Distributed Ground Station System experimental theory confirmation

Marcin Stolarski

Warsaw University of Technology
Faculty of Electronics and Information Technology
Institute of Radioelectronics
Nowowiejska Street 15/17, 00-665 Warsaw, POLAND
mstolars@gmail.com

Abstract: *In order to communicate with satellites, Ground Stations (GS) must use big antennas or antenna array. If a satellite is on Low Earth Orbit (LEO) one GS has short communication window and Mission Control Centre (MCC) must use more than one GS to enlarge satellite's access time. Distributed Ground Station System (DGSS) is a theory of how to use more than one Ground Station to communicate with satellite in the same time and compare (in computer system) received data. Comparison of the parallel received data from the same radio channel improves quality of this radio channel. Author shows base ground of this theory. He also shows formulas how to calculate RF link budget. Based on a few scenarios of building the Ground Station System (GSS), he proposes algorithms that are meant to decrease Bit Error Rate (BER) in systems using DGSS technologies. Next part of this paper shows stratospheric balloon (low cost satellite simulation) and laboratory experiments, which author has done to confirm his theory. He shows result of this experiments and compares it with this theory. This document shows that it is possible to receive data from satellite with lower BER when MCC is using GSS with implemented DGSS technologies.*
Distributed Ground Station System is a subject of author's PhD thesis and it is one of the experiments on "PW-Sat" satellite, which is being build at Warsaw University of Technology.

1. INTRODUCTION

The main idea of the DGSS (DGSS – [1]-[4]) is based on parallel reception of data from satellite by a number of ground stations and subsequent comparison of this data in the computer system. According to the very definition, if reception errors in ground stations are independent of each other, the probability of receiving an error-free packet increases together with the number of ground stations. Fig. 1 presents the general idea of the system. Telemetry sent by the satellites (both correct and erroneous) is received by a number of ground stations. Next, data is sent via the network to the server, where it is compared. This results in decreasing the number of errors. Data prepared in such a way is sent e.g. to Mission Control Center, where it is further processed.

Due to spatial arrangement of ground stations, DGSS also extends the range of communication link. Fig. 2 presents the range of a single ground station for a satellite at the Low Earth Orbit (LEO) 700 km. This range can be extended by increasing the number of distributed stations. Fig. 3 presents the expected GENSO network range ([13], [14]), where 14 ground stations have been used. When the satellite moves over Europe, 7 ground stations will be able to simultaneously receive its telemetry. Fig. 4 presents the range of DGSS based on the APRS-IS network ([10]-[12]), where 14 000 ground stations have been used. When the satellite passes over USA, Europe and Japan, up to 1 000 ground stations can simultaneously receive the telemetric data.

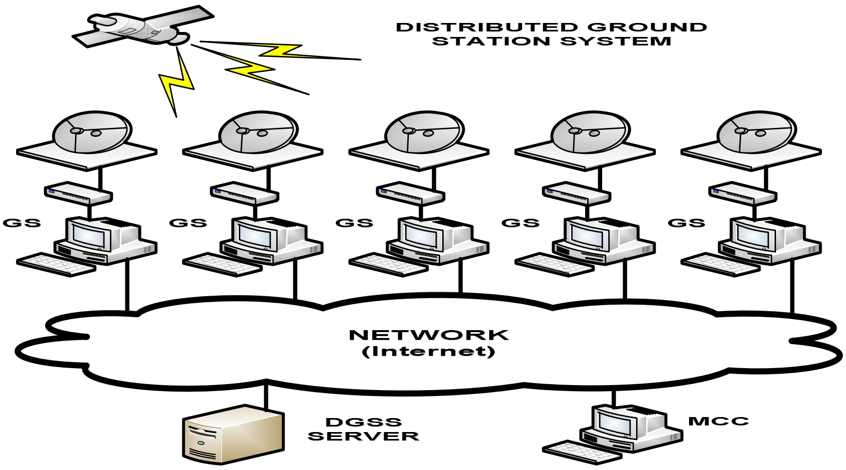

Fig 1. Visual outline of DGSS.

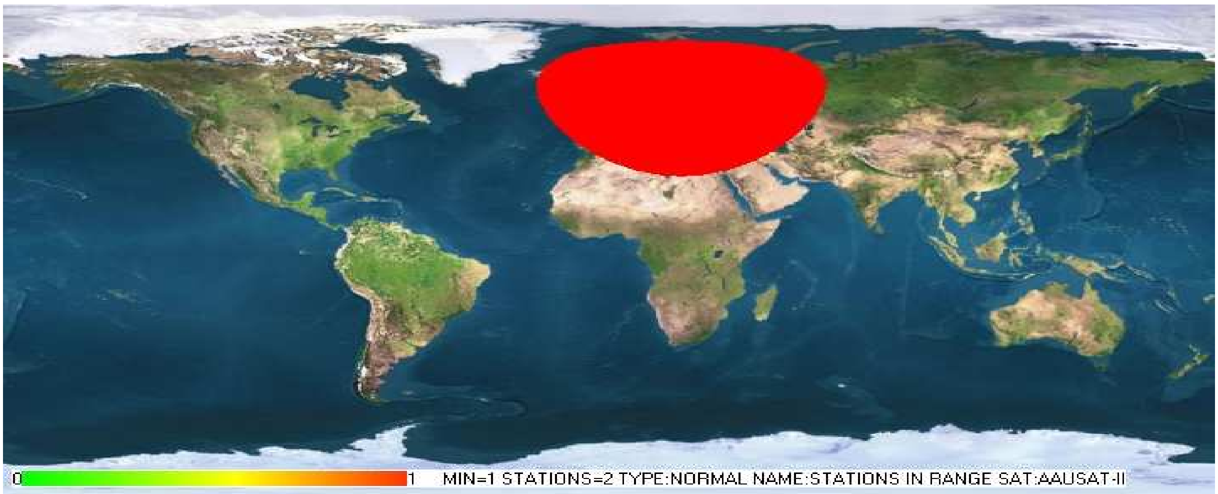

Fig 2. Range of single ground station.

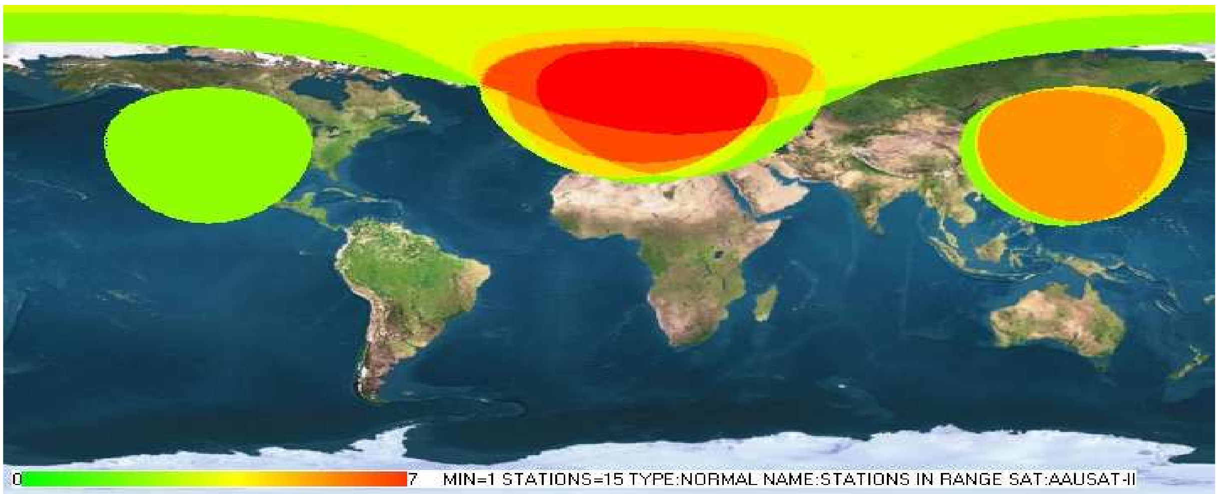

Fig 3. Range of the GENSO network.

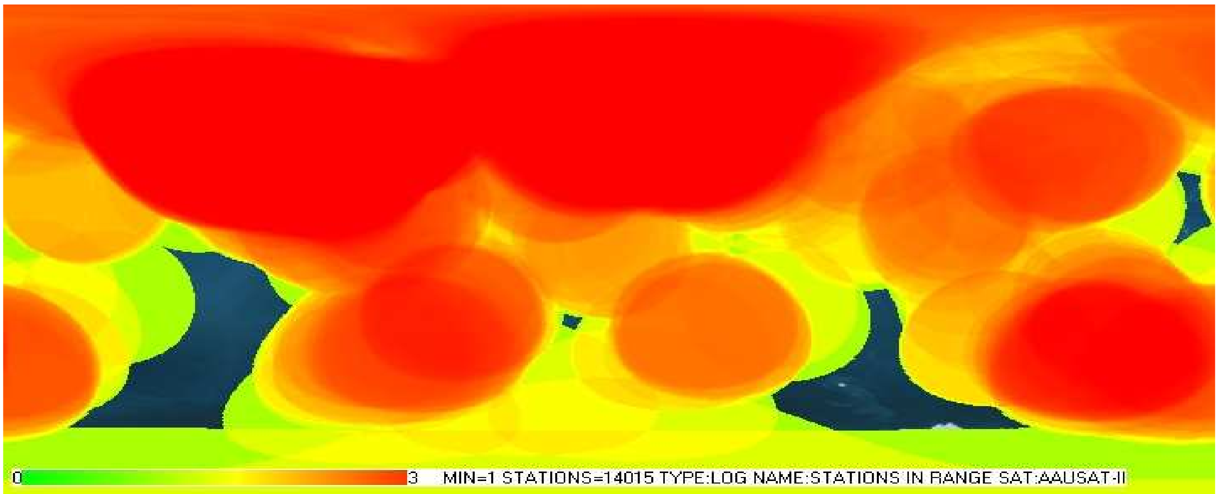

Fig 4. Range of the APRS-IS network.

For the purpose of the simulation created in order to represent the behavior of a single station, the author has used FSK modulation and its Bit Error Rate (BER) in relation to the EbNoR (Eb/No in dB – [6]-[8]) parameter. It has to be said, though, that DGSS is not dependent on this modulation.

2. MAIN FORMULAS OF THE CONCEPT

A general formula describing radio link quality in the distributed system is presented in (2.1), where BERi defines link quality, and BERx is the resulting link quality obtained after comparing data streams.

$$BER_x = \prod_{i=1}^{n} BER_i \qquad (2.1)$$

In order to make use of DGSS, certain algorithms need to be applied. The next advantage of the system is the possibility of distributed receiving of information through a couple of stations at the same time. It seems that such simultaneous receiving should improve the radio link quality. The mathematic simulations made by the author have shown that with appropriate Eb/No ratio such receiving is better than when using antenna arrays. For the simulation a number of scenarios was used, and bit error rate (BER) was calculated for each one of them.

Scenarios:

- Receiving the signal through a single ground station (BERss).
- Receiving the signal through a single ground station with an antenna array composed of five antennas (BERn - 7dB gain).
- Receiving the signal through five separate receiving systems identical to a single ground station. BER was calculated for each of the stations and the station with the highest link quality (BERmin) has been chosen.
- Receiving the signal through five separate receiving systems identical to a single ground station. BER was calculated for the case when none of the station received data correctly

(optimal solution, BERo). If one of the stations received correct data it is assumed that it has been interpreted correctly.

- Receiving the signal through five separate receiving systems identical to a single ground station. BER was calculated for the case when most of the stations did not receive data correctly (voting solution, BERv). If most of the stations received correct data it is assumed that it has been interpreted correctly in the Packet Voting System [3].

$$BER_{SS} = \frac{1}{2} * e^{\left(\frac{10^{\frac{E_b N_0 R[dB]}{10}}}{-2} \right)} \qquad (2.2)$$

$$BER_N = \frac{1}{2} * e^{\left(\frac{n * \left(10^{\frac{E_b N_0 R[dB]}{10}} \right)}{-2} \right)} \qquad (2.3)$$

$$BER_{MIN} = \underset{i=1}{\overset{n}{MIN}} (BER_i) \qquad (2.4)$$

$$BER_i = BER_{SS} \Rightarrow BER_{MIN} = BER_{SS} \qquad (2.5)$$

$$BER_O = \prod_{i=1}^{n} BER_i \qquad (2.6)$$

$$BER_i = BER_{SS} \Rightarrow BER_O = (BER_{SS})^n \qquad (2.7)$$

$$BER_V = \sum_{i=k}^{n} \binom{n}{i} * (BER_{SS})^i * (1 - BER_{SS})^{n-i} \qquad (2.8)$$

n – number of receiving stations, number of antennas in a antenna array
k – number of receiving stations required for choosing a bit
(the smallest majority)

$$n < 2 * k \qquad (2.9)$$

$$\binom{n}{i} = \frac{n!}{i!(n-i)!} \qquad (2.10)$$

Bit Error Rates presented in the scenarios are given in (2.2) – (2.10). The BERmin algorithm is the solution offered by contemporary systems, such as APRS-IS ([10]-[12]). In the calculations where all ground stations have the same BER, the value of BERmin (2.4) equals that of BERss (2.5).

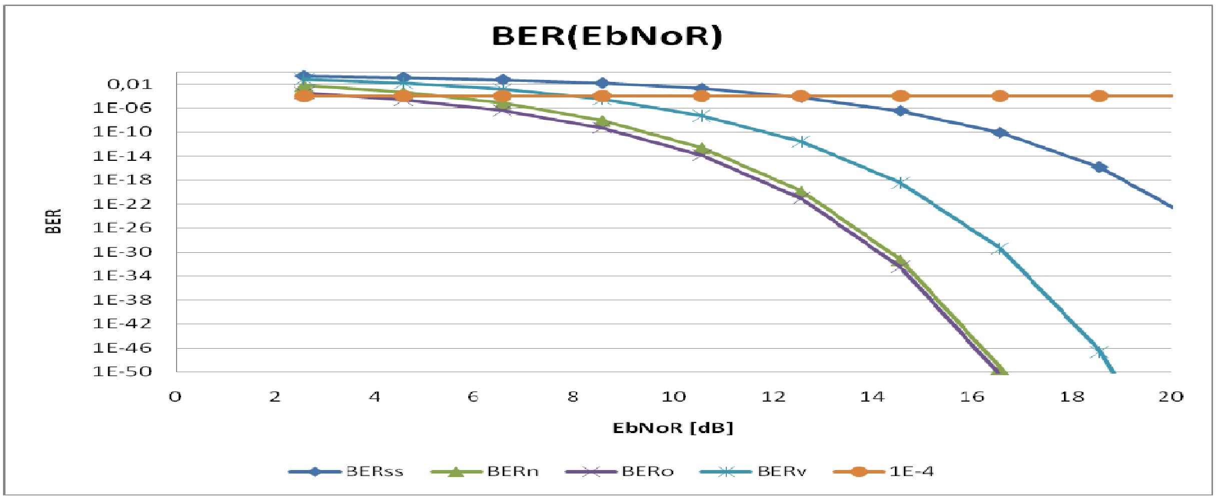

Fig 5. BER depending on EbNoR in a single station link balance.

Fig 5 shows the results of BER calculations, depending on the EbNoR parameter. BERss line presents the result for a single ground station. It is a reference line. BERn shows how much better a channel is when we use a five times bigger antenna system. BERo is the theoretical upper boundary of the system's capabilities. It is the case when we get at least one correctly result, and somehow we know which station has this result. BERv is the line that shows bit error rate when using voting algorithm. This system assumes that most of the stations will receive the data correctly, which would enable to reject the incorrectly received data through majority voting.

3. EMPIRICAL VERIFICATION OF THE CONCEPT

3.1. Real systems verification – balloon missions.

While carrying out his own research connected to satellite technologies, the author had often used stratospheric balloons during the process of devising component prototypes [5]. A stratospheric balloon enables to elevate a component ca. 40km above ground level. During the flight, the devices may experience extreme conditions, such as temperature below -70˚C, 5Pa pressure, increased radiation (e.g. at 40km devices are exposed to proton radiation 10 times stronger than that on the Earth), or microgravitation. Such a mission to some extent resembles a space one, since throughout its course the device is inaccessible and the control is possible only via radio. The author has decided to test DGSS in real conditions by using such a platform. The balloon capsule simulated a satellite, telemetry of which was received by numerous ground stations. ATMEL ATmega128 microcontroller, which was on board, collected data from various sensors and sent telemetry via CW (OOK) 10mW transmitter using Morse code.

3.1.1. The results of using DGSS technology

Data obtained during balloon missions was archived. In BOBAS and BOBAS 2 missions data was received via many ground stations. The amount of data sent was estimated on the basis of the construction of transmission protocol, telemetric frames counter and mission time and subsequently compared with the archived results. In case of multiple receiving, data was compared manually in order to achieve a smaller error rate. The experiments results are given in Tab. 1. Sings of the SQ5FNQ sort denote single ground stations. Comparing Result Error (CRE) was calculated on the basis of the compared data from numerous stations, or (in case of BOBAS 3) a single station value was rewritten. The optimal error (BERo) and voting error (BERv) were calculated according to the optimal algorithm BERo (2.6) and voting algorithm BERv (2.8) respectively.

Tab 1. Quality of receiving data from balloon missions.

Mission name	Ground station name	Percent error (Bi)	BER
BOBAS	SQ5FNQ	10%	0.10
	SQ5GVY	95%	0.95
	SQ5LTT	99%	0.99
	Comparing Result Error (CRE)	9%	0.09
	Optimal error (BERo)	9%	0.09
	Voting error (BERv)	38%	0.38
BOBAS 2	SQ5FNQ	38%	0.38
	SQ5FG	44%	0.44
	SQ5GVY	85%	0.85
	SP4XYD	100%	1.00
	Summary error (RSN)	11%	0.11
	Optimal error (BERo)	14%	0.14
	Voting error (BERv)	28%	0.28
BOBAS 3	SQ5FNQ	90%	0.90
	Summary error (RSN)	90%	0.90
	Optimal error (BERo)	90%	0.90
	Voting error (BERv)	90%	0.90

The results show that after implementing the DGSS mechanism Comparing Result Error (CRE) is smaller than the errors of single stations. In the BOBAS mission, only SQ5FNQ station received good quality data. The remaining stations received mainly erroneous data. Despite such a large number of errors in data streams from poor stations, some data was found that was not received by the SQ5FNQ station. In the following mission, stations had improved link quality, which allowed for an even better isolation of data from uncorrelated interference. This showed that using DGSS betters link quality. In the BOBAS 3 mission, DGSS technologies were not used, and a mobile receiving station received merely 10% of the data from the Cricket 4 (pol. Świerszcz 4) module. The triple redundancy technique was used in the experiment, which resulted in a far lower error rate. It is vital to point out that the comparison results are close to the BERo value (and not to BERv). This is due to two factors. The first one amounts a key role of local signal fading in receivers errors. The second one, in turn, refers to data comparison, which was not a common voting system, but rather an analysis based on the expected content (transmission protocol and the value of previous and following data frames were known). The experiment showed that in real conditions, owing to DGSS technologies, link quality can be improved considerably, almost up to the optimal capabilities. It has to be remembered that the experiment is burdened with a high parameter instability, and the quality and repetitiveness of the results may not be optimal, which is why the research should be carried out in a more controllable environment.

3.2. Laboratory verification – DGSS laboratory model.

In order to accurately verify presented theories, the author built a laboratory measurement set that simulates a Distributed Ground Station System.

3.2.1. Systems description

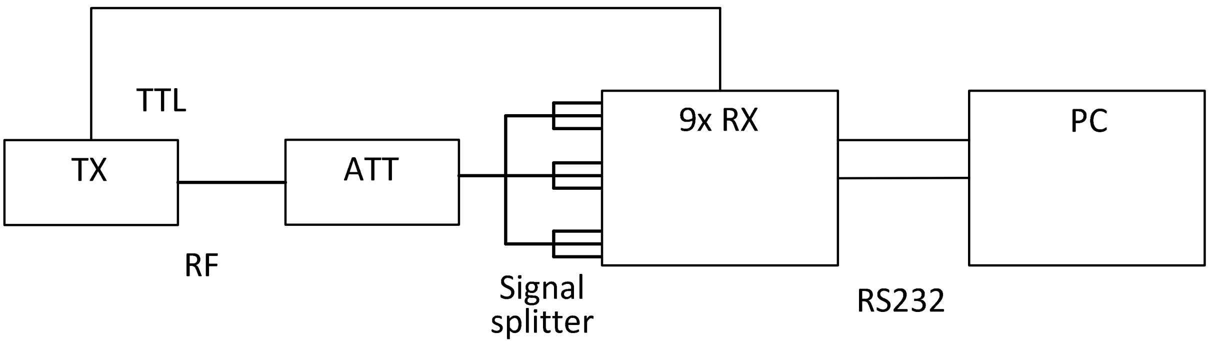

Fig 6. Diagram of the DGSS laboratory model.

Fig 6 shows a block structure of the measurement system. Its first component is a satellite transmitter simulator, where Radio Frequency (RF) signal and TTL of a transmitted sequence are generated. Next, the signal runs through a regulated attenuator (0-102 dB) and a signal splitter (1 to 9). Thusly split signal enters the receiver, which consists of, among others, nine merged receivers. Additionaly, a TTL sequence enters the receiver as well, in order to enable to measure BER. The receiver is connected to a PC through two RS232 ports, which make the receiver interface available (the first one) and send measurement data (the second one).

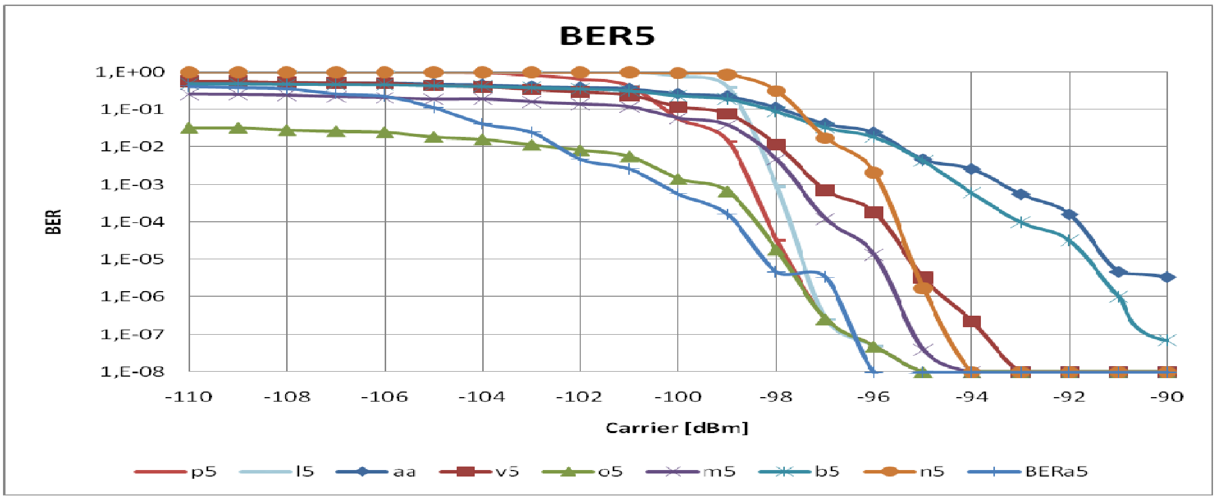

Fig 7. Comparison of the algorithms improving radio link quality when using 5 receivers.

Fig 7 presents experiment results. The graph shows BER depending on the level of signal that reaches each of the receivers.

The “aa” line indicates average BER for a single receiver and constitutes a source of reference for other results.

The „b5” line denotes the results of the “best – BERmin” algorithm. Since single receivers were adjusted for difference minimization, the best algorithm is only slightly better than a single receiver. It would give far better results, if the differentiation level of the receivers was higher and some local interference appeared on single receivers.

The „o5” line presents the result of the optimal algorithm (BERo), and at the same time marks the limitations of the DGSS technologies. It is the second reference line. What is interesting is that even for very weak signals, the algorithm yields promising results. This is due to the fact that even when there is no signal, there is a high probability of an error-free bit being received by one of the receivers, and a very low probability of an erroneous bit being received by all the receivers. This line is also indicates the information content of a received signal. If it is not strictly horizontal, it means that the signal still contains information that can be recovered through mathematical methods with a certain probability rate.

In order to make use of the optimal algorithm, it is necessary to have a good verifying function that would base either on the knowledge of the content sent or on the sending of control sum or on surplus coding. The knowledge of the content sent may lead to a test solution. The “n5” line of a next-to-optimal algorithm presents the efficiency of such a method. Awaiting a certain result, e.g. sending subsequent values of a linear function is also possible. The continuity requirement limits the subset of expected results. It has to be remembered, though, that instead of sending function values, expected differences can also be sent, which would result in data compression. A conclusion that may be drawn here is that sending function values may be treated as a surplus coding, which enables to make use of the optimal algorithm, but on the other hand has certain limitations. The data should either be sent in an interference-free packet or recovered through packet comparison. The “p5” and “l5” lines show the possibilities of packet sending. While sending short packets (32B – p5) results in a better link quality for weak signals, longer packets (256B – l5) require a set signal level for this algorithm to be more effective than a single receiver.

The BERa5 line presents the signal quality of a single receiver, which receives the 5 times stronger signal (sum power received through the antennas by 5 receivers). This is a very effective and commonly used solution. However, it has its limitations as well, such as the narrowing of antenna beam, or inability of calibrating the solution on account of connection and signal sending loss. DGSS technologies are free of such problems, and the calibration is limited only by the computing power of machines and network bandwidth. The research has shown that expanding the antenna system is very effective for very weak signals, but for stronger singles this solution seems to overlap with the optimal solution. According to the presented theory, as the signal level increases, the optimal solution should be better than constructing larger antenna systems.

The next line (v5) represents voting solution, which amounts to packet comparison. This algorithm, as it can be seen, always improves signal quality and as the level of input signal increases, its efficiency improves in relation to a single ground station. A considerable merit of such an algorithm is the simplicity of implementation and linear calculation complexity depending on the number of stations used for voting. One problem with implementation may be the signal correlation. If a signal delay between the receivers and voting system is known, all that needs to be done is to add proper delay value for receiving data streams. This may be achieved by extending the received data with proper time markers that are synchronized with a stable clock, e.g. from the GPS (Global Positioning System). The differences in distance between a transmitter and receivers, e.g. from the mathematical models of a satellite, also need to be taken into consideration. A simplified solution takes place when all receivers have an equal delay, and thanks to that the data streams are temporally correlated in the voting system. This was the case in the laboratory model. The most complicated situation would amount to the correlation of signals with unknown delay. This would require checking all mutual data streams positions, in order to obtain the smallest BER. Unfortunately, such a solution is characterized by an exponential calculation complexity, which means that it is hardly calibrateable.

The last line (m5) presents the results of mixed algorithm, i.e. simultaneous use of an next-to-optimal algorithm and voting. Both algorithms belong to the set of real solutions, and joining them results in an additional improvement of link quality.

3.2.2. Comparison of the results against mathematical modelling

Fig. 8 shows the combination of BER measurements for the optimal algorithm (o3-o9) and the result of mathematical simulation (BERo3-BERo9) of BER based on the number of receivers used (e.g. o3 represents the situation when 3 receivers are used) and their BER (aa).

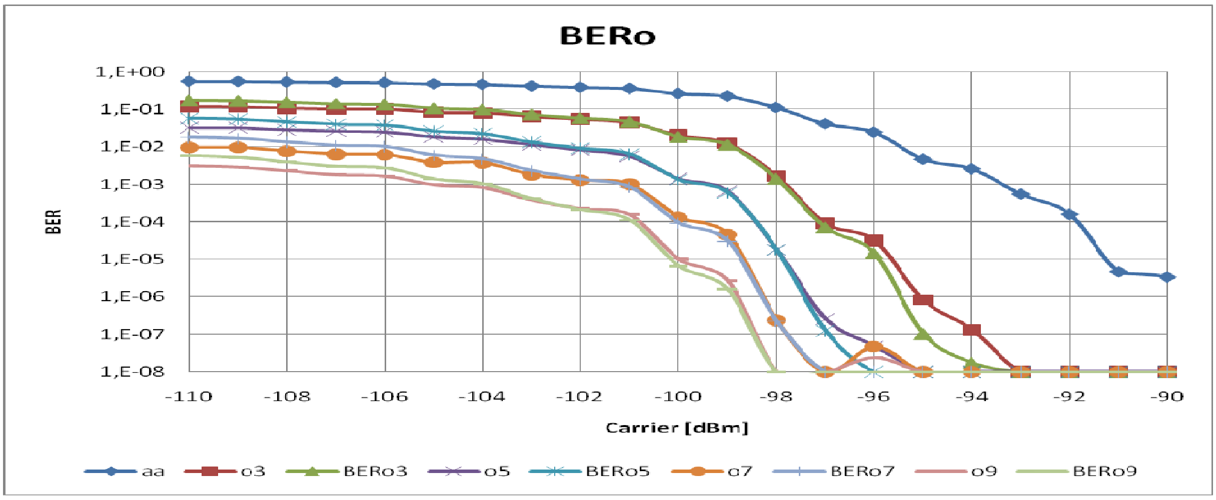

Fig 8. Comparison of the optimal algorithm improving radio link quality depending on the number of receivers.

Fig. 9 shows the combination of BER measurements for voting algorithm (v3-v9) and the result of mathematical simulation (BERv3-BERv9) of BER based on the number of receivers used and their BER (aa).

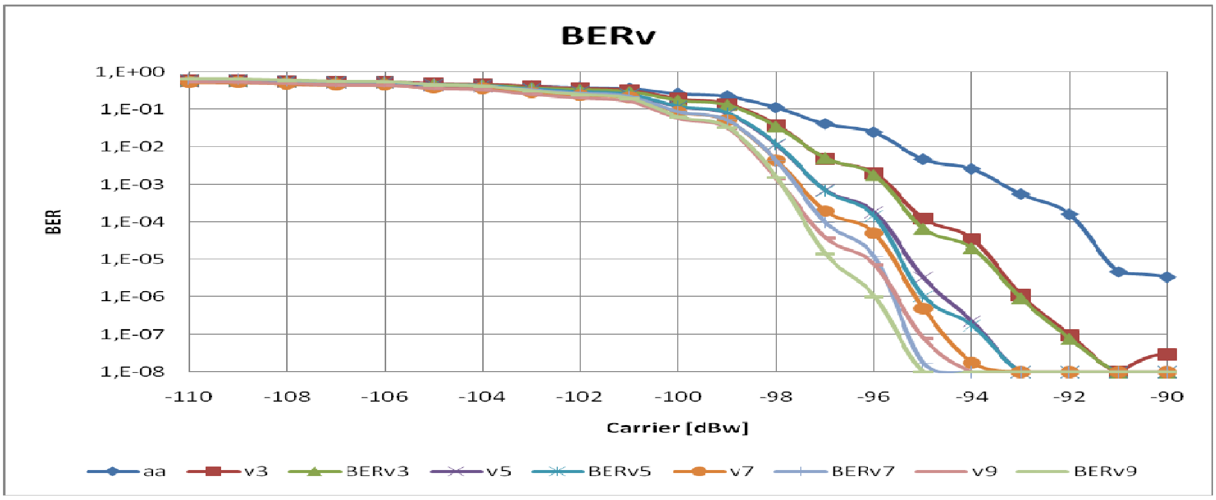

Fig 9. Comparison of a voted algorithm improving radio link quality depending on the number of receivers.

As can be seen, the author's mathematical model overlaps with experimental research in both cases. Changes in the BER domain of single stations as well as in the number of the stations themselves, do not cause variance between the mathematical model and experiment results. The graphs show small variance for low BER values. However, it has to be remembered that the scale of the BER axis is logarithmic, so the variance may seem larger.

In order to analyze the differences between the mathematical model and laboratory model measurements more precisely, the author calculated absolute error [9]. On account of BER being usually given in orders of magnitude, decimal logarithms of BER were compared (3.1), and this comparison has been called Absolute Logarithmic Difference, where Xa and Xb are the compared values. (3.2) and (3.3) present the equations for calculating error for optimal BER and voted BER respectively.

$$BRL = \left| LOG_{10}(Xa) - LOG_{10}(Xb) \right| \quad (3.1)$$

$$BRLo = \left| LOG_{10}(BERo) - LOG_{10}(o) \right| \quad (3.2)$$

$$BRLv = \left| LOG_{10}(BERv) - LOG_{10}(v) \right| \quad (3.3)$$

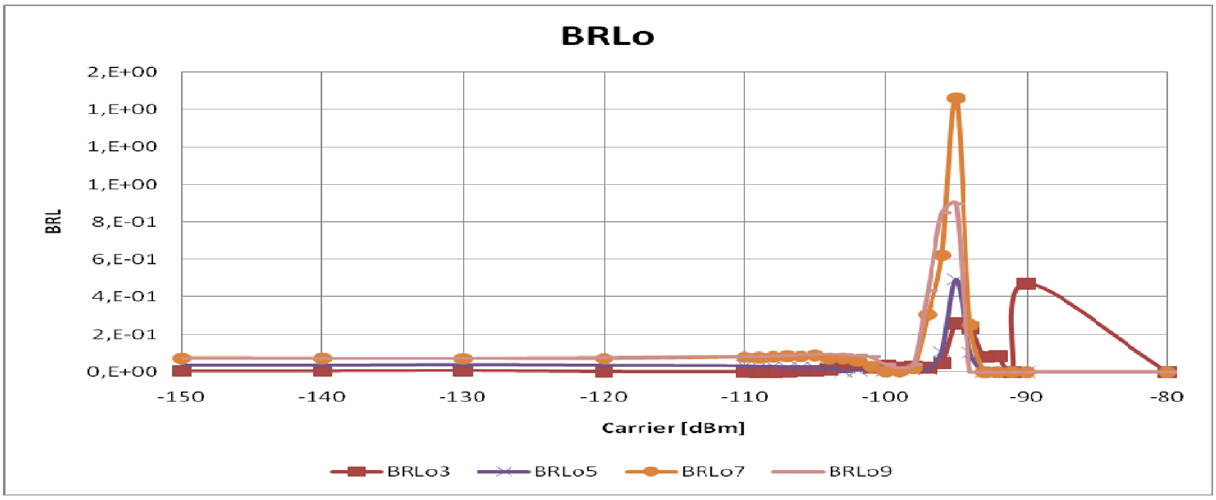

Fig 10. BRLo error.

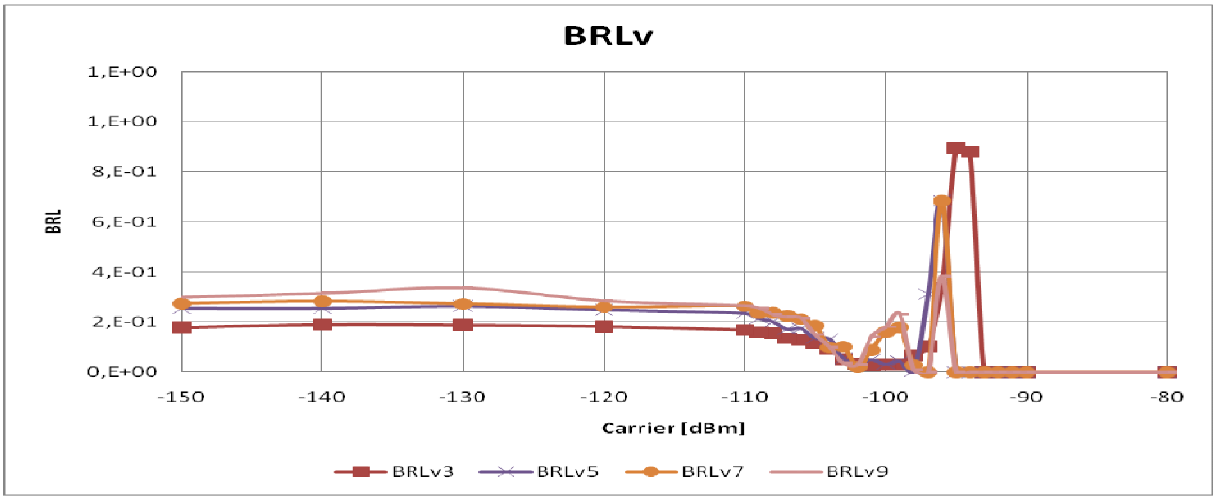

Fig 11. BRLv error.

Fig. 10 and Fig. 11 present a graphic representation of the calculated errors. In most cases the error does not exceed 0,2-0,4 of order of magnitude, which is a very good result. The error is larger only in the section, where the change of functions is the most dynamic (seven orders of magnitude). The reason for this lies in the fact that the error increases as the precision of measurements, which equals one order of magnitude for BER=1E-8, decreases. The largest values registered amount to 1,5 of order of magnitude for BRLo and 0,9 of order of magnitude for BRLv, which is still an excellent result.

4. SUMMARY

The author has presented a novel metod of communications. The experiments have proven the efficiency of DGSS Technologies. The proposed algorithms have been carried out in both laboratory and actual systems. The experiments have confirmed that, when using this technology, there exists a possibility of creating distributed reception and improving link quality. It has also been confirmed that the author's mathematical models enable to run the simulation at a high accuracy rate. The experiments have proven that the author's communication ideas are correct.

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Marcin Stolarski was born in Warsaw, Poland, in 1976. He received the M.Sc. degree in computer science at the Warsaw University of Technology in 2004. He is currently a Ph.D. student at the same university. His research interests and work are related to space technology, focusing on communication systems, distributed networks and fault tolerant systems. He is a member of the Student Space Engineering Scientific Group and works in space projects like SSETI ESEO Satellite, PW-Sat and YES2. He is the author and co-author of many documents concerning space systems.

e-mail: mstolars@gmail.com
Warsaw University of Technology
Faculty of Electronics and Information Technology
Institute of Radioelectronics
Nowowiejska street 15/19, 00-665 Warsaw POLAND