

Reliable Data Communication Over HF Link Using System On Chip Technology

Somkheart Kraisin

Department of Research and Development Defence
Technology Institute Ministry of Defence
Nonthaburi ,Thailand
Email : somkheart.k@dti.or.th

Wichai Pawgasame

Department of Research and Development Defence
Technology Institute Ministry of Defence
Nonthaburi ,Thailand
Email : wichai.p@dti.or.th

Abstract—HF communication is one of the important aspects in military radio communication, even though it has been seen as a difficult and tedious task because of instability of ionosphere layer. To make HF communication becomes easier, many digital techniques have been introduced. It is also desirable to have all these techniques implemented in a single radio. This can be achieved through software defined radio (SDR) concept. Thus, a HF radio becomes more like a computer whose radio functions can be implemented through software. This paper presents some of the modern digital techniques and software defined radio architecture for HF communication aspect using System-on-Chip and FPGA technologies.

I. INTRODUCTION

Our world has changed from the Industrial Age to the Information Age due to the renovation in the information technology and communications. Military concept has been affected as well. The developments in information technology and communications drive the battlefield into the new era of an Information Warfare, or Network-Centric Warfare by connecting different units and forces into the network and information system. The main components for the stability of the system are the Centric Warfare and the well-design infrastructure on the various support systems, including secured, flexible, compatible, and cost-effective communication and telecommunication equipment. Radio Centric Network integrates information from various networks, including radar, satellite, airborne and PC data; with the HF, VHF and UHF radio systems. This allows combination between control center and tactical units on the same network for the effective operations. Software defined radio (SDR) concept, especially for high frequency (HF) ManPack or small-size radio for mobile use, is one of the main technology applicable to this innovation. SDR consists of a general hardware platform and upgradable software that allow implementation of different frequencies, desired bandwidth, functions, and output power level. SDR also has the flexibility to allow new software installation without changing or replacing new hardware modules. This paper focuses on some of modern HF technologies and the exclusive design of the software defined HF radio.

II. BACKGROUND

A. HF Chanel

The High Frequency (HF) band is between 1.6 - 30 MHz. It is the main frequency band for maritime, military

and aeronautical systems and global communication. In this band, radio waves can propagate in two paths; the ground wave propagation path and the sky wave propagation path. There are three types of ground waves, including direct wave, ground reflected wave and surface wave. The ground waves are used to communicate within near distance due to the high rate of distortion. It is often used for communication between ships and stations on the coast since surface waves can propagate over a sea surface with less attenuation. Therefore, the communication can be produced in longer distance. On the other hand, the sky wave can propagate to a remote station at longer distance by use of reflected The High Frequency (HF) band is between 1.6 - 30 MHz. It is the main frequency band for maritime, military and aeronautical systems and global communication. In this band, radio waves can propagate in two paths; the ground wave propagation path and the sky wave propagation path. There are three types of ground waves, including direct wave, ground reflected wave and surface wave. The ground waves are used to communicate within near distance due to the high rate of distortion. It is often used for communication between ships and stations on the coast since surface waves can propagate over a sea surface with less attenuation. Therefore, the communication can be produced in longer distance. On the other hand, the sky wave can propagate to a remote station at longer distance by use of reflected

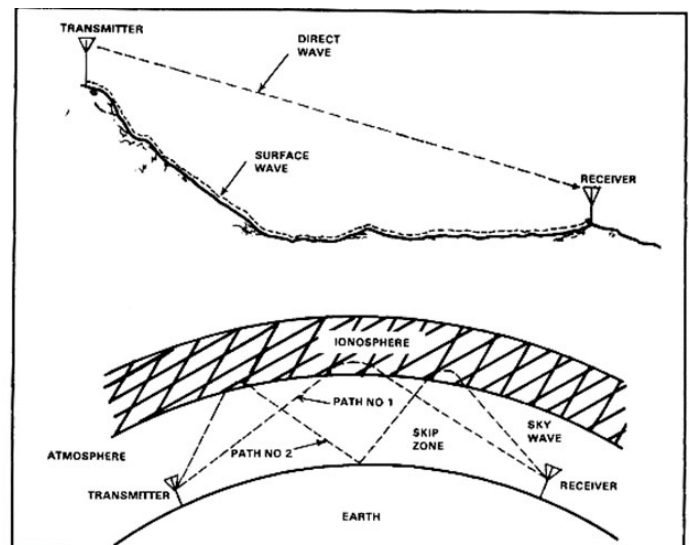


Fig. 1. Ground Waves and Sky Waves Propagation from [1]

B. Conventional HF radio

The primary components of the HF radio system fall into three groups, which are transmitters, receivers and antennas. In many modern radio sets, the transmitter and receiver are combined into a single unit called a transceiver. The transmitter consists of the exciter, which modulates the information with the carrier signal into the signal to be transmitted. The power amplifier, then, boosts the output power of the signal before sending it through the antenna. Then, the receiver side will select a desired signal, amplify it to a suitable level, and recover the information through the process of demodulation. Figure 2-2 illustrates conventional HF radio system. Conventional radio system establishes contact or connections by tuning to the appropriate channel and transmits and receives messages through the particular HF frequency or channel. In conventional voice HF operations, when the radio system loses connectivity, the radio operator must search for another channel. Various products and techniques, as well as the skill and experience of the radio operator are extremely important when determining the alternate channels. Even with a highly skilled radio operator, the time spent searching for alternate channels affects the operation of the radio system since it can be as long as several minutes. Thus, there is a need for a radio system that reduces search time associated with selecting alternate channels, an automatic algorithm that can automatically select a channel for HF operations, and a channel selection algorithm that does not affect communication on the other channels.

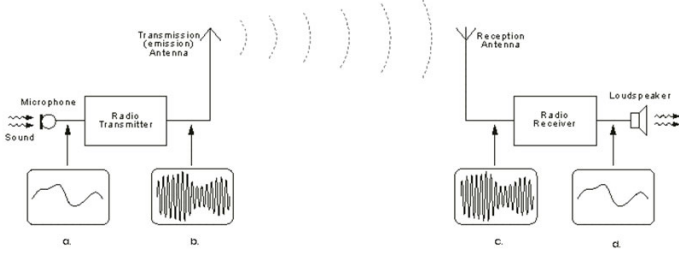


Fig. 2. Conventional HF Radio Transmission from [2]

III. MODERN HF TECHNOLOGIES

An old analog military HF radio suffers from unpredictable sky wave channel through ionosphere, unsecure communication, poor voice quality, and very slow data rate. As digital technologies have improved and become more popular, these problems have been solved. The conventional analog HF radio has transformed into digital HF radio with abilities to overcome unreliable HF channel and provide high data rate. In this section, the modern military HF radio technologies will be discussed.

A. Cognitive HF radio

According to [3], cognitive radio is a radio that can sense its operating environment and adapt its radio operating behavior to any changes in operating environment. Basically, cognitive radio should have the ability to adapt and learn. This can be achieved through artificial intelligence (AI) and software technologies. Hence, cognitive radio utilizes the concept of software defined radio to achieve its cognitive functions. According to [4], STANAG 4538 has defined an automatic radio

control function called automatic link establishment (ALE) for modern military HF radios. This ability is classified as one of cognitive radio capabilities [5]. ALE is a technique that allows HF radio to select the best HF channel automatically. In ALE system, each radio station is assigned with an address in a network and a set of channels. When a radio is not operating, it will try to link with other stations in a network using assigned channels and measure signal quality in each link. This method is called link quality analysis (LQA). According to [4], these measurements will be stored in a LQA matrix as illustrated in Figure 3-1. When station 1 wants to communicate another station in a network, a radio consults with LQA matrix to select the best channel for each communication

Address	Channels				
	01	02	04	10	15
station 2	60	30	22	85	43
station 3	10	--	51	78	21
station 4	--	--	32	55	64
station 5	23	12	--	52	--

Fig. 3. LQA matrix for station 1 according to [4]

B. Data transmission

At the very beginning, HF radios used CW modulation for data communication. CW modulation carries information by varying on-off period of carrier wave according to Morse code [6]. Data is vulnerable to noises and interferences, and data rate is very slow. As many digital modulation techniques have been developed and improved, a digital HF radio can use many digital modulation waveforms that suitable for HF channel to transmit data at higher data rate. In addition, forward error correction (FEC) coding and interleaving can be applied in HF data communication to provide reliable data. FEC adds redundancy to data while interleaving arranges data stream such that burst error has less effect on data. Voice signal can be translated into binary data stream using digital voice coder (Vocoder), hence it can take advantage of digital transmission. Figure 3-2 lists some modern waveform standards for military HF radio according to [4][7]. In modern military HF radio, it is desirable to have all these waveforms implemented in one radio. This can be achieved through software defined radio concept.

Standards	Modulations	Error Control Coding	Interleaving	Data Rate (bps)
MIL-STD-188-110A	single-tone BPSK, QPSK, 8PSK	1/2, 1/8 Convolutional code	Block-based	150, 300, 600, 1200, 2400, 4800 (uncoded)
MIL-STD-188-110B App. B	39-Tone QDPSK, OFDM	10/14, 3/7 RS code	Block-based and convolutional	75, 150, 200, 600, 1200, 2400
MIL-STD-188-110B App. C/STANAG 4539	single-tone QPSK, 8PSK, 16, 32 and 64QAM	3/4 Convolutional code	Block-based	3200, 4800, 6400, 8000, 9600, 12800(uncoded)
STANAG 4415	PSK	1/32 Convolutional Code	Block-based	75
STANAG 4285	single-tone BPSK, QPSK, 8PSK	1/2, 1/4, 1/8, 1/16, 2/3 Convolutional Code	Convolutional	75, 150, 300, 600, 1200, 2400
STANAG 4529	single-tone BPSK, QPSK, 8PSK	1/2, 1/4, 1/8, 2/3 Convolutional Code	Convolutional	75, 150, 300, 600, 1200

Fig. 4. Modern HF waveform Standards

C. Secure communication

Secure communication is a very important aspect in military radio. There are two main processes to secure communication. One is communication security (COMSEC) where data is protected. Another is transmission security (TRANSEC) where transmission is protected. COMSEC on voice communication can be done using analog scrambling or cryptography. Analog scrambling technique separates signal into a number of sub-bands, then shift each sub-band into different audio sub-band and combine all sub-band together to generate one composite output signal for transmission [4]. In cryptography, voice, which is translated into binary stream by vocoder, is digitally encrypted into extremely long binary stream based on specific key and only the receiver with the same key will be able to decrypt this long binary stream. According to [4], a binary stream created in this way provides more secure than analog scrambling technique. Cryptography can be done with external device before sending to a radio for transmission. As digital technologies improved, a software defined radio can handle complex cryptography without a need for external device. Cryptography can be applied on data as well as voice. TRANSEC applies a number of transmission techniques to prevent signal from jamming and detection. The most commonly used technique for military TRANSEC is frequency hopping [4]. In this technique, the transmitter will change transmitting frequency rapidly in a pattern only known by the receiver. This is difficult for HF channel where not all frequencies will be able to transmit. However, one study [8] shows that combining frequency hopping with link quality analysis (LQA) would make frequency hopping scheme more effective. In this study, the selection of hopping channels is made by the receiver based on LQA. This selection of hopping channels is fed back to the transmitter, so it knows what frequencies can be used for hopping. This requires a complex algorithm that can only be implemented through software.

IV. A SOFTWARE DEFINED HF RADIO

A modern military HF radio concept presented in section 3 can be implemented on single radio using software defined radio concept. According to [9], the term software defined radio is the use of hardware and software technologies to implement some of the radio functions through software operating on programmable processing technologies. In other word, a radio becomes more like a computer where its function can be programmed through software. The software defined radio architecture and technologies for modern military HF radio will be discussed in this section.

A. Basic Software Defined HF Radio Functions

A software defined radio is a transceiver where its functions are provided by programmable signal processing hardware. In military communication, a software defined radio should provide encryption capability and the ability to switch between various modulation formats, and data rates in order to counter enemys eavesdropping and adapt to various operational conditions [10]. Figure 4-1 illustrates military software defined radio functional block diagram based on [10][11][12]. As illustrated in this figure, input, which can be voice or data at different data rates, is passed into the system as defined by man-machine interface (MMI). MMI specifies how radio

interacts to user action and its function is defined by software resides in the digital signal processing unit. For voice input, voice is coded where various vocoders with different data rates are supported. Before crypto, data is called Red data whose information has not been protected yet. Then, Cryptography is applied on digital data stream. Output from crypto is called Black data whose information is protected by cryptography. Next, encrypted data will be further processed for transmission. This includes error control coding and baseband modulation. A digital signal processing unit should be able to generate many waveform standards as specified in Figure 3-2.

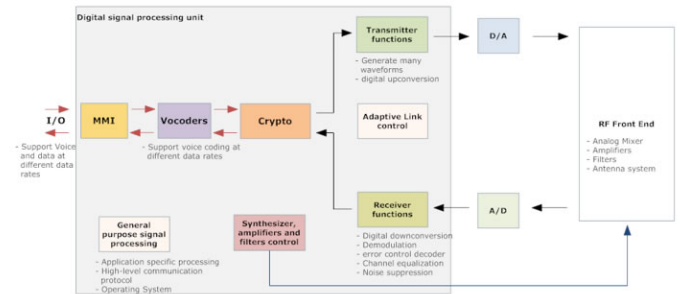


Fig. 5. Modern HF waveform Standards

An adaptive link control function is used to adapt transmission characteristic to suit any changes in the channel. The modulated baseband signal is digitally up-converted to low intermediate frequency (IF) inside digital signal processing unit. Then, digital-to-analog converter (DAC) is used to convert digital IF signal to analog IF signal, and sends to RF Front End. For transmitter functions, RF Front End basically contains reconstruction filter that smooth output signal from DAC, analog mixer that converts IF signal into passband signal at carrier frequency, band-pass filters that reduces phase noise produced by local oscillator and reject unwanted signals, power amplifier (PA) that makes transmitting signal strong enough to drive an antenna, and antenna system. For receiver functions, RF front end should contain band-pass filters that reject unwanted signal, analog mixers that convert passband signal back to low IF signal, amplifier system controlled by automatic gain control (AGC) that maintain received signal at optimal levels, and anti-aliasing filter that reduce effect of aliasing before sampling a received signal. Analog-to-digital converter (ADC) converts analog signal to digital IF signal. Digital signal is then digitally down-converted, demodulated and error control decoded by receiver function in digital signal processing unit. In addition, this unit contains necessary functions to maintain good quality of received signal such as channel equalizer and noise rejection. Received data stream is then decrypted and decoded to information signal that is usable by the user. A general purpose signal processing is used for application specific data processing that requires high-level software language and complex algorithm. It is also used for implementing high-level communication protocol. It may also contain operating system for a radio. Typically, this function processes data that does not require long and complex mathematic operation. A synthesizer, amplifiers and filters control functions is used to control synthesizer, filters, and amplifiers in RF front end. This function includes AGC that control amplifier system to maintain low noise figure in the receiver. There are many up/down-conversion solutions as

described in [12], the solution described in this paper is just one of many solutions for software defined HF radio. With today's DAC and ADC technology, it is possible to directly convert digital signal in HF band into analog HF signal. In this solution [11], a digital upconverter can directly convert baseband signal into passband signal at HF frequency, and a digital downconverter can directly convert HF passband signal to baseband signal. With this solution, there is no need for external analog mixer in the RF Front End. The digital up/down-converter presented here is based on Weaver method [13] and the design is presented in [11]. Figure 4-2 and 4-3 illustrate this design

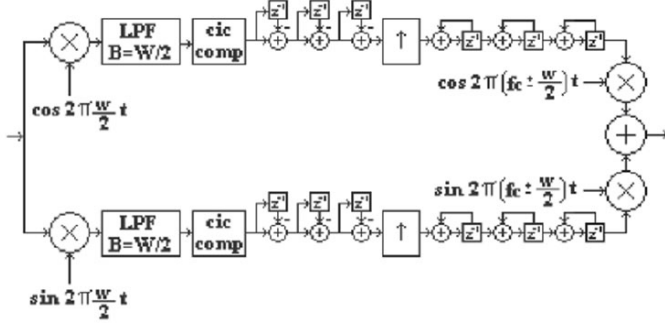


Fig. 6. Weaver digital upconversion from [11]

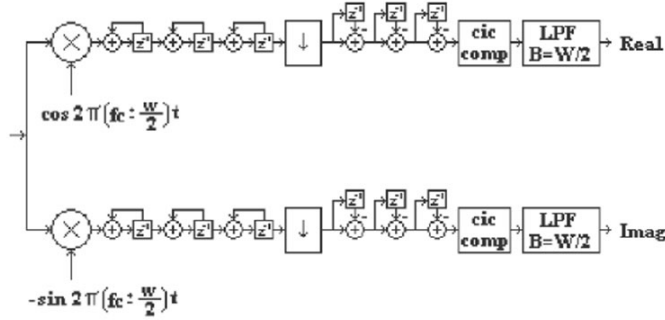


Fig. 7. Weaver digital downconversion from [11]

In Weaver upconversion method, the real digital baseband signal is mixed with sinusoidal signals at the frequency equal to half bandwidth of input signal ($W/2$). This is to translate middle of input spectrum to be center at zero frequency. Then, linear phase low-pass filter with cutoff frequency around half bandwidth of input signal is used to filter out high frequency components. The cascaded integrator comb (CIC) filters are used to upsample input to sample rate of 76.8 MHz [11], which is satisfied Nyquist rate for HF band (1.6–30 MHz). This is to guarantee that no reconstruction aliasing would occur. The output of CIC filters are then modulated with sinusoidal signals center at A plus sign indicates that upper

$$f_c \pm \frac{W}{2}$$

side-band (USB) signal is generated, where a minus sign indicates that lower side-band (LSB) signal is generated. For Weaver downconversion method, the process is just a reverse

of upconversion. The output of digital downconversion can be left as in-phase and quadrature form as illustrate in Figure 4-3.

B. Software Defined HF Radio Hardware Architecture

According to the functional model presented in Section 4.1, a software defined HF radio would have hardware architecture as illustrated in Figure 4-4. The hardware architecture presented in this paper is based on [11][12]. This architecture is for multiband radio, which supports operation in VHF and UHF bands as well. Narrowband and wideband signal processing are also possible. For the operation in HF band, the signal can be upconverted and downconverted directly in digital signal processing unit without the use of external mixer as discussed in Section 4.1. In this section, the main components of software defined HF radio will be discussed.

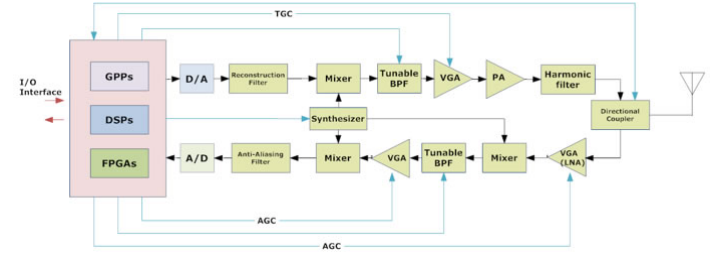


Fig. 8. Weaver digital downconversion from [11]

1) *Digital Signal Processing unit*: The digital signal processing unit is the most important part of software defined radio. It is responsible for data and signal processing. Digital signal processing unit is based on programmable processor technologies. There are a lot of such technologies exists today. In this paper, only processor technology as described in [11] will be presented. The solution can be implemented from one of processor technologies or a combination of many processor technologies

2) *General purpose processors (GPPs)*: According to [14], a name general purpose, means that this processor is not specific to any tasks or programming languages. GPPs are suitable for data processing that requires complex algorithm and high-level language (i.e. C/C++). GPPs usually run at moderate speed and are not suitable for radio waveform signal processing that require high-speed multiply accumulate (MAC) processing [5]. Hence, GPPs is usually included in a software defined radio to provide application specific data processing, operating system, or high-level communication protocol. The GPP solution as presented in [11] is Freescales MX21. The MX21 is designed to support multimedia and graphic applications for wireless platforms. The processor core runs at 266 MHz and support external 133 MHz SDRAM.

3) *Digital Signal Processors (DSPs)*: DSP is a specialized microprocessor, in which its architecture is optimized for fast mathematic operation [5]. DSPs are different from GPPs in that they can perform multiply-accumulate very fast [5]. This makes DSPs more suitable than GPPs to perform some radio signal processing functions such as digital filtering and channel coding. DSPs also support high-level programming language such as C/C++ language, which is suitable for some complex algorithm such as adaptive link control algorithm.

The limitation of DSPs is that it cannot perform complex signal processing at very high sampling rate. Therefore, DSPs is not suitable for complex high-speed signal processing such as waveform generation and CIC filter.

The DSP solution as described in [11] is divided into two parts.

- A narrow-band DSP that perform narrow-band signal processing is TMS320C5510. TMS320C5510 uses C55x DSP core that can provide 400 million multiply-accumulates per second at 200 MHz clock speed.
- A wide-band DSP that perform wide-band signal processing is TMS320C6416. TMS320C6412 uses C64x DSP core that can provide 4800 million multiply-accumulates per second at 600 MHz clock speed.

4) *Field Programmable Gate Arrays (FPGAs)*: FPGA is an integrated circuit containing many programmable logic devices that can be configured to perform specific logical function [5]. FPGAs can be programmed to perform multiply-accumulate that is a lot faster than DSPs. This makes it capable of process RF signal at high sampling rate. Typically, FPGAs is used to implement many waveforms, CIC upsampling filter, and other tasks that require high-speed signal processing. The downside of FPGAs is that it is not suitable for very complex algorithm because FPGAs is implemented using Very High-speed integrated circuit hardware Description Language (VHDL) that is not usual software development paradigm [5]. The FPGA solution as presented in [11] is Virtex-II 2V3000 that can perform over 0.5 Tera-multiply-accumulates per second.

C. ADC and DAC

The main task of DAC in software defined radio is to convert digital output signal from digital signal processing unit into analog signal. An example of DAC that is suitable for a software defined HF radio as presented in [11] is AD9744. This 14-bit DAC can support maximum rate of 210 million samples per second, which is enough to convert digital output signal from digital signal processing unit with sampling rate of 76.8 MHz. The ADC converter converts received analog HF signal into digital signal. The solution presented in [11] is LTC2249, which can provide 14-bit 80 million samples per second with 73 dB SNR. This give a digital output signal that meet the required sampling rate for an input to the digital signal processing unit is 76.8 MHz. The main considerations of ADC and DAC are that they should meet required sampling rate of the input and output to the digital signal processing unit with high SNR output and less power consumption [12].

D. RF Front End

RF front end should provide analog transmitter and receiver functions. Generally, RF front end contains analog mixers, filters, and amplifiers. The hardware solution of RF front end for software defined HF radio is presented in Figure 8. The receiver use multi-stage IF technique such that input to the digital signal processing unit is converted to low IF signal. According to [11], analog mixer would not be needed in HF operation. The reconstruction and anti-aliasing filters are usually the same filter. At the transmitter, it is used to smooth output from DAC and remove unwanted signal over 30 MHz HF band. At the receiver, it is used to limit input signal under 30 MHz HF band to prevent aliasing after ADC.

According to [11], this filter can be implemented from 10th order Butterworth low-pass filter that allow full 30 MHz HF spectrum to pass without signal degradation. The stop-band edge is designed to attenuate signal at 38.4 MHz, which is half of output sampling rate from digital signal processing unit. The frequency response of reconstruction and anti-aliasing filter according to this solution is illustrated in Figure 9.

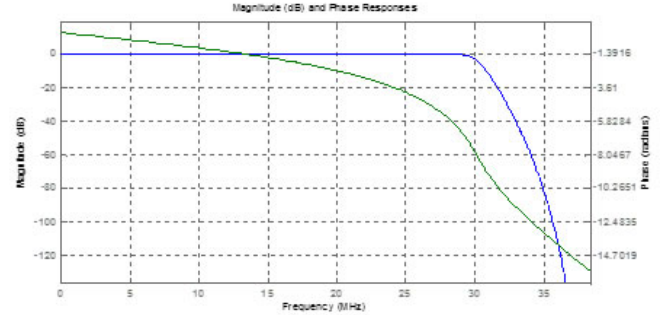


Fig. 9. Frequency response of reconstruction and anti-aliasing filter

Tunable band-pass filter is used to reject unwanted signal at the receiver and reduce phase noise at the transmitter. The solution presented in [11] uses tunable band-pass filter based on gyrator. The primary use of gyrator is to simulates nearly perfect inductor with a small integrate circuit, such that filter can be implemented without coils of wire [15]. Hence, filter circuit can use much smaller space with gyrator. Figure 10 illustrates a gyrator circuit and its equivalent circuit. In order to control these filters, tunable band-pass filter need interface to the digital signal processing unit.

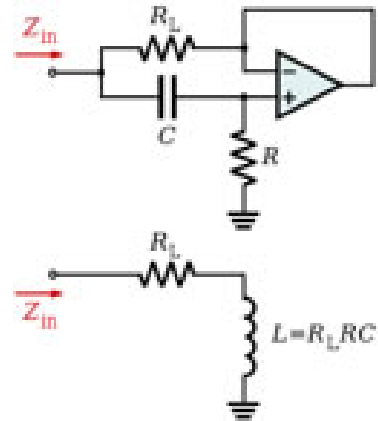


Fig. 10. A gyrator circuit and its equivalent RL circuit from [15]

Tunable band-pass filter is used to reject unwanted signal at the receiver and reduce phase noise at the transmitter. The solution presented in [11] uses tunable band-pass filter based on gyrator. The primary use of gyrator is to simulates nearly perfect inductor with a small integrate circuit, such that filter can be implemented without coils of wire [15]. Hence, filter circuit can use much smaller space with gyrator. Figure 4-7 illustrates a gyrator circuit and its equivalent circuit. In order to control these filters, tunable band-pass filter need interface to the digital signal processing unit.

V. CONCLUSION

The communication over HF channel has been seen as a difficult task. As digital communication technologies have been developed, many of these technologies are applied into HF radio. HF communication becomes easier and more effective. Hence, the concept of HF radio has changed from analog HF radio to digital HF radio which can be implemented using software defined radio concept. In military, a software defined radio should provide security communication and the ability to switch between many waveforms and adapt to any environment. The main aspects of software defined radio architecture are digital signal processing, DAC/ADC, and RF Front End technologies. The software defined radio architecture presented in this paper is one the solutions that is suitable for HF communication.

ACKNOWLEDGMENT

This work was supported in part of Basic Research Program from Research and Development Department by the Defence Technology Institute (Public Organization), Thailand.

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