A Novel Software Defined Radio Relay Method for Power Conservation

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Abstract— **To meet beyond line of sight (BLOS) communications requirements, a novel software defined radio relay method for power conservation is proposed. This method is able to achieve approximately 7.5 watt per relay node power savings for SNR challenged links (probability = 1/3), adjacent interference links (probability = 1/3), and 33% clear links (probability = 1/3). This is accomplished by dynamically adjusting the relay methodology between a low power amplify-and-forward (AF) relay method, a compress-and-forward (CF) relay method, and a power intensive decode-and-forward (DF) relay method. To demonstrate the novel architecture the following models were developed in MATLAB/Simulink and tested on an Avnet Zynq-7000 software defined radio (SDR) with Military RT 1439A radios: an audio FM transmitter model, an audio FM receiver model, an AF relay model, a CF relay model, a DF relay model, and the novel SDR relay model.**

Keywords—Relay, VHF, Radio, High Altitude, Balloon

I. Introduction

To meet beyond line of sight (BLOS) communications requirements while also meeting constraints on size, weight, and power, one possible solution is to employ a number of inexpensive relays. Modern relay systems rely on architectures that understand the modulated communications waveform in order to translate between different modulated waveforms when relaying. Modern waveforms that are designed for interoperability allow relays to forgo the power intensive operations associated with decoding and re-encoding a waveform for retransmission known as decode and forward (DF) relaying. Two such relaying methods with less complexity are amplify-and-forward (AF) and compress-and-forward (CF) relaying. This paper looks at combining all three methods and dynamically switching between them.

Prior to 1965, relays were primarily established upon securing and holding high ground [1]. Airborne voice relays were introduced in 1965 and airborne secure voice relays were introduced in 1969 [1]. The additional height of the airborne platforms increased the range of the relay but also increased radio interference. This led to the requirement for detailed frequency management [1]. Necessarily, military relaying has required full decryption and encryption and therefore only decode-and-forward relays were used. End-to-end security combined with new interoperability standards now enable relaying with less complex relaying methods. The U.S. DoD developed Tactical Secure Voice Cryptographic Interoperability Standard (TSVCIS) enables interoperability and complete end-to-end security [2, 3, 4]. It outperforms legacy military voice algorithms such as Continuously Variable Slope Delta Modulation (CVSD) in terms of mean opinion score (MOS) with less background noise [5, 6]. Recent efforts at the Naval Research Laboratory (NRL) to develop relays consist of the TacSat-4 reconnaissance and communications satellite, the Software Reprogrammable Payload (SRP), the High Altitude Router and Relay (HARR), and Surrogate TACSAT relay [7, 8, 9, 10].

Although modern relays fall under two separate categories, queuing relays and memoryless relays, this work is primarily interested in low power memoryless relays that do not have the ability to queue packets. Memoryless relays fall into the following subgroups [11].

- Amplify-and-Forward (AF) Relay Channel: In this method, the relay boosts the received signal and transmits the boosted signal to the output channel in the next time-slot. The AF method requires significantly less computing power for modern waveforms as no decoding operations are performed on the relay.
- Compress-and-Forward (CF) Relay Channel: In this method, the relay compresses the received message signal in one block and transmits the compressed message signal to the output channel in the next block timestep.
- Decode-and-Forward (DF) Relay Channel: In this method, the relay decodes the received signal to a bitstream block, optionally corrects for bit errors or noise in the decoded bitstream block, encodes the corrected bitstream block to an encoded signal, and transmits this encoded signal to the output channel in the next block timestep.

All three baseline relaying approaches were demonstrated using MATLAB/Simulink and a Zedboard equivalent Zynq-7000 software defined radio (SDR) platform connected to military VHF radios. Afterwards, the novel relay capable of dynamically switching between relay methods was implemented. The final results show that a group of software defined relays with the ability to dynamically adapt their relaying methods will outperform a group of DF relays in terms of lower total power consumption.

This paper is organized as follows. Section II provides an overview on the implementation of the baseline transmitter, receiver, and relay methods. Afterwards the novel software defined radio relay for low power is presented in Section III. A performance analysis and comparison is presented in Section IV. A conclusion and future research directions are presented in Section V.

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II. Baseline SDR Implementations

The Military RT1439A radio consists of FM voice and data communications [12]. An inspection of the publically available technical manual titled "DIRECT SUPPORT MAINTENANCE MANUAL" volume 5 reveals there are three separate voice transmission data paths, but all methods rely on the same upconversion and downconversion circuitry [13]. This radio has external COMSEC and ECCM modules and can be used without these controlled devices or with proprietary replacements for these devices. The radio transmits a squelch tone at 150Hz. The receiver uses the squelch tone to determine if an audio signal is present and to allow playback of the FM demodulated audio. Without this signal, received audio playback on the RT1439A will be clipped or muted. To verify understanding of the RT1439A schematics separate software defined radio models or the transmitter and receiver were developed in MATLAB/Simulink and were demonstrated with an actual RT1439A radio.

The transmitter model (Appendix A) consists of the squelch tone generator, microphone or audio file input, pre-emphasis, sample rate converters, FM modulator, and an SDR transmitter tuned to the carrier frequency. The amplitude of the 150Hz squelch tone is set to achieve the ±3.5kHz modulated signal as specified in the reference technical manual [13].

The receiver model (Appendix A) consists of the SDR Receiver tuned to the carrier frequency, FM demodulator, Deemphasis Filter, 1 in 5 Decimator, squelch control, volume control and audio output. The squelch control was implemented using a DFT method. The three methods that were testing include the Goertzel algorithm, a Sliding DFT, and a FFT operation with checking the appropriate frequency bin for 150Hz. The bin number can be calculated as 150 * (#FFT points)/(F_s). The FFT implementation is not as efficient as using either the Goertzel algorithm for single tone detection or the sliding DFT algorithm because a majority of the FFT computation results are discarded [14]. The sliding DFT requires more delays than Goertzel with one somewhat costly delay-by-N samples. Two variations of the FM demodulator were tested. The first one was the traditional angle modulation. The second one used an approximation and was implemented like a 2 tap filter [14].

The three types of memoryless relay methods implemented are amplify-and-forward, compress-and-forward, and decode-and-forward. The amplify-and-forward relay consists primarily of a downconverter and an upconverter. The downconverter is set to the received frequency while the upconverter is set to the transmitted frequency. In general, AF relays are the most power efficient but suffer from less reliability because they forward both the desired signal and any additional received noise. The compress-and-forward relay consists of the same components as the amplify-and-forward relay discussed above along with a compression block. The compression block is implemented with a low pass filter (LPF) but can be implemented in different ways depending on the compression methodology. The LPF block is meant to reduce the highest frequencies in the message information. Based on Carson's bandwidth rules, reducing the message bandwidth reduces the overall bandwidth of the transmissions. The decode-and-forward relay consists of the same components as the amplify-and-forward relay discussed above along with the decoder blocks. The decoder block consists of a Continuously Variable Slope Delta (CVSD) Modulation voice decoder followed by a CVSD voice encoder [5]. These blocks can be augmented with encryption and redundancy to improve the overall performance and security of such a relay method.

A comparison of these three relay methods in terms of processing blocks are presented in Table 1.

Table 1 Relay signal path processing block comparison

	Relay Signal Path Comparison		
	Amplify-and-Forward	Compress-and-Forward	Decode-and-Forward
1	SDR RX	SDR RX	SDR RX
2		FM DEMOD	FM DEMOD
3		DEEMPHASIS	DEEMPHASIS
4		DECIMATOR	DECIMATOR
5		Compress: Low Pass Filter	Decode: CVSD Decoder CVSD Encoder
6		INTERPOLATOR	INTERPOLATOR
7		PREEMPHASIS	PREEMPHASIS
8		FM MOD	FM MOD
9	SDR TX	SDR TX	SDR TX

III. Novel SDR Relay Implementation

The software defined radio relay, described in this work, is a relay that is capable of reconfiguring its relay channels to maximize power efficiency when channel conditions are optimal but can dynamically increase processing to operate in poor channel conditions. This is illustrated by the MATLAB/Simulink model developed at NRL in Figure 1. To take advantage of the dynamic conditions found in the military environment, multiple RF parameters are measured so that each channel can be optimized based on the current RF environment. The presence of adjacent channel interference requires the CF method. The CF method makes use of Carson's bandwidth rule such that reducing message frequency content reduces total occupied bandwidth. Low signal to noise ratio (SNR) requires the DF method. Finally, if the conditions are optimal, then the AF method is selected. Next, is a list of the measured parameters required to switch between modes.

1. Measure adjacent channels (on relay and from nearby transmitters) for RF transmissions to determine if CF relay method should be selected to reduce interference with adjacent channels.
2. Measure signal to noise ratio (SNR) to determine if DF relay method should be selected.
3. Measure remaining battery life and mission duration to determine if AF relay method should be selected.

Table 2 illustrates mapping the first two measurement parameter values to relay operating modes. For both low SNR and adjacent channel interference (ACI), ideally combining the CF and DF methods is best if possible. If not possible then default to DF to ensure that the relay is able to perform its job under the challenged channel conditions.

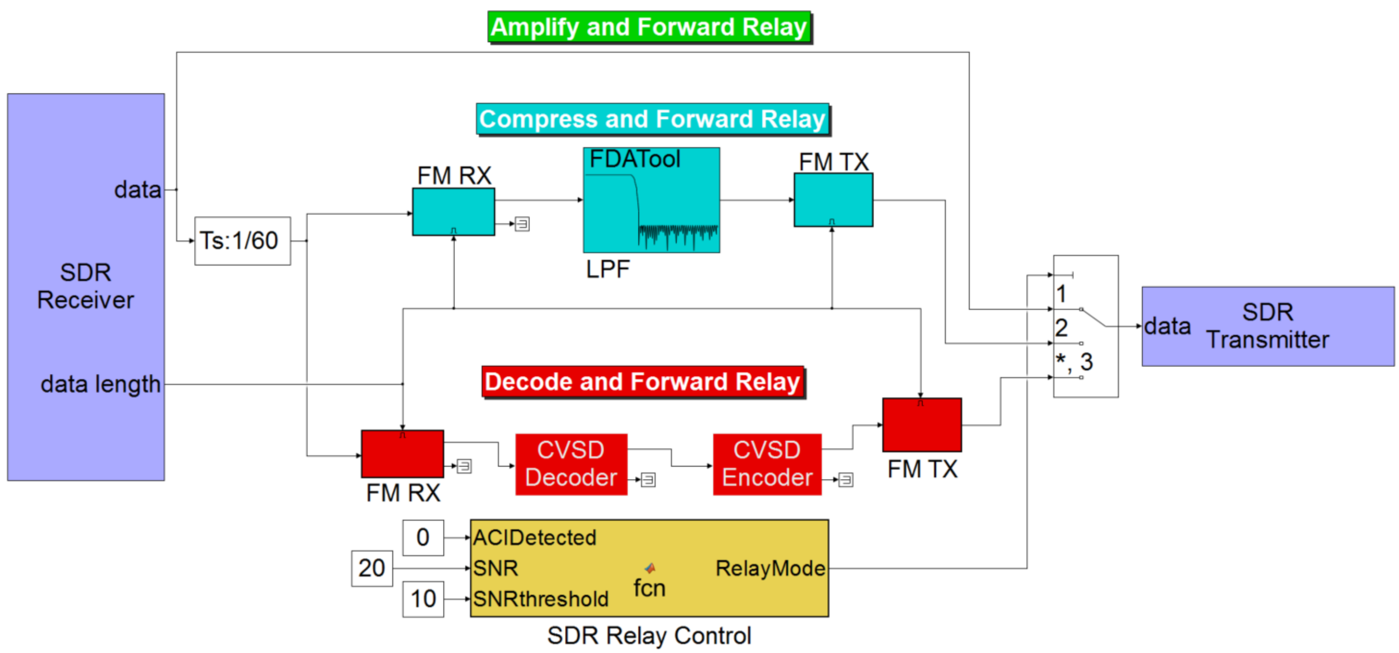

Figure 1 MATLAB/Simulink illustration of the novel software defined radio relay data path. The top path in green shows the amplify-and-forward relay method. The middle path in light blue shows the compress-and-forward relay method. The bottom path in red shows the decode-and-forward relay path as the default path. The relay path is selected by the control logic that switches the multiport switch. For testing purposes the adjacent channel interference and signal to noise ratio parameters were specified with constant blocks that can be dynamically adjusted while running the relay model.

Table 2
Measurement Parameters to Relay Operating Mode

Relay Operating Mode Decision Matrix		
	ACI	No ACI
Low SNR	DF or (DF and CF)	DF
High SNR	CF	AF

IV. Performance Comparison and Analysis

Both the transmitter model and receiver model were implemented in MATLAB/Simulink and verified between the RT1439A and the Avnet Zynq 7000 software defined radio platform. The models are step-based models where each step processes a frame of IQ samples. On the receiver side, 3 different DFT computation methods were compared. Table 3 lists the run time comparison for the three different approaches. The FFT approach made use of the FFT magnitude model, which allowed it to run in the shortest amount of time. The other two methods (Goertzel and Sliding DFT) were implemented using Simulink blocks with an iterator block.

Table 3
MATLAB/Simulink squelch DFT
run-time comparison for 1000 frame steps

DFT Method	Measured Time to Nearest ms	Compared to Fastest Approach
Goertzel	75.503 seconds	5.065 sec slower
Sliding DFT	96.152 seconds	25.714 sec slower
FFT	70.438 seconds	–

Afterwards the baseline relay models in MATLAB/Simulink were verified with two RT1439As and the Avnet Zynq 7000 SDR platform implementing each relay model separately. The computational times for the different baseline relay methods were measured by timing their respective MATLAB/Simulink models. The measured time for each model when run for 1000 frame steps is shown in Table 4. These results indicate that the AF relay method is the least computationally intensive method, the CF method is in the middle, and the DF method is the most computationally complex method.

Table 4 MATLAB/Simulink relay
run-time comparison for 1000 frame steps

Relay Method	Measured Time to Nearest ms	Compared to Fastest Approach
AF	8.150 seconds	–
CF	1015.407 seconds	1007.257 sec slower
DF	1815.549 seconds	1807.399 sec slower

Figure 2 illustrates the power savings which can be achieved by using software defined radio relays over fixed decode-and-forward relays for a group of relays with for example a fixed probability of 33% low signal to noise ratio (SNR), 33% adjacent channel interference, and the remaining 33% operating without impairments. Note that while AF and CF modes achieve lower total power, they exhibit outage 33% of the time where they are unable to assist with relaying a transmission due to their inability to operate in low signal to noise ratio conditions. Total power was measured based on number of transmissions and operating mode of the relays with percentages assigned to the different operating modes. If neglecting overhead for the software defined radio relay, this method is expected to achieve power savings over the DF relay mode for all cases except the case where the probability of low SNR is 100 percent. For the 100 percent case, it would have the same power requirement as the DF mode.

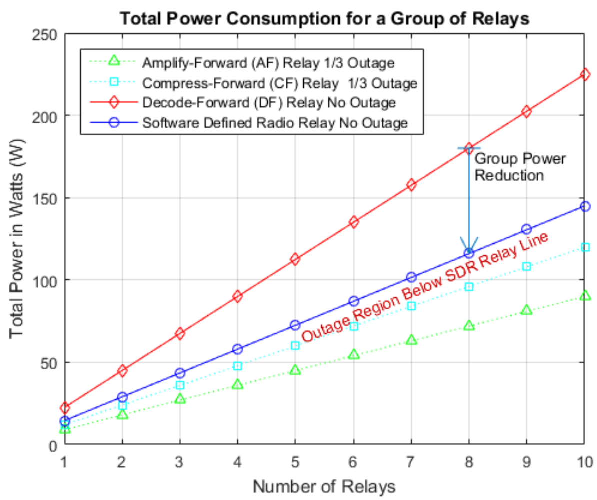

Figure 2 Total power consumption comparison between proposed software defined radio relay method and traditional methods for a group of relays for an example scenario with probability of low SNR at 33%, probability of adjacent channel interference at 33% and 33% acceptable SNR without adjacent channel interference.

V. CONCLUSION

As shown in this paper, software defined radio relays that can dynamically adapt their relay modes can achieve useful power savings over decode-and-forward relays. Thus, they can support longer mission durations. Specific advantages of the proposed software defined radio relay include lower power consumption (measurable 7.5 watt power savings per relay if dynamic switching enables 1/3 time in CF mode, and 1/3 time in AF mode), fewer outages, longer mission duration due to power savings, and ability to adapt to observed adjacent channel interference through bandwidth compression.

Although this research has focused on legacy radio transmissions, future research will be directed towards studying different probability scenarios for low SNR and adjacent channel interference. Additionally future research will be directed to develop an optimal TSVCIS software defined radio relay along with to develop replacement unclassified TSVCIS modules for the RT1439A radios for the KY-57 to interoperate with modernized military radios in an unclassified mode.

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Appendix A. MATLAB/Simulink Transmitter and Receiver Models

Appendix A.1. MATLAB/Simulink Transmitter Model

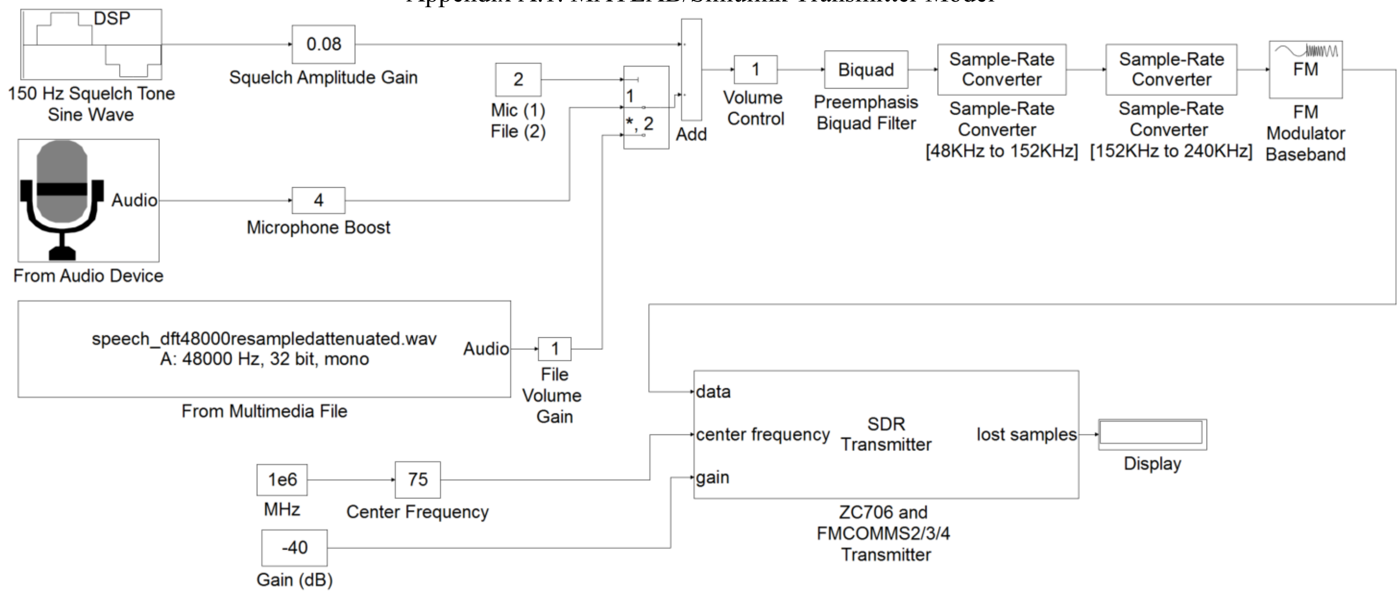
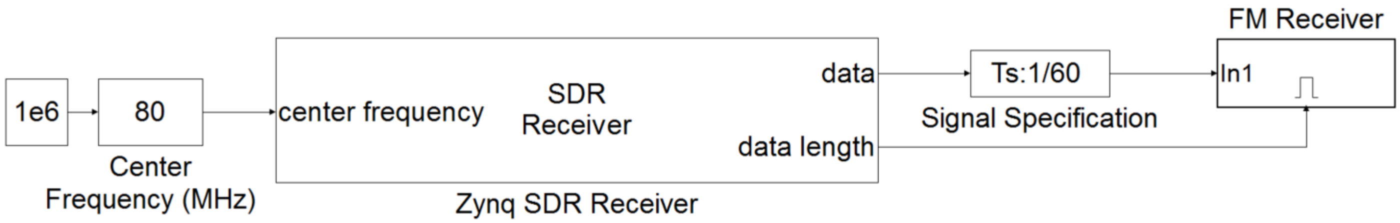
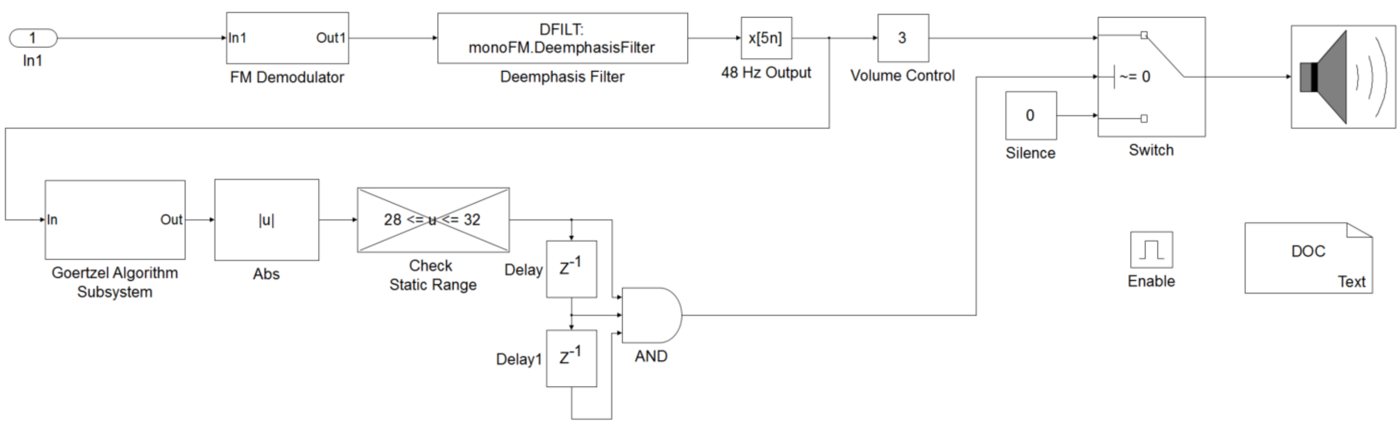


Figure 3 MATLAB/Simulink Plaintext Transmitter Model with 150Hz Squelch Tone. Audio input can be switched between the computer's microphone and a multimedia file both sampled at 48kHz. Additional FM specific functions such as pre-emphasis and FM Modulation are implemented by builtin MATLAB/Simulink blocks. The software defined transmitter model is provided in the support package from Mathworks.

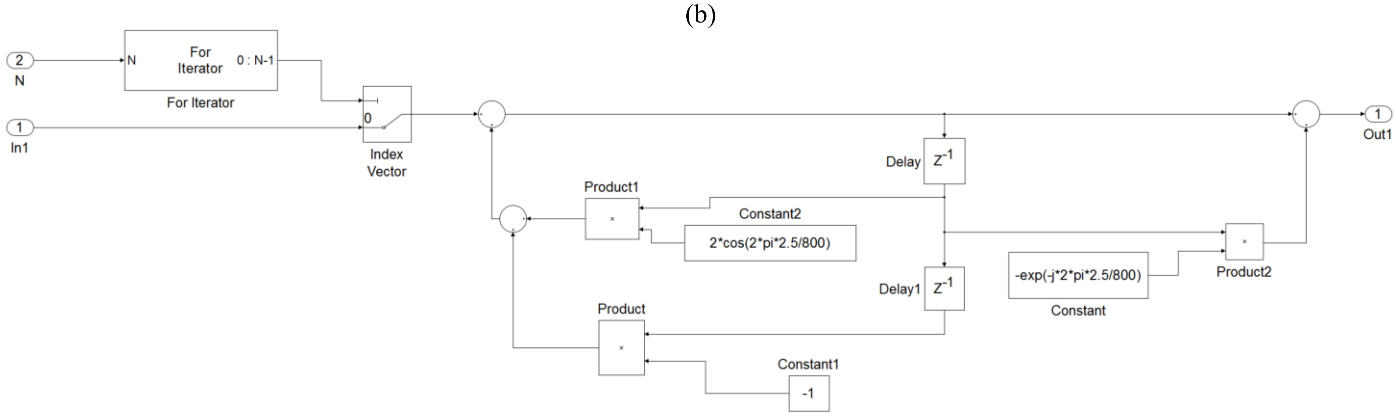
Appendix A.2. MATLAB/Simulink Receiver Model



(a)



(b)



(c)

Figure 4 (a) MATLAB/Simulink Plaintext FM Receiver Model (b) FM Receiver subsystem with 150Hz Squelch Tone Detection, FM demodulation, De-emphasis, and Decimator. Checking the range output of the previous 3 frames ensures audio is present before enabling speaker output. (c) MATLAB/Simulink single tone detection using the Goertzel Algorithm with N=800 and m= 2.5 = 150/(48e3/800).