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IMPROVING HF COMMUNICATIONS EFFICIENCY USING EVOLVED DATA RATE CHANGE ALGORITHMS[1]

MELHORIA DA EFICIÊNCIA DE COMUNICAÇÕES HF UTILIZANDO ALGORITMOS DE SELEÇÃO DE DÉBITO BINÁRIO EVOLUIDOS

Vasco Ferreira Sequeira
Lieutenant in Portuguese Army
Master in Military Electrical Engineering (Signals speciality) – Military Academy, Lisbon
Local Area Network Platoon Commander, from Signals Company of Mechanized Brigade
Support Engineering Team of Communications and Information Systems Tactical Project
2770-025 Paço de Arcos
sequeira.vf@mail.exercito.pt

Maria Paula dos Santos Queluz Rodrigues
Auxiliary Professor in Instituto Superior Técnico, Lisbon
Doctor in Electrical and Computer Engineering – Université Catholique de Louvain, Belgium
Telecommunications Institute
1049-001 Lisbon
paula.queluz@lx.it.pt

António José Castelo Branco Rodrigues
Auxiliary Professor in Instituto Superior Técnico, Lisbon
Doctor in Electrical and Computer Engineering – Université Catholique de Louvain, Belgium
Telecommunications Institute
1049-001 Lisbon
ar@lx.it.pt

José Eduardo Charters Ribeiro da Cunha Sanguino
Auxiliary Professor in Instituto Superior Técnico, Lisbon
Doctor in Electrical and Computer Engineering – Instituto Superior Técnico, Lisbon
Telecommunications Institute
1049-001 Lisbon
sanguino@lx.it.pt

Pedro Miguel Martins Grifo
Major in Portuguese Army
Master in Military Electrical Engineering (Signals speciality) – Military Academy, Lisbon
Deputy Officer in Planning and Coordination Projects Office
Support Engineering Team of Communications and Information Systems Tactical Project
2770-025 Paço de Arcos
grifo.pmm@mail.exercito.pt

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Abstract

High frequency (HF) band communications have undergone a remarkable technologic evolution, since the 80s, motivated by their potential robustness to catastrophic and emergency situations, and by the high costs involved in implementing and maintaining satellite links. Despite the renewed interest on HF communications, there are a lot of challenges involved, like the operation with very low signal-to-noise ratios (SNR) and signal variation due to the frequent changes in the Ionosphere constitution. In order to deal with the variability of the HF channel, several technologies have emerged like the Data Rate Change (DRC) algorithms. Former DRC algorithms solutions were studied (Trinder and RapidM), and based on their vulnerabilities, improved versions were proposed for both algorithms: Avoiding Cut-Off State (ACOS) and Bit Error Optimization (BEO). The first proposal reduces the occurrences of link cut-offs (corresponding to bit error rates higher than 10^{-3}), and the second increases the link availability and eliminates data rate oscillations. When compared to the original versions of the algorithms, both proposals showed significant performance improvements, either when evaluated in a simulation environment, or in real field propagation tests.

Keywords: Data Rate Change Algorithms; HF Communications; Ionosphere Communications; Satellite Communications.

Resumo

As comunicações na banda das altas frequências (HF) têm evoluído tecnologicamente, desde o final dos anos 80, sendo esta evolução motivada pela potencial robustez desta forma de comunicação em situações de catástrofe e de emergência, e pelo custo de manutenção e implementação das comunicações via satélite. Apesar do reaparecimento do interesse nas comunicações HF, existem vários desafios envolvidos, como a operação rádio com relações sinal-ruido (SNR) tipicamente muito baixas e variação do sinal devido a mudanças frequentes na camada da Ionosfera. Para lidar com as variações do canal em HF, surgiram várias tecnologias como os algoritmos de seleção automática do débito binário (DRC). As soluções existentes (Trinder e RapidM) foram estudadas, e com base nas vulnerabilidades detetadas, foram propostas versões melhoradas de ambos os algoritmos: Avoiding Cut-Off State (ACOS) e Bit Error Optimization (BEO). A primeira proposta reduz o número de ocorrências de corte na ligação (correspondente a taxas de erro de bit superiores a 10^{-3}*) e a segunda aumenta a disponibilidade da ligação e elimina as oscilações de débito binário. Quando comparadas com as versões originais, ambas as propostas demonstram melhores desempenhos, seja num sistema de simulação ou em condições reais de propagação.*

Palavras-Chave: *Algoritmos de Seleção de Débito Binário; Comunicações em HF; Comunicações via Ionosfera; Comunicações via Satélite.*

Introduction

In the current Portuguese situation, particularly in the Armed Forces, in which it is required to accomplish missions with resources contention, new solutions have emerged in military communications, and scientific developments of primordial technologies that guarantee the normal operation with a low cost of installation and maintenance were studied. This necessity fostered the application of high frequency (HF) radio waves in battlefields with hilly regions, allowing to establish radio communications without repeaters or satellites (Ceita, 2014, p. 1), using the Ionosphere as a radio wave reflector, decreasing drastically the economic costs, since only two stations are necessary, each with a radio and an antenna. In peacekeeping missions where Portugal participated, within the United Nations (UN), North Atlantic Treaty Organization (NATO) and European Rapid Operational Force (EUFOR), particularly the Stabilization Force (SFOR) and Operation Joint Endeavour (IFOR) in Bosnia-Herzegovina (1997), EUFOR Congo (2006) and Kosovo Force (KFOR) in Kosovo (2011), HF communications were used (Gonçalves, 2013 cit. by Rocha, 2013, p. 3).

Before the 60s, HF transmissions were the primary source of long-range communications, but they have declined because satellite communications allow higher data rates. However, satellite communications have high costs of production, installation and maintenance (based on their estimated lifetime), which resulted in the study and reuse of HF communications, at the beginning of the new millennium. Despite the renewed interest on HF communications, in particularly catastrophic or emergency scenarios, there are a lot of challenges involved, like the operation with (typically) very low signal-to-noise ratios[2] (SNR), multipath fading, signal variation due to the changing constitution of the Ionosphere, and a limited channel capacity. To deal with the variability of the HF channel, several technologies have emerged, like the automatic Link Quality Analysis (LQA), the Automatic Link Establishment (ALE) and the automatic Data Rate[3] Change (DRC) algorithms, eliminating the need for complex and manual operating procedures (Sequeira et al., 2017). Thus, the central question of this paper is: ***How is it possible to optimize HF communications presenting better results than the existing solutions?***

This paper is organized as follows: Section 1 extends the HF communications framework, describing its operation and their potentialities and vulnerabilities. Section 2 describes the satellite communications, explaining why the research of HF communications is important, due to satellite communications vulnerabilities. Section 3 addresses the existing solutions for HF communications optimization, presenting the DRC algorithms state-of-the-art. Section 4 presents the simulation system developed to assess the DRC algorithms and the developed proposals to improve the performance of HF communications. Section 5 describes the propagation tests under real conditions, carried out between Lisbon and Oporto, and it presents the field test results. Finally, the conclusions of the developed work are presented, in order to answer the central question.

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[2] Signal-to-Noise Ratio (dB) – It is defined as the ratio between the signal power and the noise power.

[3] Data Rate (bit/s) – It is defined as the number of bits transmitted per second.

1. HF Communications

In radio communications it is usual to consider three types of signals, according to the electromagnetic spectrum: HF signals, VHF signals (Very High Frequency) and UHF signals (Ultra High Frequency). The HF band is situated between 3 MHz and 30 MHz, with wavelengths ranging from 100 to 10 metres, allowing long-distance data and voice transmission using reflection in the Ionosphere layer. The HF band is one of the most important bands for military communications and it is used by ships, aircrafts, non-line-of-sight (NLOS) radio networks and military operations used as alternate communication system by the Command Posts with static radio stations, in vehicles or by soldiers employing manpack equipment when deployed abroad (Johnson et al., 2013). Figure 1 shows the electromagnetic spectrum division and the applications for each type of signal.

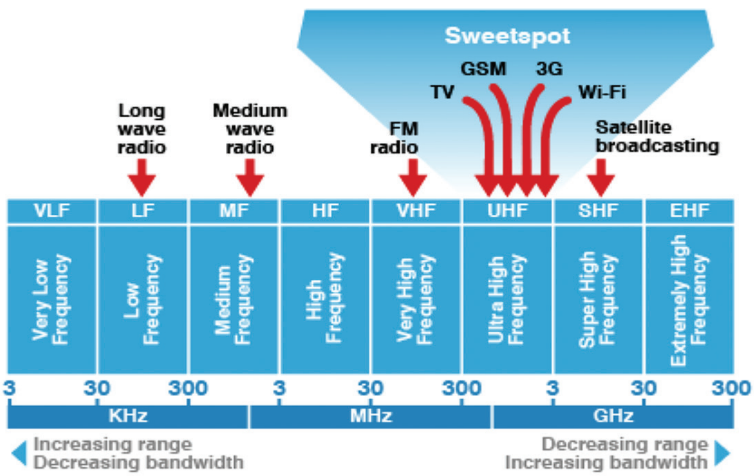

Figure 1 – Electromagnetic spectrum

Source: Retrieved from http://sciencepole.com/radio-spectrum/# (accessed in 08OCT16).

1.1. The Ionosphere Layer

The Ionosphere is an atmosphere layer composed by a cold plasma, ionized by the ultraviolet radiation coming from the Sun, and occupies a range from 50 km to 600 km from the Earth's surface (Sequeira, 2017, p. 6). During periods of high solar activity, the ultra-violet (UV) rays and other types of radiation influence the Ionosphere composition and its interaction with electromagnetic waves; therefore, it is necessary to permanently find out the optimum communication frequency, what can be accomplished with the help of an ionospheric model. This model is a mathematical description of the ionosphere as a function of location[4], altitude,

[4] The composition of the Ionosphere changes in different parts of the planet. In the poles of the Earth, the Ionosphere is less ionized compared to the Equator, since it has less exposure to the Sun rays. Therefore, in the poles the optimal frequencies are lower than in the Equator.

day of year[5], phase of the sunspotcycle[6] and geomagnetic activity. The state of the ionospheric plasma may be described by four parameters: electron density, electron and ion temperature and ionic composition. Radio propagation depends uniquely on electron density (Sequeira, 2017, p. 6). One of the most widely used ionospheric model is the International Reference Ionosphere (Bilitza, 2001); this model divides the Ionosphere into four layers (or five, if the sporadic E_s layer is also considered), based mainly on the electronic density (Hargreaves, 1995), those layers are (shown in Figure 2):

– **Layer D:** it begins at 50 km high and ends at 90 km, this is the closest layer to the Earth's surface. This layer causes attenuation of radio signals (low frequencies are attenuated more than higher ones), and heavy ionization only results in absorption of HF signals.

– **Layer E:** situated between 90 km and 140 km from the Earth's surface. HF radio signals are reflected in this layer back towards the Earth.

– **Layer F:** this layer is divided in **sub-layer F_1**, starting at 140 km to 300 km, and **sub-layer F_2**, starting at 300 km to 600 km from the Earth's surface. Most forms of sky wave propagation use the normal and cyclic ionization properties of this layer. It is a dual layer during the day, single at night.

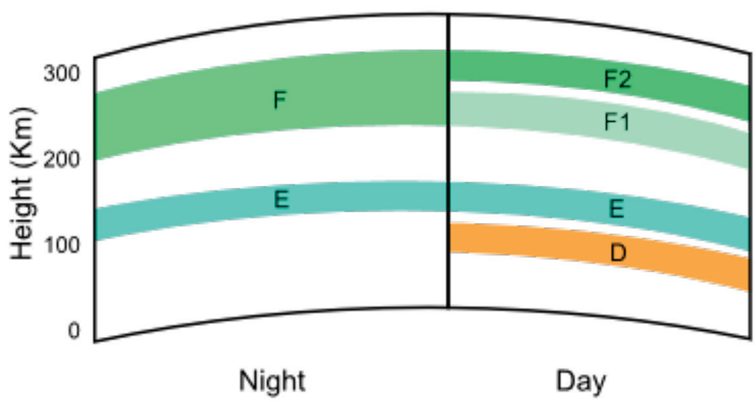

Figure 2 – The Ionosphere Layer

Source: Adapted from https://en.wikipedia.org/wiki/Ionosphere (accessed in 21DEC16).

1.2. Near Vertical Incidence Sky wave (NVIS)

The NVIS is a radio sky wave used for military communications, broadcasting and by radio amateurs. This sky wave uses high tilt-angles (between 60º and 89º) and the Ionosphere to reflect the signals back to Earth. If the frequency is too high, the electromagnetic wave breaks the Ionosphere and continues the propagation to the outer space; if the frequency is too low, the signal is reflected back to Earth in all possible angles, resulting in an omnidirectional radiation

[5] In Summer the days are longer than in Winter, therefore, the sun exposure is higher, which results in a greater Ionosphere layer ionization. So, in Summer the optimal frequencies are higher than in Winter.

[6] The Sun also has an activity cycle. The solar explosions are the Sun activities that most affect the Ionosphere layer ionization, and consequently, the radio communications in the HF band.

(Grifo, 2014). This type of propagation is very useful for overpass obstacles as shown in Figure 3, since the Ionosphere reflects the energy according to an "umbrella" shape diagram.

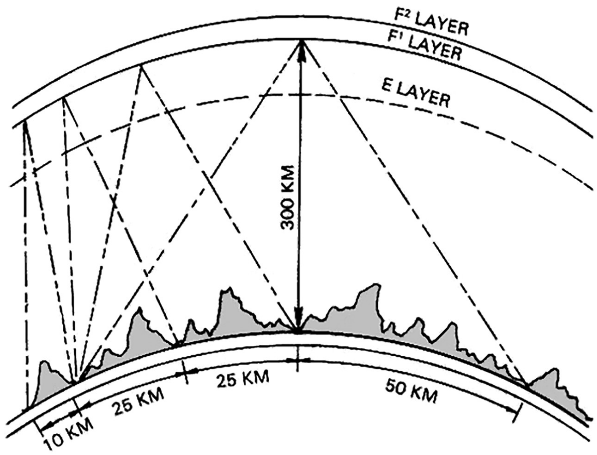

Figure 3 – NVIS propagation in an "umbrella" shape

Source: Adapted from http://raynet-hf.net/propagation/ (accessed in 21DEC17).

1.3. HF Communications Potentialities and Vulnerabilities

Currently, there is no perfect and flawless communications system, so that any of the existing communications services have their advantages and disadvantages. HF radio will never replace fixed and mobile telephony as the first communications option for the general public, but for organisations involved in emergency, remote and military communications, such as the Armed Forces, it is a vital and irreplaceable wireless communications tool (Codan, 2017). The advantages of HF communications are:

– **Long range capability:** while radio communications in the VHF and UHF bands only allow line-of-sight (LOS) communications, HF communications are capable of links above 3000 km.

– **Minimal infrastructure requirements:** unlike cellular and satellite telephony, which need land-based infrastructure and repeaters (in space or land), HF communications only need one radio and one antenna to ensure its normal operation, being the most reliable communication mean when disaster strikes.

– **Full mobility:** HF radio is simple and quick to deploy and provides communications capability for users regardless of the stations location. Fixed base stations can be used to communicate with other bases or to provide command and control (C2) for mobile (vehicle-mounted) and portable (manpack) users in the field.

– **Interoperability:** it can be used to communicate with existing VHF and UHF radio systems (rebroadcast[7]), cellular telephones and telephones networks through developments

[7] Rebroadcast – allows the interconnection of two networks that operate in different bands.

in cross-patching[8] technology. NATO standardisations regulate the HF band use to ensure the interoperability between the several alliance nations.

– **Low costs:** compared to satellite communications (the most common alternative for long distance transmission), the HF radio communications are the most economical choice. Once the initial investment has been made - approximately between 25000 € and 40000 €, the acquisition value of one E/R GRC-525 radio with a HF modem and one dipole antenna with a high gain, which may be variable depending on the requested number – associated costs does not exist (e.g., call costs, maintenance costs, or repeaters implementation). The radios were built for extreme temperature situations and have a high MTBF[9].

– **Command and Control (C2):** the HF communications permanently guarantee a C2 of the troops on the battlefield or on disasters situations, since it allows connections over long distances, with robust equipment, able to communicate with all types of stations (fixed and mobile).

– **Security:** the E/R GRC-525 has the capability to operate on a secure network, using the SECOM-H mode with the HF band. This mode operates on voice and data with COMSEC (Communication Security) protection, which encrypts the data to be sent, and TRANSEC (Transmission Security) which uses frequency hopping.

– **Independence in long-distance communications:** in the Portuguese case, longdistance communications are mostly conducted by satellite. Since Portugal does not have satellites in its possession, it has to rent to foreign countries, becoming dependent in this sector. HF communications allow independence in long-distance transmissions in a case of conflict.

HF communications also present unfavourable factors, some due to the decline of its use and scientific research, because of the satellite communications development in the 1960s. The HF communications vulnerabilities are:

– **Low data rate:** the waveforms developed in NATO standards and implemented by NATO and NATO nations, which allow a maximum data rate up to 9600 bit/s.

– **Constant changes in channel conditions:** the Ionosphere is a layer that constantly changes, due to changes in exposure and solar activity, that modifies the particles composition with reflective characteristics of HF radio waves. Thus, a frequency with good initial propagation conditions may fail a signal transmission to the receiving station. However, systems such as ALE 3G have minimized this problem, by saving a group of frequencies and automatically establishing the connection with a channel that presents better propagation conditions (higher SNR and lower BER), reducing the time duration of an unavailable link.

[8] Cross-patching technology - works with digital remote control equipment, which allows the link between different types of networks with frequencies in different bands of the electromagnetic spectrum.

[9] MTBF – Mean Time Between Failures.

2. Satellite Communications

2.1. Characteristics of Satellite Communications

Satellite communications are radio relay links using an artificial satellite as a repeater. The frequency bands used in satellite communication systems are between the UHF and SHF (Super High Frequency) band, and two different frequencies are used: upward[10] and downward[11]; these frequencies must have an appropriate spacing within the electromagnetic spectrum to avoid interference, and the upward frequency is higher than the downward frequency, maximizing the reception gain (Leitão, 2002, p. 3). Table 1 shows the available bands for a satellite transmission: S band is employed by meteorological radars and some satellite communication systems; C band is most commonly used for telephone network services or analogue and digital TV transmission; X band is strictly for military use; and Ku band is applied for satellite broadcast and data connections (Gomes, 2005, p. 2).

Table 1 – Band of frequencies used for radar and satellite systems

Type of Band	Initial Frequency	Final Frequency
L	1 GHz	2 GHz
S	2 GHz	4 GHz
C	4 GHz	8 GHz
X	8 GHz	12 GHz
Ku	12 GHz	18 GHz
K	18 GHz	27 GHz
Ka	27 GHz	40 GHz

Source: Adapted from Leitão (2002, p.3).

A revolution in satellite communication is currently occurring, through the Ka band development for data transmission, specifically on Internet connections, due to overuse of frequencies below 10 GHz; this band has the capability to offer services with high data rates. An event of great relevance in the Ka band development was the lunch of SPACEWAY 3 satellite in April 2008, with a throughput[12] capability of 10 Gbit/s and multiple directive beams with resources allocation flexibility (Baptista & Marins, 2012, p. 17). The rain attenuation is one of the most significant factors that affects Ka band communications, beside the additional factors which affect the satellite communications: antenna wetting, depolarization due to rain and ice, gaseous absorption, cloud attenuation, melting layer attenuation or ionospheric absorption (Kota, 2002). In the Ka band, for the lowest frequency (27 GHz) the rain attenuation is about 19 dB/km and for the highest frequency (40 GHz) is 25 dB/km, assuming a precipitation of 95 mm/h (Baptista e Marins, 2012, pp. 19-20).

[10] Upward frequency – it is the frequency used to communicate between the transmitter land station and the satellite.
[11] Downward frequency – it is the frequency used to communicate between the satellite and the receiver land station.
[12] Throughput (bit/s) – it is defined by the number of bits per second that arrive to the receiver without errors.

Satellites can also be classified according to its orbit (Leitão, 2002, p. 10):

– **Geostationary Earth Orbit** (GEO): the satellite remains fixed relative to the Earth on the Equator line, with the same angular velocity of the Earth at approximately 36 000 km from the surface. This type of satellite is applied in communications (radio, television, cell phones and Internet), meteorological observation of hurricanes and tornadoes, environmental analysis[13] and for military purposes by supporting the C2 of troops and acquisition of Enemy information.

– **Low Earth Orbit** (LEO): it is situated at 500 km to 1500 km from the Earth's surface. This type of satellite is used for communications that covers a short land area and to send information with few delay; it is also applied to Earth observation.

– **Medium Earth Orbit** (MEO): it is situated at 11 000 km to 20 000 km from the Earth's surface. The MEO satellites are applied to communications and navigation (GPS triangulation system).

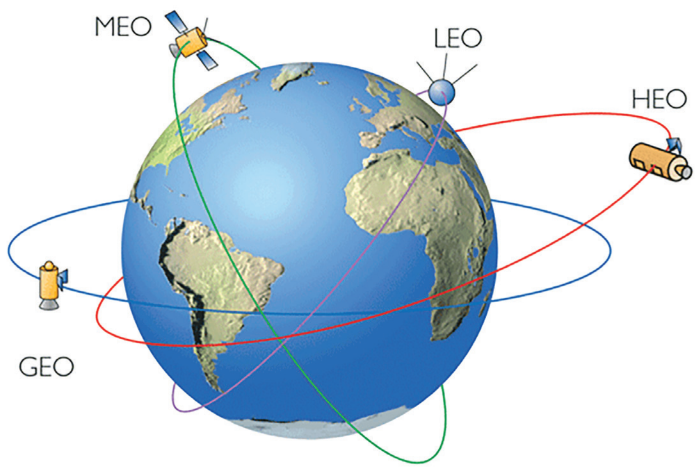

Figure 4 - Existing artificial satellite orbits
Source: Adapted from Herrera (2016).

– Another existing orbit is the **elliptical** (HEO – Highly Elliptical Orbit) where satellites have the function to cover the poles land surface, which is not possible through the GEO satellites. Figure 4 shows the mentioned orbits.

2.2. Satellite Communications Potentialities and Vulnerabilities

Satellite communications have some characteristics similar to HF communications. The potentialities in common with HF transmissions are the long range capability, interoperability and full mobility; in addition to these advantages, the satellite communications have the following potentialities:

[13] Environmental analysis - control of $CO2$ emissions into the atmosphere, detection of the ocean temperature variations, control of the ozone layer evolution, etc.

– **Fast data transmission:** as mentioned before, this type of communication allows high data transmission speeds, with a maximum recorded throughput of 10 Gbit/s. The reason why this system is the most used in long distance communications is the high speed of transmission.

– **Military applications to get information about Enemy:** in the Cold War period, the satellites for military applications were developed, with the purpose of getting information about Enemy troops, equipment, movements and military facilities.

– **Economic development:** satellite communications allow the connection between large economic centres and rural or remote localities, providing the economic development of these places.

However, satellite communications have the following vulnerabilities:

– **High costs:** The estimated lifetime of a satellite is 20 years (Carvalho, 2017). The production cost of a satellite is around 250 to 300 million USD, and the installation cost of a GEO satellite is 20% of its production cost, therefore, 50 million USD (Lima, 2016). Additionally to the costs, it should be considered the maintenance and the land stations spending values, which can be variable. To implement a satellite communication system it is necessary to invest around 600 to 800 million USD (including land stations), which represents 1% of the Portuguese Gross Domestic Product (GDP), which according to World Bank (2016), its valued at 204.6 billion USD. Therefore, to recover the investment, it is required a very high price per call and mobile data.

– **Security:** although data in satellite communication are encrypted, this system is supported by a computer network, and in recent years some hacking incidents have been noticed. One of the most famous cases of hacking to military satellite systems was in 2014, by the British Sean Caffrey, who entered into the United States Department of Defence (US DoD) system, accessing personal data (as password and e-mail) of 800 military (Kumar, 2017). There are also hack records by a Russian group called Turla APT, that has taken several commercial satellites to get data on the Internet from European and American governments, military, diplomats and organizations of research and education (Khandelwal, 2015).

– **Anti-satellite weapons (ASAT):** they are space weapons designed to destroy satellites with strategic military purposes. This threat began with the launch of the first Sputnik satellite by the USSR, in 1957. Currently the countries that have developed this weapon are the USA, Russia and China, although India claims to have technical capacity for ASAT development (Rediff India Abroad, 2007).

– **Rain attenuation:** as mentioned before, the satellite communications bands, with frequencies above 10 GHz, can be unavailable when rainfall occurs.

3. State-of-the-art: Data Rate Change Algorithms

The main objective of a Data Rate Change (DRC) algorithm is to select the highest possible transmission data rate, based on the channel propagation conditions (e.g. SNR and Bit Error

Rate[14] measurements at the receiver). In the past, some DRC algorithms were proposed, but this technology was poorly developed with only two structured algorithms: Trinder (Trinder & Gillespie, 2001) and RapidM DRC (Schulze & Hancke, 2005). These algorithms were conceived according to the NATO standards STANAG 4539 (NATO, 2000) and STANAG 4285 (NATO, 1989), with the data rate values of 75, 150, 300, 600, 1200, 2400, 3200, 6400, 4800, 8000 and 9600 bit/s (Sequeira et al., 2017). Both DRC algorithms use the SNR requirements for a BER of 10^{-5}, also defined in the NATO standards and presented in Table 2 for the three types of channels defined by ITU - Gaussian Noise (AWGN), ITU Poor and ITU Good; it is assumed that the very long interleaver, described in the standards, is used.

Table 2 – SNR requirements for a BER of 10^{-5}

Data Rate (bit/s)	SNR (dB)		
	AWGN	Good	Poor
75	-6.75	1.75	-2.50
150	-4.00	2.00	-1.00
300	-1.50	5.50	1.00
600	2.02	12.18	7.10
1200	5.25	14.95	10.10
3200	7.60	21.40	15.00
4800	12.29	25.21	19.75
6400	14.69	30.71	22.20
8000	15.44	35.56	25.50
9600	20.48	42.02	29.75

Source: Adapted from Schulze & Hancke (2015, p. 55).

3.1. Trinder Algorithm

The Trinder algorithm, proposed in Trinder & Gillespie (2001), is one of the first DRC algorithms; its main task was to serve as a guideline for implementers of STANAG 5066 (NATO, 2015). This algorithm uses the computed frame error rate[15] (FER) to select the transmission data. Since the radio only measures the SNR and BER values, the FER value can be computed by using equation (1), where is the frame size (in bits) and BER is the bit error rate, which is estimated from the measured signal-to-noise ratio (SNR) at the receiving station.

$$FER = 1 - (1 - BER)^L \qquad (1)$$

The Trinder algorithm selects the data rate based on the FER thresholds presented in Table 3, established by Trinder & Gillespie (2001): if the FER, measured at the receiving station, is

[14] Bit Error Rate (BER) – it is defined by the reason between the number of bits with errors and the total number of bits sent to the receiver.

[15] Frame Error Rate (%) – it is defined by the ratio between the number of frames (or data packets) with errors and the total number of frames sent to the receiver.

greater (or lower) than the minimum (maximum) FER, the data rate should be decreased (increased) by one step.

Table 3 – FER thresholds used to select data rate in Trinder algorithm

Data Rate (bit/s)	Minimum FER (Decrease Data Rate)	Maximum FER (Increase Data Rate)
75	-	10%
150	50%	10%
300	50%	10%
600	50%	10%
1200	50%	10%
3200	50%	10%
4800	35%	5%
6400	20%	5%
8000	15%	2%
9600	5%	-

Source: Retrieved from Trinder & Gillespie (2001).

3.2. RapidM DRC algorithm

The RapidM DRC algorithm (Schulze & Hancke, 2005) is based on four rules:

– **Rule 1:** the data rate is selected based on the measured SNR, and taking as reference the requirements for a BER of 10^{-5} (*cf.* Table 2). As an example, assuming an AWGN channel with a measured SNR of 14 dB, the chosen data rate should be 4800 bit/s (*cf.* Table 3).

– **Rule 2:** computes the change to be applied on the data rate, based on the current SNR variation, given by equation (2), and assuming that the data rate variation is proportional to ΔSNR (the linear equation relating these variations is obtained by curve fitting the SNR and data rate values of Table 2).

$$\Delta \mathrm{SNR} = \mathrm{SNR}_{measured} - \mathrm{SNR}_{required} \qquad (2)$$

– **Rule 3:** selects the new data rate by comparing the current BER with the BER thresholds presented in Table 4: if the BER is greater than or equal to 10^{-4}, then the data rate is decreased; if the BER value is lower than10^{-6}, then the data rate is increased; otherwise, the previous data rate is maintained.

Table 4 – BER Thresholds for the RapidM algorithm Rule 3

BER	DRC Algorithms Action
$\geq 10^{-4}$	Decrease Data Rate
$\in [10^{-6}, 10^{-4}[$	Maintain Data Rate
$< 10^{-6}$	Increase Data Rate

Source: Adapted from Schulze & Hancke (2015, p. 96).

– **Rule 4:** implements safety controls that does not allow the increase of the data rate in more than two levels (e.g., if the current data rate is 600 bit/s, the new data rate may be, at most, 3200 bit/s), or to decrease the current data rate in more than three levels.

Rule 1 is applied when: 1) the SNR value drops 12 dB or more between two consecutive SNR measurements; or 2) the current data rate is lower or equal than 300 bit/s and the SNR value is greater or equal than 20 dB. Rule 2 is applied when the SNR value increases more than 9 dB, or drops 9 to 12 dB, between two consecutive channel measurements. Rule 3 is applied whenever conditions are not met to apply Rules 1 or 2. Rule 4 ensures that the data rate does not increase by more than two steps, and does not decrease by more than three, when Rule 1 and 2 are applied.

4. DRC Algorithms Implementation and Assessment

The simulation system developed to implement and analyse the DRC algorithms is represented by the flowchart of Figure 5, and the corresponding Matlab code is available in Sequeira (2018). It starts with an initialization process that loads the SNR channel requirements for a BER of 10^{-5} and for the considered channel types, which can be AWGN, ITU Good or ITU Poor. This process continues with the reading of the current channel SNR, which leads to the computation of the initial data rate, by comparing the current SNR with the SNR channel requirements. As an example, for the ITU Good channel with an initial SNR value of 25 dB, the initial data rate is 3200 bit/s (*cf.* Table 2).

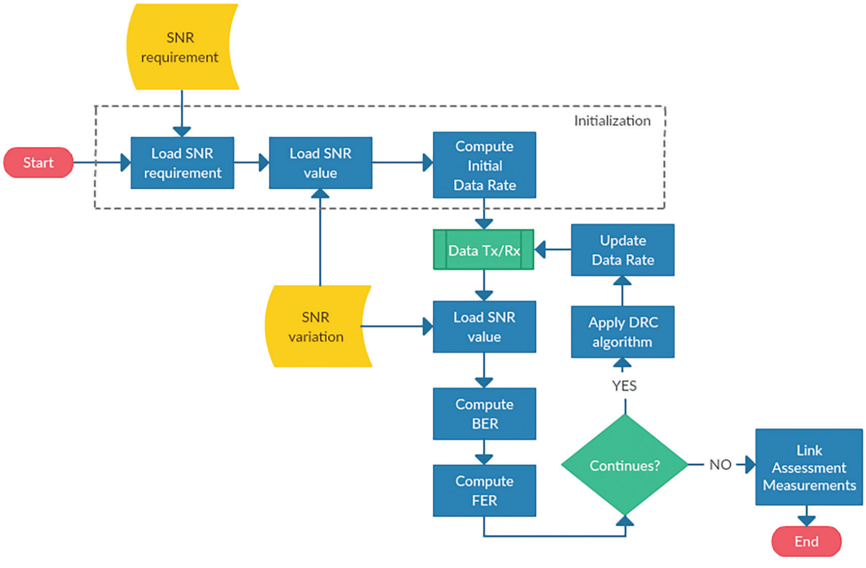

Figure 5 – Simulation system flowchart.

Source: Retrieved from Sequeira (2017).

After the initialization process, the data transmission starts. Periodically, the system reads the current channel SNR and computes the corresponding channel BER and FER using equations (1), (2) and (3); the latter assumes a BER *vs* SNR variation of 1 decade (in BER) per 1 dB (in SNR), valid for low BER values, as shown in Figure 6.

$$\mathrm{BER} = 10^{-5} \times 10^{-\Delta\mathrm{SNR}} \tag{3}$$

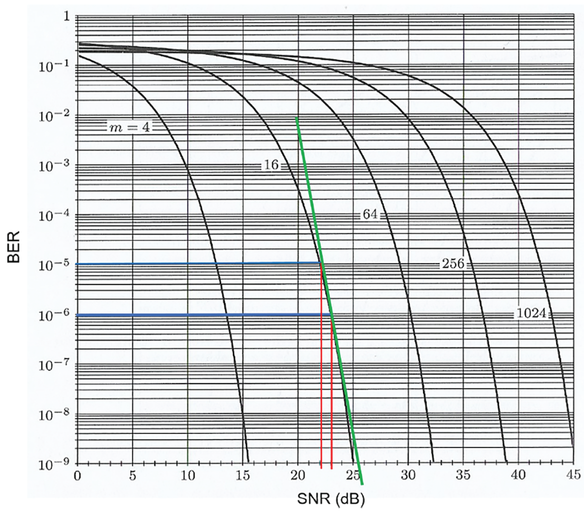

Figure 6 - BER as a function of SNR, for M-QAM modulation, with a straight line (in green) representing a BER variation of 1 decade per dB.

Source: Adapted from Salema (2011).

Based on these values, and on the current data rate, a new data rate value is computed by the DRC algorithm that will be applied to the next transmission interval. At the end of the transmission, the following link assessment metrics are computed:

1) **Average BER** - defined by equation (4), where BER_i is the value of the computed BER for interval number i, T_i is the interval duration and N is the total number of intervals. Whenever the BER value is higher than10^{-3}, it is considered that the link is in cut off state; an auxiliary variable, τ_i, computed by equation (5), accounts for the time intervals that are not in the cut-off state. This metric is only accounted when the link is available

$$\overline{BER} = \frac{\sum_{i=1}^{N} BER_i \times \tau_i(BER_i)}{\sum_{i=1}^{N} \tau_i(BER_i)_i} \tag{4}$$

$$\tau_i(BER_i) = \begin{cases} T_i & if\ BER_i \leq 10^{-3} \\ 0 & if\ BER_i > 10^{-3} \end{cases}. \tag{5}$$

2) Average FER (in %) - defined by equation (6), where FER_i is the value of the computed FER for interval number i. As in average BER, this metric is only accounted when the link is available

$$\overline{FER} = \frac{\sum_{i=1}^{N} FER_i \times \tau_i(BER_i)}{\sum_{i=1}^{N} \tau_i(BER_i)} \times 100\ [\%]\,. \qquad (6)$$

3) Link Availability (in %) - defined by (7), is the percentage of time for which the BER value is lower than 10^{-3}.

$$LA = \frac{\sum_{i=1}^{N} \tau_i(BER_i)}{\sum_{i=1}^{N} T_i} \times 100\ [\%]. \qquad (7)$$

4) Average throughput (in bit/s) - defined by equation (8), represents the number of correct bits/s at the receiver

$$\overline{Th} = \frac{\sum_{i=1}^{N} DR_i \times \tau_i(BER_i) \times (1 - BER_i)}{\sum_{i=1}^{N} T_i}\ [\text{bit/s}]\ . \qquad (8)$$

5) Average goodput (in frames/s) - defined by equation (9), represents the number of correct frames/s at the receiver; is the frame length in bits and is the data rate value for the interval number i,

$$\overline{Gp} = \frac{\sum_{i=1}^{N} \frac{DR_i}{L} \times (1 - FER_i) \times \tau_i(BER_i)}{\sum_{i=1}^{N} T_i}\ [\text{tramas/s}]. \qquad (9)$$

The DRC algorithms were assessed for four types of SNR variations: downward, upward, sinusoidal and step-wise. All these SNR variations were tested for the three types of channel - AWGN, ITU Good and ITU Poor – resulting in a total of twelve different simulations per algorithm. Due to space constraints, the results reported in this paper are relative to the upward SNR variation only and, in most of the cases, for the ITU-R Poor channel; additional results are available in Sequeira (2017). The following parameters values were used: interval duration (T_i) of 120 seconds; total number of measurement intervals (N) of 100; and a frame size (L) of 250 bytes.

4.1. Trinder and RapidM Algorithms: Results and Vulnerabilities

Figure 7 shows the data rate adaptation using the Trinder algorithm, for an upward SNR variation and for the three considered channels; the resulting link assessment metrics are presented in Table 5.

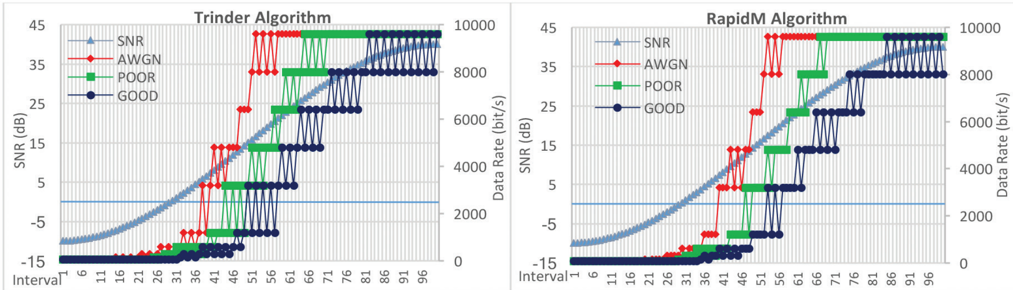

Figure 7 – Data rate adaptation for an upward SNR variation, using Trinder and RapidM

Source: Retrieved from Sequeira (2017).

Table 5 – Trinder and RapidM assessment metrics results

	DRC Algorithm	
Metrics	**Trinder**	**RapidM**
$\overline{BER}$	4.91E-05	1.10E-05
$\overline{FER}$	6.59%	1.96%
LA	66%	72%
$\overline{Th}$ **(bits/s)**	4001	4189
$\overline{Gp}$ **(frames/s)**	1.942	2.066

Source: Adapted from Sequeira (2017)

The main vulnerability detected on these algorithms is the occurrence of data rate oscillations, which lead to the link cut-off state (BER $\geq 10^{-3}$), reducing the link availability. This is confirmed by Figure 8, that shows the resulting BER values, where it can be noticed that the data rate oscillations coincide with BER values above 10^{-3}. As expected from the state-of-art, the RapidM algorithm performs better than the Trinder algorithm; however, it still presents several data rate oscillations that lead to high BER values.

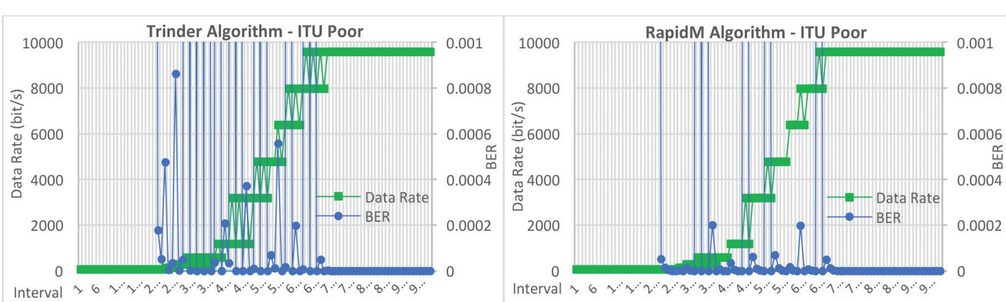

Figure 8 - BER vs Data Rate variation, for an upward SNR variation using an ITU Poor channel

Source: Retrieved from Sequeira (2017).

4.2. Trinder and RapidM Improvement Proposals

This section describes and evaluates the proposed solutions to improve the Trinder and RapidM performance: Avoiding Cut-Off State (ACOS) and Bit Error Optimization (BEO). As before, results are shown for the upward SNR variation with an ITU-R Poor channel case; results for all the considered test conditions can be consulted in Sequeira, (2017).

4.2.1. Avoiding Cut-Off State (ACOS) Algorithm

The ACOS algorithm is based on the BER value prediction computed by equations (2) and (3): if the new data rate leads to a predicted BER higher than 10^{-3}, then it will not be applied, being its value reduced according to the flowchart shown in Figure 9.

Table 6 presents the resulting link assessment metrics after applying the ACOS solution to the Trinder and RapidM algorithms, showing that there is a clear improvement in *LA*, $\overline{Th}$ and $\overline{Gp}$. The increase in average BER and FER is a direct consequence of an higher link availability. However, some data rate oscillations still occur in both cases, which can be visualized in Figure 10 for the RapidM with ACOS solution. These oscillations coincide with BER values higher than 10^{-4}, which is the BER threshold that triggers the data rate decrease in the RapidM algorithm (*cf.* Table 4).

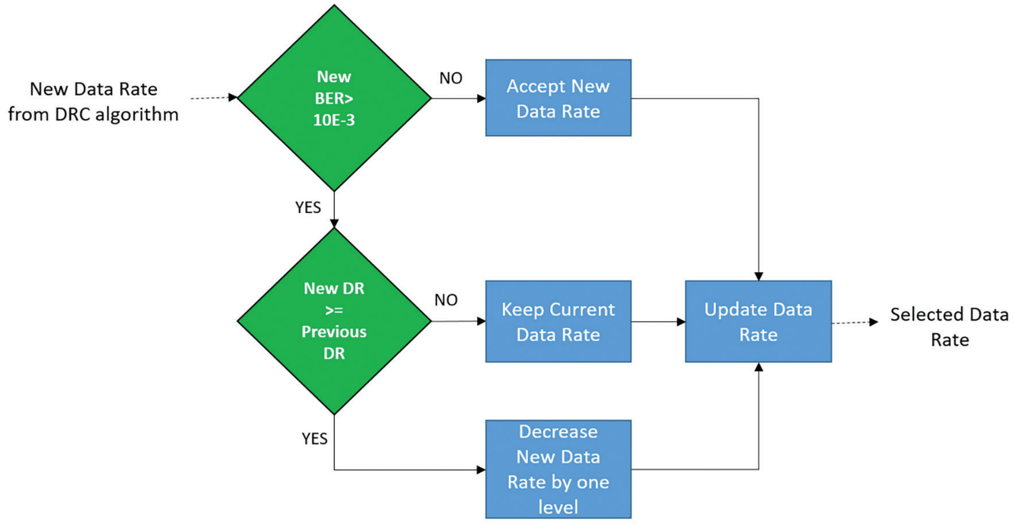

Figure 9 – Avoiding Cut-Off State Algorithm flowchart

Source: Adapted from Sequeira (2017).

Table 6 – Link assessment metrics for DRC algorithms with ACOS

	DRC Algorithm	
Metrics	**Trinder ACOS**	**RapidM ACOS**
$\overline{BER}$	5.14E-05	2.11E-05
$\overline{FER}$	7.01%	3.28%
LA	78%	77%
$\overline{Th}$ **(bits/s)**	4350	4319
$\overline{Gp}$ **(frames/s)**	2.091	2.101

Source: Adapted from Sequeira (2017).

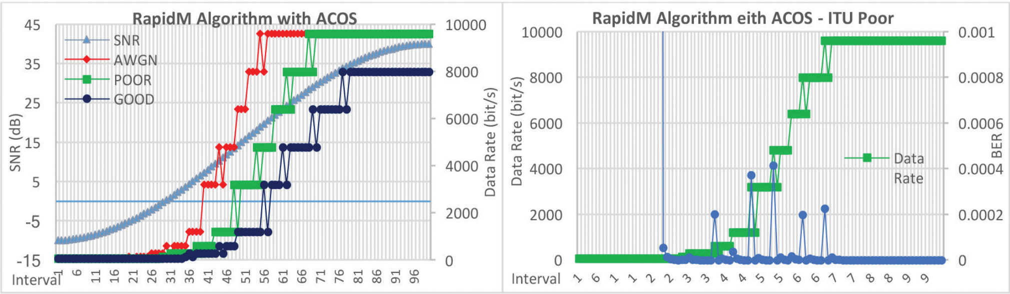

Figure 10 - Data rate adaptation for an upward SNR variation, using RapidM with ACOS

Source: Retrieved from Sequeira (2017).

4.2.2. Bit Error Optimization (BEO) Algorithm

The main difference between ACOS and BEO algorithms is the condition that follows the computation of the predicted BER: instead of comparing it with the BER value corresponding to the link unavailability (10^{-3}), it is compared with the BER threshold value that triggers the data rate decrease in the original versions of the DRC algorithms; in the RapidM algorithm case, it is a BER of 10^{-4}, and in Trinder algorithm is the BER corresponding to the minimum FER presented in Table 4, for each data rate level. The flowchart of the BEO solution is identical to the one of Figure 9, except for the reference BER used in the first comparing block.

Table 7 presents the resulting link assessment metrics after applying the BEO solution to the Trinder and RapidM algorithms: as for ACOS, there is a clear improvement in the relevant metrics. BEO algorithm presents slightly improvements in the average goodput, compared to ACOS algorithm. It is also worth to note that using the BEO solution, the difference between Trinder and RapidM becomes marginal. Figure 11 confirms that the BEO solution eliminates the data rate oscillations which were still present in the RapidM with ACOS; the same happened for the Trinder with BEO solution.

Table 7 - Link assessment metrics for DRC algorithms with BEO

	Algoritmo DRC	
Medidas	**Trinder BEO**	**RapidM BEO**
$\overline{BER}$	1.95E-05	6.05E-06
$\overline{FER}$	3.44%	1.16%
LA	78%	77%
$\overline{Th}$ **(bits/s)**	4334	4319
$\overline{Gp}$ **(frames/s)**	2.144	2.142

Source: Adapted from Sequeira (2017).

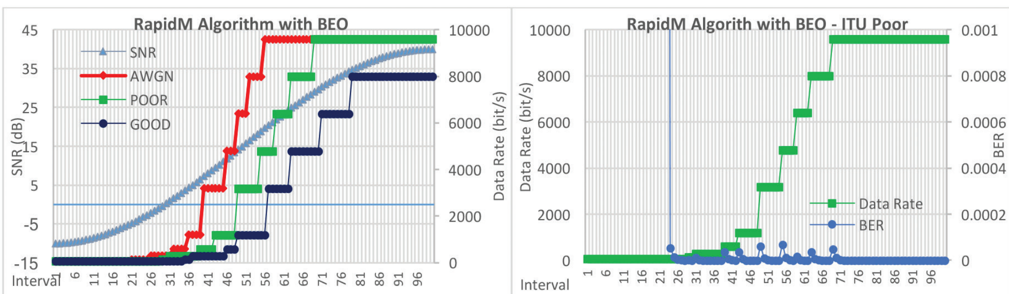

Figure 11 - Data rate adaptation for an upward SNR variation, using RapidM with BEO

Source: Retrieved from Sequeira (2017).

5. Field Propagation Tests

This section details the field propagation tests of the considered DRC algorithms (original versions and improved ones), conducted during the period of 30th August 2017 to 07th September 2017, as well as the algorithms assessment results.

5.1. Description of Field Propagation Tests Conditions

The field propagation tests were conducted with two stations located in the Portuguese cities of Lisbon (Support Unity of Logistic Command) and Oporto (Signals Regiment), with a link distance of about 282 km. Each station was equipped with one E/R GRC-525 radio and one RF1936P dipole antenna, as shown in Figure 12.

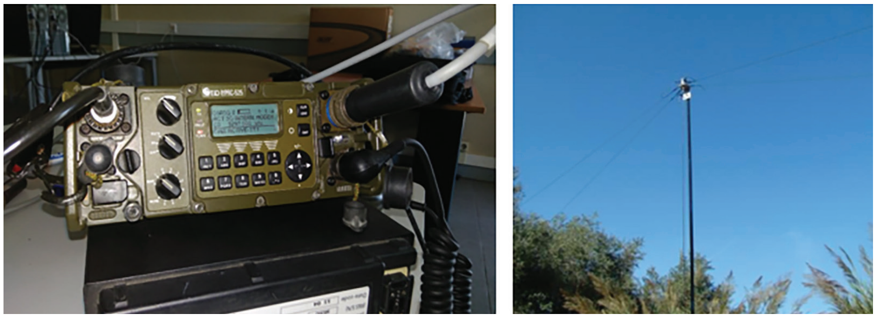

Figure 12 – E/R GRC-525 radio and RF-1936P dipole antenna

Source: Adapted from Sequeira et al. (2017).

Before assembling the stations, it was necessary to plan the communication mission and study the behaviour of the Ionosphere for the testing days, by analysing the critical frequency of the F2 layer (foF2) and the Maximum Usable Frequency (MUF), available in *Associação Observatório AeroEspacial Amadores de Satélite-CT* [AMSAT-CT] (2017). Based on these values, eight frequencies on the 4 MHz to 8 MHz range were selected to compose the ALE scan group. During the communication, the E/R GRC-525 radio will search for the frequency with the best link propagation conditions (i.e., higher SNR and lower BER). Since the algorithms performances should be compared in similar propagation conditions, other ionospheric and meteorological measures were recorded from AMSAT-CT (2017) and Impala Multimedia (2017), for each testing day, namely geomagnetic storms and HF fadeout warnings.

To assess the DRC algorithms in the field, an 8 Mbytes text file was transmitted between stations. The long interleaver and a frame length of 250 bytes were chosen for the data transmission, as in the simulations.

5.2. Field Propagation Test Results

The overall results of the field propagation tests are presented in Table 8. The RapidM algorithm with BEO achieved the best performance, increasing the link availability in 15% and the throughput by a factor of 6.4, compared with the RapidM original version; the meteorological and the ionospheric measures during the corresponding test days may be considered similar, as proved in Sequeira (2017, pp. 111-112).

Table 8 – DRC Algorithms assessment in real propagation conditions.

Algoritmo	Dia	*LA*	$\overline{SNR}$ (dB)	$\overline{BER}$	$\overline{Th}$ (bit/s)
RapidM	30/08/17	84%	9.50	5.08E-06	380
RapidM ACOS	31/08/17	96%	9.33	6.69E-05	892
RapidM BEO	01/09/17	99%	9.55	2.76E-04	2425
Trinder	04/09/17	83%	3.97	3.69E-04	246
Trinder ACOS	05/09/17	86%	4.98	1.82E-04	1509
Trinder BEO	07/09/17	96%	3.38	2.68E-04	719

Source: Adapted from Sequeira (2017).

However, it is not possible to directly compare the performance of the RapidM algorithm with the performance of the Trinder algorithm and its improved versions, since the propagation conditions on the corresponding test days were quite different (e.g., the average SNR at the receiver station was much lower for the tests with the Trinder algorithms than for the tests with the RapidM algorithms, as can be seen in Table 8); still, it is possible to verify that the improved Trinder versions lead to better performances than the original version. Although the Trinder algorithm with BEO was tested in a day with the lowest average SNR value (3.38 dB), it still showed a great performance improvement over the original version, increasing the link availability in 13% and the throughput by a factor of 2.9.

5.3. Simulation System Validation

One of the parameters recorded by the radio equipment during the field propagation tests was the SNR measured at the receiving station; these SNR values were then given as input to the simulation system, and the correlation coefficient between the real and simulated data rate change were computed. The highest correlation value, 0.91, was obtained for the Trinder algorithm with ACOS, tested on 5th September 2017. Figure 13 shows the data rate adaptation in real propagation conditions and obtained in the simulation system, where it is possible to check an identical behaviour between both results, which validates the simulation system.

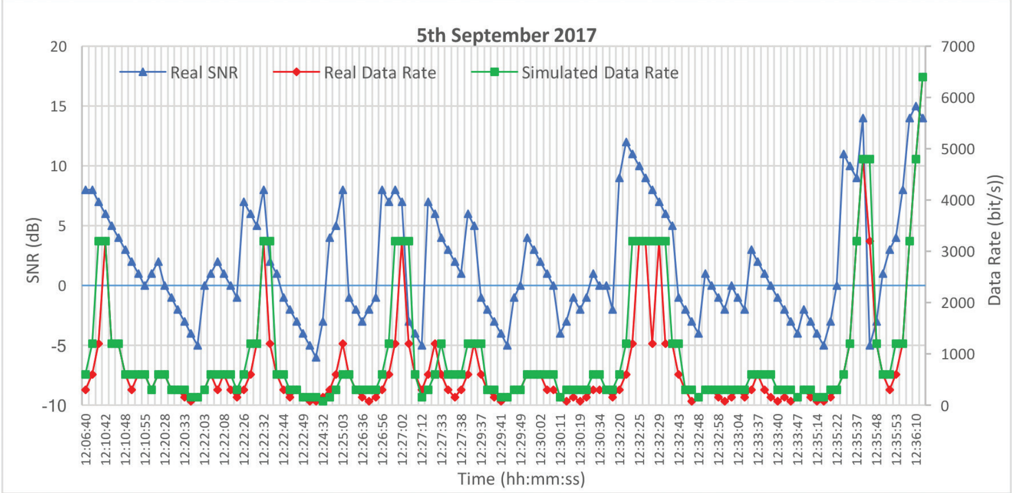

Figure 13 – Data rate adaptation (real and simulated) for a SNR variation measured in 5th September 2017, using the Trinder algorithm with ACOS

Source: Adapted from Sequeira (2017).

Conclusions

The main objective of the master dissertation was the design and implementation of an efficient DRC algorithm for HF communications, to be used in the Portuguese Army radio communications equipment, namely the E/R GRC-525 military radio.

Firstly, the HF communications were described, presenting its characteristics and operating mode for data transmission in long range distance, using the Ionosphere layer as a natural reflector of radio waves. Its vulnerabilities and potentials were described and compared with satellite communications (an alternative communications solution for long distances). After a comparative analysis between the two forms of long range transmission, it was determined that HF communications provide greater robustness to catastrophic and emergency situations, lower implementation and maintenance costs, greater security in encryption and transmission of data, and independence in the military communications of a country without great economic power. The determining factor for the mass use of satellite communications is the high speed of data transmission, which is substantially higher compared to HF communications.

To answer the central question of this paper: "***How is it possible to optimize HF communications presenting better results than the existing solutions?***"; the existing Data Rate Change (DRC) algorithms for HF communications were studied, namely the Trinder (2001) and RapidM (Schulze e Hancke, 2005), where its characteristics were presented in the state-of-the-art.

A simulation system in Matlab was created to assess the original DRC algorithms and detect their vulnerabilities. After implementing the Trinder and the RapidM DRC algorithms, its main detected weakness was the data rate oscillations, which lead to many cut-off states, reducing the link availability and the average throughput and goodput. In order to increase the performance of the original Trinder and RapidM algorithms, two new versions of each one were proposed: Avoiding Cut-Off State (ACOS) and Bit Error Optimization (BEO). When implemented on the simulation environment, these new versions showed huge link performance improvements relatively to the original versions; however, some data rate oscillations were still detected in the ACOS based versions.

After assessing all the algorithms in the simulation system, two radio stations, one in Lisbon and another in Oporto, were assembled. Each station was composed by one E/R GRC-525 military radio and a RF-1936P dipole antenna. An application in Visual Studio C#, implementing all the considered DRC algorithms (original and improved versions) was developed, allowing to assess the algorithms on the field. The algorithm that showed the best performance results was the RapidM DRC with BEO, increasing the link availability by 15% and the throughput by a factor of 6.4, compared with the RapidM original version, with similar propagation conditions. Trinder with BEO algorithm showed the worst propagation conditions (with an average SNR of 3.38 dB), and even with a bad link showed better performance than the original version, increasing the link availability by 13% and the throughput by a factor of 2.9.

This paper has the following main contributions: a simulation system developed to assess DRC algorithms, which was validated through a correlation with the results obtained in the field propagation tests, presenting a correlation value of 0.91 for the tests conducted on 5th September 2017; two DRC algorithms versions which present better performances than existing solutions; and for the first time, the performance of DRC algorithms were recorded, since in the work developed by Schulze & Hancke (2005) the DRC algorithms were only tested in a HF channel simulator. Therefore, the identified advantages are the optimization of HF communications, providing a higher average throughput and a lower BER in data transmission; and one first real test of DRC algorithms on the field.

As new lines of investigation, it is necessary to implement the developed DRC algorithms with the STANAG 5066 (NATO, 2015), which provides e-mail services through radio communications in the HF band. It is proposed to design and assess a DRC algorithm with variable frame size, by analyzing the propagation conditions.

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