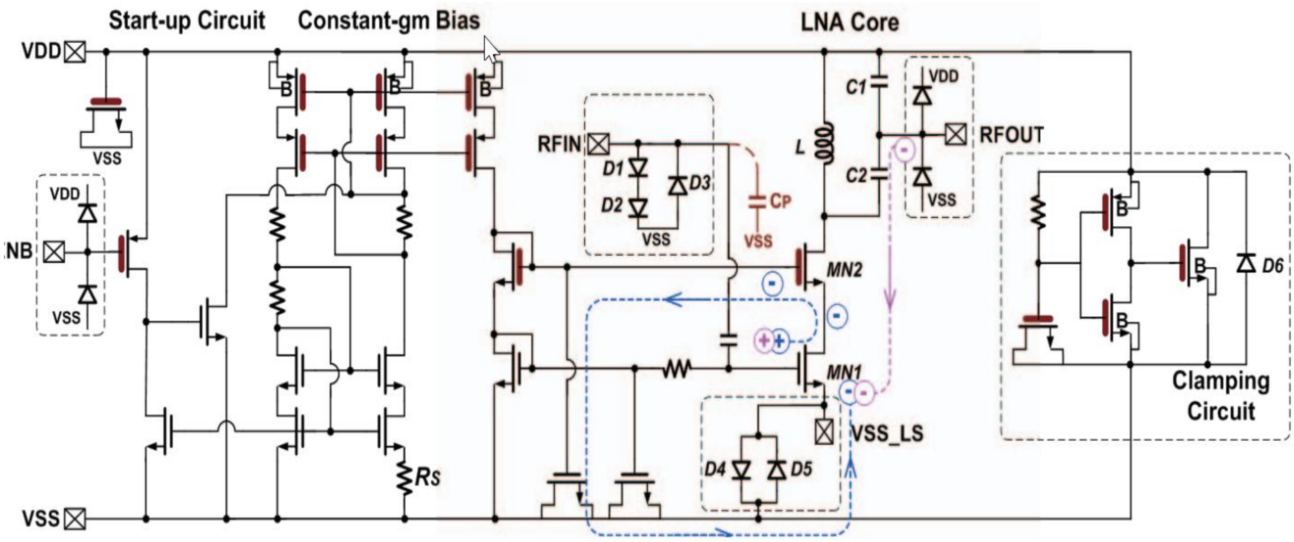

Figure 13. Circuit schematic of SOI LNA [28].

The MN1 transistor is operated as a class AB amplifier to improve power efficiency and mitigate distortion. For a reduced die area and unwanted magnetic coupling between Ls and L, the length and orientation of bond wire is chosen and verified by Electro-Magnetic (EM) simulation, which results in contributing less NF. The width of the MN2 transistor is chosen to be larger than 1.5 times the width of the MN1 transistor for better linearity, gain and NF. C_1 and C_2 form a capacitor divider circuit for output matching. C_p is the input parasitic capacitance. Increase in input parasitic capacitance will affect the input impedance of the LNA. Hence An ESD protection circuit is designed using diodes D1, D2, and D3 to minimize the C_p value. The proposed ESD circuit offers smaller parasitic capacitance and better protection capability. Due to the kink effect in floating body FETs, body contacted FETs are used in power clamping circuits, resulting in less than 1 µA off-state leakage current for 2.8 V VDD. By proper ground planning of the LNA circuit, more excellent stability is achieved. The constant g_m biasing circuit is used to maintain constant gain over process, voltage, and temperature variations. The designed LNA achieves a gain of 19.2 dB, NF of 0.65 dB, output P1 dB of +10 dBm by consuming 5.9 mA from a 2.8 V supply.

Navneeta Deo et al., [2015] developed a low power wideband LNA for GNSS applications using SiGe HBT technology [29]. Figure 14 shows the LNA layout created using Advanced Design System (ADS) software, and the design is fabricated on a printed circuit board. BFP640F SiGe transistor is considered for obtaining minimum NF and unconditional stability. A collector feedback configuration is selected as DC bias network to achieve minimum NF and low power consumption. The design also includes input and output network to achieve low NF and unconditional stability. An NF of 0.84–0.91 dB is measured within the frequency range of 1.1–1.6 GHz using N8973A Agilent NF meter. A simulated NF of <1 dB is achieved in the entire L-band. The gain of 13 dB and 25 mW power consumption is obtained [29].

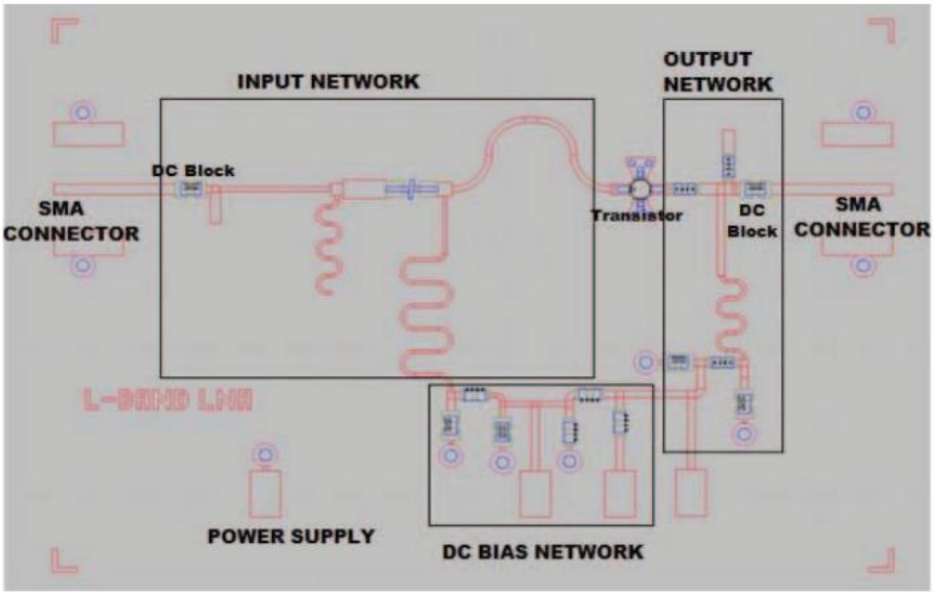

Figure 14. GNSS LNA Layout using SiGe HBT technology [29].

Aleh Halauko et al., [2015] presented the LNA design using a 28 nm FD-SOI (Fully Depleted Silicon on Insulator) technology for GNSS receivers operating in the Galileo/GPS E1/L1 band [30]. The design of LNA using four transistors available in 28 nm FD-SOI technology is discussed by comparing the performance parameters with CMOS and BiCMOS technology. Figure 15 shows the cascade LNA topology with common source and common gate stages. The common source stage contributes in achieving better gain and good noise performance, whereas the common gate stage reduces the Miller's effect by providing good reverse isolation of output from the input and improves the stability of the circuit. Adding CEXT in parallel to Cgs1 provides low NF. LD and CD improve the gain of the circuit. The Fully Depleted (FD)-Silicon On Insulator(SOI) LNA design provides low NF, high gain, and low power consumption compared to CMOS/Bi CMOS process.

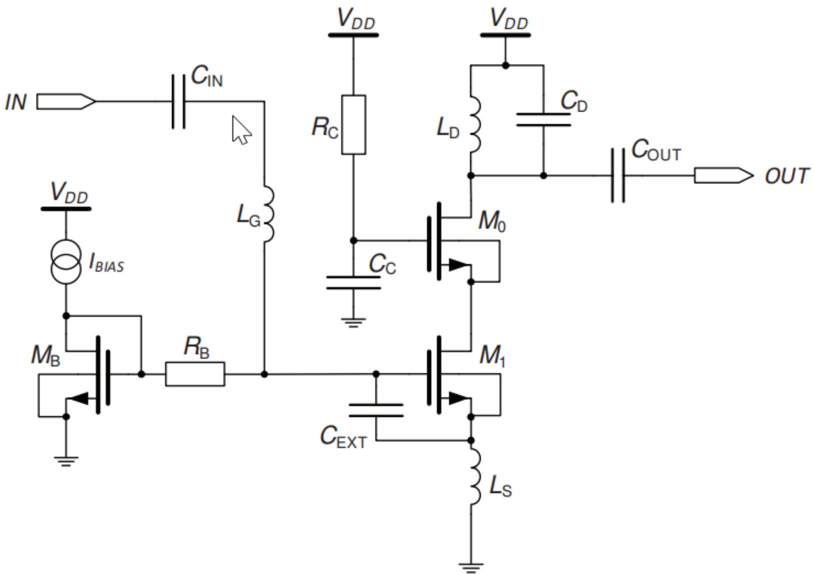

Figure 15. Circuit schematic of inductively degenerated cascode LNA [30].

Singh S et al., [2016] implemented LNA using an Artificial Neural Network (ANN) approach [31]. The paper presents Multilayer perceptron architecture in designing an LNA for a GPS receiver operating at 1.5754 GHz. For LNA design, the ANN toolbox of MATLAB software tool is trained using Levenberg-Marquardt back propagation algorithm according to MGA72543 GaAs pHEMT LNA datasheet. The approach provides an enhanced input and output matching network that can be utilized for future work to acquire maximum gain and minimum NF [31].

Benqing Guo et al., [2017] proposed a wideband common gate LNA exploiting the Complementary Multi Gated Transistor (CMGTR) technique to enhance the linearity of the circuit. The proposed LNA design is shown in Figure 16 and fabricated using 0.18 μm CMOS technology [32].

The CGLNA uses differential topology with cross-coupled capacitors to reduce the NF. The stacked PMOS/NMOS configuration reduces the power consumption at specific input impedance by employing the current reuse technique. The inductors Lsn and Lsp are used in providing a wideband input matching. The proposed design yields a 19.5 dB gain with 2.1 dB of NF over a wide frequency range of 0.2–1.6 GHz. The circuit consumes power of 7.7 mW from 2.2 V supply voltage, which makes it suitable for wideband receiver applications.

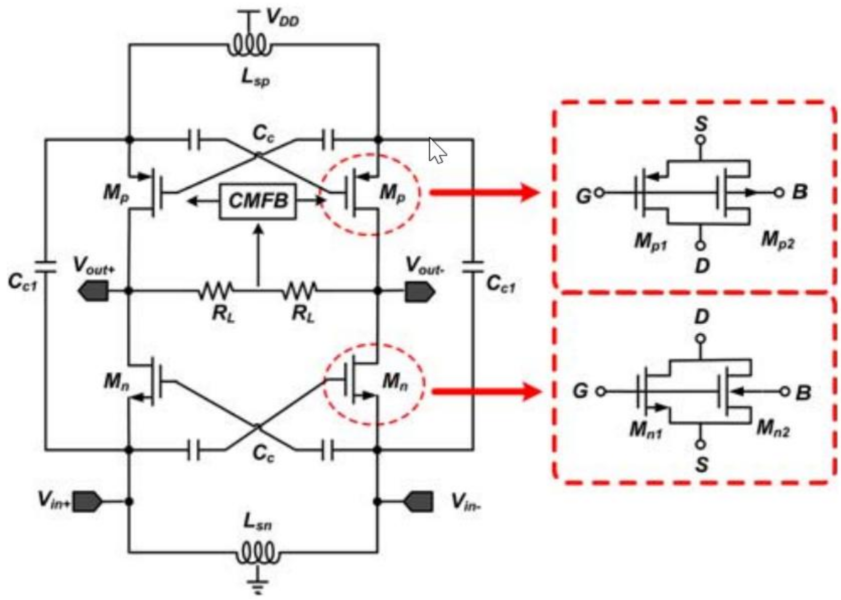

Figure 16. Circuit schematic of LNA using CMGTR Technique [32].

Maheen Hafeez et al., [2019] developed a two-stage CS (common source) LNA with feedback topology of the effective ways to achieve high gain, matching, and low power consumption using feedback topology. The feedback technique is used to achieve high stable amplifiers and wideband matching. The chip area can also be reduced using feedback topology as it requires fewer inductors in the design. Figure 17 shows the two-stage LNA design with a common source configuration using RC feedback topology. The first stage of the design is implemented using HEMT transistor with a gate width of 50 μm, which produces NF_{min} of 0.3 dB. The second stage transistor is implemented with a gate width of 100 μm. Both the stages are biased with 5.5 V. The design uses GaN HEMT on silicon carbide substrate, which can be employed for GNSS applications. The feedback topology achieves a low NF of 0.9–1.05 dB with a high gain of 33–34 dB across the frequency range of 1.5 GHz to 1.7 GHz. The power consumption of 0.7 W from a supply voltage of 5.5 V using the ADS tool [33].

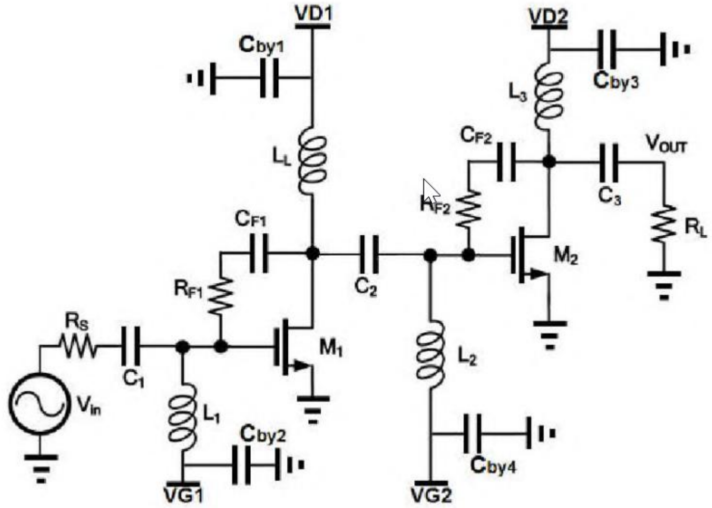

Figure 17. Circuit schematic of GNSS LNA using HEMT, Ref [33].

Mopuri Ramanaidu et al., [2019] presented a pHEMT LNA design for the GNSS upper L band. The primary goal is to design a low-cost LNA compact in size without degrading the circuit's performance. Figure 18 shows the pHEMT LNA designed on FR-4 substrate with a thickness of 1.6 mm and permittivity of 4.3 and simulated using ADS software tool. For a compact design, the microstrip lines are bent in the circuit. pHEMT transistor is chosen because of its high linearity, high gain, and low NF.

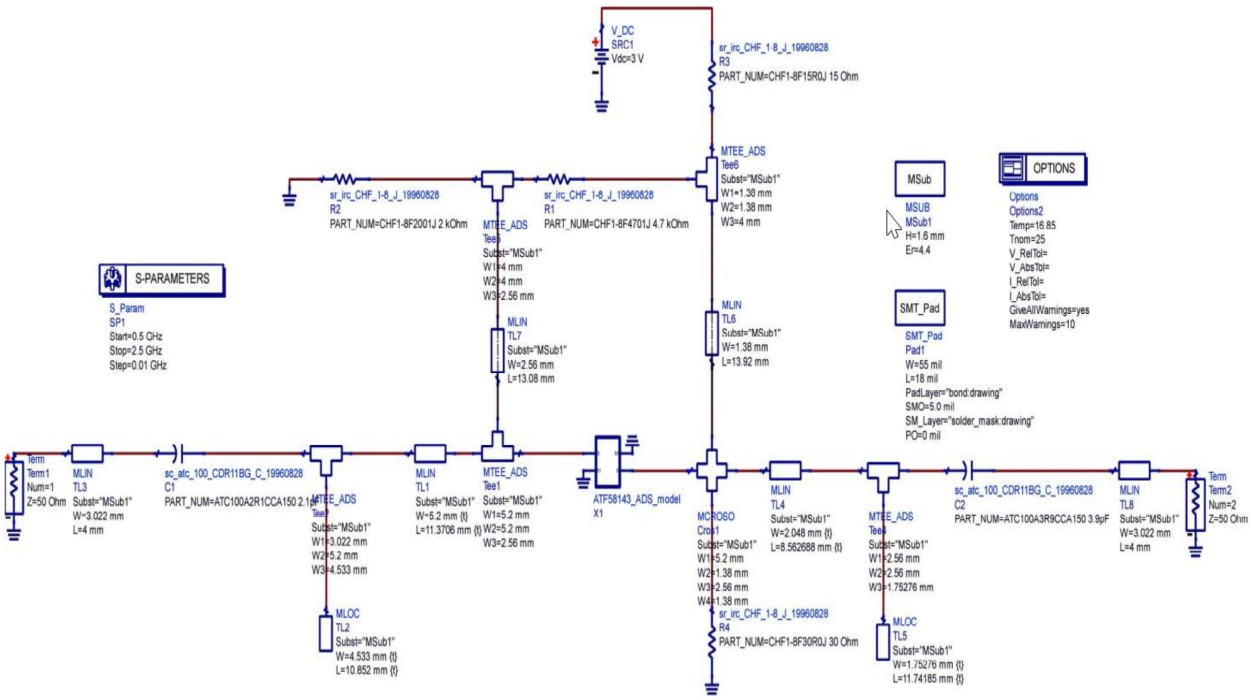

Figure 18. pHEMT LNA design using ADS software, Ref [34].

The LNA is unconditionally stable within the frequency range 1.53–1.73 GHz providing a gain of 10.3 dB and NF of 0.9 dB, which can be used for the GNSS upper L band. Furthermore, the perfect input impedance matching of 50 Ω is also attained from the design [34].

Yang Luo et al., [2020] designed a 0.18 μm CMOS technology based Reconfigurable LNA using an active inductor. The traditional LNA design employs passive inductors which are non-tunable, low-quality factor, occupies large chip area, and narrow frequency band. Active inductors overcome this disadvantage by occupying a small chip area, tuneable, and used for multiband applications. Active inductors can be used for LNA input-output matching or as an active load. Figure 19 shows the Design of LNA using active inductor as load designed by transconductance gyrator structure. The LNA design constitutes four stages: tunable active inductor, independence of self-bias with supply voltage, cascode amplifier with RC feedback, and two source followers. Tunability in the active inductor is achieved by varying the PMOS bias voltage.

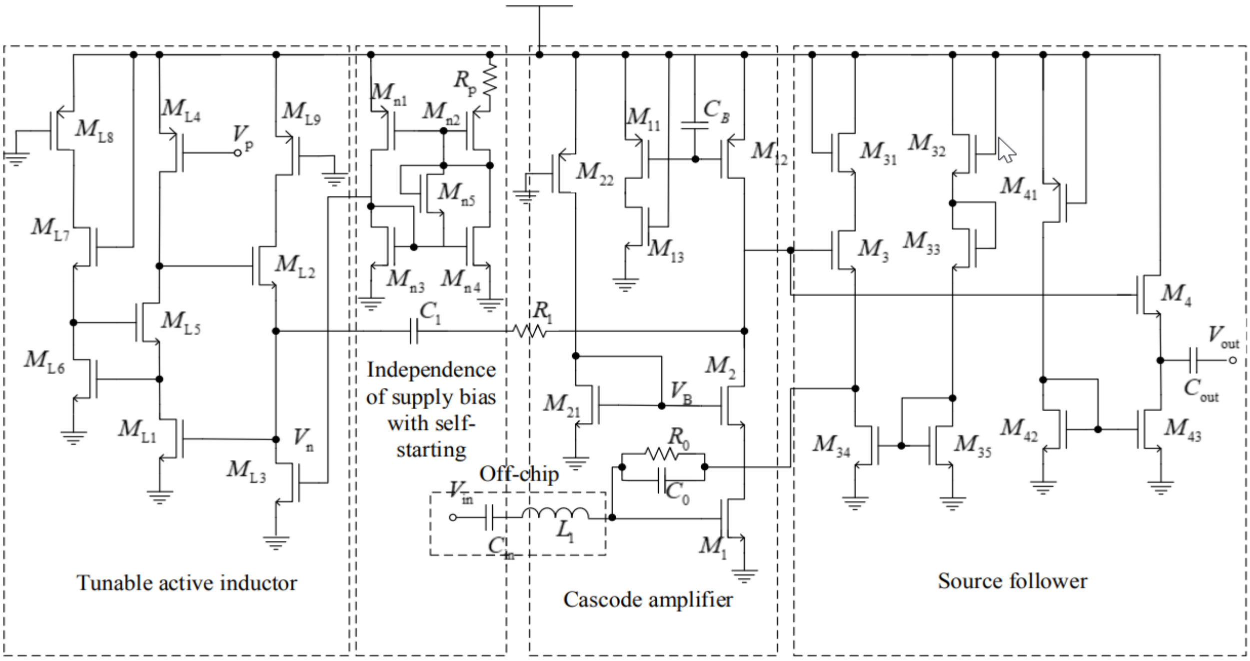

Figure 19. CMOS LNA design using Active Inductors, Ref [35].

M_1 and M_2 are the cascade transistors that reduce the Miller effect, provides high reverse isolation and low NF. M_3 and M_4 constitute two source followers, such as a tunable active inductor, and R_1 acts as a load of the amplifier. The resistor R_0 provides input impedance matching and the capacitor C_0 prevents voltage overshoot. The output impedance matching is obtained by adjusting W/L of M_4 and the current mirror M_{41}-M_{43}. The circuit provides a gain of 18~20 dB with an NF of 2.5~2.8 dB. The power dissipation of the circuit is 20.1 mW. The circuit's operating frequency ranges from 1~3.7 GHz, which can be used in various applications like GPS, Bluetooth, LTE, WIMAX, UMTS [35].

Mohammed Jasim Alali et al. [2020] designed and simulated an ultra-low noise SiGe Heterojunction Bipolar Transistor (HBT) LNA using microwave CAD package and ADS tool as shown in Figure 20. The simulated results indicated that the HBT device offers a superior Noise figure of less than 1 dB and greater than 20 dB gain at 1.227 GHz frequency [36]. In addition, the DC blocking and bypass capacitors minimize the parasitic effect and improve the circuit stability. Capacitors C_1 and C_2 are used for tuning the circuit.

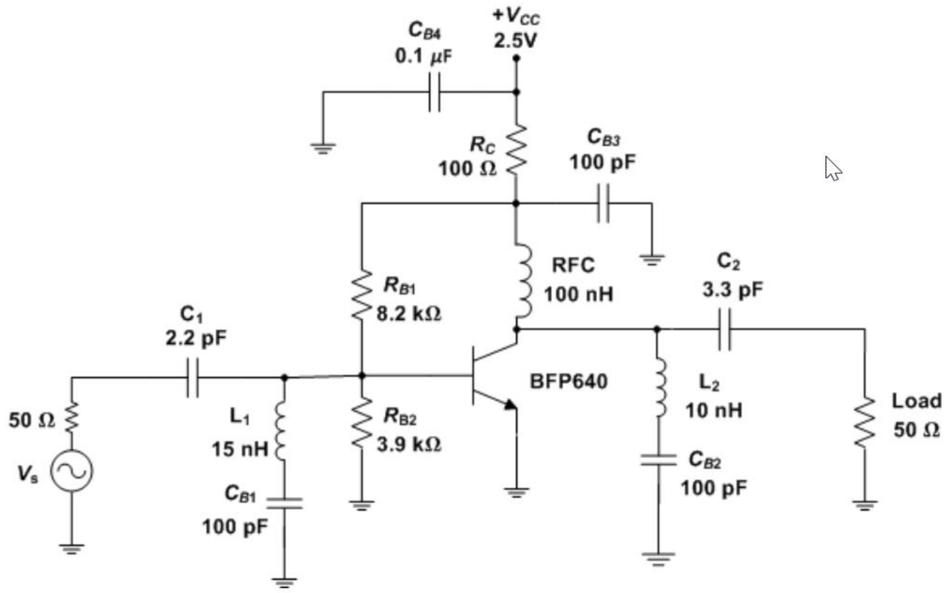

Figure 20. HBT LNA Design, Ref [36].

Dian Rusdiyanto et al., [2019] designed and simulated an Antenna integrated with a low noise amplifier (AILNA) using CST microwave studio and ADS tool, which operates at L1 frequency for GPS application. Figure 21 shows the two-stage cascode LNA design, which exploits NE3509M04 HJ-FET. The design employs a T-shaped inductor for input matching and a single inductor for output matching. The simulated results show the LNA gain of 26.071 dB, NF of 1.2 dB [37].

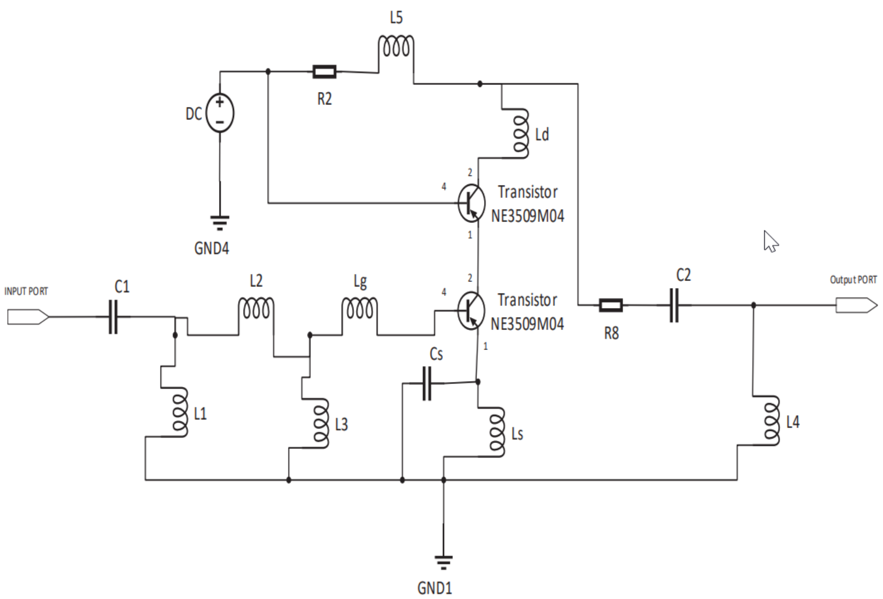

Figure 21. Two stage cascode LNA [37].

Peihui Yan et al., [2020] designed a reconfigurable GNSS receiver for GPS, Galileo, and Beidou systems [38]. The design employs 0.18 µm CMOS technology for portable Internet of Things (IoT) applications. Figure 22 shows the cascade partial source degeneration topology with noise cancellation. The common source stage consists of transistors M_1 and M_2, which contribute to the higher gain of the amplifier. The NF of the LNA can be minimized by choosing the appropriate ratio of the M_1 and M_2 transistor sizes. In distortion cancellation structure, M_4 is biased in the sub-threshold region to improve the linearity of the LNA. The overall reconfigurable receiver produces a maximum gain of 108 dB and an NF of 1.78 dB while drawing 16 mA current from a 1.8 V supply [38].

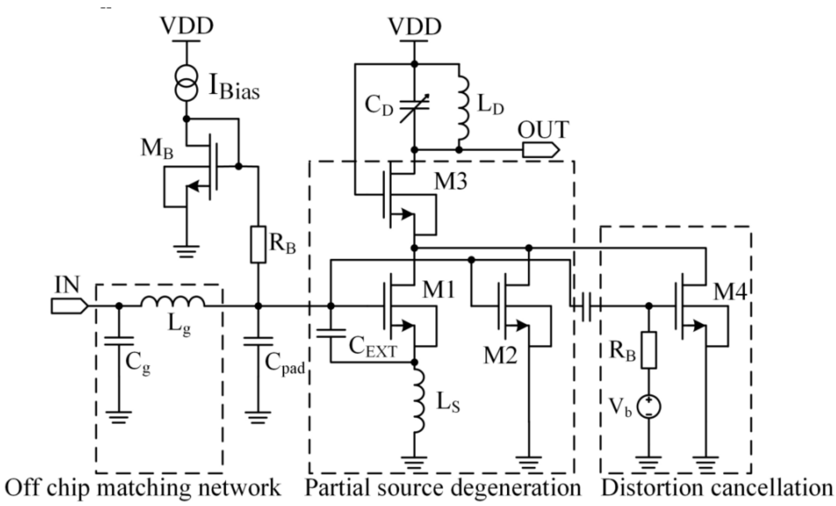

Figure 22. LNA Circuit architecture [38].

Vijay Kumar Kanchetla et al., [2021] presented a compact, fully integrated reconfigurable receiver with low intermediate frequency suitable for various satellite navigation systems like IRNSS/Galileo/Beidou/GPS. In this paper, 65 nm CMOS technology-based common source with resistive shunt feedback topology is demonstrated in designing a wideband input matched noise cancellation balun LNA as shown in Figure 23.

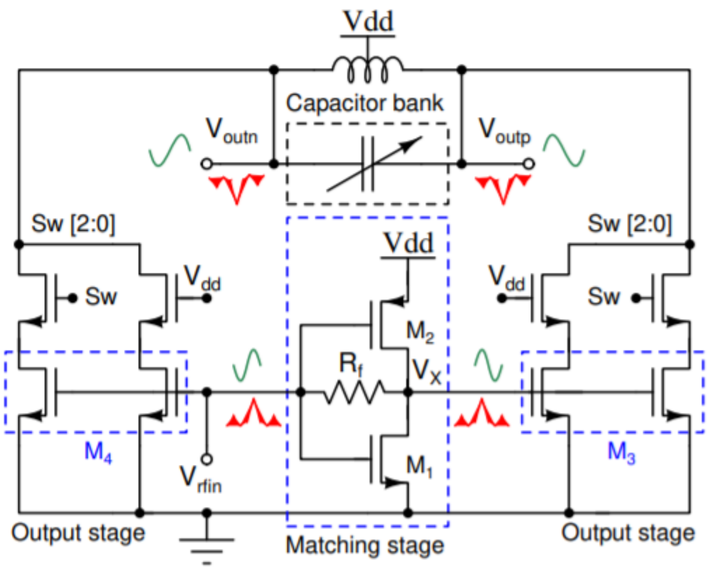

Figure 23. Wideband input matched noise cancellation balun LNA [39].

The output stage transistors M_3 and M_4 with LC tank load convert the single-ended input to a differential output to avoid external balun. The designed LNA cancels the thermal noise by employing the same phase at matching stage input and output nodes. A programmable capacitor bank is used to tune the LNA to any desired navigation signal frequency of 1–2.5 GHz. The LNA produces a varied gain of 12.4 dB to 23 dB. The overall receiver design achieves a maximum gain of 101 dB and a minimum of 3.8 dB with 41 mW of power consumption for provided 1.2 V power supply [39]. Table 2 illustrates the performance of various GNSS LNA topologies. It is evident that the HBT LNA offers minimal NF compared to HEMT.

Table 2. The comparison of various GNSS LNA topologies.

Author	Topology	Technology	Gain (dB)	NF (dB)	Power dissipation (mW)	Supply voltage(V)
R. Benton et al [21]	Resistive Feedback LNA	GaAs	28	2.7	200	±4
Fred Bonn [22]	Two stage cascode LNA using current sharing technique	GaAs	18.4	1	-	2-5
Derek K. Shaeffer et al [23]	Two stage cascode LNA	0.6 μm CMOS	22	3.5	30	1.5
Zhangfa Liu et al [24]	-	0.18 μm CMOS	28.7	0.2	-	1
Sarang Thombre et al [25]	-	BJT	18.5	2.18	-	5
Jun Wu et al [26]	Inductively degenerated common source LNA	0.18 μm CMOS	22-25	2.1-2.3	-	1.8
G. Rivela et al [27]	Single ended cascode LNA	65 nm CMOS	18-18.5	1.7-2.4	33.6	1.2
Fei Song et al [28]	Inductively degenerated common source LNA with LC network	0.18 μm SOI CMOS	19.2	0.65	-	2.8
Navneeta Deo et al [29]	-	SiGe HBT	13	0.84-0.91	-	5
Aleh Halauko et al [30]	Cascaded CS and CG LNA	28 nm FD-SOI CMOS	22.3	1.92	-	0.6
Benqing Guo et al [32]	CG LNA using CMGTR technique	0.18 μm CMOS	19.52	2.1	-	2.2
Maheen Hafeez et al [33]	Two stage CS LNA with feedback topology	0.25 μm GaN HEMT	33-34	0.9-1.05	-	5.5
Mopuri Ramanaidu et al [34]	-	pHEMT	10.3	0.9	-	-
Yang Luo et al [35]	Reconfigurable LNA using active inductor	0.18 μm CMOS	18-20	2.5-2.8	20.1	1.8
Mohammed Jasim Alali et al [36]	-	SiGe HBT	>20	<1	-	2.5
Dian Rusdiyanto et al [37]	Two stage cascode topology	HJ-FET	26.071	1.2	-	-
Vijay kumar kanchetla et al [39]	CS with resistive shunt feedback topology	65 nm CMOS	12.4 to 23	3.8	-	1.2

Radio Frequency Carbon nanotube field-effect transistors (RF CNTFETs) are one of the promising devices which overcome the RF CMOS technology shortly. Their high carrier mobility, small size, high operating frequency, thermal stability, high current drive capability, having both semiconducting and metallic tubes make CNT as frontrunners over CMOS technology [40].

4. Conclusion

The design and implementation of efficient LNA is the biggest challenge as it is the first stage of the GNSS receiver. Designing an LNA with low NF is predominant as it contributes to the system's overall NF and enhances the receiver sensitivity. CMOS LNA design over GaAs FET LNA provides an advantage of obtaining higher gain and an ESD protection circuit which protects the overall circuit against electrical overstress failures. Alternatively, the HEMT LNA design overcomes using additional ESD circuitry, as the circuit itself contributes an additional noise of 0.5–2 dB degrading the circuit's overall performance. On the other hand, HBT LNA offers minimal NF compared to HEMT. CNT (carbon nanotube) is the future technology for developing high frequency and wide bandwidth LNA with high linearity over HEMT. However, while designing a successful LNA, multiple trade-offs between the parameters must be considered. Therefore, future work will be focused on designing an LNA with ANN using HEMT or HBT technology.

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Conflict of interest

The authors declare that there is no conflict of interest.

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