

Digital Hopping of Narrowband Waveform using Wideband Frontend

Sumbul Gulzar ^a, Shoab A.Khan ^b, Muhammed Zeeshan ^c

^{a,c} Department of Electrical Engineering

^b Department of Computer Engineering

College Of Electrical and Mechanical Engineering, National University of Sciences and Technology,
Rawalpindi, Pakistan

^a sumbulgulzar79@ee.ceme.edu.pk, ^b shoabak@ceme.nust.edu.pk, ^c ranazeeshan@ceme.nust.edu.pk

Abstract—In many wideband networking waveform applications, there are scenarios where the network requires more range and low data rate. To cover these scenarios, a hybrid networking waveform front-end is proposed in which a narrowband waveform will be running in a wideband networking time slot to connect a user which is present at a long distance. To achieve this, a modification is proposed in the front-end of the physical layer of the wideband networking waveform. The receiver digitally hops between frequencies synchronously with the transmitter as the narrowband signal is sent over seemingly random series of frequencies. The same wideband filters are used to receive both the narrowband and wideband signals.

Keywords—Gaussian Minimum-Shift Keying (GMSK); Direct Digital Frequency Synthesizer (DDFS); Linear Feedback Shift Register (LFSR); Wideband Frontend; Digital Frequency Hopping

I. INTRODUCTION

As the applications for wireless communications increase, so do the requirements of functioning well across a range of modes, bands and waveform standards. Software Defined Radio (SDR) addresses these challenges by allowing for dynamic spectrum management. SDR defines a collection of hardware and software technologies where some or all of the radio's operating functions on the physical layer are implemented through modifiable software or firmware, operating on programmable processing technologies to reproduce several communication standards. Given the compelling case of adopting SDR, the challenge lies in designing a low cost flexible RF frontend which is realizable if the physical layer functions can be agile to run different waveforms and applications by providing them a common platform. SDR equipment provides flexibility to incorporate these functionalities without having to upgrade or replace hardware components [1][2][3]. Frequency band of operation comes with an optimized RF frontend with maximized range, throughput and reliability, where the focus is on migrating one or more waveforms across a broader portfolio of products for all services — ground soldier platforms, air, and sea [2].

In [4], it is identified that tactical military radios need wideband and narrowband networking waveforms for fulfilling most of the military requirements. Wideband networking waveform (WBNW) enables high data rates for advanced

network enabled capabilities whereas narrowband networking waveform (NBNW) enables long range transmission. Being disparate in nature, narrowband waveform requires different handling of the frontend as compared to the wideband waveform. Many suggestions have been made, worked out and implemented for realizing the concept that same apparatus should be used for both the NBNW and WBNW.

In [5], a transmitting station transmits a wideband signal which is a composite of a few narrowband signals. It embeds one or more overlapping narrowband signals in a wideband signal using conventional transceivers (FDMA, TDMA, CDMA). The system includes a receiving station for receiving the composite wideband signal which has a CDMA processing circuitry to separate the embedded narrowband signal(s) from the wideband signal. The patent [6] explains a transmitter and receiver where a mode controller selects receiving and transmitting a narrowband or a spread-spectrum modulated signal. The adjustable bandpass filters and the system are adjusted to transmit and receive a wide or a narrow bandwidth for passing the spread-spectrum signal or the narrowband signals respectively. It has been patented in [7] that the receiver uses wideband filter apparatus having a wide filter bandwidth adapted to wideband signals utilizing a wideband standard such as GSM or a narrowband standard such as IS-54 for transmitting and receiving respective signals. Frequency hopping can be effectively used in adversarial jamming environment where encryption is needed to protect the data which is realizable by using right tools[8]. The price to pay for implementing this protocol is a constant additive overhead on each message signal's size.

The invention patented in [9] includes redundantly retransmitting digitized voice data on multiple sequential frequencies, holding N number of blocks of digitized voice data from the frequency-hopping receiver and, estimating and providing the block of digitized voice data having the best quality of signal at the output terminal. Without any error correction means within the erroneous block, the bit error rate may fall for all the bits within that block that it may render this frequency-hopping system from providing useful voice communication.

Focus of this paper is on transmission and reception of NATO networking waveform for which a wideband RF frontend is proposed which is used to receive a narrowband

networking waveform as well. A frontend architecture is proposed where the wideband waveform frontend is modified with minimum changes to support narrowband networking waveform. And for that, a narrowband baseband signal is generated, up-sampled and brought to that level where it can be fed to the RF frontend settings for the wideband waveforms. Similarly, at the receiver, the RF frontend is configured to the wideband mode but actually the radio is receiving the narrowband waveform. The narrowband signal is digitally hopped to different channels available in the wide bandwidth. The choice of channel at transmitter and receiver is done in a coordinated manner and the carrier frequencies are selected from a pseudo randomly generated list to provide frequency-hopping for the system.

II. PROPOSED RF FRONT-END OF SDR

A. Proposed Transmitter Side of RF Front-end of SDR

The proposed architecture for the transmitter side is shown in the Figure.1.

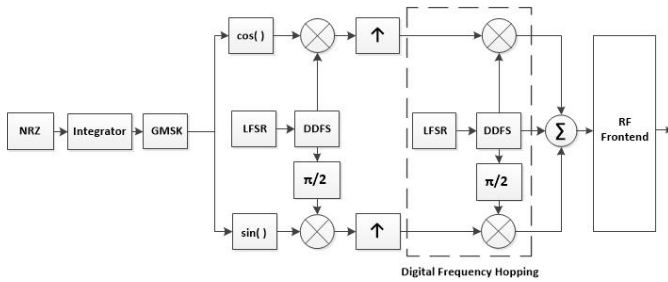


Fig. 1. Transmitter Side of Proposed Methodology

1) *Gaussian Minimum Shift Keying Modulation*: GMSK modulation is characterized by a narrow spectrum and maintaining a constant envelope. It can be effectively demodulated using differential detection [10]. Here NRZ pulses are convoluted via a Gaussian filter, as shown in Figure.1, to get a Gaussian modulated signal. Its in-phase and quadrature components are multiplied with their respective carrier components using quadrature modulator structure [11]. The GMSK modulated signal generated by this structure is given by

$$\begin{aligned} s(n) &= I(n)\cos(2\pi fn) + Q(n)\sin(2\pi fn) \\ &= x_I(n) + x_Q(n) \end{aligned} \quad (1)$$

2) *Linear Feedback Shift Register*: An n-bit LFSR has maximal length if it cycles through all $2^n - 1$ possible states, beginning with s_i , the seed, in pseudo-random order. The specific order in which various states are traversed is defined by feedback primitive polynomial, specified by LFSR bits used in determining the next state (the taps) [12]. In this paper, LFSR's pseudo-randomly generated states are used as indices to different frequencies which in turn become the offset to DDFS [13]. This offset changes the frequency to which the narrowband signal is hopped in wide bandwidth.

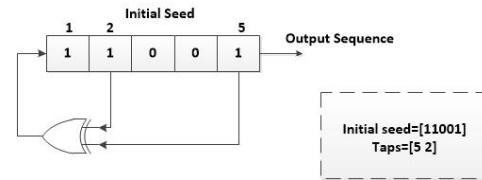


Fig. 2. Primitive Polynomial Implementation of Linear Feedback Shift Register

3) *Direct Digital Frequency Synthesizer*: A direct digital frequency synthesizer (DDFS) provides many significant advantages over the phase locked loop (PLL) approach, major one being that its output frequency, phase and amplitude are precise. These characteristics make DDFS technology popular in military RADAR and communication systems [14] [15] [16]. Increment in the offset increases the frequency generated by DDFS. It is used here to generate sinusoidal signals of precisely selected frequency over a wide bandwidth.

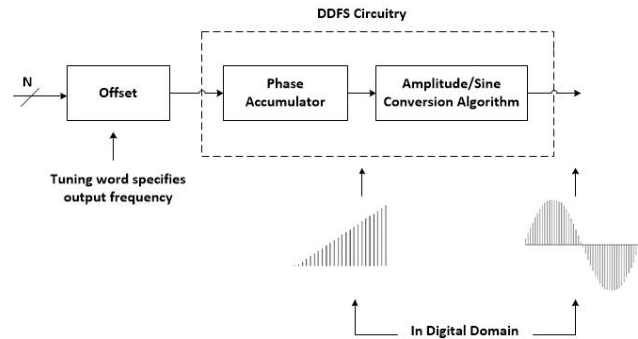


Fig. 3. Direct Digital Frequency Synthesizer Circuitry

The signal generated by quadrature digital mixing of GMSK modulated signal with quadrature components of output of DDFS is given by

$$\begin{aligned} u(n) &= x_I(n)\cos(2\pi fn) + x_Q(n)(-\sin(2\pi fn)) \\ &= I(n)\cos(\phi)\cos(2\pi fn) - Q(n)\sin(\phi)\sin(2\pi fn) \end{aligned} \quad (2)$$

where

$$\phi = 2\pi fn \quad (3)$$

Therefore,

$$u(n) = I(n)\cos^2(\phi) - Q(n)\sin^2(\phi) \quad (4)$$

4) *Digital Frequency Hopping*: Synchronization of transmitter and receiver is a challenging issue when designing a frequency-hopping system. To resolve it, here transmitter and receiver are provided with a look-up table of channels that represent the allowable frequencies for frequency hopping. Hopping is done pseudo-randomly where transmitter and receiver use pseudo-random numbers generated by linear feedback shift registers (LFSRs) with the same seed. This

number sets the offset of direct digital frequency synthesizers (DDFSs) to select the frequency to which the signal is hopped. This digital frequency hopping is highlighted in Figure.1.

At the transmitting side, the quadrature components of the signal are up-sampled [17] to 30M samples/sec. This signal is then quadrature mixed with a very high frequency carrier signal generated by another block of LFSR and DDFS. As a result, the signal hops to that frequency [9], which is given by

$$w(n) = I(n)\cos^2(2\pi f_n)\cos(2\pi f_c n) - Q(n)\sin^2(2\pi f_n)\sin(2\pi f_c n) \quad (5)$$

This is the signal which is transmitted using transmitter's wideband frontend.

B. Proposed Receiver Side of RF Front-end of SDR

The proposed architecture for the receiver side is shown in the Figure.3.

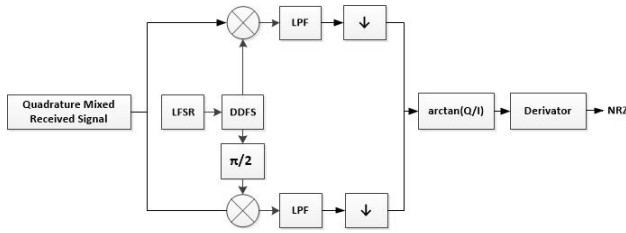


Fig. 4. Receiver Side of the Proposed Methodology

1) *Digital Frequency De-Hopping & Demodulation:* LFSRs are used with the same seed at both the transmitter and receiver to ensure that synchronization is not lost. Offset of LFSR selects the same frequency from DDFS's look-up table as that of the transmitter. This signal of very high frequency generated by DDFS is used to de-hop the quadrature mixed received signal.

The resultant signal is given by

$$\begin{aligned} x(n) &= I(n)\cos^2(2\pi f_n)\cos^2(2\pi f_c n) \\ &\quad - Q(n)\sin^2(2\pi f_n)\sin^2(2\pi f_c n) \\ &= I(n)\left(\frac{1 + \cos(4\pi f_n)}{2}\right)\left(\frac{1 + \cos(4\pi f_c n)}{2}\right) \\ &\quad - Q(n)\left(\frac{1 - \cos(4\pi f_n)}{2}\right)\left(\frac{1 - \cos(4\pi f_c n)}{2}\right) \end{aligned} \quad (6)$$

Low-pass filtering is used to remove high frequency components, leaving us with only $I(n)$ and $Q(n)$, i.e., the complex baseband signal, given by

$$y(n) = I(n) - Q(n) \quad (7)$$

This complex baseband signal is down-sampled to the sampling rate of the GMSK modulated signal at the transmitter. It is then GMSK demodulated to achieve the original NRZ sequence [11].

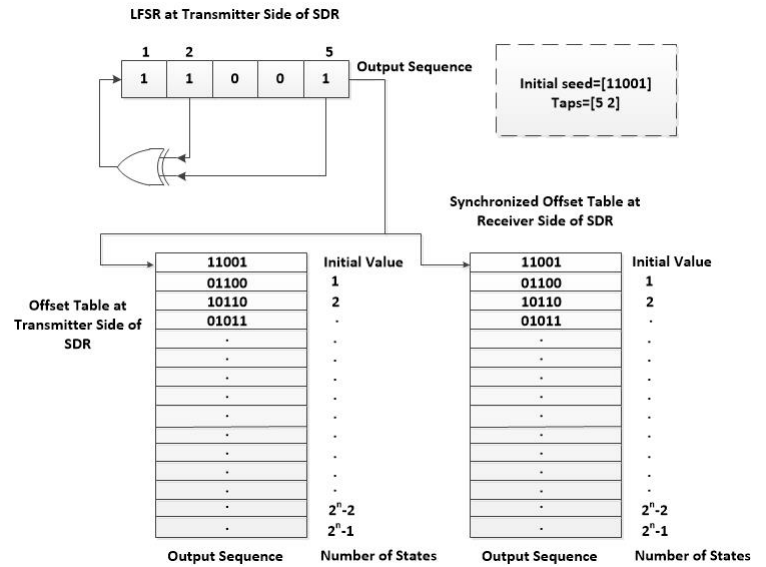


Fig. 5. Synchronized LFSR at Transmitter and Receiver of SDR

III. SIMULATION VERIFICATION

The proposed SDR transceiver is simulated in MATLAB to verify the required functionality. We generate a GMSK modulated signal first, the bandwidth(B) of which is pseudo-randomly selected in KHz range. For one case 20KHz is selected. Its in-phase and quadrature components are generated with 100K samples/sec data rate. After upsampling to 30M samples/sec, we use mixers to shift these quadrature components to pseudo-randomly selected signal in MHz range, which is 14MHz for this particular case. The baseband $I(n)$ and $Q(n)$ waveforms are shown in Figure.6.

Quadrature components of the received signal are digitally mixed with the same 14MHz signal, low-pass filtered and downsampled to 100K samples/sec. These components are used for demodulation to get the original NRZ signal.

The spectrum shift during modulation and demodulation are shown in the following figures. Figure.7 shows the GMSK modulated baseband signal. After being quadrature mixed with 14MHz signal, the spectrum hops to 14MHz, as is shown in Figure.8. Received baseband signal is shown in Figure.9 and Figure.10 shows the demodulated result, which is identical to the baseband signal of Figure.6.

IV. DISCUSSION

Narrowband signals usually have a far greater range of reception as narrower filters are used which cancel out unwanted wideband noise. The transmitted energy also concentrates on a smaller portion of the spectrum. Wideband communication puts high demands on the linearity of filters and the respective filter bandwidths are also higher. So both the waveforms need different kinds of receiving front-ends.

Wideband networking waveform occupies wide band of frequency. The narrowband networking waveform, occupying narrowband of frequency, is digitally hopped to occupy some

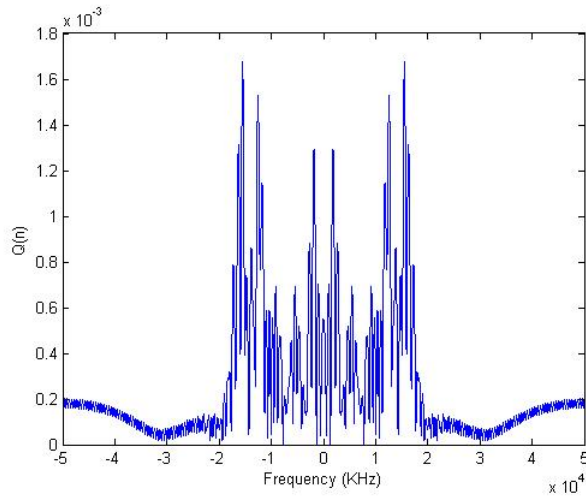
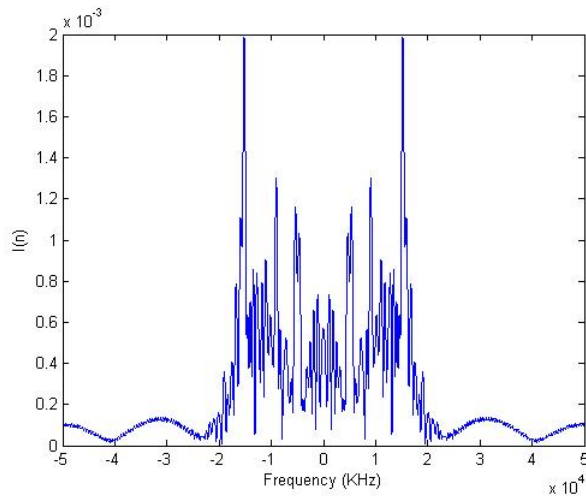


Fig. 6. Transmitter Side Baseband I(n) and Q(n) Signals

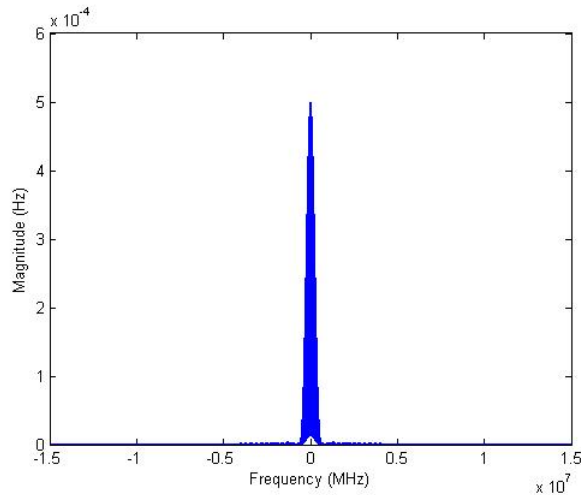


Fig. 7. Up-sampled Baseband Signal at Transmitter End

specific band within the wide spectrum and use the same RF front-end as that of WBNW. For WBNW, we use wide filters

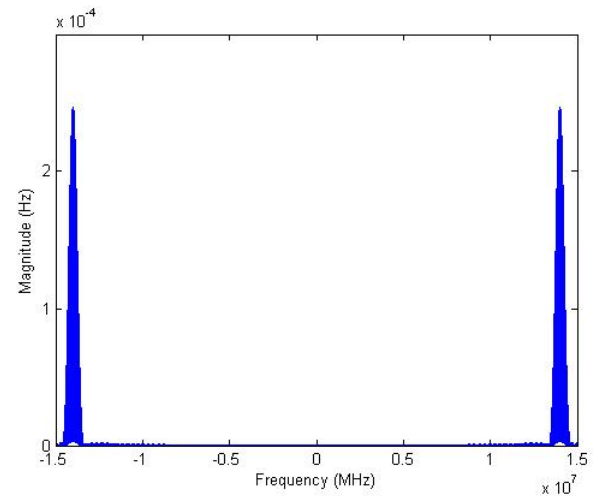


Fig. 8. Digitally Hopped Signal Spectrum

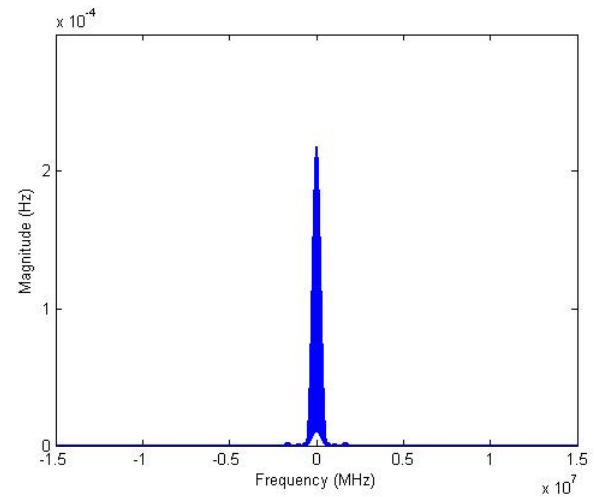


Fig. 9. Baseband Signal Spectrum at Receiver End

at the RF front-end. A technique is proposed in this paper which uses wideband RF front-end to transmit and receive a narrowband networking waveform as well.

The technique shown in Figure.1 and Figure.4 explains how a single narrowband frequency frontend can be used to transmit and receive both narrowband and wideband signals. For example, if we have 40 SDRs out of which 39 are present within 30Km range and one is 50Km away then this SDR cannot be connected with this network with the wideband waveform because it only covers small distances. When this SDR transmits, we switch to let it transmit in narrowband — less data rate because it concentrates all its power in narrowband and longer distance coverage. So all the SDRs are pre-configured to switch this waveform to narrowband waveform for this particular case.

The proposed SDR transceiver is actually part of complete waveform development. It will be implemented practically on actual SDR platforms using Digital Signal Processor (DSP) or

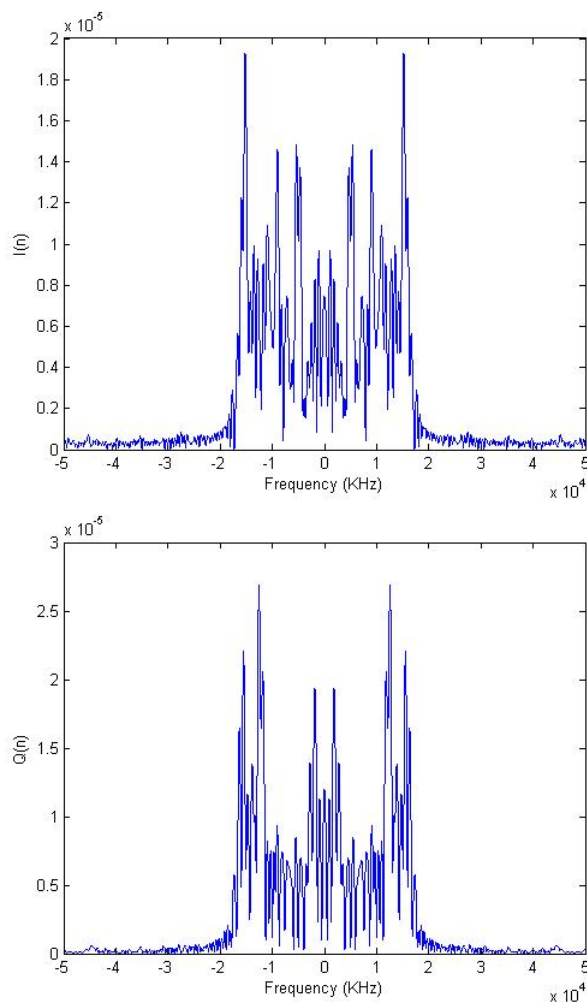


Fig. 10. Receiver Side Baseband I(n) and Q(n) Signals

field-programmable gate array (FPGA) and will be tested in field for the claimed higher communication range.

V. CONCLUSION

A hybrid networking waveform front-end for SDR is proposed in which a narrowband waveform will be running in a wideband networking time slot to connect a user which is present at a long distance. The proposed technique uses digital hopping within a specified band allocated to the wideband receiver. The same wideband filters are used to receive both the narrowband and wideband signals. The complete transceiver system is simulated for communication in SDR where modulation scheme employed in the transmitter is Gaussian Minimum Shift Keying (GMSK). The waveform corresponding to NRZ pulses undergoes digital frequency hopping which is then transmitted at 30M samples/s data rate. The data at the receiver is downconverted to baseband before any digital processing. The data is down sampled to 100K samples/sec as it was before upsampling in the transmitter. The data undergoes a slicer and the original NRZ pulses are retrieved.

REFERENCES

- [1] Tuttlebee, Walter HW, ed. "Software defined radio: enabling technologies." John Wiley & Sons, 2003.
- [2] Wiesler, Anne, and Friedrich K. Jondral. "A software radio for second- and third-generation mobile systems." IEEE Transactions on Vehicular Technology 51.4 (2002): 738-748.
- [3] Jondral, Friedrich K. "Software-defined radio: basics and evolution to cognitive radio." EURASIP journal on wireless communications and networking 2005.3 (2005): 275-283.
- [4] Leduc, Jan, Markus Antweiler, and Torleiv Maseng. "Spectrum issues of NATO narrowband waveform: On the spectral efficiency of CPM-Modulation with small modulation indices." Communications and Information Systems Conference (MCC), 2012 Military. IEEE, 2012.
- [5] Long, James F., and Robert C. Elder. "Method and apparatus for simultaneous wideband and narrowband wireless communication." U.S. Patent No. 5,640,385. 17 Jun. 1997.
- [6] Dixon, Robert C., and Jeffrey S. Vanderpool. "Dual mode transmitter and receiver." U.S. Patent No. 5,291,516. 1 Mar. 1994.
- [7] Dent, Paul W. "Dual-mode radio receiver for receiving narrowband and wideband signals." U.S. Patent No. 5,668,837. 16 Sep. 1997.
- [8] Emek, Yuval, and Roger Wattenhofer. "Frequency hopping against a powerful adversary." International Symposium on Distributed Computing. Springer Berlin Heidelberg, 2013.
- [9] Pandula, Louis. "Bit error performance of a frequency hopping, radio communication system." U.S. Patent No. 5,640,415. 17 Jun. 1997.
- [10] Cochran, Bruce A. "Development and application of m-ary gaussian minimum phase shift keying modulation." Communications, 1995. ICC'95 Seattle, Gateway to Globalization, 1995 IEEE International Conference on. Vol. 3. IEEE, 1995.
- [11] Pradeep Kumar Govindaiah. "Design and Development of Gaussian Minimum Shift Keying (GMSK) Demodulator for Satellite Communication", Bonfring International Journal of Research in Communication Engineering, Vol. 2, No. 2, June 2012
- [12] Jason H. Anderson, Yuko Hara-Azumi, Shigeru Yamashita "Effect of LFSR Seeding, Scrambling and Feedback Polynomial on Stochastic Computing Accuracy", 2016 Design, Automation & Test in Europe Conference & Exhibition (DATE)
- [13] Crouch, Alfred L., and Matthew D. Pressly. "Self re-seeding linear feedback shift register (LFSR) data processing system for generating a pseudo-random test bit stream and method of operation." U.S. Patent No. 5,383,143. 17 Jan. 1995.
- [14] Vankka, J. (2000). "Direct Digital Synthesizers: Theory, Design and Applications" (Doctoral dissertation). Retrieved from <http://lib.tkk.fi/Diss/2000/isbn9512253186/> isbn9512253186.pdf
- [15] Kroupa, Y. F. "Spectral properties of DDFS: computer simulations and experimental verifications." Frequency Control Symposium, 1994. 48th., Proceedings of the 1994 IEEE International. IEEE, 1994.
- [16] Genovese, Mariangela, et al. "Analysis and comparison of Direct Digital Frequency Synthesizers implemented on FPGA." Integration, the VLSI journal 47.2 (2014): 261-271.
- [17] Oppenheim, Alan V.; Schafer, Ronald W.; Buck., John R. (1989). "Discrete-time signal processing", Volume 2. Englewood Cliffs: Prentice-hall.



Sumbul Gulzar received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan in 2012. She was a recipient of ICT R&D fund for her final year project. She is currently a student of M.Sc. electrical engineering at the College of Electrical and Mechanical Engineering, National University of Sciences and Technology (NUST), Pakistan. Her research interests include wireless communications and

software defined radio.



Shoab Ahmed Khan received the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 1995. He has been actively involved in research and development, has authored over 200 publications in international conferences and journals, and holds six U.S. patents. He has 17 years of industrial experience in companies like Scientific Atlanta, Picture Tel, Cisco

Systems, and Avaz Networks. As a Chief Architect, he designed a high density media processor for carrier class voice processing system. He is currently a Professor and the Head of the Department of Computer Engineering with the College of Electrical and Mechanical Engineering, National University of Sciences and Technology (NUST), Pakistan. He is also the Founder of the Center for Advanced Studies in Engineering and the Center for Advanced Research in Engineering, two prominent organizations working for the promotion of research and development in Pakistan. He was a recipient of the National Education Award 2001 in the category of Outstanding Services to Science and Technology, the NCR National Excellence Award in the category of IT Education, the prestigious Cisco System Research Grant, and ICT R&D and PTCL R&D research funding.



Muhammed Zeeshan received the B.Sc. degree from the University of Engineering and Technology, Taxila, Pakistan, in 2008, and the M.Sc. and Ph.D. degrees with a specialization in wireless communications from the College of Electrical and Mechanical Engineering, National University of Sciences and Technology (NUST), Pakistan, in 2010, all in electrical engineering. Since 2008, he has been actively involved in research in the

fields of software defined radio, wideband waveform design, and radar signal processing. He is currently an Assistant Professor with the Department of Electrical Engineering, College of Electrical and Mechanical Engineering, NUST. His research interests include spread spectrum-based wireless communications, synchronization techniques, and digital design of communication systems.