New Realization Methods of Frequency Agile Filters for Encrypted Communications and Multi-Standard Transceivers

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Abstract: Telecommunication is widespread in all areas of society. Although digital signal processing emerges on analog counterpart, analog signal processing is an indispensable part of the telecommunication. Some analog parts, especially band selection filter and oscillator of the transceivers must be reconfigurable for more convenience. Multi-standard transceivers increase the universality of the designed transceiver circuit for all applications to implement on a single chip. For example, for more convenience 4G cellular system transceivers must be suitable more than one standard for best connectivity. GSM, GPS, WCDMA, Wi-Fi (IEEE 802.11a/b/g/n), WiMAX, Bluetooth, Zee Bee and Ultra Wideband (UWB), are certain prospective standards that can be considered as pieces in the circuit of the final wireless network. The reconfigurable filter called as frequency agile filter is one of the background circuit for the multi-standard transceivers. The frequency agile filter allows to sense different protocols with only one circuit. Such a circuit can be a signal processing part of different positioning system’s bands (GPS, GLONASS, Beidou, GNSS and Galileo) to process different positioning system protocols in the same circuit. Also, the design of reconfigurable low pass filter is one of the most critical part of the Zero-IF receivers. Furthermore, frequency agile filter can be considered as a part of frequency hopping system used in military applications for secure communication.

Frequency hopping spread spectrum known as (FHSS) and direct-sequence spread spectrum (DSSS) are two types of encoding system. In FHSS transmission technology, the data signal is modulated with a narrowband carrier signal hopping arbitrarily frequency to frequency. The random modulation can be predicted by only the desired receivers by the aid of frequency agile filters. In this talk, new recent CMOS realization methods for agile filters suitable for encrypted communication will be presented including the concept, topologies, IC design, layouts and simulation results. All data is taken from the recent research works performed in Istanbul Technical University. Two different technology (TSMC 0.18μm and AMS 0.18μm) are used to design frequency agile filters.

Keywords: Multi-standard transceivers, Encrypted communications, analog filters, gomore-C filters, Analog Baseband, Frequency agile filters

I. INTRODUCTION

Communication technology stands out as an important part of our lives and has a large share in the prosperity of society and the economy. GSM, GPS, biomedical applications and etc. are the essential part of our daily lives. Analog part of these technologies play the key role relatively to the digital circuits. Especially, analog filtering is the indispensable part of the transceivers of such examples [1-40]. Many kinds of communication such as Wi-Fi, Bluetooth, Global Positioning Systems and so on require capability of transceivers to these communication standards. Generally, the commercial items must be compatible to the standards listed above. For example, cell phone transceivers must process all GSM, GPS, WCDMA, Wi-Fi (IEEE 802.11a/b/g/n), WiMAX, Bluetooth, ZigBee and Ultra Wideband (UWB) and so on for more convenience. Such a transceiver named as multi standard transceivers can process all standards with single chip by changing only software codes. This type chip production decreases cost and area. Software Defined Radio (SDR) transceivers provides these requirements [3-5]. A multi-standard receiver might be realized by stacking different receivers for different standards into a single receiver. However, the area and power consumption would be extremely high. Instead, a well-designed architecture of a multi-standard receiver should optimally share the available hardware resources and make use of the tunable and programmable devices [6]. To design multi-standard transceiver, LNA, local oscillators, mixers, filters and such architectures must be reconfigurable. The general aspect of the conventional transceiver and receiver architecture are given in Fig. 1. To make the encrypted communications or secure communications not exploitable by an unauthorized receiver, various techniques of encoding are used. The encoding can be done either on the level of information or on the level of frequency.
Encoding on the level of information consists in applying coding algorithms with addition of keys to the binary information, to make it indecipherable when the suitable key of deciphering is absent.

The second technique of coding is at the frequency level. This technique is called “Spread Spectrum”: it proceeds by spreading out of the spectrum. The spreading out of the spectrum is currently widely used for wireless communication (the 802.11 family of standards), Military, Industrial Avionics, Scientific and Civil uses, [10]. This technique makes the emitted signal resistant to the interferences of other signals and the reflections due to multi-path. The transmitted signals can thus share bands with other types of transmission, which makes it possible to use the bandwidth more effectively.

The spreading out of spectrum can be carried out in two different ways: by direct sequence (DSSS), [10], or frequency hopping (FHSS), [11-13]. In a DSSS system, the spreading function is a code word used to modulate the RF carrier. In FHSS the spreading function controls the specific frequency. So that for a signal to be audible by a receiver it is necessary that its frequency hopping pattern be the same as the frequency hopping pattern of the transmitter. It will be inaudible for other receivers. Note that for FHSS systems, reconfigurable filters can be used.

This technique was first introduced with an aim of making military communications safe. It consists in emitting on different carriers. Thus a receiver which does not have the code to synchronize with transmissions will not be able to receive the transmitted signals. In that transceiver system the frequency of the carrier is periodically modified (hopped) following a specific sequence of frequencies as for example shown in Fig. 2.

For civil use, some walkie-talkies that employ FHSS technology have been developed for unlicensed use on the 900 MHz band.

Typical applications also include cellular deployments for fixed Broadband Wireless Access (BWA). These applications in the unlicensed spectrum use the frequency band known as “2.4 GHz”. On the other hand, this technique is still widely used in many military equipment. Additional equipment of encoding of the voice like KY-57, and of information are added to overcome limitations. In the state of the art of current military equipment which uses frequency hopping one can quote, TRANSEC, HAVEQUICK and SINCgars, for which the frequency hopping or agility range is up to 500MHz.

HAVE QUICK (HQ) is a frequency-hopping system used to protect military UHF radio traffic. Progress in electronics in the 1970s reached a point where anyone with an inexpensive radio frequency scanner or receiver set could intercept military communications. HQ program was a response to this problem.

HAVE QUICK is not an encryption system, though many HAVE QUICK radios can be used with encryption, e.g. the KY-58 VINSON system. Single Channel Ground and Airborne Radio System (SINCgars) is a Combat Net Radio (CNR) currently used by U.S. and allied military forces.

Furthermore, the complexity of the multi standard transceivers require new design techniques. For example, multi-standard transceivers must suit for more than one protocol as GSM, GPS, WCDMA, Wi-Fi (IEEE
802.11a/b/g/n, WiMAX, Bluetooth, Zee Bee and Ultra Wideband (UWB). Despite, cost effectiveness of the multi-standard transceivers, the background of the multi-standard transceivers are more and more complicated than the conventional transceivers. The signal coming from antenna of any receiver is passing through band-pass filter, low noise amplifier (LNA), respectively. The signal needs one or more down-conversion to achieve base band. New trend to design multi-standard receivers is direct conversion receivers to minimize the complexity and chip occupation of the circuit. In this case, the incoming signal to the receiver is passing through directly base-band without channel selection. The block diagram of the direct-conversion receiver is given in Fig. 3. Direct conversion receiver is also called as Zero-IF receivers. The reconfigurable low pass filter has great importance in the design of Zero-IF receiver’s structures.

At the same time, frequency agile filter is the critical part in the design of receiver circuits to support different global protocols positioning systems (GPS, Beidou, GNSS and Galileo) [15].

In this talk, new recent CMOS realization methods for agile filters suitable for encrypted communication will be presented including the concept, topologies, IC design, layouts and simulation results.

The paper composes of four different methods to design frequency agile filter.

In the first method, frequency agile filter is designed with feedback technique. This method can be applicable to the conventional second order filters which has at least two outputs; low pass and band pass. The low pass output is fed back to the input by passing through a gain stage.

In the second method; frequency agile filter is designed with MOS-Only technique. The core of this design is constructed over the previous method. Because of that, the recommended MOS-Only circuit also must have at least low pass and band pass outputs.

In the third method, VDTA (Voltage Differencing Transconductance Amplifier) based frequency agile filter circuits are recommended. This method can be classified as gm-C filter. The agility is realized by changing the transconductance.

In the last method, a new method to design variable transconductance amplifier (VTA) is proposed. This new cellbased VTA is inspired from cell based variable gain amplifier. Furthermore, the CMOS implementation of the Operational Transconductance Amplifier is realized with this new VTA circuit.

All circuit layout and post-layout simulations are realized in CADENCE environment. All data is taken from the recent research works performed in Istanbul Technical University [40]. It is desirable that the designed circuits give new opportunities to the electronic designers.

II. PROPOSED METHODS FIRST METHOD DESIGNED WITH FEEDBACK TECHNIQUE

Frequency agile filter designed by Fabre and Lakys is constructed with a classical second order filter which has low pass and band pass filter given in Fig. 4 [1-2]. This method is constituted with this basic element as low-pass filter output and band-pass filter output. Low-pass output is fed to the input by passing through an amplifier as given in Fig. 5.

The general equations for classical voltage mode band-pass and low-pass filter are given in (1) and (2), respectively.

\[
F_{BP}(s) = \frac{V_{BP}(s)}{V_{IN}(s)} = \frac{a's}{1 + as + bs^2}
\]  
(1)

\[
F_{LP}(s) = \frac{V_{LP}(s)}{V_{IN}(s)} = \frac{d}{1 + as + bs^2}
\]  
(2)

The center frequency of the band pass filter is \( f_0 = 1/2\pi\sqrt{b} \). This value also corresponds to -3dB cut off frequency of low pass filter. Quality factor, the gain at \( f_0 \) for the band pass, the band pass -3dB bandwidth and the gain of the low pass filter at low frequencies are given as \( Q = \sqrt{b/a}, g_{BP} = a'/a, \Delta f = a/2\pi b \) and \( g_{LP} = d' \), respectively.

All circuit layout and post-layout simulations are realized in CADENCE environment. All data is taken from the recent research works performed in Istanbul Technical University [40]. It is desirable that the designed circuits give new opportunities to the electronic designers.
The new voltage mode circuit given in Fig. 5, the input signal of the system is changed as given in (3). The further calculation for band pass output prove that band pass function unchanged as given in (4). Equation 5 also prove the low pass filter output remain low pass. All these equations are same for current mode approach.

\[ V_L = V_{IN} - AV_{LP} \]  
(3)

\[ F_{BP}(s) = \frac{V_{BP}}{V_{IN}}(s) = \frac{as}{1 + (1 - Ad') \left( \frac{bs^2}{1 + (1 - Ad')} \right)} \]  
(4)

\[ F_{LP}(s) = \frac{I_{LP}}{I_{IN}}(s) = \frac{\frac{d}{(1 - Ad')}}{1 + \left( \frac{as}{1 + (1 - Ad')} \right) \left( \frac{bs^2}{1 + (1 - Ad')} \right)} \]  
(5)

Another example of this feedback method is realized with CDTA’s (current differencing transconductance amplifier) second order biquadratic filter given in Fig. 6 [14].

The complete implementation of the frequency agile band-pass filter operating in current-mode that has been directly deduced from the scheme in Fig. 5 for gain A, is shown in Fig. 8 [16, 17]. The output of the frequency agile filter is given in Fig. 9.
The configurability of the agile filter is realized with switches. All feedback CDTA’s $g_m$ is designed according to the positioning systems and SINCGARS.

The transconductance of CDTA’s used in frequency agile filter structure are given in Fig. 10. It is obviously seen that the higher $g_m$ is used to achieve higher frequencies. The transient analysis of the designed filter at 54.9MHz is given in Fig. 11. The distortion for 100μA pp input current is 3.8%. The layout of the overall design is given in Fig. 12.

The total chip area occupies 132μm x 73μm. Further completion of layouts is required to obtain clean DRC, and ESD protected IC for fabrication. The maximum power consumption of the frequency agile filter working at 88MHz is 8.53mW.

The new band pass function is given in (13). The center frequency and quality factor of the designed filter are changed according to the (14) and (15), respectively.
The Butterworth filter is designed for the military application of SINCGARS. Fig. 9 proves that the proposed filter can operate between the range of 30-87.975MHz. There is no more information about SINCGARS due to security reasons. Some criteria as quality factor, stop band attenuation, pass band gain and etc. characteristics of the designed filter can be adjusted for the application frequency range of 30-87.975MHz.

\[
\begin{align*}
I_{BP} &= \frac{C_2}{g_{m2}(1-g_{m,fb}R_Z)} s^2 \\
I_E &= \frac{C_2}{g_{m2}(1-g_{m,fb}R_Z)} s + \frac{C_1C_2}{g_{m1}g_{m2}(1-g_{m,fb}R_Z)} s^2 \\
\omega_0 &= \sqrt{1 - g_{m,fb}R_Z} \sqrt{g_{m1}g_{m2}} \\
Q &= \sqrt{1 - g_{m,fb}R_Z} \frac{C_1}{g_{m1}g_{m2}C_2}
\end{align*}
\]

(13) (14) (15)

The Butterworth filter is designed for the military application of SINCGARS. Fig. 9 proves that the proposed filter can operate between the range of 30-87.975MHz. There is no more information about SINCGARS due to security reasons. Some criteria as quality factor, stop band attenuation, pass band gain and etc. characteristics of the designed filter can be adjusted for the application frequency range of 30-87.975MHz.

III. SECOND METHOD BASED ON MOS-ONLY TECHNIQUE

The demand of the low supply voltages and power consumptions affect the development of microelectronic technologies [8, 18-19]. The size of the transistors is decreasing day by day. CMOS 20nm gate length production can do as of 2014. However, the small size integrated circuit technologies that can be used easily in digital circuit design are not widely available in analog circuit design. The main reason for this is that analog processing blocks with small sized MOS transistors operating with low supply voltages, does not allow all transistors to operate in saturation mode. For this reason, the existing analog signal processing building blocks must be adapted to small size technologies [20].

The CMOS realization of these conventional analog blocks contains great number of transistors. The growing number of the transistors reduces not only the operation frequency range but also the chance of the low power consumption. MOS-only technique can be sufficient for analog filter design instead of complex active elements. Moreover, transconductance \( g_m \) and gate-to-source capacitance \( C_{gs} \) of the MOS transistors are employed instead of passive resistors and capacitors [21-23].

The design criteria of the proposed Butterworth band pass filter in this part is operating range of HAVEQUICK and SINCGARS. HAVEQUICK operates in the ultrahigh frequency (UHF) FM band, from 225–400MHz and SINCGARS operates in the very high frequency (VHF) FM band, from 30-87.975MHz.

Fig. 13. shows the generated core of the MOS-Only circuit [21]. The designed MOS-Only frequency agile filter circuit is given in Fig. 14.

The designed filter’s band pass and low pass output’s formulas are given in (16) and (17), respectively. The quality factor and center frequency of the MOS-Only design are shown in (18) and (19), respectively.
Fig. 14 Proposed frequency agile filter structure [22].

\[
\begin{align*}
\frac{i_{LP}}{i_{in}} &= \frac{g_{m1}g_{m2}}{g_{m1}g_{m2} + g_{m2}C_{gs1}g_{m1} + C_{gs1}C_{gs2}} \\
\frac{i_{BP}}{i_{in}} &= \frac{g_{m2}C_{gs1}s}{g_{m1}g_{m2} + g_{m2}C_{gs1}g_{m1} + C_{gs1}C_{gs2}} \sqrt{ \frac{C_{gs2}g_{m1}}{C_{gs1}g_{m1}}} \\
Q &= \sqrt{ \frac{C_{gs2}g_{m2}}{C_{gs1}g_{m1}}} \\
\omega_0 &= \sqrt{ \frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}}} 
\end{align*}
\]

The parasitic capacitances, \(g_m\), \(g_{mb}\) etc. of the transistors are given in Table I. The other important parasitic of two feedback transistors (\(M_{F1}\) and \(M_{F2}\)) are additionally given in Table I. The effects of the parasitics as \(g_{ds1}\), \(g_{ds2}\), \(C_{gd1}\), \(C_{gd2}\) and \(g_{mb1}\) are very small compared with the \(g_{m1}\), \(g_{m2}\), \(C_{gs1}\) and \(C_{gs2}\) as seen from Table I.

The new band pass function is modified as seen in (20). The quality factor and the angular pole frequency are changed as shown in (21), (22), respectively. The gain of the band pass function is fixed as seen from (20).

A is the change of \(g_m\) of the \(M_F\) transistors. \(g_m\) is proportional with the W/L ratio. Also, the parasitic capacitances are growing with the W/L ratio. \(C_{gs}\) growing is an extra effect for the frequency variation.

\[
\begin{align*}
\frac{i_{BP}}{I_E} &= \frac{C_{gs1}}{g_{m1}(1-A)} + \frac{C_{gs2}}{g_{m1}g_{m2}(1-A)} + \frac{C_{gs1}C_{gs2}}{g_{m1}g_{m2}(1-A)^2} \\
Q &= \sqrt{1-A} \sqrt{ \frac{C_{gs2}g_{m1}}{g_{m2}C_{gs1}}} \\
\omega_0 &= \sqrt{1-A} \sqrt{ \frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}}} 
\end{align*}
\]

The quality factor and the angular pole frequency is proportional with the (1-A) multiplier. ±0.9V symmetrical supply voltage is used. The biasing voltages are selected as \(V_{b1}=200\text{mV}, V_{b2}=-600\text{mV}, V_{b3}=-100\text{mV}\).
There are several methods to realize frequency agile filter. In this example, the designed frequency agile filter is implemented with gm-C.

The design criteria of the proposed Butterworth band pass filter in this part is operating range of HAVEQUICK. HAVEQUICK operates in the ultrahigh frequency (UHF) FM band, from 225–400MHz. There is no more information about HAVEQUICK due to security reasons.

VDTA is a building block for analog signal processing which has two different transconductance values. Also, these transconductance values are electronically controllable by external biasing currents. VDTA driven biquadratic filters, oscillators and FDNR (frequency dependent negative resistor) can be easily realized employing only one VDTA block by the aid of these different transconductance values [25-26].

The circuit description of the VDTA is given in (23). The symbol of the voltage differencing transconductance amplifier is given in Fig. 18.

\[
\begin{bmatrix}
I_Z \\
I_{X+} \\
I_{X-}
\end{bmatrix} =
\begin{bmatrix}
g_{m1} & -g_{m1} & 0 \\
0 & 0 & g_{m2} \\
0 & 0 & -g_{m2}
\end{bmatrix}
\begin{bmatrix}
V_P \\
V_N \\
V_Z
\end{bmatrix}
\]

(V23)

Fig. 18. VDTA block diagram.

The CMOS realization of the VDTA can be implemented by using two floating current sources proposed by Arbel and Goldminz [27]. But the improved version of the floating current source is more flexible to obtain high quality factor Q for analog filter design [28]. The CMOS realization of the voltage differencing transconductance amplifier is given in Fig. 19 [29].
The layout of the voltage differencing transconductance amplifier is given in Fig. 20. There are nine big pieces in the layout. These pieces are bipolar transistors of temperature independent current source. Two of the bipolar transistors are used as dummy for good matching.

The layout occupies 248μm x 90μm area (0.022mm²) with biasing circuit and temperature independent current generator. The voltage differencing transconductance amplifier occupies only 35μm x 54μm area on the chip. The capacitor sizes are selected as 4μm x 6.5μm to realize the value of 50fF.

\[
\frac{V_{BP}}{V_{in}} = \frac{sC_1g_{ml}}{s^2C_1C_2 + sC_1g_{ml} + g_{ml}g_{m2}} \quad (24)
\]

\[
\frac{V_{LP}}{V_{in}} = \frac{g_{ml}g_{m2}}{s^2C_1C_2 + sC_1g_{ml} + g_{ml}g_{m2}} \quad (25)
\]

\[
\omega_0 = \sqrt{\frac{g_{ml}g_{m2}}{C_1C_2}} \quad (26)
\]

\[
Q = \frac{C_2g_{m1}}{C_1g_{m2}} \quad (27)
\]

Fig. 20. Layout of the frequency agile filter enhanced with g_m-C.

The CMOS implementation is a significant advantage of the designed VDTA based voltage mode filter. In contrary to BiCMOS implementation, CMOS production is very cheaper. Thanks to improved floating current source’s very basic CMOS implementation, the chip size occupies very less chip area. Furthermore, the same technique is also considered to be used in passive radar receivers which are operating up to 1GHz frequencies.

Single block VDTA second order frequency agile filter structure is given in Fig. 21 [26]. The transfer function of the low pass and band pass output are given in (24) and (25), respectively. Equation 26 shows the pole angular frequency. Equation 27 gives the quality factor of the filter.

![Fig. 21. VDTA second order frequency agile filter structure.](image)

TABLE II: SWITCHES ON/OFF POSITIONS

<table>
<thead>
<tr>
<th>Center Frequency</th>
<th>Switches On</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17GHz</td>
<td>S1, S2, S3, S4, S5</td>
</tr>
<tr>
<td>1.02GHz</td>
<td>S2, S3, S4, S5</td>
</tr>
<tr>
<td>891.25MHz</td>
<td>S3, S4, S5</td>
</tr>
<tr>
<td>676.08MHz</td>
<td>S4, S5</td>
</tr>
<tr>
<td>549.54MHz</td>
<td>S1</td>
</tr>
<tr>
<td>371.54MHz</td>
<td>S5</td>
</tr>
</tbody>
</table>

The maximum noise of the designed filter with g_m-C filter is 152nV / sqrt(Hz). Worst cases analysis is performed for the maximum frequency of the designed circuit to check its behavior under various conditions of temperature and supply voltages. The fabrication conditions are selected with six parameters (wp, ws, wo, wz, fff, ssf). The temperature conditions are selected (-50°C, 120°C) The supply voltage conditions are selected (±1.1 V, ±0.9V). The band pass characteristics are preserved under these worst cases conditions. The standard deviation of the center frequency for two hundred random cases is found 49.417MHz. All these
solutions are acceptable for the analog filter design procedure. The variation of process, temperature and supply voltage (PVT) can be eliminated with automatic tuning circuits.

V. FOURTH METHOD CONSTRUCTED WITH CELLBASED VARIABLE TRANSCONDUCTANCE AMPLIFIER

Many kinds of communication such as Wi-Fi, Bluetooth, Global Positioning Systems and so on require capability of transceivers to these communication standards. Generally, the commercial items must be compatible to the standards listed above. For example, cell phone transceivers must process all GSM, GPS, WCDMA, Wi-Fi (IEEE 802.11a/b/g/n), WiMAX, Bluetooth, Zee Bee and Ultra Wideband (UWB) and so on for more convenience. Such a transceiver named as multi standard transceivers can process all standards with single chip by changing only software codes. This type chip production decreases cost and area. Software Defined Radio (SDR) transceivers provides these requirements.

Analog baseband (ABB) [31-32] has two main parts as filter and programmable gain amplifier (PGA). Specially, low pass filter must provide different standard requirements to realize SDR transceivers. Because each standard has different channel bandwidth [33-34]. In this chapter, a new OTA realization method, its voltage mode and current mode reconfigurable ABB low pass filter are proposed for the application of Bluetooth, CDMA2000, Wideband CDMA, and IEEE 802.11a/b/g/n wireless LANs and, also is suitable for other wireless applications as 2G/3G/4G. The basis of the recommended OTA circuit is based on cellbased variable transconductance amplifier (VTA).

The main problem for designing reconfigurable ABB filter bring together the selection of the low frequencies and the high frequencies. To collect all these standards in a single filter, there are some design in the literature [38-39]. The realization method of the cell-based variable gain amplifier is given Fig. 25. The very basic fully differential pair consists each unit cell. The frequency analysis of the transconductance with activated single, double and triple cells is given Fig. 26. $g_m$ changes between 1.23$\mu$S-549$\mu$S.

Second order low pass filter structure is given in Fig. 27. The low-pass filter transfer function, center frequency and quality factor are given in (28), (29) and (30), respectively. $C_1$, $C_2$ are 5pF.
Fig. 26. Frequency analysis of transconductance according to activated cells.

The layout of the designed filter is given in Fig. 28. The core of the filter occupy 150μm x 70μm (0.01mm²). Clean (Design Rule Checking) DRC, and (Electrostatic Discharge) ESD protected IC for fabrication are required.

Fig. 27. Second order voltage mode OTA based low pass filter.

The AC and transient analyses for the application of Bluetooth, CDMA2000, Wideband CDMA, and IEEE 802.11a/b/g/n wireless LANs and 2G/3G/4G are realized to prove the performance of the designed filter. Fig. 29 shows the AC and the transient analyses for 2G. The analyses are performed for the edges of the application of GSM (93kHz - 340kHz). It is activated only one cell to achieve GSM operating frequency. 2.63μS transconductance value is obtained with 3μA biasing current. ABB low pass filter must assure high $f_{3dB}$ frequency at the same time. The cell-based design is very appropriate for reconfigurable ABB filter. Fig. 30 shows the AC analysis for 4G. ABB filter must provide 1.4M~20MHz cut-off frequency for LTE.

Fig. 28. Layout of overall circuit constructed with cell-based variable transconductance amplifier.

Fig. 29. AC and transient analyses for 2G.

Fig. 30. AC analyses for 4G.

$$\frac{V_{LP}}{V_{in}} = \frac{g_{m1}g_{m2}}{s^2C_1C_2 + sC_1g_{m1} + g_{m1}g_{m2}} \quad (28)$$

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad (29)$$

$$Q = \sqrt{\frac{C_2g_{m2}}{C_1g_{m1}}} \quad (30)$$
The AC analysis for the overall circuit is given in Fig. 31. The overall filter operates between 93kHz-20MHz for the value of $g_m \cdot 2.63\mu S - 353\mu S$. The operation range can increase for 50μA biasing current to 30MHz for 549μS transconductance. But, 2.63μS-353μS values are enough for the selected applications. Table III shows the comparison of the designed filter with conventional designs.

![Fig. 31 AC analyses of overall circuit](image)

**VI. CONCLUSIONS**

In this work, four different methods are applied to design new frequency agile filters. Two different technology (TSMC 0.18μm and AMS 0.18μm) are used to design frequency agile filters.

I. In the first method, frequency agile filter is designed with feedback technique. This feedback technique is improved alternatively with useful analog building blocks. A new implementation of frequency agile filter based on CDTA and ECCII is presented. AMS 0.18μm technology is used to design the proposed circuits in this method. The designed circuits with this method is proposed for GPS protocols and Single Channel Ground and Airborne Radio System (SINCGARS).

II. In the second method, a new concept of the frequency agile filter is proposed with MOS-Only technique. The frequency agile filter designed with MOS-Only circuit is firstly proposed in the concept of this work. TSMC 0.18μm technology is used to design the proposed circuits with this method.

III. In the third method, two different VDTA (Voltage Differencing Transconductance Amplifier) based $g_m \cdot C$ frequency agile filter are recommended. The designed circuits with this method are proposed for HAVEQUICK. AMS 0.18μm technology is used to design the proposed circuits in this section.
IV. In the last method a new design for variable transconductance amplifier is proposed. The cell-based variable transconductance amplifier CMOS implementation is used for new reconfigurable ABB low pass filter. The designed frequency agile filter can operate in large spectrum, occupies very less area and dissipates less power. The design circuit with this method is realized with TSMC 0.18μm technology.

The worst case analyses are performed for all recommended circuits to check its behaviors under various conditions of temperature and supply voltages. The fabrication conditions are selected with three parameters (ss, tt, ff) for TSMC technology, six parameters (wp, ws, wo, wz, fff, ssf) for AMS technology.

The temperature conditions are selected (-50°C, 120°C). Supply voltage conditions are selected (±1.1 V, ±0.9V). The band pass characteristics are preserved under these worst cases conditions. Also, all circuit performances are tested with post-layout simulations in Cadence environment. Table IV shows conditions. Also, all circuit performances are tested with post-pass characteristics are preserved under these worst cases conditions.

### Table IV: Classifications of designed filters

<table>
<thead>
<tr>
<th>Design Method</th>
<th>Technolgy</th>
<th>Filter Type</th>
<th>Selected Applications</th>
<th>Operating Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Method</td>
<td>Feedback</td>
<td>BP</td>
<td>Secure Communication (SINCgars) and IF selection</td>
<td>88MHz–108MHz</td>
</tr>
<tr>
<td>Second Method</td>
<td>MOS-Only</td>
<td>BP</td>
<td>Secure Communication (SINCgars) and IF selection</td>
<td>88MHz–400MHz</td>
</tr>
<tr>
<td>Third Method</td>
<td>G2/C</td>
<td>BP</td>
<td>Secure Communication (HAVEQUICK)</td>
<td>200MHz–1GHz</td>
</tr>
<tr>
<td>Fourth Method</td>
<td>Cell Based G2/C</td>
<td>BP</td>
<td>Zero-IF transceivers ABB filter</td>
<td>35kHz–20MHz</td>
</tr>
</tbody>
</table>

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