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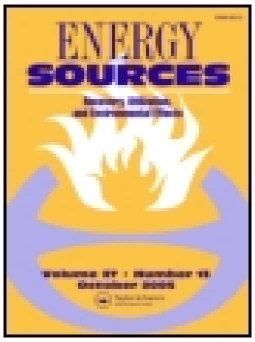

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ABSTRACT

This paper presents an analysis work for suitable signal modulation schemes on Narrowband 3 kHz HF channels. The most efficient power for each constellation size in QAM and PSK schemes are calculated in the 3 kHz channel. In addition to simulation proofs, the results were proven in real experiments. In a simulated work, the data were tested through two channel types; AWGN and Waterson channel. While in real scenario data are transmitted from Tehran to Semnan city. For both the simulated and real scenarios, two modulation schemes, QAM and PSK, were tested. It was proved that 32 QAM has the best performance over Narrow Band 3 kHz HF channels. The results are considered a good reference for later enhancement of non-contiguous techniques or 3 kHz single tone in order to enhance the bit rate for any HF link.

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HF communication; SDR; QAM modulation; PSK modulation; HF narrow band; AWGN channel; Watterson channel

Introduction

By definition, High Frequency HF band is a set of individual broadcasting bands with a frequency range of 3 to 30 MHz (2009). Recently, HF communications attracted the attention of the researchers due to their importance in many applications such as long-distance broadcasting, military and maritime communications, and aeronautical systems. The increase demand of developing HF systems is due to its inherent features: 1) low cost; there is no need to use expensive equipment. 2) More robust to jamming and hacking. 3) The ability to provide long-distance communications at relatively low-transmitted power (Xu, Yang, and Wang 2005). On the other hand, many challenges need to be solved before using HF communications. HF communication suffers from the instability of the ionosphere layer which is very sensitive to changes in temperature. This instability affects the quality of the link (Diakhaté et al. 2016) and leads to a decrease in the available and usable channels. In addition, by the existence of the large number of users, traffic and interference between signals will also increase. For this reason, HF systems usually operate on 3 kHz channels to overcome the abovementioned issues (Lamy-Bergot et al. 2015; Bernier et al. 2013). Note that 3 kHz channels are the minimum width channel to work with single tone signals in HF systems. In addition, fading resulting from the multipath of the traveling wave (more than 5 Hz) is one of the issues to be respected to ensure a good connection between the transmitter and the receiver (Department of Defense 2011; Measurement 2006). Furthermore, the size of the antenna is another problem of the wideband HF communication systems. In this case a big antenna (30x30m-sloping VEE antenna) is needed to ensure that all the band has been used, however, this tends to reduce the mobility property of the transceiver. In addition, the work studied the ability to use some advanced modulation schemes in HF communication systems in order to minimize the tremendous energy used in such systems especially in military applications. In addition, the environmental effects were studied and

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analyzed to facilitate the selection of appropriate scheme and power level based on the data rate needed.

Summary of the Anticipated Problems:

(1) Difficulty to reserve channels with capacity more than 3 kHz, where all the previous studies indicate that non-contiguous 3 kHz can be found easily in the band. This issue is not available when the bandwidth becomes bigger (Dalgleish et al. 2007).
(2) Problems in fading and interference that might affect the quality of the connectivity of the receiver.

In the previous research work, Xu et al. applied an efficient modulation scheme differential Amplitude Phase Shift Key 64-DAPSK for HF communication systems. Simulation results have shown that the Bit Error Rate BER performance of differentially detected 64-DAPSK is approximately 1 dB better than that of coherent detection 64-QAM at HF channel while Greater improvements are made at inferior HF channels. Xu et al. did not specify the used channel bandwidth (Xu, Yang, and Wang 2005).

In another work done by the Department of Defense Interface Standard, bandwidth have been used from 3 to 24 kHz, RF carrier using a single tone PSK/QAM modulation which reached a rate of up to 120 Kb/s using 24 kHz. In another work for the same department the following standards were defined:

(a) STANAG 5066 – Profile for HF Radio Data Communications.
(b) STANAG 4539 – HF Waveforms (PSK, QPSK, QAM).
(c) STANAG 4538 – Automated Radio Control System (ARCS).
(d) STANAG 4444 HF EPM Waveform (FH-PSK/FH-QPSK).
(e) STANAG 4415 – Robust HF Waveform @ 75 bps
(f) STANAG 4203 – HF Radio Standards (~3 kHz, ~1.4 kHz).

The drawback of the abovementioned works is in using the single tone that needs reserving continuous 24 kHz in the channel to reach the 120 Kb/s which is rarely available (Department of Defense 2011; Measurement 2006).

Catherine et al. developed a new technique which reserves many narrow bands, contiguous or not, 3 kHz PSK/QAM modulated carriers each distributed over a 200 kHz bandwidth and this was called HF XL technique where the rate is increased up to 138 Kb/s. This technique uses non-contiguous narrowband channels such that each channel is 3 kHz of 9600 b/s maximum and apply the following experiments:

(a) 19.2 kb/s (2-channel).
(b) 28.8 kb/s (3-channel).
(c) 38.4 kb/s (4-channel).
(d) 57.6 kb/s (6-channel).
(e) Rates as high as 138 kb/s (8-channel, 256 QAM) for surface wave (Diakhaté et al. 2016; Bernier et al. 2013).

The performance of HF XL is tested in both simulation and real scenarios. It is obvious that the bit rate has been increased but the maximum constellation of the modulation for the 3 kHz channel is not specified and it will be proven later in this article that the 256 QAM used by Catherine et al. in 3 kHz channel is unpractical.

Nieto in Harris applied a comparison between OFDM and CE-OFDM in 3 kHz channel (Nieto and Harris 2008). But this study does not specify the maximum capability a narrow band 3 kHz can carry.

As mentioned above we can see that many papers analyzed the use of narrowband 3 kHz channel for HF communication. Yet either of them mentioned the maximum rate in bits per second or the best modulation technique that can be used in different channel states. Being interested in the technique developed by Catherine et al., in this paper, we aim at completing her work and analyzing the performance of her technique in different channels both in simulation and real experiments. The final results will be compared to her results and reference data will be generated to show the best modulation schemes and achievable bit rates associated with each channel type and power levels.

The main problem in increasing the data bit rate in HF channels is the inability to reserve a wide bandwidth in such channels. And this issue is considered a real obstacle in the way of optimizing HF communications. In order to more understand the capabilities of HF channels, this paper study the performance of QAM and PSK modulation schemes if used over the available 3 kHz Narrowband channel. The analyses will determine the capabilities of the Narrowband channel by finding the amount of symbols it can carry and the suitable power needed for each constellation and modulation scheme. Using the above analyses and results, researchers can now easily specify achievable rate in each of the available 3 kHz Narrowband channel by using HF XL techniques. As a result, they can specify the number of channels required to achieve a certain bit rate. These analyses are very important for exploiting HF channels for data aided applications later on.

For more diverse and concrete results, different modulation schemes are tested over the 3 kHz channel and performances are compared to each other. Based on both a simulation and real scenario experiments, the best modulation scheme, constellation size and signal-to-noise ratio SNR are determined. Simulation contributions are as follows:

(1) Constructing a transmitter-receiver system by the help of Simulink Matlab, and using two different channels to measure the BER with respect to SNR. The first channel is a Gaussian random channel AWGN, and the second is the Waterson channel (Rayleigh + AWGN) with multipath that are 2 ms separated and 5 HZ Doppler shift.
(2) Comparing BER to SNR for the following modulations: 16, 32, and 64 QAM, in addition to QPSK, 8 PSK and 16 PSK.

It should be noted that in PSK scheme it is impossible to use greater than 16-PSK modulation due to the increase in the Doppler shift which directly affects the phase of the signal. When the constellation size becomes bigger the phase selection becomes more sensitive, so it is better to use QAM for increasing the bit rate per symbol.

In the real scenario, the simulation work is repeated by building a similar communication system under the help of the Software Define Radio SDR. Real experiments are held as a concrete proof of the simulation results of the best efficient transmit power for different modulation schemes.

The article is organized as follows. In Section 1, the HF Channel and its model are defined. In Section 2, proposed system model in both simulation and real scenario are described. In Section 3, corresponding numerical results are derived for both simulation and real scenario, and those numerical results are analyzed in line with real narrowband 3 kHz spectrum occupation measurements. Finally, conclusions are drawn in Section 4.

HF channel

In the simulation work, two channels were modeled. The first channel is the stationary Gaussian random channel (AWGN) with one path and no Doppler shift, while the second one is a Watterson channel model which consists of a tapped delay line in which each tap is relative to a resolvable propagation path. Each tap has two magneto-ionic components: each one is modeled as a complex Gaussian random process with a given gain and frequency shift, and whose Doppler spectrum is Gaussian with a given standard deviation (Watterson, Juroshek, and Bensema 1970) (Furman and Nieto 2001).

Figure 1 shows HF channel Model according to Watterson definition while setting all the taps to Zero except the first two taps that are separated by 6 ms and 3.6 Hz Doppler shift. Parameters of Channel no.6 as defined in (2009) (Mondiale 2014) are shown in Table 1. It is considered as imperfect channel where a transversal filter will be used to estimate the signal at the receiver.

The model of channel can be implemented using the following formula:

$$y(t) = \sum_{k=1}^{l-1} h(t)x(t - \Delta_k) + n_0$$

Where:$y(t)$ and $x(t)$are the output and input signals, respectively. aAnd Δ are the attenuation and relative delay of k^{th} path, respectively. The time-variant tap weights b_k are zero mean complex-valued stationary Gaussian random process. Finally,$|b_k|$ is the Rayleigh distributed that models the effect of multipath channel (Xu, Yang, and Wang 2005). All the simulation work are tested and analyzed over the 3 kHz channel.

On the other hand, we have:

$$|H_k(f)|^2 = \frac{e^{-2f^2/(a_k b_k)^2}}{\sqrt{\frac{\Pi(a_k b_k)^2}{2}}}, -\infty < f < \infty$$

By computing the Inverse Fourier Transform of $|H_k(f)|$ the time-domain filter taps become:

$$f_k(t) = \sqrt{2}e^{-\Pi^2 t^2 (a_k b_k)^2}, -\infty < t < \infty$$

As mentioned above signal over two taps channel separated by 6 ms and 3.6 Hz Doppler shift is sent due to the imperfect channel no.6 where the parameters are unknown for the receiver. So in order to

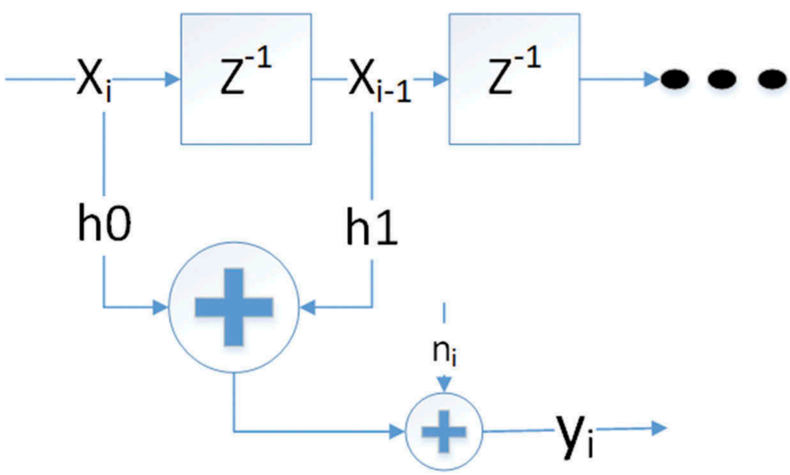

Figure 1. HF channel model.

Table 1. Parameters for the HF channel models in (2009) (Mondiale 2014).

Channel no 6	HF path 4
Delay (Δk)	6 ms
Path gain, rms (ρk)	0.0625
Doppler shift (Dsh)	3.6 Hz
Doppler spread (Dsp)	7.2 Hz

estimate the signal at the receiver, a two-pole Butterworth filter is considered with deviations greater than 5 Hz.

In the real work, the available frequencies are discovered using the "ITSHF VOACAP" program where the locations of the transmitter and the receiver are selected directly from the map loaded to the program. This program provides an illustration of all the frequencies that can be used at a specific time and for a specific antenna. In order to build up the real scenario experiment, two sloping VEE antennas are used. One is placed in Tehran as a transmitter and the other one is placed in Semnan as a receiver with a straight line distance of 179 KM. Figure 2 shows the Tehran Semnan HF validity spectrum and the SNR of different frequencies with respect to time (during 24 h on the day). The white color represents the best channel having three high SNR while the deep gray colors corresponds to the worst scenarios.

In fact, the usage of the VOACAP program only gives a general idea of the valid frequencies at a certain time between two specific places. But most of these frequencies are reserved by other HF users. In order to find the available frequencies, a small HF monitor is implemented using the SDR toolkit under the Linux operation system, and a SQL database where the pool of frequencies that are not usable during the 24 h for 10 days are saved and a lookup table for the valid frequencies for every range of time are made. After that, these discovered frequencies are experimented by sending a random signal to study the channel performance on these frequencies and check the spectrum in the receiver place (Semnan). If the signal level is higher than the noise level, then the frequency is valid to use. Results showed a lot of valid frequencies that were found and used later in our project.

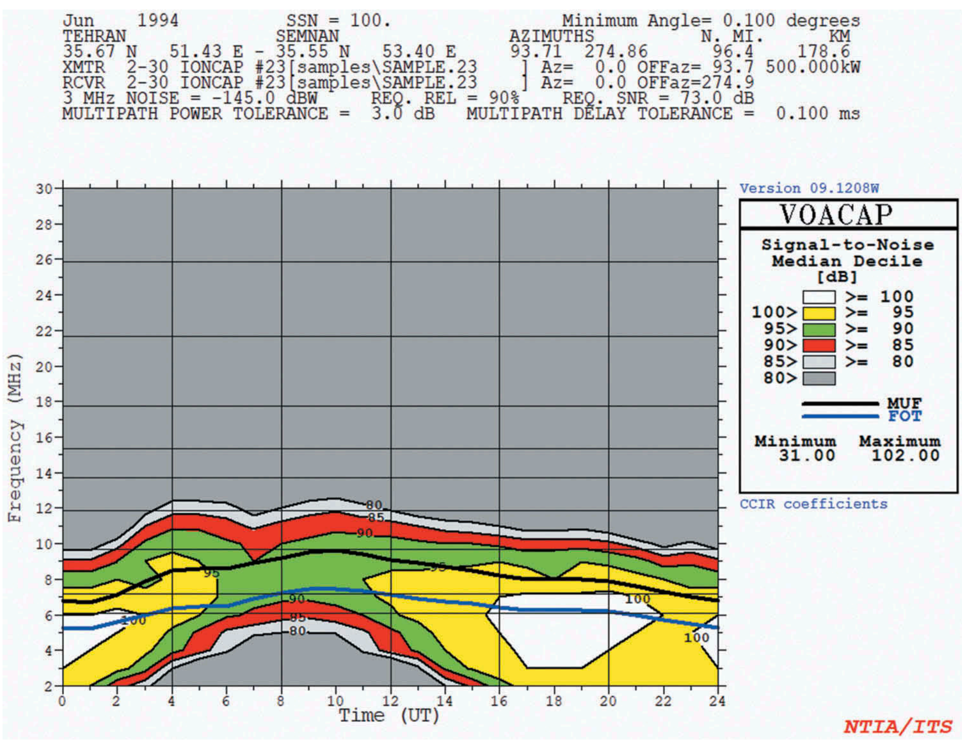

Figure 2. Tehran Semnan HF validity spectrum.

System model

Simulation work

Each of data or voice source has been encoded according to the nature of data in order to enhance data reliability. Redundant data have been introduced prior to data transmission using the Forward error correction FEC that maps the data for error detection and correction processes. After that, the data is interleaved to a short interleave 1.08 s and modulated with a suitable digital modulation (16 QAM 32 QAM 64 QAM, also QPSK, 8 PSK and 16 PSK are tested). The output, In-phase and Quadrature signal, is filtered using a normal-raised cosine FIR (Finite impulse response) filter. Finally, the signal is converted from digital to analog and up converted to the Radio frequency RF in order to transmit through one of the two modeled channels as shown in Figure 3.

As mentioned above, there is two kinds of channels, 1) AWGN stationary channel without fading of multipath; this kind of channel is considered as an ideal channel with high performance. 2) Watterson channel is applied with two separate multi-path signals with 6 ms separate time and 3.6 Hz Doppler shift. The two channels have a 3 kHz narrow band.

In the receiver, the signal is first down converted to the intermediate frequency IF and then is converted to digital signal. After that, it is transformed to the automatic gain control AGC to amplify to the modulator limiters. The output of AGC is filtered with a receiver square root raised cosine FIR filter. After that, the signal Demodulated and D-interleaved. Finally, errors are detected and corrected using FEC to get the original signal.

Real scenario

Real transceiver is implemented using Hack RF one (1 MHz to 6 GHz operating frequency) half-duplex transceiver and 20 million samples per second and open-source hardware (Greatscottgadgets 2019) using the (GNU) radio program. At the transmitter side, a wave voice file is queued and resampled using rational resampler, then Encoded using CODEC2 algorithm. CODEC2 is used to compress speech using sinusoidal coding and it is a method specialized for human speech. The output of coding is streamed and packed before being modulated using the different modulations that are to be compared and studied later in this paper. The tested modulation are 16 QAM, 32 QAM, 64 QAM also QPSK, 8 PSK and 16 PSK. After that the signal sent to the Osmocom sink which is a block in GNU radio that is responsible for converting the signal to the target RF frequency (4, 8, 11 and 18 MHz). Finally, the signal is transferred through the real sloping VEE Antenna from

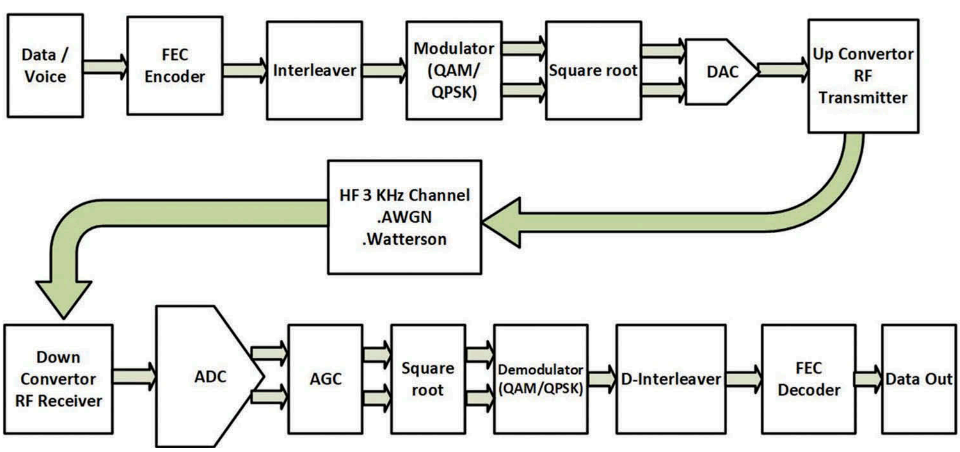

Figure 3. Transceiver block diagram consisting all the data processing steps for simulated work.

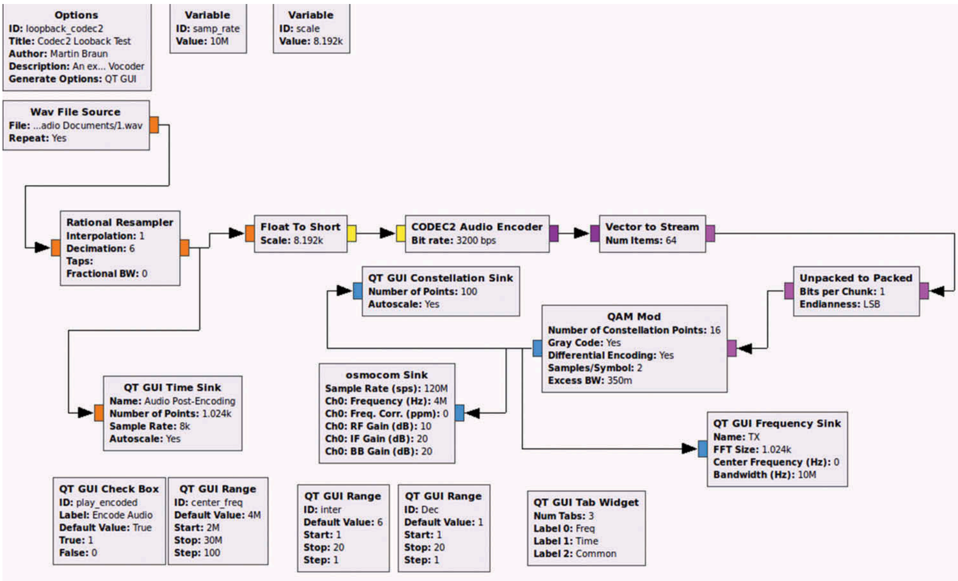

Figure 4. Real 16-QAM transmitter using hack RF one SDR under GNU radio.

Tehran to Semnan city (receiver location). Figure 4 shows the block diagram of a real 16-QAM transmitter Using Hack RF.

At the receiver side, Real 16-QAM receiver is implemented using Hack RF block diagram as shown in Figure 5. The signal is down converted to the baseband using the OSMOCOM Source block which also filters the desired signal. After that, the signal is demodulated, unpacked and decoded using the same algorithm as in the transmitter (CODEC2).

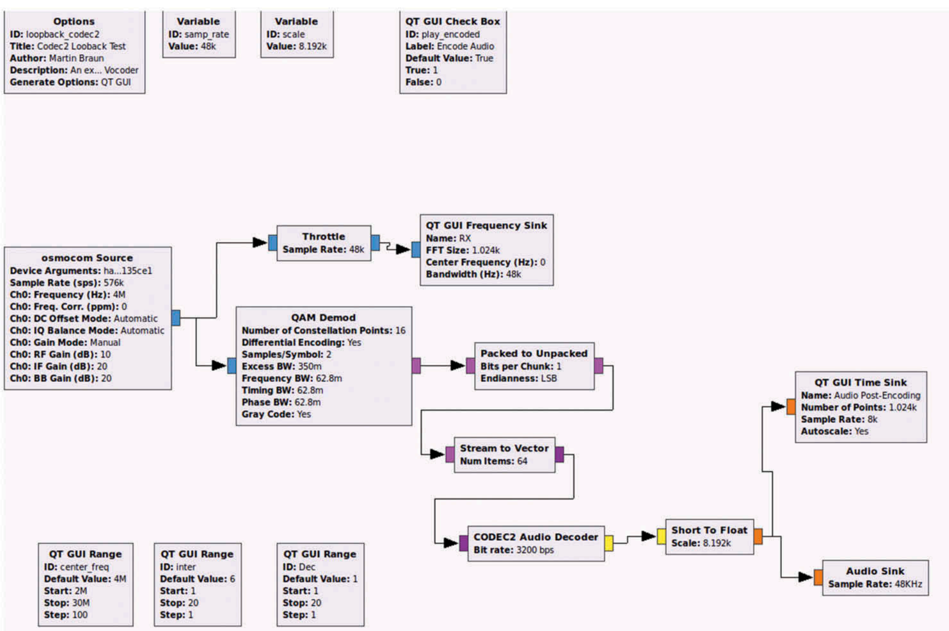

Figure 5. Real 16-QAM receiver using hack RF one SDR under GNU radio.

To calculate the BER, a prerecorded file, 10 s of recorded voice, is transmitted. Same file is put at the receiver. By using a file binary comparator program, the number of bit error and BER for each SNR is calculated.

Simulation and results

This section presents a complete numerical and comprehensive results of the ability to use QAM and PSK modulations on 3 kHz Narrowband channels. The results are derived out from both simulations and real experiments where each experiment is repeated several times to get more reliable results on the ability to increase HF channel data rate.

Simulated scenario

Figure 6 shows the results of sending 10 sec encoded voice data over AWGN channel at numerous times and with different SNRs in order to ensure that the results are not randomly founded. The results show that PSK modulation for 16 constellations and below are better than QAM because PSK is not affected by amplitude distortions that may hit the signal through the channel. So, QPSK, 8 PSK and 16 PSK with 2, 3 and 4 bits per symbol can be used with low power, below than 10 dB, in 3 kHz narrowband channels. While 16 and 32 QAM needs 10 and 15 dB power, respectively, for them to be used with suitable BER. On the other hand, 64 QAM did not have any practical results so the BER of this constellation was very bad with respect to the need power. And this is the proof that 256 QAM used in Catherine paper is totally unpractical knowing that the used channel is still simple (AWGN).

The second simulated scenario is to send the signal over the Watterson channel with two different paths that are 2 ms separated and 5 Hz Doppler shift. Figure 7.shows more reliable results than AWGN channel results. The effect of fading on the signal is clear where it needs approximately 4 dB more than the case of AWGN channel. In addition, the 64 QAM can only work with very high power and high BER which is a power efficiency problem. On the other hand, the modulations QPSK, 8 PSK, 16 PSK, 16 QAM and 32 QAM can be used in the narrow band 3 kHz channel.

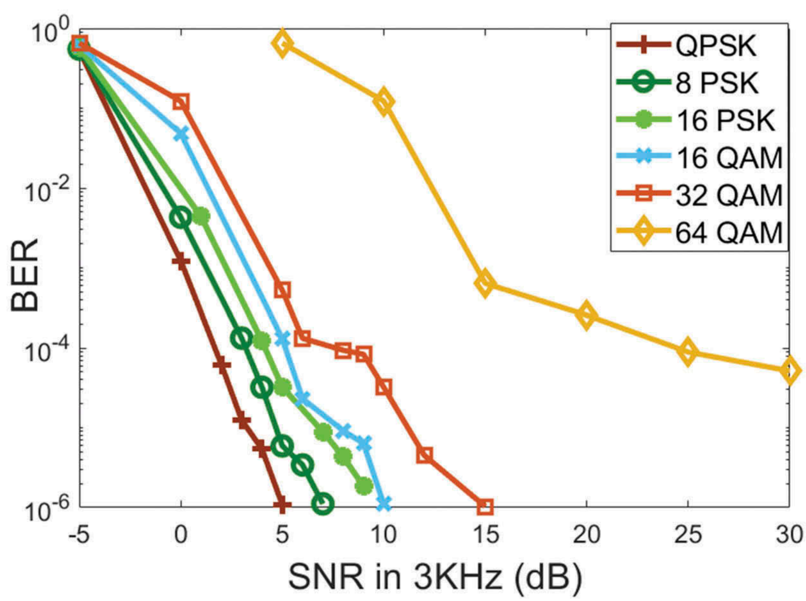

Figure 6. Results for different modulations in AWGN channel.

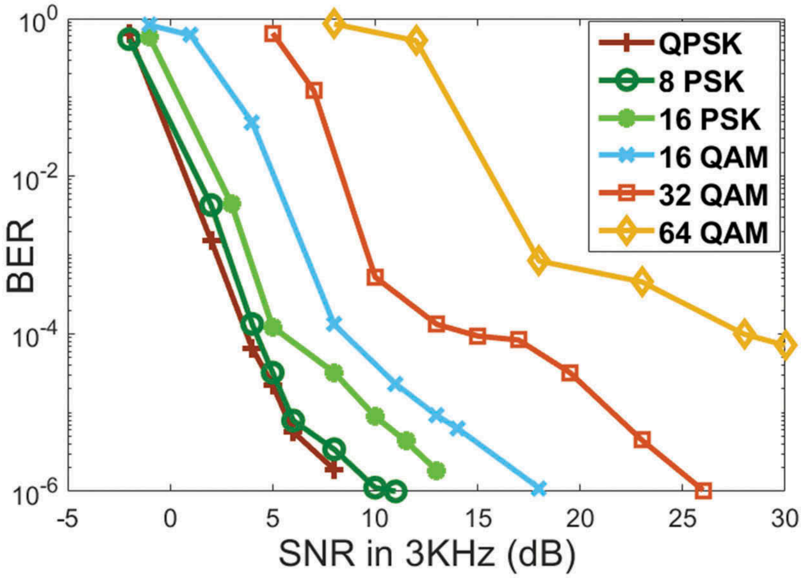

Figure 7. Results for different modulations in Watterson channel no.6.

Real scenario

In the real experiment, the scenarios from Tehran to Semnan is repeated in order to have more reliable results. As mentioned above a 10 sec voice signal is sent at numerous times for each of the tested modulations (QPSK, 8 PSK, 16 PSK, 16 QAM, 32 QAM, and 64 QAM) and in different weather conditions and at different power levels (5, 10, 15, 20, 25 and 30 dB).

The file was sent repeatedly at different times and at different weather conditions. Later the mean values of the result are calculated to be analyzed. In each time the received file is saved at the receiver and by using a comparator file program the BER is calculated at every SNR.

Figure 8 shows the constellation diagram of 16 QAM at the receiver of a real voice transmission. GNU model SDR was used to generate this diagram. The data distribution over the 16 constellations makes a good pattern and original data can be easily retrieved using FEC.

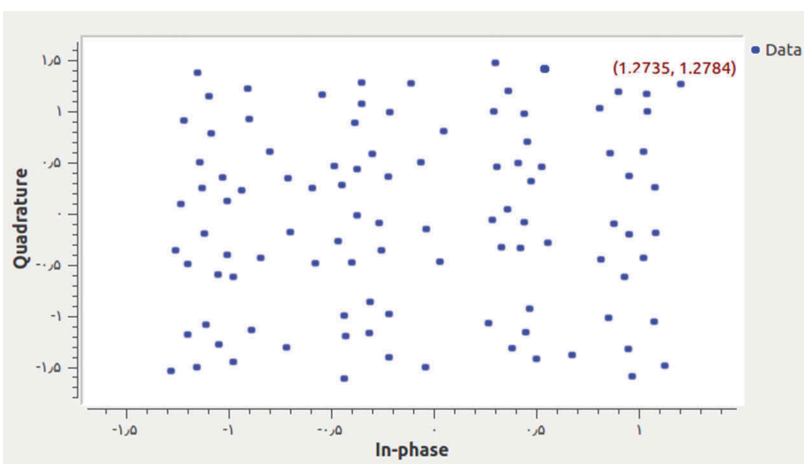

Figure 8. Constellation of real 16-QAM signal.

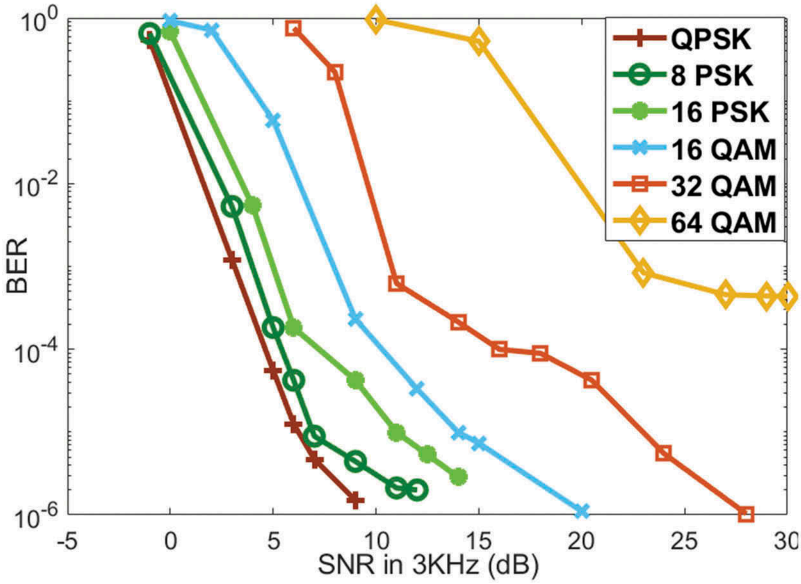

Figure 9. Results for different modulations in a real scenario.

Finally, Figure 9 presents the BER with respect to the SNR. It is noted that the results between Watterson channel (simulation) and real scenario results are very similar. Results show that at 3 kHz narrow band, the modulations QPSK, 8 PSK, 16 PSK and 16 QAM can be used with low power (less than 15 dB) while 32 QAM needs 20 dB power. However, 64 QAM needs a high power and a very efficient FEC with a high gain antenna. For more than 64 QAM all our experiments failed to transmit the signal to the receiver side with an acceptable BER. This shows that 64 QAM is not a good choice for Narrow Band 3 kHz channel.

Results comparison

Useful results are extracted from all the above experiments and summarized in Table 2. This data can be used as a reference for all current and future applications of HF communications. The importance of such results lay in eliminating the excess power used by current military and civilian applications. This can be done by sending just the right amount of power based on the needed bitrate and the channel type.

In Table 2 shows different channels under various modulation schemes and a comparison of the power needed for each one. Note that 32 PSK and 64 QAM modulations are not available in 3 kHz Narrowband HF channels where 16 PSK can be considered the best choice for low powers. If there is a need to increase the bit rate in 3 kHz Narrowband channel, 30 dB amplifier is required by using 32

Table 2. Comparision of needed power for different modulations on different channels in 3 kHz narrowband channels.

Modulation/channels	AWGN channel	Watterson channel	Real channel	Number of bits per symbol
QPSK	5 dB	8 dB	9 dB	2 bits
8 PSK	7 dB	10 dB	12 dB	3 bits
16 PSK	10 dB	13 dB	15 dB	4 bits
32 PSK	N.A	N.A	N.A	5 bits
16 QAM	10 dB	17 dB	20 dB	4 bits
32 QAM	15 dB	25 dB	27 dB	5 bits
64 QAM	N.A	N.A	N.A	6 bits

QAM modulation. By comparing the different scenarios it can be seen that Watterson channel is very similar to real channel.

The results of this paper can be mostly compared to results from (Lamy-Bergot et al. 2015). By studying the efficiency of different modulation schemes over Narrowband 3 kHz HF channels, the results show a better BER to SNR with FEC than that in (Lamy-Bergot et al. 2015). Knowing that (Lamy-Bergot et al. 2015) used Turbo codes as error correction method. In addition, the imperfect channel no.6 with 6 ms delay and 3.6 Hz Doppler frequency that is used in this article is considered more realistic model than that used in CCIR channel model used (Lamy-Bergot et al. 2015) with 2 ms delay and 1 Hz Doppler. Moreover, in addition to the simulations done, real experiments are hold on to get more realistic and dependent results. And this is very important for HF systems to use directly the results of this paper in their future applications.

Conclusion

To investigate the best modulation and signaling for very narrow band HF link (3 kHz), different modulation schemes such as QPSK, 8 PSK, 16 PSK, 16 QAM, 32 QAM and 64 QAM have been tested via simulation and real experiment scenarios. Both simulation and experiment results show that QPSK, 8 PSK and 16 PSK are efficient schemes to be used along with low power and FEC algorithm. While 32 PSK or higher schemes cannot be used due to the Doppler shift that affects the phase of the signal where 32 PSK scheme has a very sensitive phase selection and higher constellation PSK schemes have even more sensitive phase selection. For QAM it is tested and proofed that 16 QAM and 32 QAM are efficient schemes to be used on the narrowband channels along with a median power levels and a normal FEC. However, 64 QAM, due to its high amplitude selection sensitivity, cannot be used on 3 kHz HF channel. The above results along with the technical and numerical results are very good basic results for future use in the development of HF-based communication systems and algorithms.

Notes on contributors

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