An Interference Avoidance Waveform for the UHF Downlink on the New NOAA GOES-R Satellite

Brian Kopp
Department of Electrical Engineering
University of North Florida
Jacksonville, FL 32224
Email: brian.kopp@unf.edu

Duane Preble and Brett Betsill
NOAA Contractor: Microcom Design, Inc.
Hunt Valley, MD 21030
Email: {dpreble or bbetsill} @microcomdesign.com

***Abstract*— The Data Collection System, onboard the NOAA GOES satellites, receives environmental data from more than 25,000 meteorological platforms in the western hemisphere using a one-way UHF uplink. There is strong interest in the DCS user community to establish a two-way system to permit the remote control and reconfiguration of these platforms. The first of the next generation of NOAA GOES satellites, GOES-R, was launched on November 19, 2016. Onboard, there is a 100 kHz transponder that will permit NOAA and the DCS user community to establish a DCS two-way link with meteorological platforms. However, there is a challenge facing the DCS two-way users. The spectrum they must use for this downlink is at 468.8 MHz. The DCS two-way service has a secondary allocation in this frequency band which means it cannot interfere with and must accept all interference from the primary user group at this frequency band. The primary user group in the United States is the business and industrial, land-mobile, radio community. A successful DCS two-way signal coming from geostationary orbit must be able to coexist in this band with these much more powerful, terrestrial, and mobile transmitters. The challenge in designing a successful signal is in understanding the spectral content and statistics of the land-mobile radio "interference". This paper first reviews the regulatory issues and dominant types of land-mobile interference associated with the 468.8 frequency spectrum. An interference avoidance waveform is then proposed and simulated. The proposed waveform is a coherent slow-hopping PSK waveform that utilizes the narrow interstitial notches between the emission masks of adjacent 12.5 kHz land mobile radio channels. A shortened Reed Solomon (250,218) code is added to assist with overcoming interference while at the same time providing the potential to use the GPS timing reference on DCS platforms to assist with decoding.**

***Keywords*—NOAA, GOES, Satellite Communications, Geostationary, UHF, interference avoidance, adjacent channel, FCC, NTIA, NBFM, DMR, link budget, frequency hopping, BPSK, QPSK, Reed-Solomon.**

I. Introduction

There is a need for low data rate communications from GEOstationary (GEO) orbit to the earth using spectrum near 468.8 Mega-Hertz (MHz). Globally, in all three regions of the International Telecommunications Union (ITU) Radio-Communications Sector, the spectrum near 486.8 MHz is used, on a primary basis, by fixed and mobile communications and, on a secondary basis, by meteorological satellite service space-to-earth communications [1, pp. RR5-56][1].

In ITU Region 2, which includes the United States (US), the National Oceanic and Atmospheric Administration (NOAA), Geostationary Operational Environmental Satellite (GOES) program launched its next generation, GOES R, satellite on November 19, 2016. The Satellite has a 468.8 MHz transmitter onboard that can support low data rate communications to earth. The NOAA Data Collection System (DCS) is planning to use this link to begin providing two-way communications to the DCS Data Collection Platforms (DCPs) located throughout the Americas. Currently, the DCS program provides one-way environmental monitoring services using an Ultra-High-Frequency (UHF) uplink to GOES, near 401 MHz, from the more than 25,000 DCPs in the western hemisphere. By adding a receiver to existing DCPs, or replacing the transmitter-only configuration with a transceiver, the DCS program will be able to send brief commands and configuration changes to DCPs. This new service will permit the DCS program and its user community to more quickly and cost effectively make changes to DCPs and troubleshoot DCP communication issues. This improvement is expected to enhance system utility and reliability.

The challenge for the DCS downlink is that primary users with fixed and mobile communication assets may be transmitting at or near 468.8 MHz at the same time NOAA DCS DCPs are trying to receive commands from GOES. In the United States the Federal Communications Commission (FCC) regulates the civilian use of the spectrum [2, part 2.106]. Specifically, near 468.8 MHz, the FCC permits "land mobile" users to transmit [2, part 90.35]. In this UHF band, land mobile users typically include hand held transceivers, vehicle-mounted transceivers, or stationary transceivers with an antenna mounted lower than 6.1 meters (referred to as a control station). The Effective Isotropic Radiated Power from these devices varies and is almost always vertically polarized and omni-directional. For handheld transceivers the EIRP is typically 4-5 Watts (W), for vehicle-mounted transceivers the EIRP is typically 40 W, and for control station transceivers the EIRP ranges between 40 W and 100 W. The FCC typically licenses these mobile users to operate in a local area, within

[1] Several ITU region 1 and region 3 countries, including the Russian Federation, China, and Japan afford primary status to the meteorological services using space-to-earth frequencies near 468.8 MHz.

some radius of a specific location. The radius of operation can vary. Radii of operation from 1 kilometer (km) to approximately 40 km are common, depending on the type of licensee. In addition, on frequencies near 468.8 MHz, higher elevation, fixed land mobile stations, operating with a similar power level to that of control stations, can also be licensed.

For the US Federal NOAA GOES program, the National Telecommunications Information Administration (NTIA) regulates the 468.8 MHz transmitter onboard the spacecraft. In its secondary status, the NTIA regulations require the NOAA GOES 468.8 MHz transmitter to produce a power flux density at the earth's surface of no more than -152 decibel Watts (dBW) per Square Meter (m^2) per 4 kilo-Hertz (kHz) [3, pp. 4-141, Footnote US289]. Assuming the use of a matched antenna with an effective area of 1 m^2 and 4kHz of useable bandwidth, the received power at a DCP on earth would be no more than -152dBW. This is significantly less power than the typical maximum transmitted "interfering" land mobile user EIRP of +20 dBW, as stated above. To ensure a reliable system is constructed, the NOAA DCS program desires the two-way command system to function whether UHF land mobile users are present or not. To accomplish this will require the use of a GOES DCS command waveform (functionality) that can survive in the presence of significant interference.

II. GENERAL INTERFERENCE PROFILE

For mobile users the FCC partitioned the spectrum near 468.8 MHz into channels that are allocated for industrial and business users (as opposed to public safety users). The channels are separated by 6.25kHz and have different requirements that direct how they are ultimately assigned by FCC frequency coordinators. Example FCC channel centers, given in MHz, in the band of interest are 468.75000, 468.75625, 468.7625, 468.76875, 468.775, etc.

Two popular voice modulation schemes in the US market for industrial and business users are analog Narrow-Band Frequency Modulation (NBFM) and Digital Mobile Radio (DMR). The NBFM scheme uses 2.5 kHz deviation of 3 kHz voice audio for an approximate 11 kHz transmission bandwidth. The DMR scheme is a global, open, digital modulation standard that sends pulse-shaped 4 Frequency Shift Keying (FSK) at a symbol rate of 4800 symbols per second (sps), utilizing approximately 7.6 kHz of bandwidth. The DMR modulation can send two conversations simultaneously by using two-slot Time Division Multiple Access (TDMA). When transmitting, a DMR subscriber unit sends 4 FSK symbols for just 27 milli-seconds (ms) out of every 60 ms, allowing another subscriber unit to utilize the second time slot in a 60 ms frame.

The FCC uses approved commercial frequency coordination agencies to process requests for frequency assignments in the channels near 468.8 MHz. These agencies must make new assignments that do not interfere with incumbent spectrum license holders. This is accomplished by avoiding making overlapping channel assignments in the same geographic area and for some radial distance away from an incumbent license holder. The FCC commercial coordinators typically assign radio systems on the 12.5kHz channels, 468.75 MHz, 468.7625 MHz, 468.775 MHz, 468. 7875 MHz, etc. There is only one popular digital modulation scheme that has a narrow enough transmission bandwidth to meet the 6 kHz bandwidth requirement for assignment to the interstitial 6.25kHz channels at 468.75625 MHz, 468.76875 MHz, 468.78125 MHz, 468.79375 MHz, etc. The scheme is called NXDN and sends a single voice signal using pulse-shaped Continuous 4 Frequency Modulation (C4FM), at 2400 sps, in 4 kHz of bandwidth. Ironically, while the industry is predominately using wider bandwidth schemes there is little incentive to assign NXDN systems to the 6.25kHz channels. As a result, the majority of frequency assignments for NBFM, DMR, and NXDN are assigned to 12.5 kHz channels [4]. Until such time as the FCC decides to begin a migration process, requiring radio users to reduce their spectrum usage it is unlikely that the coordination assignment process will change significantly. The previous FCC required migration, called "narrowbanding", started in the mid-1990s and was completed in December 2013.

One additional land mobile digital modulation scheme to be aware of when considering the interference profile is called Tetra. It uses wider channels of 25 kHz to send 4 conversations simultaneously with pulse-shaped $\pi/4$ Differential Quadrature Phase Shift Keying (DQPSK) operating at 18000 sps. While popular globally, this scheme has only been deployed at a handful of sites in the US.

The modulation schemes discussed above are used to send mostly human voice. The communication transactions typically involve short interchanges between two users, one classified as a mobile user and one classified as a fixed base user (often a dispatcher). Mobile user-to-mobile user interchanges are also possible. Interchanges involving more than two users are rare but can also occur. Cohen, et.al. [5], characterized traffic in land mobile communication channels by analyzing actual radio communication interchanges in 13 categories of users. Combining the statistics from Cohen, et. al., for the industrial and business user categories indicates that a channel associated with a typical mobile user talking to a base station user, e.g., a dispatcher, would appear on average to have 2-3 transmissions of 2.5 seconds (s) duration each and separated by 4.8 s of silence (while the base station is responding on another channel). Cohen et. al., found that the statistical standard deviation in these transmissions is large so significant variation in these numbers is possible.

In the late 1970's the FCC undertook a series of spectrum utilization studies in metropolitan areas including New York, Los Angeles, San Francisco, Detroit, Chicago, and San Diego [6]. The studies determined that the average busy-hour channel utilization between 450-470 MHz (which includes public safety, business, and industrial channels) was 28%. It should be noted there is significant variation in the data. More recently, and notably now in the age of the cell phone, the Illinois Institute of Technology (IIT) performed a spectrum utilization study in Chicago in 2008 and 2009 [7], that included the frequency range of 450-465 MHz. Their results indicate an average busy-hour channel utilization (on public safety and business channels combined) of approximately 21% and specifically a business band utilization of approximately 14%. Again the dataset displays significant variation. In both the FCC and ITT studies, busy hour utilization is greater than utilization during other times of the day. In addition, the ITT study indicates a significant drop in spectrum utilization for business channels on the weekend.

III. SPECIFIC INTERFERENCE PROFILE

The FCC channels in the business and industrial pool of frequencies that overlap with the 100 kHz of spectrum centered at 468.8 MHz are listed below in Table 1. There are nine 12.5 kHz channels (the odd numbered channels in Table 1), and eight interstitial channels (the even numbered channels in Table 1). Included in Table 1 is an analysis of the current license assignments in the United States for each channel [2]. There are over 8000 license assignments in the 100 kHz bandwidth of interest. Of those, 99.6% are assigned to the nine 12.5 kHz channels. There are 31 interstitial channel assignments in the entire country. As stated above, NXDN is the only popular modulation technique that can occupy the 6 kHz maximum bandwidth required to operate on these interstitial channels. Since such operation would prevent the use of the two adjacent 12.5 kHz channels for NBFM or DMR (or another wider scheme), there is little incentive to make assignments on the interstitial frequencies. The Industrial and business license assignments (denoted I/B in Table 1) are divided into conventional and trunked systems with 86.8% of the assignments associated with conventional systems. The frequency channels at 468.8 MHz are usually assigned to mobile users and not to fixed base stations. In a trunked system the mobile channels can see some increased usage, compared to conventional channels but the conversation profiles look similar. In the rare occasion with a fixed station associated with a trunked system is assigned to a mobile frequency in this band, the usage profile can be dramatically different. In fact, a fixed station, functioning as the control channel in a trunked system, transmits continuously. It is interesting to note that a very few Public Safety (PS) entities (11 in the entire country) have licensed industrial business assignments at 468.8 MHz. This can happen when the available local public safety pool of frequencies becomes small.

When the FCC assigns a mobile frequency, the licensee is required to estimate the number of radios that will be operated on the frequency. These estimates can range from a handful to several hundred. Assuming 50 radios per current frequency assignment, the 100 kHz spectrum around 468.8 MHz can be expected to support conversations from approximately 400,000 radios in the US. These radios constitute the source of the interference that must be mitigated to support a DCS two-way command signal. An FCC license is issued for 10 years. While this does not give any direct evidence as to the validity of the license data over time, it does reflect the time period associated with a typical return on investment for radio system components and thus offers at least an indirect suggestion that these license statistics do not change dramatically over short periods of time (just a few years) but instead, may reflect the spectrum landscape near 468.8 MHz for many years to come.

TABLE 1. FCC License Assignments near 468.8 MHz.

Channel Center Frequency in MHz	Number of Active Radio License Assignments in the US as of June 27, 2016				
	Total	*I/B Conventional*	*I/B Trunked*	*PS Conventional*	*PS Trunked*
468.750	607	494	112		1
468.75625	3		3		
468.7625	1855	1755	98	2	
468.76875	7	3	4		
468.775	557	449	108		
468.78125	2	1	1		
468.7875	690	539	149	2	
468.79375	3		3		
468.800	620	484	135		1
468.80625	1		1		
468.8125	787	666	118	2	1
468.81875	5		5		
468.825	600	488	112		
468.83125	4		4		
468.8375	1848	1728	119	1	
468.84375	6	1	5		
468.850	619	510	108	1	
Totals	8214	7118	1085	8	3

IV. NOAA DCS TWO-WAY REQUIREMENTS

The NOAA DCS two-way command waveform must meet specific requirements to satisfy the desired performance criteria, regulatory rules, and GOES spacecraft specifications. The power density at the earth's surface was stated above. In addition, the transponder Effective Isotropic Radiated Power (EIRP) is rated at a minimum of 21.3 dBW with full disk earth coverage. Additional atmospheric losses on the UHF downlink should be expected to be 0.7 dB (beyond path loss). The desired data rate performance is between 200-400 bits-per-second (bps) at a 10^{-6} Bit Error Rate (BER). Two GEO satellites should be supported simultaneously, one over the Atlantic ocean and one over the Pacific ocean. The transponder will support a bandwidth of at least 100 kHz and also support root raised cosine pulse shaping with a bandwidth factor of 1.0.

V. AN INTERFERENCE AVOIDANCE WAVEFORM

To be successful, the two-way signal from the GOES satellite must either mitigate the land mobile radio "interference" or avoid it. Mitigating the interference with, for example Direct-Sequence Spread Spectrum (DSSS), would require that the spreading gain exceed the interference to signal power ratio. Using a one-sided bandwidth of 50 kHz and transmitting data at a 200 sps rate suggests at most 24 dB of processing gain is possible. All of the power from a single land mobile radio operating in the same 100 kHz must be mitigated by this processing gain. A typical land mobile radio operating at 40 W from a line-of-sight distance of 40 miles, with a unity gain antenna system, would encounter 122 dB of Free Space Loss (FSL) and present -76 decibels referenced to a milli-Watt (dBm) of interference power at the theoretical, unity-gain antenna system of a NOAA DCS two-way receiver. Assuming, in fact, the actual two-way receiver antenna directivity provides 20 dB of isolation in the direction of the land mobile radio, the two-way receiver will encounter -96 dBm of interference. After de-spreading with 24 dB of processing gain, the demodulator would see -120 dBm of de-spread broadband "noise". This interference signal link budget is shown below in Table 2.

[2] This data was collected from the FCC Universal Licensing System, available online at wireless.FCC.gov/uls.

TABLE 2. Interference and DSSS two-way signal link budgets.

Interference Signal Link Budget		DSSS Desired Signal Link Budget	
Transmit Power	46 dBm	**Transmit Power**	51.3 dBm
Free Space Loss @ 40 Miles	-122 dB	**Free Space Loss @ 35786 km**	-177 dB
Antenna Directivity	-20 dB	**Additional Atmospheric Loss**	-0.7 dB
De-spreading Gain	-24 dB	**Antenna Gain**	10 dB
Interference Power at Demodulator	-120 dBm	**Desired Signal Power at Demodulator**	-116.4 dBm
Signal-to-Interference Ratio	3.6 dB		

For reference and comparison, consider the noise power in a received bandwidth of 400 Hz (twice the 200 sps data rate). At UHF, assuming a sky noise temperature of 250 Kelvin (K), the noise power in 400 Hz is -158.6 dBm. Clearly any interference that is present would be the dominant affect in determining performance.

The GOES DCS two-way command transponder is specified to deliver a minimum of 51.3 dBm EIRP at 468.8 MHz. On the surface of the earth, at a distance of 35786 kilometers, the spreading loss per square meter[3] is 162 dB. There is also the 0.7 dB of expected additional atmospheric losses noted above. As a result, a 51.3 dBm EIRP transmitter will deliver -111.4 dBm to a square meter of the Earth's Surface. For DSSS using a 100 kHz bandwidth, the delivered power flux density per 4 kHz will be -125.4 dBm/m^2/4 kHz or -155.4 dBW/m^2/4 kHz, meeting the NTIA requirement by 3.4 dB. Returning to the link budget, starting with a DCS two-way transmit power of 51.3 dBm, using a free space loss of 177 dB, then assuming an additional 0.7 dB of atmospheric losses and finally a receive antenna gain of 10 dB yields a desired received signal power of –116.4 dBm. For DSSS, this yields an effective signal to interference ratio of 3.6 dB over the spread land mobile radio interference. The link budget for the DSSS waveform is shown in Figure 4. If a similar second land-mobile radio also transmitted at the same time on one of the other nine, 12.5 kHz channels, doubling the interference power in the process, the effective signal to interference ratio at the DCS two-way receiver would reduce to 0.6 dB.

At this point it is useful to answer the question: How often will land mobile radio "interference" occur? Returning to the ITT study in Chicago [7], if the busy-hour, business band, channel utilization is considered to be 14%, then depending on the number of licensed channels in a particular area, the probability of interference will increase as the licensed channel count increases. Using combinatorial probabilities, the likelihood of interference (one or more land mobile radios being active) is presented in Table 3. To successfully mitigate such a frequent interference condition with DSSS would require very high processing gains that would result in achievable data rates of just a few bits per second.

[3] Spreading loss per square meter is simply 10 times the log of the spherical area at a radius of 35,786,000 meters.

Avoiding the land mobile radio interference is another approach to consider for designing the NOAA two-way signal. There is a striking characteristic about the land mobile radio license data in the 100kHz around 468.8 MHz, presented in Table 1: There is little utilization of the eight interstitial frequencies. On a national level there are only 31 assignments. Some of these are on the same license, suggesting colocation and fewer than 31 distinct locations where interstitial frequencies are used. A narrowband signal that is positioned on the interstitial frequencies could take advantage of the under-utilized spectrum while avoiding most of the energy from 99.6% of the land mobile radio interference signals.

TABLE 3. Percent probability of busy-hour active UHF radio channels.

Number of Active Land Mobile Channels	Number of Licensed Channels in a Particular Location								
	9	*8*	*7*	*6*	*5*	*4*	*3*	*2*	*1*
At least 1	74.3	70.1	65.2	59.5	53.0	45.3	36.4	26.0	14.0
At least 2	36.6	31.1	25.6	20.0	14.7	9.7	5.3	2.0	
At least 3	12.0	8.9	6.2	3.9	2.2	1.0	0.3		
At least 4	2.7	1.7	0.9	0.5	0.2	0.0			
At least 5	0.4	0.2	0.1	0.0	0.0				

Using this interstitial spectrum would mean coexisting with the adjacent frequency assignments that may be active. Consider the spectral masks presented in Figure 1, using example frequencies near 468.8 MHz. These masks reflect the FCC requirements for radiated emissions when considering 12.5 kHz channel operation [2, parts 90.209-210][4]. The notch between the masks indicates that the interstitial frequency between the two 12.5 kHz channels is protected by a requirement for the signals in the 12.5 kHz channels to be reduced by at least 24.5 dB at the interstitial frequency. In reality, the clearance is usually larger since most radio manufacturers include a margin between their mobile transmitter specifications and the FCC spectral mask. In particular, frequency drift in the mobile equipment reference sources can cause displacement of the transmitted frequency. The FCC requires that mobile radio transmitters in the 12.5 kHz channels at UHF maintain a minimum frequency stability of 2.5 parts-per-million (ppm) [2, part 90.213, Note 8]. At 468.8 MHz this represents a potential maximum drift of 1172 Hz. An excursion in frequency is seldom that large, and as a result the clearance up to the amplitude reference can exceed 40 dB in the center of the notch. Figure 2 displays an example of two NBFM portable radio signals operating in adjacent channels with the associated spectral masks superimposed. The data was collected using commercial radio equipment.

[4] This is Emission Mask D in FCC rule Part 90.210 (d).

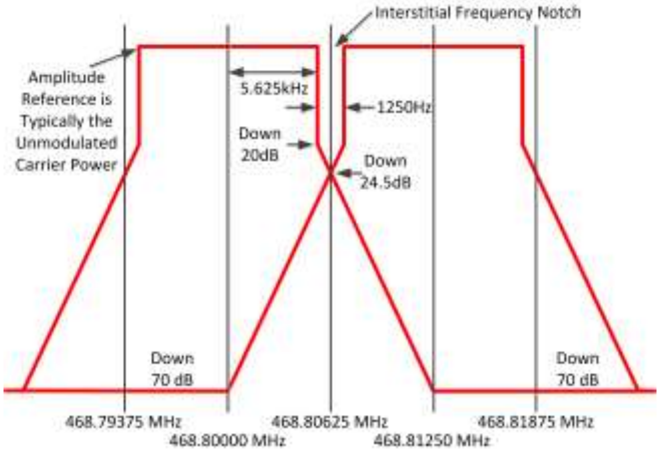

FIGURE 1. FCC 12.5 kHz Emission Mask D.

In the 100 kHz bandwidth between 468.750MHz and 468.850 MHz there are potentially 8 of these interstitial notches, positioned 12.5 kHz apart. To be clear, the notches exist only when land mobile radios are transmitting. If no radios are transmitting, the spectrum can be considered to be clear[5]. Nevertheless, designing a two-way signal that uses these notches would avoid the majority of the power from the land mobile interference signals on 12.5 kHz channels, when it occurs.

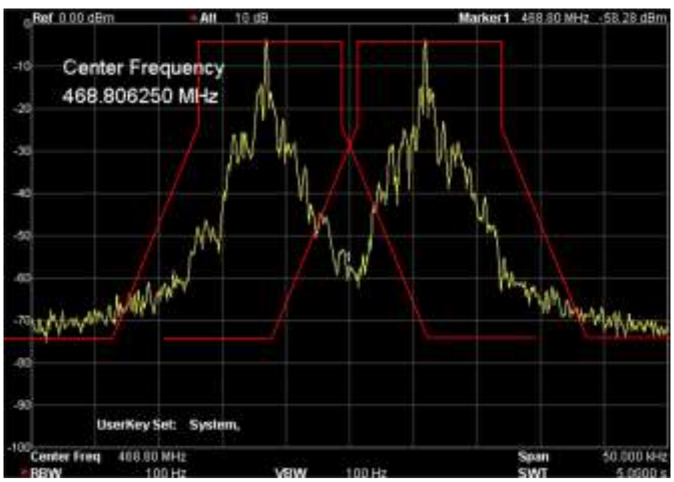

FIGURE 2. 2 NBFM signals with FCC emission masks.

With eight interstitial notches available, the option to use more than one for the two-way signal must be considered. There are two NOAA GOES satellites so it makes sense to use different interstitial notch channels for each one. In addition, only temporarily using a notch would reduce the power flux density measured in a 4 kHz bandwidth by the duty cycle of the notch occupancy time. By spending equal amounts of time in each of the 8 available notches then any one notch would only be active 12.5% of the time. Consider also that changing to a different interstitial notch reduces the probability of interfering with the operation of a land mobile radio, which has a primary allocation at 468.8 MHz, compared to NOAA's secondary allocation. These considerations lead to the idea to consider frequency hopping between the interstitial notches.

To understand the potential improvement that an avoidance scheme such as frequency hopping has over a mitigation scheme, in this case, consider the following example. Starting with the same land mobile radio interference signal, presented above, it is assumed that the DCS two-way receiver encountering an interference noise power of -96 dBm concentrated in a single 12.5 kHz channel. Assuming a 40 dB adjacent channel reduction between the 12.5 kHz channel emission and the adjacent interstitial notch reduces the interference power to -136 dBm at the input to a DCS two-way interstitial notch receiver. As discussed above, the 51.3 dBm EIRP DCS two-way transmitter will deliver -111.4 dBm to a square meter of the Earth's surface or -141.4 dBW/m^2. If all of this energy is transmitted continuously in a single interstitial notch, the NTIA power flux density limit will be exceeded by 10.6 dB. However if frequency hopping among the 8 notches is implemented, then assuming a 12.5% duty cycle for notch occupancy time reduces the delivered power flux density in a 4kHz bandwidth by 9 dB and the NTIA limit is now exceeded by only 1.6 dB. Adjusting the satellite transponder output power down 1.6 dB to 49.7 dBm will bring the power flux density of the frequency hopping system into compliance with the NTIA requirement. Returning again to the link budget and starting with a 49.7 dBm EIRP DCS two-way transmitted signal, then adjusting for the same 177 dB free space loss, additional 0.7 dB atmospheric loss, and 10 dB antenna gain, results in -118 dBm of desired signal and an interference to signal ratio of 18 dB. The link budgets for the interference and the interstitial frequency hopping scheme are shown below in Table 4.

To implement frequency hopping for two separate two-way command signals, one from each satellite, among 8 possible interstitial notches, it is necessary to coordinate the hopping between both satellite's signals so that they do not both hop into the same notch at the same time (it will be possible for many two-way receivers to have coverage on the same antenna from both satellites). There is no reason to randomly hop interstitial notch frequencies so it is possible to have the satellites hop a sequential pattern. It is also possible to separate the satellites patterns so that the two-way signal from one satellite does not enter the same notch that the two-way signal from the other satellite has just finished transmitting in (this will reduce the chance of temporal interference in the patterns).

The speed of the hopping pattern must be considered carefully. The interference in the 12.5 kHz land mobile radio channels at 468.8 MHz increases in magnitude as the frequency shifts away from the center of the interstitial notch and toward the 12.5 KHz channels. It is therefore a benefit to consider more spectrally efficient modulation schemes that concentrate the signal near the center of the notch, where

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[5] In dense urban locations the UHF radio spectrum can also experience a localized increased in the noise floor from the presence of a significant number of intentional and unintentional radiators emitting wideband energy. In addition, narrowband interference may be present which is often due to intermodulation between licensed transmitters or due to passive intermodulation between licensed transmitters and infrastructure anomalies such as a corroded ground connection. All of these spectrum issues can present significant challenges.

interference is less. In this case with a fixed number of notches, using fast hopping spread spectrum schemes is less spectrally efficient, compared to using slow hopping schemes, since the individual hop bandwidth is driven by the faster hopping rate, rather than the slower data symbol rate. Slow hopping spread spectrum systems dwell longer than several data symbol periods before hopping, so the utilized bandwidth for each hop is driven by the data symbol modulation rate.

TABLE 4. Interference and FH two-way signal link budgets.

Interference Signal Link Budget		**FH Desired Signal Link Budget**	
Transmit Power	46 dBm	**Transmit Power**	49.7 dBm
Free Space Loss @ 40 Miles	-122 dB	**Free Space Loss @ 35786 km**	-177 dB
Antenna Directivity	-20 dB	**Additional Atmospheric Loss**	-0.7 dB
Adjacent Channel Reduction	-40 dB	**Antenna Gain**	10 dB
Interference Power at Demodulator	-136 dBm	**Desired Signal Power at Demodulator**	-118 dBm
Signal-to-Interference Ratio	18 dB		

In addition, by using coherent modulation schemes such as pulse shaped BPSK or QPSK, the spectral efficiency is also maximized, compared to a traditional frequency hopping modulation like non-coherent FSK. The trade-off here between fast and slow hopping schemes is that the fast hopping scheme will experience significantly more interference when a land mobile radio transmits on the 12.5 kHz frequency adjacent to the active interstitial notch hop frequency. The only advantage from an interference standpoint for fast hopping is that if land mobile radio interference is transmitted directly on an interstitial frequency, only 1/8 of each data symbol will be lost, whereas blocks of symbols will be repeatedly lost during the interference with slow hopping. As discussed above, the FCC license assignment data suggests nearly all of the interference will come from 12.5 kHz land mobile radios, therefore slow-hopping is favored.

The use of a coherent modulation scheme does increase the complexity of the receiver. Carrier and symbol synchronization are required and the receiver must quickly reestablish synchronization after each hop. In a slow hopping scheme such as this, it may instead be possible to maintain coherence through the hop, recovering from minor frequency hop discrepancies without significant phase perturbations that would cause cycle slips in the carrier and symbol tracking loops. Since a GPS receiver is present the intention is to coordinate data and hop transmissions in the uplink with GPS time so that the receiver can discipline its acquisition and tracking processes with a GPS receiver providing timing and position information, enhancing synchronization performance.

In the FCC rules for land mobile radio operation, the use of spread spectrum frequency hopping is discussed. Specifically for public safety operation, frequency hopping is permitted on a secondary basis with a dwell time not to exceed 0.1 seconds [2, part 90.20]. This dwell time is significant since the frequency hopping operation is on frequencies that are actively used for voice communications, on a primary basis, by public safety entities[6]. Adopting this dwell time for the NOAA two-way signal will permit 20 symbols per hop given a 200 sps data rate.

VI. SIMULATION

Having established that the proposed NOAA two-way waveform is a slow hopping spread spectrum signal, simulations were developed to give an initial, high-level evaluation of the concept of using an interstitial notch waveform to transmit data in the presence of the most likely interference signals, NBFM and DMR. The simulations that were developed are not intended to be a rigorous analysis of the proposed interstitial notch waveform's performance. The project plan was to use simulations to establish only that the waveform can function in the presence of interference. Follow-on project tasking to develop demonstration hardware will be used to more fully analyze performance.

The primary purpose of the simulations is therefore to demonstrate that a narrowband coherent BPSK two-way signal can be successfully transmitted on an interstitial notch frequency, encumbered by the presence of higher power land mobile interference signals on adjacent 12.5 kHz channels. To simplify the simulations, several assumptions were made. First, if the worst case interference condition is assumed, where interference is present continuously on all nine 12.5 kHz channels, then all of the interstitial channels can be considered to be nearly identically encumbered. Using this worst case interference condition can help simplify the simulator by removing the requirement to simulate hopping interstitial notches. This also helps establish a worst-case performance baseline in the presence of interference.

For the simulations it was assumed that the receiver is synchronous with the transmitter. This removes the requirement to develop a simulation of the carrier, symbol, data frame, or any decoder synchronizers. Inherent in this assumption is that the synchronization issues associated with slow frequency hopping are mitigated. Again, since slow hopping with PSK is a well-established technique, this assumption is not considered a challenge that needs to be addressed in this simulator.

To simulate with interference it was assumed the interference signal power is fixed for the duration of the simulation, at 20 dB above the desired two-way signal power. This is roughly the condition established with the link margin example given above, and also a condition encountered by the authors when they surveyed adjacent channel interference using the current GOES east 468.8 MHz transponder during testing in 2015.

[6] FCC Part 90.20 permit public safety entities to use 2 Watt frequency hopping schemes that utilize a minimum of 20 channels so that an individual hop lasting 0.1 seconds is not revisited more than once every 2 seconds. This minimizes the impact of the secondary spread spectrum data service on the primary voice communications service.

In addition, the interference signals are considered to have a worst case offset in frequency toward the desired signal. This increases encroachment by 1200 Hz (2.5 ppm at 468.8 MHz per the FCC rules) for each interference carrier signal. This encroachment is maintained throughout the simulation. In reality an interference signal that encroaches on one interstitial frequency would simultaneously retreat from the adjacent interstitial frequency. This "benefit" was ignored to preserve the simplified simulator structure.

To simplify the number of interference model types to consider, only two combinations were tested. Either a NBFM interference signal both above and below the desired signal, or a DMR interference signal both above and below the desired signal was used. In addition, the two NBFM interference signals were generated from a recording of a male voice and a recording of a female voice.

Bandpass simulations were used due to the presence of real and different interference conditions in the passband that prevent translation to baseband. Said another way, the interference signal on one side of the interstitial notch is different from the interference signal on the other side. The bandpass spectrum was kept low in frequency to maintain moderate fidelity at a low sampling rate of 250 ksps. Specifically, the desired signal was transmitted at 31250 Hz with the interference signals transmitted at 26200 Hz and 36300 Hz (the offset equivalents to 25000 Hz and 37500 Hz, respectively). This arrangement established a scenario with a pair of interference-carrying 12.5 KHz channels (25000 Hz and 37500 Hz) and a desired signal-carrying interstitial notch channel (31250 Hz) in the middle.

Interference models were developed and used to generate interference datasets of sufficient duration to allow for Bit Error Rate (BER) measurements of the desired signal. Recognizing that the models may need to run for many simulated minutes at high SNRs, the interference signals were generated as 60 second test vectors and then concatenated many times to create a dataset for simulation that was long enough for the SNR of interest in a particular run.

All of these assumptions allow the simulators to be developed as BPSK bandpass simulators with an additive white Gaussian noise channel and interference signals that can be switched on and added to the channel. When one of the simulations are run the only variable that is modified from run to run is the Gaussian noise SNR in the BPSK channel. The BPSK symbol (bit) rate was chosen as 200 sps with a raised root cosine filter using a roll off factor of 1.0 (the roll-off factor is a specification of the satellite transponder).

To implement the simulations a combination of Mathworks Simulink models and Matlab scripts were used. A Windows 7 workstation with 48 Gigabytes of Random Access Memory (RAM) was used as the primary simulation platform. The large RAM size permits the manipulation of large interference test matrices. While actual system operation at higher Gaussian noise SNRs is anticipated, data was collected at SNRs near 5 dB to avoid long simulation runs. Follow-on simulation work, if needed, can improve speed performance by more fully utilizing frame based simulation techniques, and by leveraging the Mathworks parallel computing toolbox to implement simultaneous runs on multi-core processors or clusters if available.

A baseline simulation was used to calibrate the overall simulation approach to BPSK theory. The two types of interference (NBFM and DMR) were then added. The NBFM interference appeared to cause performance degradation to the baseline BPSK and the degradation increases with increasing Signal to Noise Ratio (SNR). However, the DMR interference did not cause significant interference to the baseline BPSK signal.

To mitigate the impact of the interference (NBFM in particular), while operating under what should be normally high SNR conditions, the use of Reed Solomon (RS) coding was investigated. Specifically, a Reed Solomon (255,223) code was implemented. Human speech has temporal patterns associated with individual words that, from a communications standpoint, will create an NBFM interference signal with channel memory. Operating the BPSK signal at 200 sps with RS (255,223) would provide protection against a burst error approximately 1.25 seconds long. This period is longer than the duration of most spoken words and will thus provide protection against occasional error bursts where the NBFM modulation is wide enough to encroach on the interstitial BPSK signal.

The simulations with RS codes were first baselined against theory and then interference was injected. The results indicate that the use of RS coding can assist with mitigating the interference. A modification to the RS (255,223) code was made so that a shortened RS (250,218) code was used. This permits the RS code frame to be easily synchronized to GPS time, which can assist with the receiver decoding task[7]. The results of the simulations are shown in Figure 3 where the shortened RS code demonstrates its assistance with mitigating interference. In all cases, to compare with uncoded BPSK, RS coded data was adjusted before plotting to compensate for the use of energy to send code bits.

VII. CONCLUSIONS

The simulation results suggest the proposed slow frequency hopping of PSK, in combination with a shortened Reed Solomon (250,218) code in the 8, 6.25 kHz interstitial notch frequencies between 468.75 MHz and 468.85 MHz will successfully avoid the expected interference profiles operating in the 9, 12.5 kHz channels in the same band. The use of a shortened Reed Solomon (250,218) code provides an added advantage of potentially simplifying decoding while not compromising performance.

The project to develop a successful DCS two-way waveform has moved into its next phase. Open demonstration hardware is being developed that will verify that the simulations were correct. In addition, the demonstration hardware is expected to establish that the assumptions made during the simulation phase were correct and also that the proposed slow hopping PSK scheme can be implemented with

[7] At 200 sps, using BPSK, the RS (250,218) completes a frame every 10 seconds. Using QPSK, each RS frame is completed every 5 seconds. At a system design level this knowledge can be exploited using GPS timing to identify the individual code bit demarks at the start of each frame.

acceptable implementation losses. This demonstration hardware phase will also provide a path forward for the stakeholders in the project. Specifically NOAA will require system monitoring receivers at their earth station uplink locations and they will be based on the demonstration hardware. In addition, DCS field equipment vendors will utilize the open demonstration hardware design to accelerate the development of the products necessary to realize a successful start to the DCS two-way service.

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REFERENCES

[1] International Telecommunications Union, "Radio Regulations," International Telecommunications Union, 2012.

[2] Federal Communications Commission, "Telecommunicatoins, Title 47, US Code of Federal Regulations," Federal Communications Commission, October, 2015.

[3] National Telecommunications and Information Administration, "Table of Freqency Allocations, Manual of Regulations and Procedures fopr Federal Radio Frequency Management," National Telecommunications and Information Administration, September 2015.

[4] P. Moncure, Interviewee, *CEO of Radiosoft, the FCC AASHTO frequency coordinator.* [Interview]. February 2015.

[5] P. Cohen, H. H. Hoang and D. Haccoun, "Traffic Characterization and Classification of Users of Land Mobile Communications Channels," *IEEE Transactions on Vehicular Technology,* Vols. VT-33, no. 4, pp. 276-284, 1984.

[6] L. D. Reed and K. A. Plourd, "Land Mobile Spectrum Utilization, San Fransciso, Ca. and Chicago, Il.," Federal Communications Commission, Report No. PRB/RDL 80-01, August 1980.

[7] R. Bacchus, T. Taher, K. Zdunek and D. Roberson, "Spectrum Utilization Study in Support of Dynamic Spectrum Access for Public Safety," in *IEEE Dynamic Spectrum Access Networks Proceedings*, Singapore, 2010.

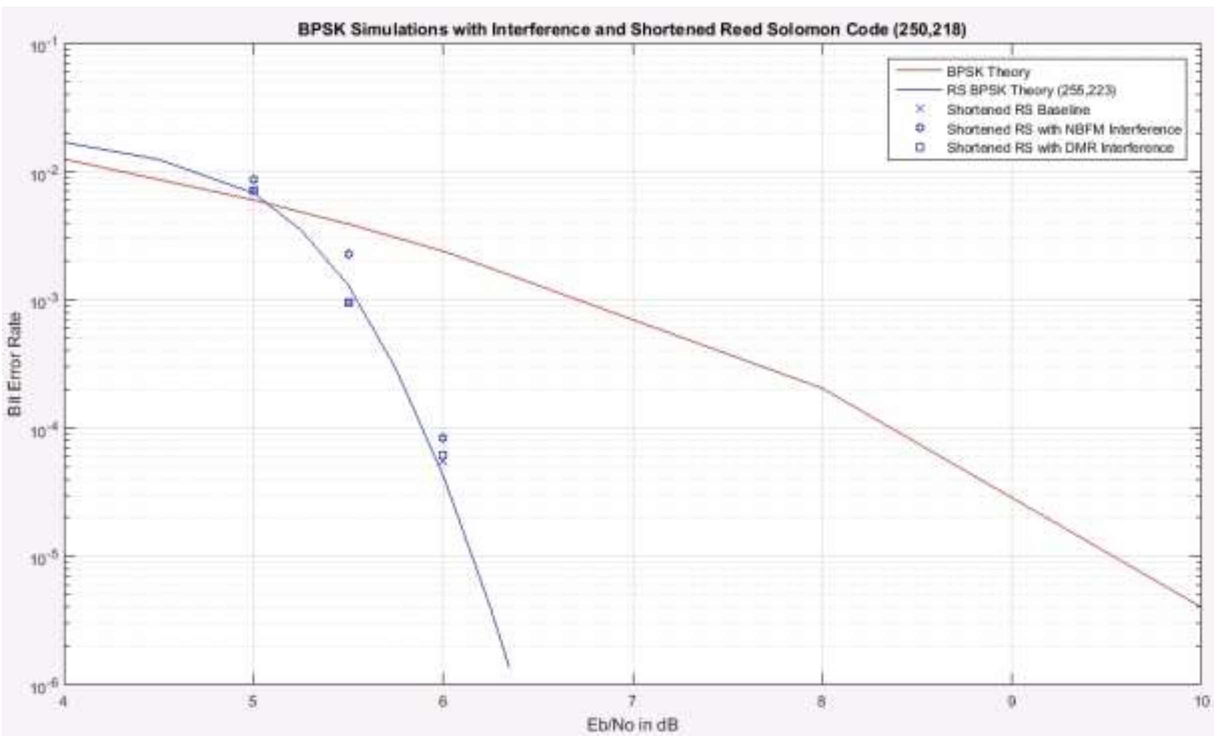

FIGURE 2. BPSK Simulation Results.