NETWORK CODED COOPERATION FOR DEEP SPACE NETWORKS

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Abstract: *In this paper, we investigate the disruptive effects of solar scintillation in Deep Space Networks (DSNs) and we apply Network Coded Cooperation (NCC) in DSNs to improve the throughput, the robustness and the security of the communication systems. Simulations illustrate the comparisons between direct links and NCC links for both Rayleigh and Rician fading channel models. The effects of solar scintillation are modelled based on previous studies and the outage probabilities of these links are given. In addition to the computer simulations, the proposed system model is implemented with Software Defined Radio (SDR) nodes and the error performances are illustrated with Bit Error Rates (BER) and Signal-to-Noise Ratios (SNR) metrics. Based on simulation and test results, it can be seen that NCC systems can decrease the outage probability, improve the error performance, and also decrease the transmission time between transmitters and receivers.*

Keywords: *Network Coded Cooperation, Deep Space Networks, Solar Scintillation, Rayleigh Fading Channels, Rician Fading Channels, Outage Probability.*

1. Introduction

Over the past decade, there has been a great struggle to reduce the impact of fading channels over wireless communication systems. For a reliable data transmission between transmitters and receivers, one effective tool which helps to prevent data loss, to reduce the data transmission time and to increase spectral efficiency in wireless transmission systems with the use of relay (intermediate) nodes, is network coding (NC).

NC can decrease the difficulties of intermediate node operations by combining and compressing all data from sources in order to improve the throughput, the robustness and the security as well as to decrease the energy and bandwidth consumption of the communication system [1]. Intermediate nodes such as routers or relay stations can combine data flows from source nodes in different ways such as XOR operation and then relays transmit this combined data to destinations. For the decoding process, the encoding matrix must be available in the destination.

In contrast to traditional routing as an intermediate node where routers send the same number of data packets that they receive, NC can reduce the number of data packets delivered to destinations by the help of relay operations that results in throughput advantage over classical routing solutions [2]. Furthermore, NC can decrease packet losses and increase robustness in communication channels. NC also can reduce transmission delays [2].

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Although NC has several advantages and application areas in communication systems, it could be insufficient for usage in wireless (unguided) transmission environments. For these environments Network Coded Cooperation (NCC) can provide a better performance [3]. In environments where multipath fading affects transmission links, yet improvements on throughput and robustness of that wireless network are needed [4], cooperative communication systems that provide spatial diversity can be used. Cooperative communication systems can minimize fading effects and thus decrease error rates between sources and destinations in the system [5]. When sources send their data both individually and jointly to destination nodes, the reliability and efficiency of the system can be improved [6]. Due to all of the benefits of cooperation strategies, by interpreting a cooperative communication aspect to NC, NCC systems provide a reliable and robust performance in wireless environments. Here we focus on the performance of NCC systems.

NCC system is more efficient than other transmission systems significantly such as decode-and-forward (DF) systems in terms of transmission duration. In DF systems, intermediate node does not apply any connective operation between received source signals to reduce number of packets received. Thus, intermediate node transmits the same number of packets which takes more time with the increment of source node number. For our system model, transmission duration of the direct link that covers three symbol period would be the same for both systems. However, transmission between relay and destination nodes would last three symbol duration time for DF system which is quite higher than the corresponding one symbol duration time for NCC system. This difference occurs because of ability of combining user data at relay by NC and sending combined data at one symbol duration efficiently. Thus NCC system is efficient and this provides a significant advantage for Deep Space Networks (DSNs).

Differently from our previous paper [7], we consider a communication system in deep space environment with high delays and high disruptions. The system model is tested with Software Defined Radio nodes (SDRs) by using LabVIEW, the same model is also simulated in MATLAB. We consider a wireless communication scenario in DSNs. DSNs are special networks which were built by National Aeronautics and Space Administration (NASA) in order to avoid creating different space networks between each spacecraft and Earth station with different missions [8]. For disruptive effects on DSNs, solar scintillation is a major problem which should be considered in a DSN scenario. While signals are exposed to severe channel impairments characterized by solar scintillation, communication links cannot even be available for transmission processes and all data from sources may be lost. Although deep space channels were firstly determined as Additive White Gaussian Noise (AWGN) channels [9] due to the uncertainty of fading channel model in there, this thought was deficient. The propagation conditions in deep space channels such as absorption, reflection, free space loss, solar scintillation, medium change and all other effects may cause fading. AWGN channel cannot model these effects. Therefore, two possible channel models are discussed as Rayleigh fading channels and Rician fading channels in this paper, based on the earlier works given in [12,13,14].

The rest of the paper is organized as follows. Section 2 provides background information about DSNs and related literature about DSNs and NC. The system model of this paper is widely explained and presented in Section 3. The simulation results are given in Section 4 with comparisons with theoretical expressions. Test set-up details and test results are given in Section 5 and Section 6, respectively. Section 7 concludes the paper.

2. Deep Space Networks

DSNs target a reliable bidirectional communication system between spacecrafts and Earth stations as well as better control on spacecrafts, investigations on asteroids, planets and moon [8]. This bidirectional communication system is obtained by placing large antennas on Earth to collect data or track spacecrafts that are quite distant from Earth. However, there are some restrictive factors in such communication systems, such as path losses between ground stations and spacecrafts, noise of the environment, channel fading effects and solar scintillations. As indicated in [10], microwave signals propagate similarly in interplanetary space and free space, which implies that path losses between Earth stations, spacecrafts and distant planets can be calculated with free space loss formulation.

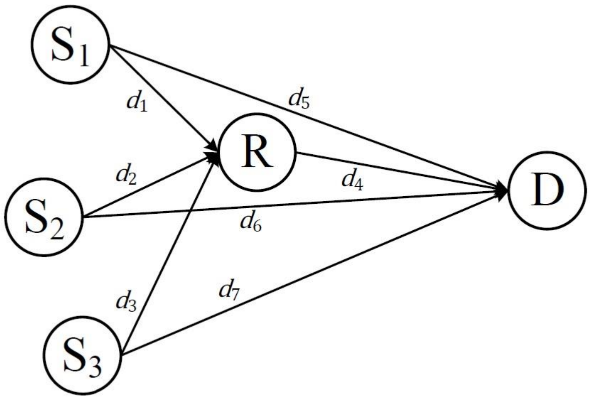


Figure 1. The system model of DSN scenario

Telemetry is another important property of DSNs as well as spacecraft tracking. It is a special transmission system located inside spacecrafts, allowing them to transmit their scientific data or images to ground stations by using radio waves [11]. Since communication link distances are long and the amount of attenuation is high, there can be some difficulties in the decoding process in ground stations. However, these difficulties can be solved by error detection and correction algorithms in accordance with the target Signal-to-Noise Ratio (SNR) levels. In presence of a high SNR, it would be possible to reduce bit error rates (BER) after decoding process in ground stations whereas there would be high BER after decoding process when the SNR level is low. As result, it is important to design these space communication systems with consideration of restrictive factors to achieve a high SNR.

Since DSNs provide a wireless communication path between Earth and distant stations such as Mars with spacecrafts and the design of space communication systems should have a high SNR, and robustness against disruptive effects, it is possible to state that spacecrafts are intermediate nodes to transfer data flows from source node to destination node similar to relay node in NC applications. Hence we propose that, NCC can be applied to DSNs to minimize disruptive effects of the harsh environment on data transfer.

Since spacecraft behaves like relay node and communication system is affected by solar scintillation according to the considered model, we apply the model studied in [12] where perpendicular distance from spacecraft to Sun "R" is $4R_0$ (R_0: radius of the Sun). Due to the drop of solar scintillation effects at high frequencies [13] and the relationship between frequency and the distances between Sun, Earth and spacecraft, carrier frequency is determined at X-band whose scintillation index can be as follows:

$$U_x = 4.97 \times \left(\frac{R}{R_0}\right)^{-3.05} + 252 \times \left(\frac{R}{R_0}\right)^{-6}$$
$$for\ 4R_0 \leq R \leq 20R_0$$

where R defines the perpendicular distance from spacecraft to the Sun and R_0 defines the radius of the Sun. U_x is the first Born approximation to the ratio of the variance of the fading intensity to the square of the mean intensity [14]. After defining U_x, scintillation index m can be calculated by;

$$m = \begin{cases} \sqrt{U_x}, & 0 \leq U_x \leq 1 \\ 1, & U_x > 1 \end{cases}$$

[16], states the calculation of Rician K-factor from scintillation index as:

$$K = \frac{\sqrt{(1-m^2)}}{1-\sqrt{(1-m^2)}}$$

In this paper, solar scintillation effects are investigated in DSNs with the assumption of DSNs are Rician fading channels and these scintillation effects are compared to Rayleigh fading channels.

3. System Model

Our proposed system model is given in Figure 1 with three source nodes as ground stations, one relay node as spacecraft and one destination node as a planet station. Source nodes are represented with S_1, S_2, S_3 whereas relay node and destination node are represented with R and D, respectively. There are totally 7 links between nodes with different Rician fading channel and AWGN coefficients which three of them are direct links from S_1, S_2, S_3 to D and four of them contribute for NC operation as S_1-R, S_2-R, S_3-R and R-D. S_1-D, S_2-D and S_3-D are the direct links that will be used in NCC.

DSNs have high delays because of long distances between transmitter-receiver nodes in space, thus the delays according to their location are also shown on the Figure 1. It is assumed that delays have relationships as

$$d_k \leq d_{k+1} \quad for\ k = 1, \ldots, 6$$

where direct links have the highest delay because of long distances between ground stations and the planet station.

The transmission process of the proposed system model has been completed in two orthogonal transmission phase. In the first phase, source nodes transmit $S_i[n]$ signals to relay and destination nodes. The received signals at relay node with S-R links and at destination node with S-D direct links can be modeled as:

$$Y_{S_iR}[n] = H_{S_iR}[n]S_i[n] + W_{S_iR}[n], i = 1,2,3$$
$$Y_{S_iD}[n] = H_{S_iD}[n]S_i[n] + W_{S_iD}[n], n = 1,..,N$$

where $Y_{S_iX}[n]$, $H_{S_iX}[n]$, and $W_{S_iX}[n]$ represent received signal, Rician fading channel coefficient, and Gaussian noise components between S_i-X where $X \in$ {R,D}, respectively. Here we consider a multi-carrier system such as Orthogonal Frequency Division Multiplexing (OFDM). Subcarrier index is denoted by n and N is the total number of subcarriers. Relay node operates NC to received source signals to send the encoded symbols, $S_R[n]$ to destination node in the second transmission phase. Thus received signal at destination from relay node can be represented as:

$$Y_{RD}[n] = H_{RD}[n]S_R[n] + W_{RD}[n]$$

where $Y_{RD}[n]$, $H_{RD}[n]$, and $W_{RD}[n]$ represent received signal at destination, Rician fading channel coefficient, and Gaussian noise components between R-D link, respectively. In addition to these received signals, the global encoding matrix of the system is given as:

$$\mathbf{E} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

First three rows indicate direct source and destination links S_1-D, S_2-D and S_3-D whereas the last row indicates NC in relay node.

4. Simulations

Simulation results are given in Figure 2. After generating bit sequences (0s and 1s) to be transmitted from source nodes, Binary Phase Shift Keying (BPSK) modulation is applied. At each time slot, one of the source nodes transmits its symbols via its source-relay link and its source-destination link simultaneously. Modulated symbols are exposed to fading and Gaussian noise. After relay node receives all symbols from source nodes, Maximum Likelihood Estimation (MLE) [15] is applied to correctly estimate the transmitted symbol. Then, relay node, where NC is applied, combines these estimated symbols with XOR operation and transmits to the destination node. At the destination node, a decoding process is applied to obtain the source symbols. For this purpose, rank-based detection rule is applied at the destination node.

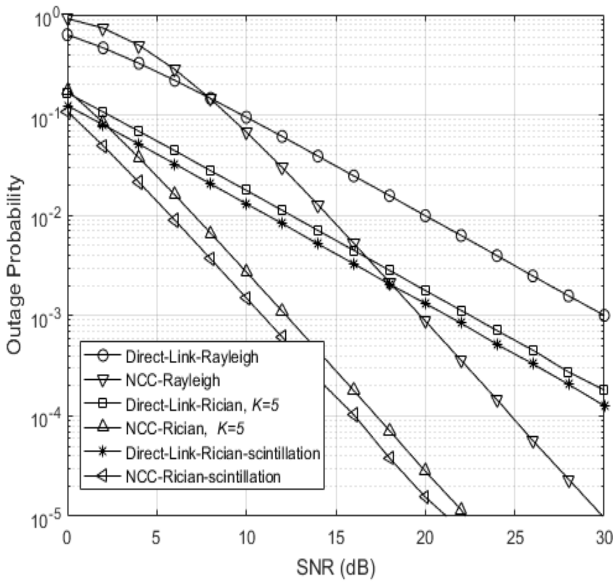


Figure 2. Outage Probability to SNR graphs in direct links and NCC links

It is known that Rayleigh fading channels are a form of Rician fading channel with $K = 0$ [12] and the communication performance through Rician fading channels improves as the value of K increases. We consider Rician fading channel with K-factor 5 as a suitable scenario for DSNs where there is no solar scintillation. After the calculations for U-parameter of X-band solar scintillation index, third channel model is obtained as Rician fading channel with $K \approx 13$ where scintillation index m = 0,366. Consequently, outage probabilities of direct links and NCC system are graphically illustrated as Rayleigh fading channel, Rician fading channel (K = 5) and Rician fading channel with solar scintillation ($K \approx 13$).

From Figure 2, it can be seen that direct link has the highest outage probability according to NCC link in DSNs. As mentioned earlier, Rayleigh fading channel assumption is not a realistic model for DSNs, which struggle with outage more than Rician fading channel. Thus, Rayleigh curves in both direct and NCC links have worst characteristics in the simulation. For the effects of solar scintillation, NCC-Rician link has the lowest outage probability with $P_{out} \approx 10^{-5}$ at 21 dB SNR where the outage probability of direct link without applying NCC has $P_{out} \approx 10^{-3}$ at the same SNR level. This means that NCC improves the performance of DSNs.

5. Test Setup

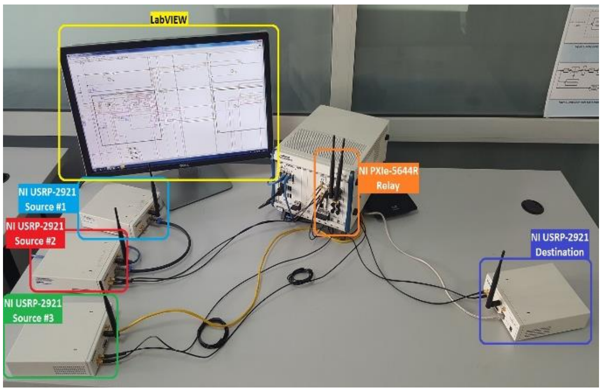


Figure 3. Testbed for the proposed NCC system model with SDR nodes

We also consider a basic SDR based testbed. Our testbed given in Figure 3 consists of three source, one relay and one destination nodes as the same scheme with Figure 1. USRP devices are used at source and destination nodes as transmitter and receiver pairs. For relay node, PXI device is used for NC operations as in the case of our previous study [7]. OFDM is used and this test is implemented in LabVIEW program which is working compatible with hardware components as USRPs and PXI.

5.1. Hardware and Software Components

NI USRP 2921 device is used for three source and one destination nodes while NI PXIe-5644R Vector Signal Transceiver in the NI PXIe-1082 is used for relay node. USRPs can work in between 2.4-2.5 GHz and 4.9-5.9 GHz frequency bands and PXI can work in between 65 MHz to 6 GHz. The system parameters are given in Table 1.

Accurate time synchronization is a necessity for DSN scenario to decrease energy consumption as much as possible. It can be used for sleep scheduling mechanism that wakes up the nodes in a coordinate manner. So that energy consumption is reduced. In order to regulate the time synchronization, nodes use guard intervals which add extra time intervals. When these intervals become larger, energy consumption increases. Therefore, precise time synchronization is important [17]. Synchronization is also the leading problem for the OFDM systems which render synchronization crucial to maintain OFDM functionality. In order to obtain reliable real-time performance, synchronization problem should be resolved. For this purpose, in the hardware part, NI PXI-6683 module that ensures 10 MHz synchronization clock source from GPS module, is used. In addition, software configurations are altered for synchronization sources and relay node by configuring LabVIEW code. Thus, system synchronization is provided successfully.

Table 1. Measurement Set-up Parameters.

Carrier frequency	2.45 GHz
I/Q data rate	1 MS/sec
Number of bits used in one frame	640 bits
Number of data subcarriers	320 samples
Number of reference subcarriers	40 samples
Number of source/relay/destination nodes	3/1/1
Zero padding/DFT/CP length (N)	120/480/120 samples
Distance between sources and destination	60 cm

5.2. Packet Transmission Approach

A packet transmission approach is applied for NCC systems which generates pseudo-random bit arrays from original data in order to help manage large data sequences from source nodes by dividing them into packets. Consequently, management of the packets can be done correctly. The packet index portion is designed to be 5 % of the frame length, and added to the beginning of the frame. Source nodes are configured to be managing different number of packets. Thus packet structure is provided for transmission process and packets are sent to the relay and destination nodes.

5.3. Data Processing Method

LabVIEW is used for OFDM based NCC system in DSN scenario. For every node as well as network coding

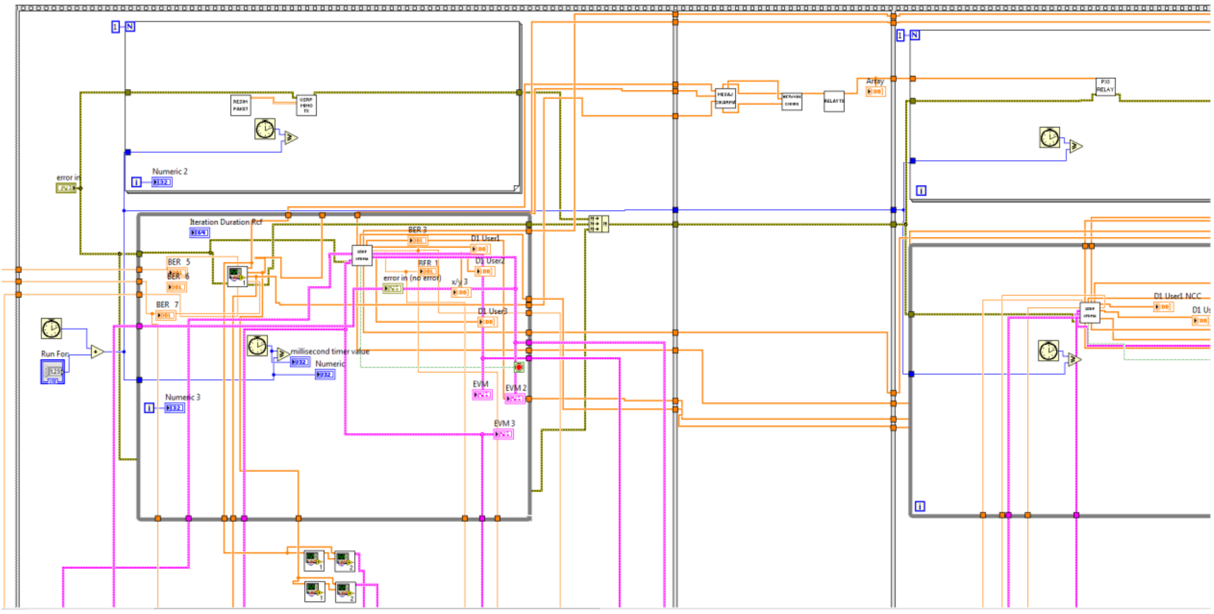


Figure 4. LabVIEW screenshot of network coding and decoding processes

and decoding processes, sub-virtual instruments (SubVI) are created.

In the source SubVI part, in order to arrange the coordination between USRP hardware and LabVIEW software, USRP virtual instruments (VIs), which control the USRP parameters that are responsible for transmission process, are used. With the aid of LabVIEW's array functions, subcarrier assignment and frame structure are generated. Array VIs are also used in the interleaving process that is for combination of the reference symbols that are constant, and data symbols as one reference symbol comes per eight data symbols. Moreover, zero padding is applied and zero subcarriers are inserted to the frame. After implementing Inverse Fast Fourier Transform (IFFT) by IFFT VI, cyclic prefix is added to beginning of the frame using Array VIs. Eventually, source nodes' SubVIs are generated.

The relay part consists of the transmitter and receiver parts. As relay node, NI PXIe-5644R VST is used. VST makes use of the RFSG VIs and RFSA VIs necessary for the signal generation and signal acquisition respectively. RFSA VIs control the start and end of the session and parameter configurations like USRP VIs. Carrier frequency offset (CFO) VI is used for the estimation of CFO and removal of its destructive effects on the received data. After estimated CFO is discarded and cyclic prefix is subtracted, Fast Fourier Transform (FFT) is applied by using FFT VI. Then source data are extracted by removing zero padding subcarriers. Similarly, information and reference subcarriers are separated for each source data. Moreover, by using generated channel estimation and equalization VIs, the channel effects are removed. Thus receiver SubVI part of the relay node is constituted.

Then, received information symbols from three sources are used for NC implementation by using network coding SubVI that implements NC according to our system model and network coded combinations are generated for to be used in frame preparation. Then transmitter SubVI is implemented similarly to the source nodes' SubVIs. As main differences, RFSG VIs are used for session processes and transmission parameter configurations. Network coded data are interleaved with reference symbols. Then zero padding and IFFT are applied. Thus, the OFDM frame is produced. At the end, cyclic prefix is added, thus relay node's SubVI is created.

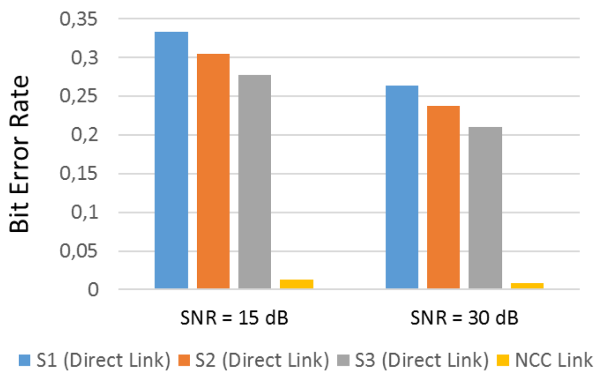
Finally, destination node SubVI is implemented similar to the relay nodes' receiver part SubVI. Instead of RFSA VIs, USRP VIs are used for session processes and parameter configurations. Following this, the CFO is estimated and removed, cyclic prefix is removed and FFT is applied. After removing the zero padding, information data are extracted from reference symbols. In the last section of the destination node part, channel estimation and equalization is implemented to obtain network coded information. In the end, developed MLE and network decoding block is implemented to the coded data, so source data are obtained successfully. In result, the timed flat sequence structure is completed and LabVIEW code is generated successfully.

A portion of content of the LabVIEW code is shown in Figure 4. In this figure, the VI which has title of "USRP MIMO TX", generates required user bits for all source nodes and manages transmission of generated symbols by controlling necessary USRP configuration steps. At the same time instance, relay and destination nodes receives these data with the realization of "Relay Rx" and "USRP Rx" VI. Here, VST and USRP modules are configured respectively, and demodulations of transmitted symbols are conducted. As the result of these processes, obtained BER and EVM results as well as constellation diagrams are given as output. In the following time instance, demodulated data is used by "Network Coding" VI and network coding is applied to corresponding symbols. Then coded symbols are inserted into corresponding frequency positions of OFDMA symbol. Created symbols are transmitted by relay node in the next time instance, by using "PXI Relay" VI. At the same time, "USRP Rx" VI is run again and symbols are received by the destination node. After demonstration of demodulation results, this time distance is completed. As the last step, received symbols are demodulated to bits by "ML Detector" VI with the network decoding process. Some unexplained parts are related to data management and demonstration processes, where some of them are visible in the figure.

6. Test Results

In this section, the advantages of NCC systems for DSNs are shown by the measurement results that are extracted from LabVIEW. In order to observe the system performance in a diverse set of conditions, system parameters are changed in the LabVIEW. BER measurements are captured for all source nodes to see how NC improves the data transfer comparing direct link systems and NCC systems in Table 2. In order to compare link performances, two reference SNR levels are chosen as 15 dB and 30 dB. It is clear that direct links between S_1-D, S_2-D and S_3-D have approximately 30 times higher BER than NCC link in both 15 dB and 30 dB SNR levels. With the implementation of NC at relay nodes, it is possible to recover more information data which improves throughput of the transmission system. In other words, the visible effects of noise, channel fading and long distances can be alleviated with NCC systems.

Table 2. BER comparisons of direct links and NCC link.



7. Conclusion

Although there are various studies based on DSNs, the implementation of DSNs with NCC system and the consideration of solar scintillation effects on this cooperative communication system are studied for the first time in this paper, to the best of our knowledge. As indicated with simulations and implementations on SDR nodes, NCC provides several advantages in terms of a tunable design for high robustness, improved throughput and/or high spectral/energy efficiency. Our simulation results illustrate that the influence of corruptive effects in DSNs can be decreased with NCC based design. In simulation results where solar scintillation is considered, the outage probability of direct links is significantly higher than NCC link, providing a proof for NCC systems' suitability for DSNs. Our test results demonstrate that error performance can be improved after applying NC to the system. Direct links have higher BER compared to NCC links in 15 dB and 30 dB SNR levels which is a proof of NCC systems for decreasing error rates in the system.

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