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# Collaborative Network of Ground Stations with a Virtual Platform to Perform Diversity Combining

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***Abstract*—A conventional ground station can establish a single downlink with only one satellite at a time through steerable high-gain antenna. In addition to the lack of tracking more than one satellite at once, such single radio communication is highly vulnerable to outages when experiencing severe degrading circumstances or even with steering engine failures. Accordingly, such problematic single radio link would leave the operator with no alternative options to overcome the consequences. This work exhibits a solution to the ground station through networking. Multiple ground stations, with omnidirectional antennas instead of the steerable directive ones, can be engaged in a collaborative network to receive multiple versions of the same transmitted data for processing and combining. The suggested receive diversity combining is performed at a virtual ground station which utilizes a combining algorithm to help detect the original data from the received versions with less errors and hence reflecting more efficient and reliable services. To exploit this aimed diversity gain, a simple combining algorithm is also developed in this article. The simulation results from the proposed scheme have indicated significant performance enhancement over the single site ground station. This cooperative scheme will not only improve the system performance but also offer to track more than one satellite at a time.**

**Keywords— Bit error rate, collaborative detection, diversity combining, receive diversity, SIMO, virtual receiver.**

## I. INTRODUCTION

Small satellites have recently attracted the attention of research institutes and universities worldwide to establish their own affordable space programs. One subcategory of these small satellites designed for such purposes is the CubeSat [1]. CubeSats are constructed based on multiple of the volume unit U where 1U is a cube of (10 x 10 x 10) cm for outstandingly lower launching cost to the low earth orbit (LEO) [2]. However, this size limitation has also reflected some restrictions such as limited transmitted power of about 1-Watt, limited data rates of few Kbps, low antenna gain of about (2-3) dBi, high speed to orbit the earth several times a day, short communication window, and high Doppler effect. On the other side, the related ground station can only establish a single downlink with a satellite at a time through a high-gain antenna [3]. The receiving directive antenna is pointed towards the satellite through a steering engine mounted on the antenna mast. The established satellite-to-ground single radio link could be very problematic when the signal is deeply attenuated or when the steering engine unexpectedly fails to rotate. Such scenarios will cause an outage with no options to manage the consequences [4]. Besides the system's high vulnerability to outages and inability to track more than a satellite, another drawback of the related ground stations is the operation frequencies in VHF, UHF, and S bands. These bands are amateur radio frequencies with disproportion levels of interference measured in LEO above certain regions than others [5, 6]. Having addressed the main downsides of the conventional ground stations, this article proposes a solution to enhance the reception quality of small satellites' signals through a collaborative network with receive diversity combining. Instead of the single-site ground station with expensive steerable antennas, multiple omnidirectional ground stations can be engaged in a collaborative network where multiple received copies of the transmitted message are processed and combined. The suggested receive-diversity scheme, known in the literature as single input multiple output (SIMO), is demonstrated in Fig. 1, where the original signal propagates through N uncorrelated and independent channels to be finally received by N receivers. These several uncorrelated propagation paths will leave different impacts on the same signal. Therefore, if one or two channels are deeply affecting the signal, there will be other good quality versions to detect the original signal from.

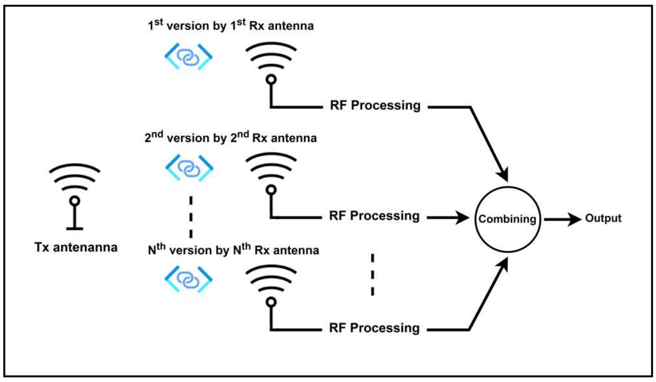

Fig. 1. Receive diversity system.

Related studies, motivated by the receive diversity scheme, are reported in [7] to improve location services in autonomous-driving cars, in [8] to reduce detection errors in analogue feedback communication system (AFCS), and in [9] to acquire more immunity to multiple interferers. Moreover, receiving multiple replicas of modulated images, collected from monitored smart homes or factories, has remarkably increased the 5G system performance in serving such smart cities applications [10]. In the area of energy harvesting, the receive diversity configuration is deployed in [11, 12] to increase the harvested RF energy. To reduce the probability of outages in mobile networks, the study conducted in [13] recommends the receive diversity rather than increasing the transmitted power. Despite the hostile underwater environment, the SIMO structure is effectively utilized in [14] to precisely locate the target in the underwater sonar and in [15] to enhance the performance of the underwater optical communications (UWOP).

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This paper is organized as follows: Section II analyzes the performance of the current single-mode ground station system; Section III presents the suggested solution; The simulation results from Sections II and III are provided and discussed in section IV, while section V concludes the findings.

## II. CURRENT STATE OF THE ART: SINGLE-MODE

Fig. 2 simply demonstrates the downlink communication between the satellite and the ground station. This section intends to analyze the performance of this single radio communication system and for that purpose, the bit error rate (BER) will be considered and evaluated as a quality metric. This work considers the binary frequency shift keying (BFSK), widely used digital modulation scheme in amateur radio links, to generate the transmitted symbols. Moreover, the transmitted signals are degraded using the additive white Gaussian noise (AWGN), a simple but powerful model in satellite communications [16]. Possible configuration of such system can be illustrated in Fig. 3.

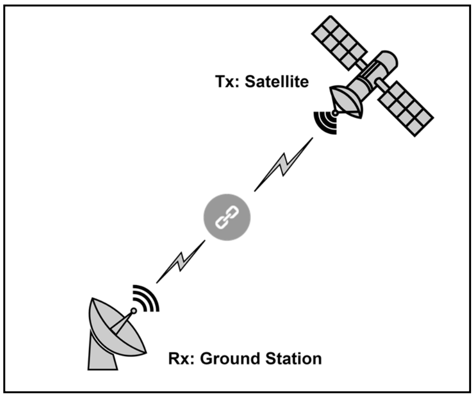


Fig. 2. Single downlink communication system.

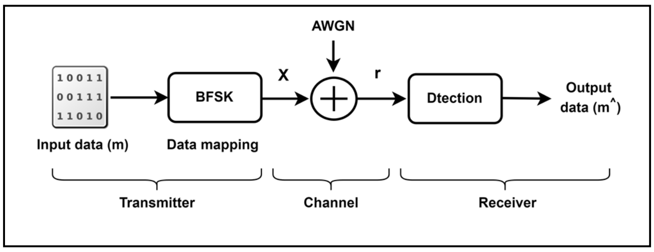


Fig. 3. Single link block diagram.

The detailed simulation steps can be then provided as follows:

1. Input data of 0s and 1s to represent the message (m).
2. BFSK mapping of (m): Input (1) is mapped to (1) while input (0) is mapped to (j). This step will form the transmitted complex signal (X).
3. The channel is represented by adding complex noise to the transmitted signal (X) to get the received complex signal (r) with one of the two states: $\{(1 + n) + (0 + n)j\}$ or $\{(0 + n) + (1 + n)j\}$ , which correspond to inputs 1 and 0, respectively.
4. Therefore, the detection hypothesis is set to compare the real to the imaginary parts of (r) and accordingly decide the message signal to be (1) if $\{\text{real}\ (r) > \text{imag.}\ (r)\}$, and (0) if the other way around.
5. After completing the detection, the BER can be evaluated to indicate the system performance.
6. The performance is also tested against different signaling rates and varying levels of energy per transmitted bits ($E_b/N_0$).
7. The theoretical BER curves using Q and Error functions from equations (1) and (2) will be compared to the simulation BER [8].

$$BER = \frac{1}{2}\, erfc\, \left(\sqrt{\frac{E_b}{2N_o}}\right) \tag{1}$$

$$BER = Q\, \left(\sqrt{\frac{E_b}{N_o}}\right) \tag{2}$$

## III. PROPOSED METHOD: COLLABORATIVE NETWORK

This paper proposes a solution to the conventional ground station through networking. Assembling a network of omnidirectional ground stations creates a receive diversity scheme, also known in literature by single input multiple output (SIMO) configuration, as shown in Fig. 4. Therefore, multiple versions of the same transmitted data will be received by multiple ground stations with different impairment levels and can be shared within the network for more reliable collaborative detection.

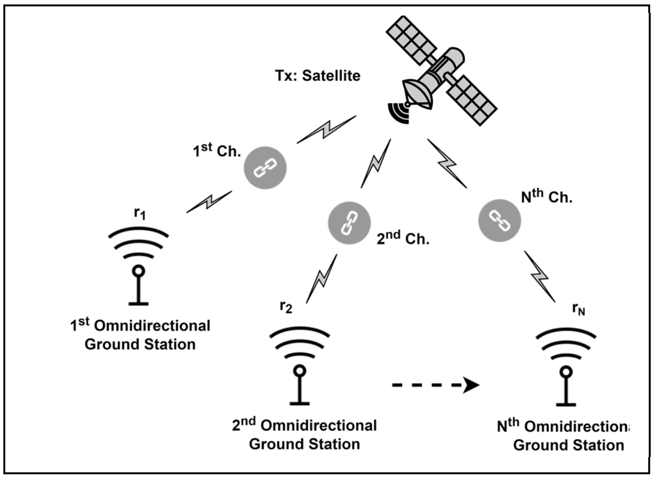


Fig. 4. Proposed Collaborative reception scheme.

To emphasize the system's resistance against outages from a statistical concept, we assume that N earth stations are individually operating in a single mode. Then, their attenuations are: ($A_1(t)$, $A_2(t)$, … , and $A_N(t)$), where $A_{n_{th}}$ (t) is the attenuation recorded at the $n^{th}$ station. However, when these N earth stations are cooperatively working in a diversity mode, the collaborative receiving system would then have a joint attenuation of:

$$A_S(t) = \min\, [A_1(t), A_2(t), \dots , \text{and } A_N(t)],$$

where $A_S(t)$ is the system attenuation when N ground stations are involved. This statistical proof expresses the motivation behind diversity. As a result, the diversity gain of the proposed scheme can compensate the lesser gain of the receiving omnidirectional antennas compared to the current directive antennas. Meanwhile, to get that diversity payoff, a simple diversity combining algorithm is also developed in this work and suggested to take place at a virtual ground station. Thus, before moving to the details of the proposed combining method, the suggested virtual combining platform should be demonstrated.

### *A. The combining platform: Virtual ground station*

The virtual ground station is a computer-based radio receiver where all cooperative ground stations are going to send their detected streams for processing. Thus, no more modifications at each involved station are necessary but to be connected to the network for sharing data. As soon as these multiple copies of the transmitted signal reach the virtual ground station, it starts synchronizing them and forms the combining-ready matrix. Then, the virtual station applies the diversity combining algorithm to take advantage of each version achieving more efficient and reliable detection of the original data. Therefore, the ground stations should have omnidirectional antennas, LNAs, SDRs with soft / hard demodulation tools, and a PC for streaming out. The virtual ground station should then have a processor to perform the combining of multiple candidates. An illustration of the cooperative network with its virtual platform is provided in Fig. 5.

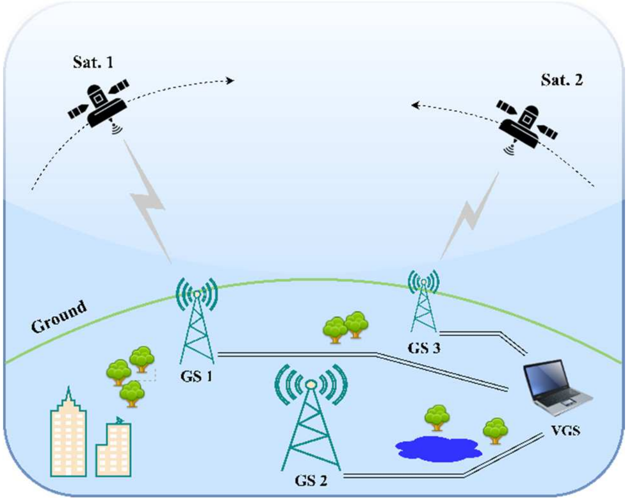


Fig. 5. Diversity system with virtual combining platform.

Based on this concept, the proposed virtual ground station isn't only promising to improve the system performance, but also making it capable of tracking more than a satellite at once. This is achieved through more frequent passes over the cooperative network of ground stations than an individual station. Having the necessary combining platform overviewed, the next step is to develop the combining algorithm.

### *B. The combining algorithm*

Brief investigation of the already existing combining methods is as follows: The simplest combining technique is the selection combining (SC) which evaluates the signal to noise ratio (SNR) of each received version and then selects the signal with the highest SNR value [17]. However, this selection ignores the non-selected versions' valuable information that can be used for more efficient detection. The second combining method is the equal gain combining (EGC). As the name implies, this technique involves equal-gain weighting of all received signals and then adds them up for detection [18]. The most efficient combining algorithm is the maximal ratio combining (MRC) where all versions are evaluated for their SNRs and accordingly weighted [19]. Therefore, MRC applies adaptable weighting process based on the SNR value. The signal version with the highest SNR is weighted with the highest gain. In summary, the SC requires SNR evaluation of all received versions but selects the highest SNR signal. EGC does not involve SNR evaluations, however, it weights all versions with the same gain regardless their quality metrics. MRC is the most efficient combining method, nevertheless, it is the most complex as it requires SNRs evaluation and adaptable weighting of all versions.

In this work, a simple yet efficient receive diversity combining algorithm is proposed to be deployed in satellite communications. The algorithm combines multiple copies of the same broadcasted signal received by different ground stations. The presented algorithm aims to take advantage of every received version to reflect reliable and rich combined stream. To realize the concept of the proposed algorithm, the following detailed MATLAB simulation is provided.

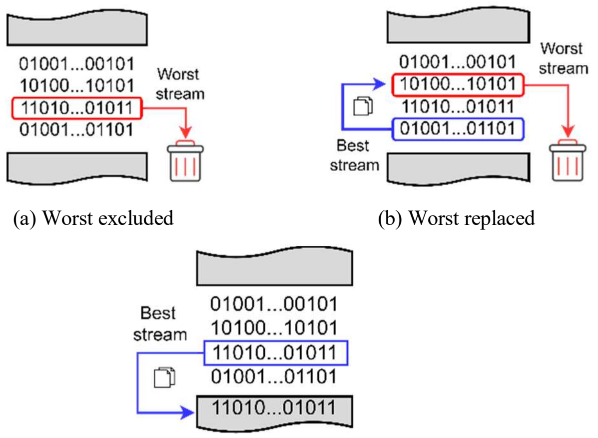
1. Unipolar data generation.
2. BFSK mapping of the input data.
3. Generating N uncorrelated streams of AWGN.
4. Adding up the BFSK symbols from step (2) to the N uncorrelated AWGN streams from step (3) to finally form the N uncollated versions of the received signal.
5. Detection of each version in step (4).
6. The detector passes over the N detected streams to the virtual station to form the combining-ready matrix where the n$^{th}$ row corresponds to the n$^{th}$ version of the detected streams in step (4).
7. The virtual ground station applies the combining algorithm on each column in that matrix. The maximum likelihood of each bit will then impose the most frequent bit and hence considered the right bit.
8. The algorithm assigns all other entries to have the decided bit in step (7) and finally evaluates BER.
9. The algorithm accomplishes the step (7) and (8) in an ascending tempo. The first combining trial will include only the first row to represent a single site conventional system. The second trial is for two rows and that represents two-site combining and so on until the algorithm reaches all N streams combining trial. This will help visualize the improvement as we gradually increase the collaborative sites.

In this simulation, 14 sites are involved with SNRs of (0-13) dB in a million-bit length of the input data. The likelihood-based algorithm is promising to provide reliable detection since it relies on how frequent each bit is in all entries. Nevertheless, this hypothesis will bring some possible errors only when the number of the entries is even with equal entries of 0s and 1s. Consequently, further techniques are suggested to compensate these possible few errors:

1. Worst stream is excluded.
2. Worst stream is replaced by the best one.
3. Best stream is always tailed.

where the best/worst streams are identified by evaluating the quality metrics such as BER or SNR.

These three techniques will impose more detection weight to the lowest BER stream since they exclude the highest BER stream, replace it with the lowest BER one, or always tail the lowest BER stream to the combining matrix. Illustrations of these three techniques are provided in Fig. 6.



(a) Worst excluded (b) Worst replaced

(c) Best tailed

Fig. 6. Illustrations of improvement techniques.

## IV. RESULTS AND DISCUSSIONS

The theoretical and simulation BER curves from the conventional single ground station system are quite identical as in Fig. 7. The single site system performance, at Eb/No of 10 dB, is tested versus different data rates as in Fig. 8.

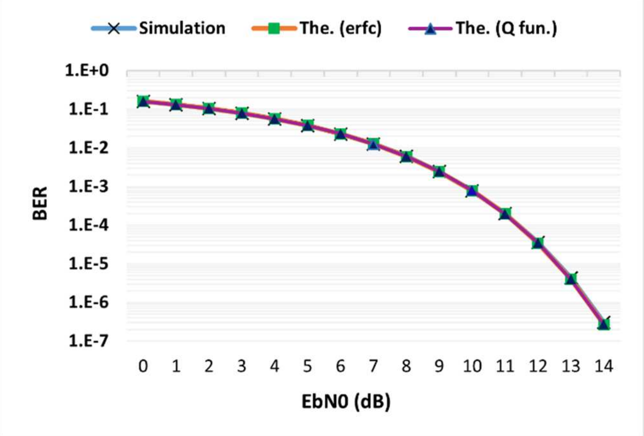


Fig. 7. BER versus $E_b/N_0$.

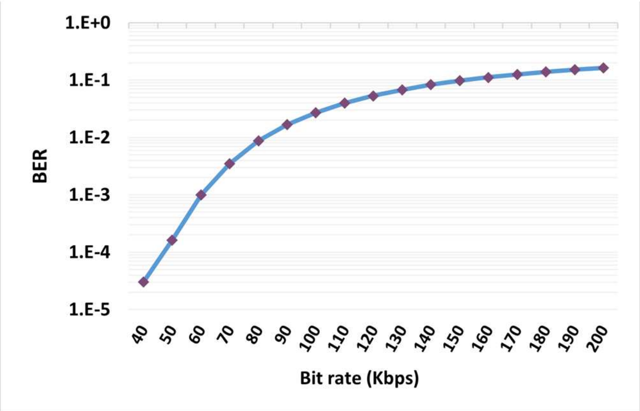
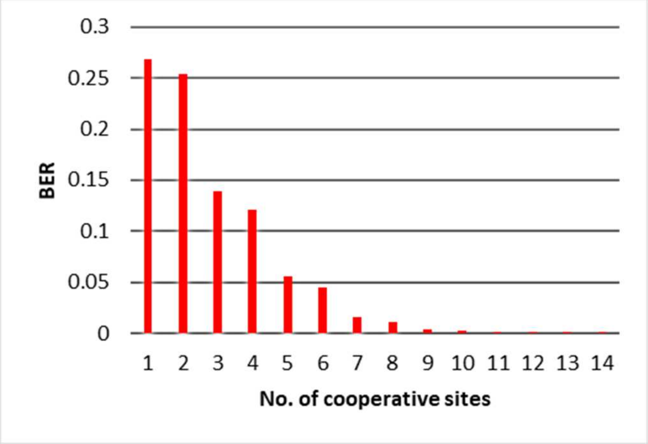


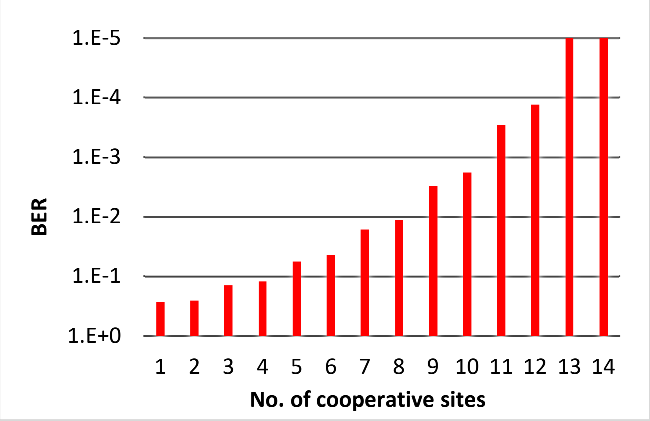
Fig. 8. BER versus bit rate.

From these two figures, it is clear to see that the solo-site system functions well only with low bit rates and/or with high transmission power. However, that is totally impractical and in contradiction to the trends of the future technologies. New generations of wireless communications involve high data rate signaling and yet serving hostile environments. That is simply why such conventional single radio link systems are not sufficient to satisfy new technologies' aspirations.

On the other hand, the BER results of the proposed combining algorithm at each trial are shown in Fig. 9 in both scales, linear and logarithmic. Obviously, the BER gets decreased as more receiving sites are involved with significant BER reduction when moving from an even number of sites to an odd number. However, slight BER improvement occurs when moving from an odd number of sites to an even one. This is attributed to the possible hypothesis errors as explained earlier in section III (B).



(a) Linear scale



(b) Logarithmic scale

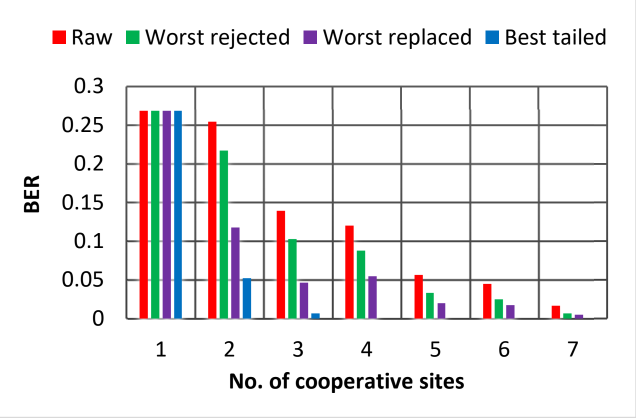
Fig. 9. BER results from the proposed system.

Table-1 lists the BER results of the suggested improvement techniques as well as the raw combining algorithm so they can be conveniently compared.

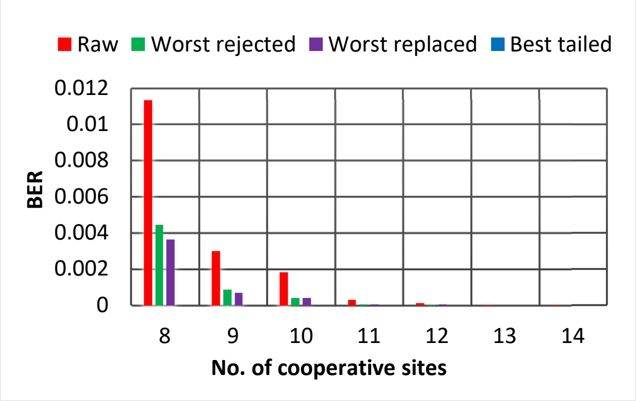
TABLE I. BERs RAW AND IMPROVEMENT TECHNIQUES

| **No. of sites** | **Combining techniques** | | | |
|---|---|---|---|---|
| | ***Raw*** | ***Worst excluded*** | ***Worst replaced*** | ***Best tailed*** |
| 1 | 0.26859 | 0.26859 | 0.26859 | 0.26859 |
| 2 | 0.25391 | 0.21689 | 0.11769 | 0.05225 |
| 3 | 0.13869 | 0.10280 | 0.0471 | 0.00642 |
| 4 | 0.12021 | 0.08722 | 0.05481 | 0.00044 |
| 5 | 0.05602 | 0.03376 | 0.01923 | 2e-5 |
| 6 | 0.04436 | 0.02512 | 0.01754 | 0 |
| 7 | 0.01677 | 0.00687 | 0.00509 | 0 |
| 8 | 0.01129 | 0.00421 | 0.00346 | 0 |
| 9 | 0.00322 | 0.00081 | 0.00071 | 0 |
| 10 | 0.00187 | 0.00045 | 0.0004 | 0 |
| 11 | 0.00030 | 5e-5 | 6e-5 | 0 |
| 12 | 0.00012 | 2e-5 | 4e-5 | 0 |
| 13 | 3e-5 | 0 | 0 | 0 |
| 14 | 1e-5 | 0 | 0 | 0 |

In comparison to the BER values from the raw combining algorithm, slight BER reduction can be seen if the worst stream is excluded out of the combining matrix. When that most corrupted stream is replaced with the best one, the performance is improved even more. The best BER results are achieved when the best stream is repeatedly tailed to the combining matrix reaching zero detected errors with six sites combining trial. The collected BER results from the raw combining algorithm and the suggested three improvement techniques are plotted in linear and logarithmic scales in Fig. 10 and Fig. 11, respectively. Usually, BER values are presented in logarithmic scale. However, BER findings in this study are also visualized in linear scale due to the possible plotting errors with infinite logarithmic values when the BER reaches zero. Fig. 11-a indicates how fast the third improvement technique in achieving low BER results overcoming the other improvement techniques. The same figure, though, oppresses the achievements of this improvement technique after the 5-site combining trials when the BER is zero and hence reflecting infinite logarithmic quantities. This explains the reason of including linear-scale figures as they are more informative here.

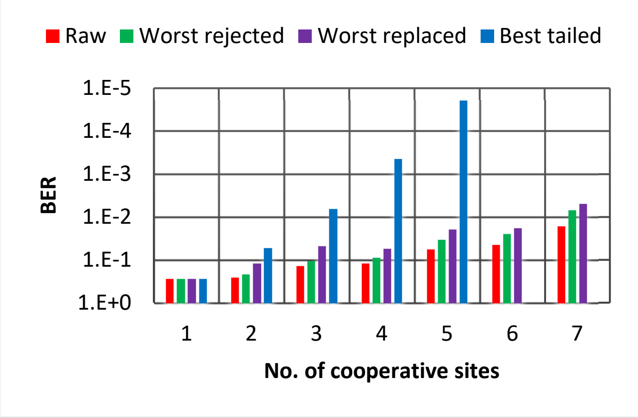


(a) 1-7 sites combining trials.

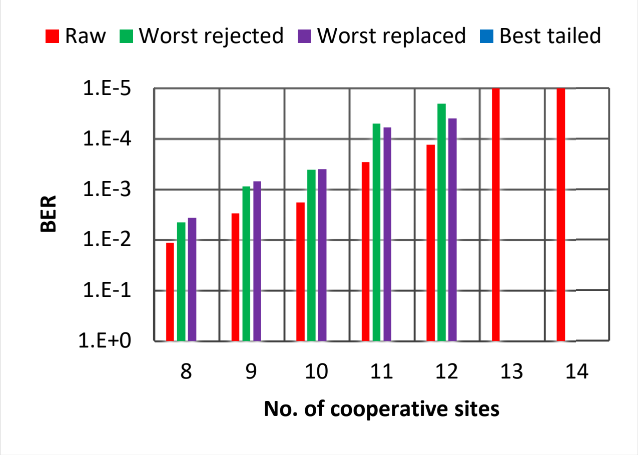


(b) 8-14 sites combining trials.

Fig. 10. BERs from the raw and improved combinings in linear scale.



(a) 1-7 sites combining trials.



(b) 8-14 sites combining trials.

Fig. 11. BERs from the raw and improved combinings in logarithmic scale.

## V. CONCLUSIONS

In conclusion, the conventional single site ground station is not in favor of the future wireless communications, highly vulnerable to outages, and can communicate with only one satellite at a time through expensive steerable high-gain antennas. Instead, this works proposed a terrestrial solution to improve the reception quality of satellites signals. Multiple ground stations can utilize omnidirectional antennas to receive different versions of the transmitted signal. Combining these multiple uncorrelated copies of a satellite downlink signal, helps reduce detection errors and compensate errors caused by the lesser-gain omnidirectional antennas. To achieve the aimed diversity gain, this study suggests a simple but efficient combining technique. The presented combining algorithm has achieved a remarkable BER reduction once applied on the suggested SIMO configuration. It requires no information about the SNR values of the received streams neither does it involve any weighting process.

For further improvement, three techniques are suggested: Excluding the worst stream out of the ones in the combining matrix, replacing it with the best one, and repeatedly tailing that best candidate to the combining matrix. Indeed, the best BER results achieved when always tailing the best candidate into the combining matrix which has significantly improved the system performance achieving zero detected errors at the six sites combining trial. Nevertheless, these techniques require the SNR information of the received streams, but no weighting process is involved.

The proposed collaborative network of omnidirectional ground stations along with its administrational virtual station doesn't only improve the BER and reduce outages, but also offer to track more than a satellite at once, extend the communication window, replace the expensive high-gain antenna with affordable omnidirectional ones and hence exclude the need for antenna steering engines, and finally provide complex and different services in the network's area.

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