ISSN: 2455-2631 July 2023 IJSDR | Volume 8 Issue 7

Study on Digital Wireless Communication: Hybrid Satellite Terrestrial Network (HSTN)

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Abstract- **Wireless communication refers to the transmission of information or data over a distance without the need for physical connections such as wires or cables. It enables the exchange of information between devices or systems using electromagnetic waves, allowing for flexible and convenient communication. Wireless communication has become an integral part of our daily lives, powering various technologies such as smartphones, Wi-Fi networks, Bluetooth devices, and more. It offers numerous benefits, including mobility, flexibility, and scalability. It has revolutionized the way we communicate, enabling us to connect and share information effortlessly across different locations.**

Hybrid Satellite-Terrestrial Network (HSTN) plays a pivotal role in wireless communication by combining the capabilities of satellite and terrestrial networks. It extends coverage to remote areas, ensures reliable connectivity, offers scalability and flexibility, enables high-speed data transmission, enhances disaster resilience, and provides global connectivity. HSTN optimizes resource allocation, addresses limitations of individual networks, and bridges the digital divide, resulting in comprehensive wireless communication solutions in diverse scenarios. In this review paper, we have thrown some light on system architecture, performance analysis, design optimization, and secure communication schemes for different cooperative and cognitive HSTN network architectures. In its wake, several emerging technologies have been compared and based on that several open-ended issues for future research are discussed.

Keywords: **HSTN; Relay Communication; diversity; Selection Combining; Maximum Ratio Combining; Switched Combining; Cooperative HSTN; Cognitive HSTN; NOMA; SIC; Performance Evaluation; Beamforming; Frequency Hopping; Shannon-Hartley Law; BER; SNR.**

1. INTRODUCTION:

A Hybrid Satellite Terrestrial Network (HSTN) is an amalgamation of satellite and terrestrial networks, leveraging various components in both terrestrial and space-based communication infrastructure. This integrated approach enables the provision of comprehensive global communication services, connecting diverse points worldwide. The advancement of wireless networking relies heavily on the adoption of Hybrid Satellite Terrestrial Networks (HSTNs) to deliver wireless services with high data rates and global coverage. However, the performance and operation of satellite terrestrial networks are influenced by various positive and negative factors on a global scale, which have been explored in-depth in our research.

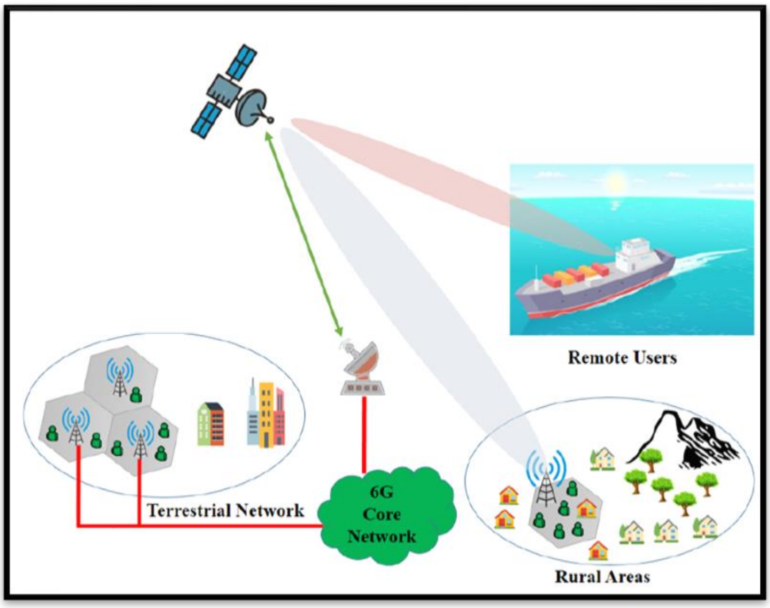
2. Basic Architecture of HSTN:

The HSTN (Hybrid Satellite-Terrestrial Network) architecture offers a promising solution for the next-generation 5G network and beyond. By combining the strengths of both terrestrial and satellite networks, it aims to provide global coverage and ubiquitous Internet access, catering to the needs of various applications including IoT (Internet of Things).

HSTN comprises of conventional terrestrial networks augmented with satellite infrastructure, as depicted in the figure. The terrestrial network utilizes cellular networks and backhaul links to connect base stations (BSs) to the core network, delivering high-speed broadband services primarily in developed urban areas. On the other hand, satellites provide extensive coverage, enabling connectivity to remote and rural regions where terrestrial infrastructure is limited. In areas where terrestrial coverage is lacking, users can rely on their own terminals to connect to the satellite network, although there may be capacity limitations based on the number of users and their terminals.

To enhance service availability, satellite-based BSs and access points can be deployed, offering relatively high-speed broadband connectivity. Users can then connect to these devices using advanced technologies like 6G or Wi-Fi. This hybrid satellite base station model ensures improved coverage and capacity for users across different locations.

By leveraging the benefits of both terrestrial and satellite networks, HSTN presents a comprehensive solution for achieving global connectivity and enabling seamless communication for a wide range of applications, including IoT.



The Satellite and terrestrial network for 5G (SAT5G) initiative aims to revolutionize 5G connectivity by integrating satellite and terrestrial networks, offering affordable and seamless communication solutions. Its primary goal is to accelerate the global deployment of 5G technology, while also creating new opportunities for the satellite communications industry. By leveraging this integration, telecom operators and service providers can enhance their offerings and cater to diverse markets. The overarching objective of SAT5G is to ensure widespread access to high-speed 5G broadband, providing users with a minimum of 50 Mbps 5G broadband service. Additionally, the initiative seeks to optimize satellite communication within the 5G network infrastructure, enabling the provision of services across various sectors such as media and entertainment, transportation, health, logistics, and agriculture industries. These advancements will benefit both developed and emerging markets alike.

3. Brief Insight on Relay Based Communication:

Relay-based communication plays a vital role in satellite networks, employing relay satellites as key components. Similar to passing a baton in a relay race, these satellites receive command messages from ground stations and transmit them to user satellites via RF cross-links. Telemetry data from the user satellites is then sent back to the relay satellite through another cross-link, which relays it to the ground station. This process involves a forward link (up-link and cross-link to the user satellite) and a return link (cross-link and down-link from the user satellite).

One example is the NASA Training and Data Relay Satellite System (TDRSS), a constellation of geostationary data relay satellites that provide extensive coverage to user satellites orbiting between 200 and 1200 km. TDRSS supports "S-band" (2.1–2.3 GHz) communications, offering forward rates of up to 10 kbps and return rates of up to 50 kbps for around 20 user satellites. Additionally, it allows two users to have "S-band" support with forward rates up to 300 kbps and return rates up to 12 Mbps. It can also accommodate up to two users with "Ku-band" (13.8–15.0 GHz) support at forward rates up to 25 Mbps and return rates up to 300 Mbps.

In the field of communications, microsatellites are employed as data relay satellites. For instance, the Whale Ecological Observation Satellite (WEOS) monitors ecological data of whales in the Antarctic Ocean. Polar orbit microsatellites collect and store data from probes attached to whales before transmitting it to the ground station. WEOS, along with the probes developed by the Chiba Institute of Technology, is ready for a flight opportunity. Similar missions focusing on various animals and birds contribute significantly to our understanding of their global activities.

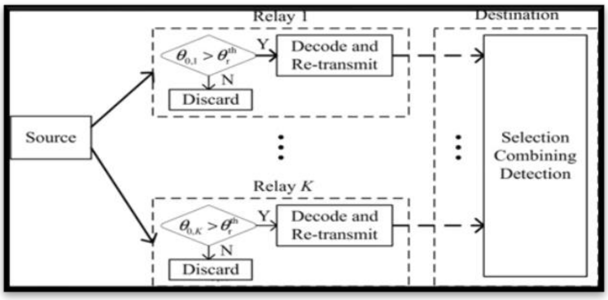
In HSTN architecture, the terrestrial network has been effectively implemented in developed areas to offer broadband Internet access at reasonable cost. Further, the satellite network, which can work hand-in-hand with the terrestrial network, can provide ubiquity over a wide coverage area.

3. a. Diversity in Relay Based Communications:

Diversity techniques are employed in communication systems to mitigate the effects of fading by combining multiple copies of the transmitted signal. These techniques vary in their methods of combining. In relay-based communication, cooperative relays assist in forwarding data from source nodes to destination nodes. When network conditions are poor, a source node employs both direct and relay-based communication to send messages to the hub/coordinator. The hub/coordinator node receives the same packet through different paths and utilizes diversity combining techniques to extract the transmission with the highest signal quality.

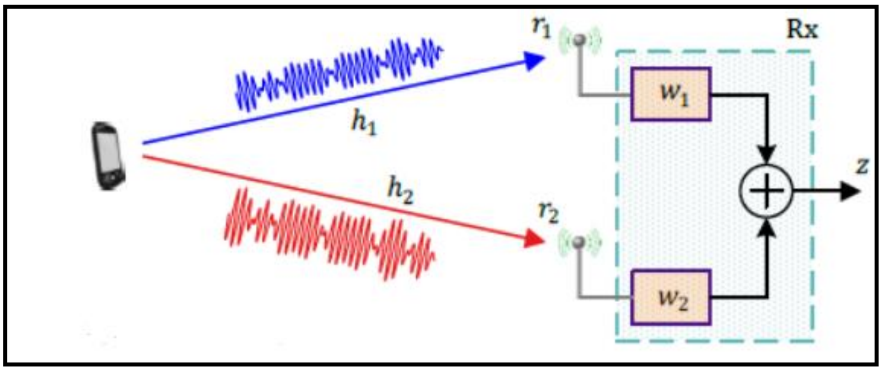
Here are three popular diversity combining techniques:

- ***Selection Combining (SC):*** The hub/coordinator selects the transmission with the strongest signal among all received signals, based on parameters such as signal-to-noise ratio (SNR) or channel gain. This technique chooses the transmission path with the highest quality. In all the transmission paths, the worst case scenario of SNR or gain is considered to be checked for selection at the receiver hub, where the maximum, i.e., the optimal one is selected. SC is a widely used and simple method for combining signals in a diversity system. It estimates the current SNR values in all branches and selects the one with the most favorable SNR.



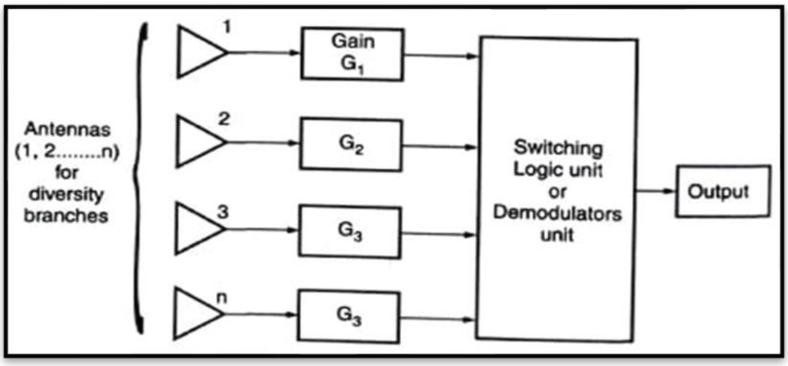
Selection Combining Technique:

- ***Maximum Ratio Combining (MRC):*** Received signals are assigned weights based on their SNR values, thereby equating their phases. The signal with the highest SNR is given the highest weight, and the weighted signals are combined to form a single signal. MRC combines multiple signals using their SNR-based weights, ensuring that the signal with more power contributes more to the received sum of signals. However, implementing MRC can be expensive due to the need for SNR measurement in all branch signals. It is considered the optimal linear technique for signal combination in a diversity system, providing the best statistical results in mitigating the impact of fading.



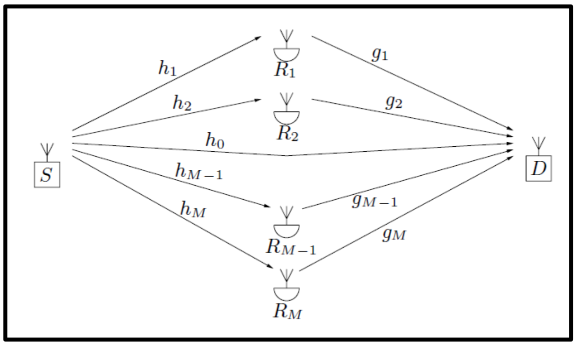
Maximum Ratio Combining Technique

- ***Switched Combining (SwC):*** This technique involves using a predefined threshold of channel quality, typically based on channel gain or SNR. If a signal's quality falls below the threshold in a particular channel, communication is switched to another channel that meets the defined threshold. Switching logic circuits can be used to ensure which channel will be taken, and as such it will be switched on and the others which are below threshold criteria will be switched off. Different strategies, such as two-branch or three-branch switching, can be employed in SwC.



Switched Combining Technique

3. b. Mathematical Analysis of Relay-based Communication:



Relay Communication System: Schematic Diagram

In the relay communication system depicted in the diagram, we have a transmitter (S), a receiver (D), and multiple relays (R_1, R_2, ..., R_M). These relays work in a low-complexity non-regenerative (amplify-and-forward) mode, where they amplify and forward the received signal from the transmitter without decoding and re-encoding it. The system operates in a time duplex mode, meaning the first time slot is used for receiving information from the transmitter, while the second time slot is used for forwarding the information to the final destination (receiver).

The channel coefficients, represented by h_i and g_i, illustrate the radio channel characteristics between the transmitter and Relay i, and between Relay i and the receiver, respectively. These coefficients account for the effects of fading in the channel. The system considers both flat fading and frequency-selective fading channels. Importantly, the relays are located far apart from each other, ensuring that the channels are uncorrelated. Additionally, each relay introduces a delay τ_i to the signal before forwarding it. This delay can either be predetermined or purely random within a predefined time guard interval.

On the receiver side, assuming a slowly varying frequency-selective fading channel, the received signal at the mobile unit from the base station (in the first time slot) can be represented by an equivalent low-pass signal. This signal characterization helps in understanding the system's behavior under these specific conditions. It is shown as below:

$$r_0(t) = \sum_{l=0}^{L-1} h_{0,l} s(t - \upsilon_{0,l}) + z_0(t)$$

where $s(t)$ is the equivalent low pass of the transmitted signal, $z_0(t)$ is the additive thermal noise which is modeled as zero mean complex Gaussian process with a power spectral density of N_0, L is the number of paths of the channel, $h_{0,l}$ is the attenuation coefficient of path l and $\upsilon_{0,l}$ is its corresponding delay. In the first time slot, the received signals at the relays are represented by the equation:

$$y_i(t) = \sum_{l=0}^{L-1} h_{i,l} s(t - \tau_{i,l}) + z_i(t), \qquad i = 1, 2, \cdots, M.$$

where $y_i(t)$ is the received signal at relay i, $ht(\tau\,;\,t)$ represents the channel impulse response from the base station to relay i with delay $\tau_{i,l}$, and $z_i(t)$ is the zero-mean complex Gaussian noise. In the second time slot, when the relays transmit, the received signal at the mobile unit is given by the equation:

$$\begin{aligned} r_1(t) &= \sum_{i=1}^{M} \beta_i \sum_{l=0}^{L-1} g_{i,l} y_i(t - \tau_i - \tau_{i,l}) + z_{M+1}(t) \\ &= \sum_{i=1}^{M} \sum_{l=0}^{L-1} \sum_{k=0}^{L-1} \beta_i g_{i,l} h_{i,k} s(t - \tau_{i,l} - \upsilon_{i,k} - \tau_i) \\ &\quad + \sum_{i=1}^{M} \sum_{l=0}^{L-1} \beta_i g_{i,l} z_i(t - \tau_{i,l} - \tau_i) + z_{M+1}(t) \end{aligned}$$

This equation includes contributions from all the relays and represents the frequency selective fading introduced by the relays.

To mitigate the frequency selectivity introduced by the relays, frequency domain equalization is employed at the receiver. This technique uses a one-tap equalizer per sub-carrier and relies on the cyclic prefix for equalization. By using frequency domain equalization, the fading channel is transformed into a set of frequency nonselective channels in parallel, simplifying the equalization process. The equalized signals are obtained by taking the Discrete Fourier Transform (DFT) of the received signals and applying the equalizer taps. The equalized signals can then be demodulated to extract the transmitted symbols. The performance of the relay communication scheme is assessed through numerical simulations. The results demonstrate the performance gain achieved by the relay delay diversity. Both Zero Forcing Equalizer (ZFE) and Minimum Mean Square Equalizer (MMSE) schemes are considered, and the performance is evaluated for flat Rayleigh fading and frequency selective Rayleigh fading channels.

i.SC: Mathematical Analysis:

For slow flat fading channel, the equivalent low-pass received signal for the branch i can be written as:

where *s(t)* $r_i(t) = A_i e^{j\theta_i} \cdot s(t) + z_i(t), \quad i = 0,\ 2,\ \dots,\ M\text{-}1,$ is equivalent to low-pass transmitted signal, $A_i e^{j\theta} i$ is the fading attenuation for the branch i, $z_i(t)$ is Additive White Gaussian noise, AWGN. M replicas of transferred signal are obtained from M branches:

$$r = [r_1(t), r_2(t) \dots r_{M-1}(t)].$$

For SC, combining the outputs, it is obtained:

$$y(t) = A_i e^{j\theta_i} \cdot s(t) + z_i(t), \text{ with } A = \max\{A_0, A_1, \dots\dots, A_{M-1}\}.$$

Received SNR can be written as follows:

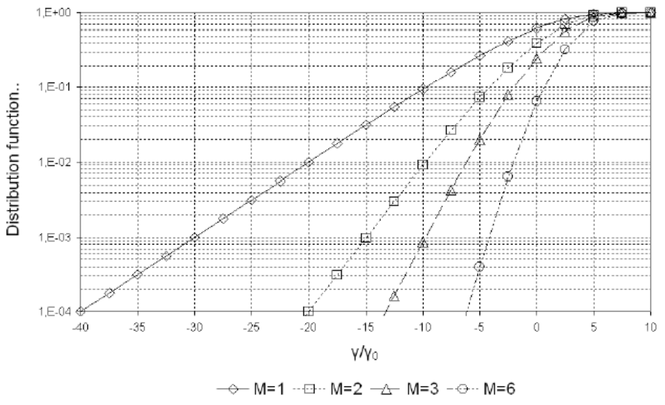
$$\Gamma = \frac{A^2 \cdot E_b}{N_0} = \max\{\Gamma_0, \Gamma_1, \dots\dots, \Gamma_{M-1}\ \}.$$

With uncorrelated branches, the CDF for independent and identically distributed branch is:

$$p_\Gamma(\gamma) = M \cdot p_{\Gamma_0}(\gamma)[P_{\Gamma_0}(\gamma)]^{M-1}.$$

The following illustration is given for the Rayleigh Fading Channel. Probability is expressed by equation shown below and is presented in the graph below as well for M = 1, M = 2, M = 3, M = 6 (M is the number of antennas):

$$P_\Gamma(\gamma) = (1 - e^{-\gamma/\gamma_0})^M, \gamma_0 = 2 \cdot \sigma^2 \cdot E_b / N_0$$



Selection Combining in Rayleigh Fading Channel for the case of M receiving antennas

The Bit Error Rate (BER) for BPSK with AWGN can be expressed as:

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

Here E_b/N_0 represents the ratio of bit energy to noise power spectral density. In the case of Selective Diversity with multiple receiving antennas, the effective ratio of bit energy to noise is denoted as γ. To determine the overall Bit Error Rate (BER) for Selective Diversity, the conditional BER is integrated over all possible values of γ. The equation for the total BER in Selective Diversity is a complex expression involving the Error Function (erfc), the number of receiving antennas (M), and the probability density function (pdf) of γ. By employing mathematical manipulations, the equation can be simplified into a more concise form. The calculation is shown below:

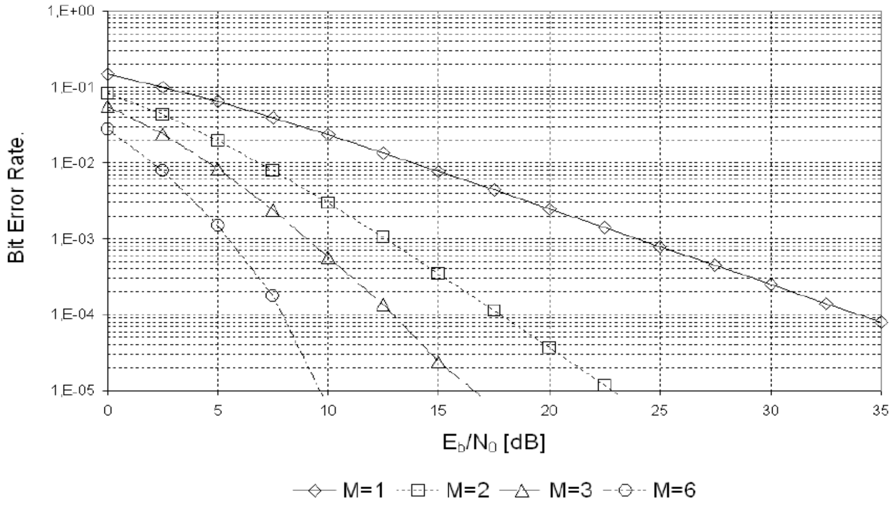
$$P_e = \int_0^\infty \frac{1}{2} erfc\left(\sqrt{\gamma}\right) \cdot p(\gamma) \cdot d\gamma =$$

$$= \int_0^\infty \frac{1}{2} erfc\left(\sqrt{\gamma}\right) \cdot \frac{M}{(E_b / N_0)} \cdot e^{\frac{-\gamma}{(E_b / N_0)}} \cdot \left[1 - e^{\frac{-\gamma}{(E_b / N_0)}}\right]^{M-1} \cdot d\gamma$$

This equation is reduced to

$$P_e = \frac{1}{2} \sum_{k=0}^{M-1} (-1)^k \binom{M}{k} \cdot \left(1 + \frac{k}{(E_b / N_0)}\right)^{1/2} ,$$

Figure given below illustrates the BER performance of BPSK in a Rayleigh channel with Selection Diversity. It shows that using two receiving antennas provides an improvement of approximately 16 dB compared to a single receiving antenna when the BER is 10^(-4).



ii.MRC: Mathematical Analysis:

Combined output is expressed by:

$$y(t) = \sum_{i=0}^{M-1} w_i \cdot r_i(t)$$

Weighting factors are chosen in such a way that channel gain is conjugate (must be estimated):

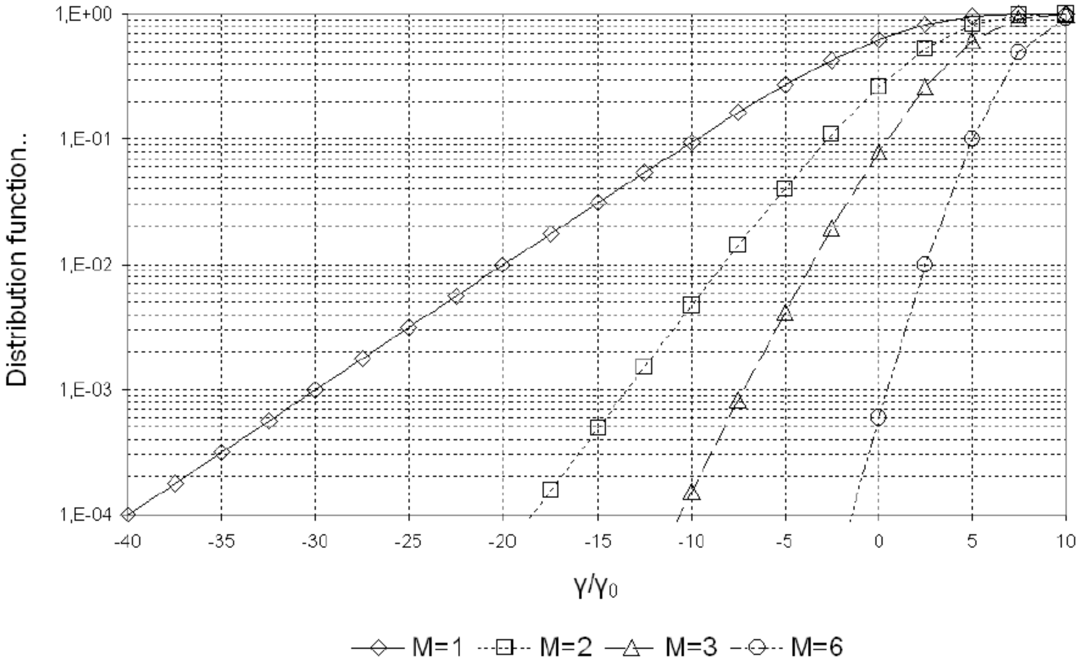
$$y(t) = \left(\sum_{i-0}^{M-1} A_i^2\right) \cdot s(t) + \sum_{i-0}^{M-1} A_i\, e^{-j\theta_i} \cdot z_i(t)$$

The SNR of the combined signal is:

$$\Gamma = \frac{\sum_{i=0}^{M-1} A_i^2 \cdot E_b}{N_0} = \sum_{i=0}^{M-1} \Gamma_i$$

For Rayleigh Fading channel, the outage probability is given by the follow shown below and is shown in the graph for M = 1, M = 2, M = 3, M = 6 (M is the number of antennas):

$$P_\Gamma(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_0}} \sum_{i=0}^{M} \frac{(\gamma / \gamma_0)^{i-1}}{(i-1)!}$$



In the presence of channel h_i, the current ratio of energy and noise for the *i* th receiving antenna is:

$$\gamma_i = \frac{|h_i|^2 E_b}{N_0}$$

Taking into consideration that we equalized all channels and marked them by h_i, the effective ratio of bit energy to noise, for M receiving antennas, is:

$$\gamma = \sum_{i=1}^{M} \frac{|h_i|^2 E_b}{N_0} = M \cdot \gamma_i \,.$$

Considering the chi-square random variable, we can infer that if h_i is Rayleigh distribution of the random variable, then h_i^2 is the chi-square random variable with two degrees of freedom. Then the PDF for γ_i is:

$$p(\gamma_i) = \frac{1}{(E_b / N_0)} e^{\frac{-\gamma_i}{(E_b / N_0)}}$$

Therefore, the effective ratio of bit energy to noise, γ, is the sum of M random variables, where the PDF of γ is the chi-squared random variable with 2M degrees of freedom. PDF of γ is:

$$p(\gamma_i) = \frac{1}{(M-1)!\,(E_b / N_0)^M} \cdot \gamma^{M-1} \cdot e^{\frac{-\gamma_i}{(E_b / N_0)}}, \gamma \geq 0$$

If we designate the relation of bit energy to noise as E_b/N_0, BER for BPSK with AWGN can be expressed as:

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

If the designate by γ, the efficient ratio of bit energy to noise for the MRC, then the total BER is integral, for the conditional BER, calculated over all possible values of γ, as presented below
:

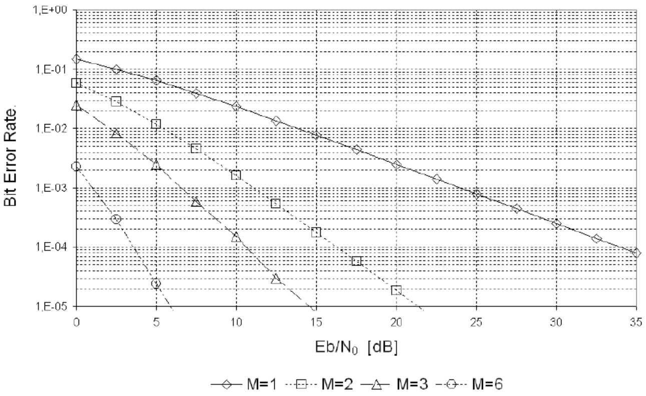
$$P_e = \int_0^{\infty} \frac{1}{2} erfc\left(\sqrt{\lambda}\right) \cdot p(\gamma) \cdot d\gamma =$$

$$= \int_0^{\infty} \frac{1}{2} erfc\left(\sqrt{\lambda}\right) \frac{1}{(M-1)!\,(E_b / N_0)^M} \cdot \gamma^{M-1} \cdot e^{\frac{-\gamma_i}{(E_b / N_0)}} \cdot d\gamma$$

Equation is reduced to:

$$P_e = p^M \sum_{k=0}^{M-1} \binom{M-1+k}{k} \cdot (1-p)^k$$

BER for BPSK in Rayleigh channel with Maximal Ratio Combining is presented in Figure 9. From this figure, it can be seen that the improvement for the two receiving antennas, compared to one receiving antenna, is about 13dB for BER=10^{-3}.



BER plot for BPSK in Rayleigh channel with Maximum Ratio combining for the case of M receiving antennas

Overall, the relay communication scheme with frequency selective fading channels and frequency domain equalization offers improved performance and can be advantageous in scenarios where time equalization techniques are complex or impractical.

3.c. Shannon Hartley Law:

In information theory, the Shannon–Hartley theorem tells the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the presence of noise. It is an application of the noisy-channel coding theorem to the generalized special case of a continuous-time analog communications channel subject to Gaussian noise.

i.Statement –

The Shannon–Hartley theorem states the channel capacity, (C) , meaning the theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrarily low error rate using an average received signal power (S), through an analog communication channel subject to additive white Gaussian noise (AWGN) of power (N) :

ii.Mathematical Formula :-

$$C = B \log_2(1 + S/N)$$

where:

➢ C is the channel capacity in bits per second, a theoretical upper bound on the net bit rate

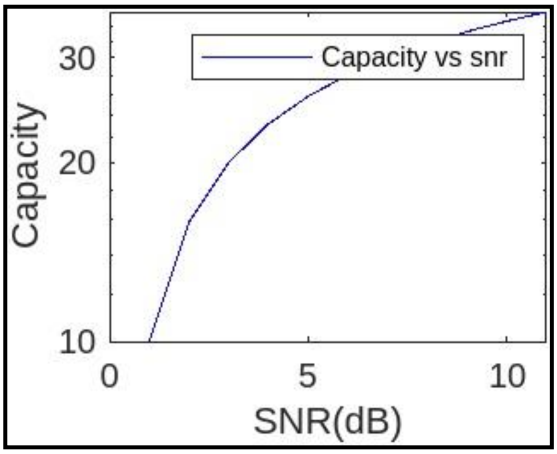
- B is the bandwidth of the channel in hertz (passband bandwidth in case of a bandpass signal)
- S is the average received signal power over the bandwidth, measured in watts
- N is the average power of the noise and interference over the bandwidth, measured in watts
- S/N is the signal-to-noise ratio (SNR) or the carrier-to-noise ratio (CNR) of the communication signal to the noise and interference at the receiver (expressed as a linear ratio)

3.d. MATLAB algorithm for minimum BIT ERROR RATE (BER) from relay network channel and calculating CAPACITY of channel using Shannon-Hartley theorem:

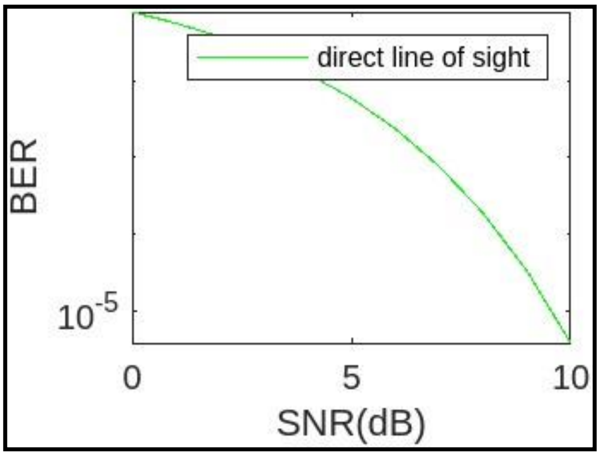
- Initializing bit energy with variable, Eb as 1.
- Taking input from user of the total number of input bits and storing it in variable num_bit.
- Taking input from user of the number of SNR bits from transmitter to relay channel and storing it in variable bitsnr.
- Taking input from user of the number of SNR bits from relay to receiver channel and storing it in variable bitsnr1.
- Taking input from user of the number of SNR bits from direct line of sight channel and storing it in variable bitsnr2.
- Taking input from user of the bandwidth of the channel in hertz and storing it in variable bw.
- Scaling the input data bitsnr into an array with interval [0,1] and storing it in variable SNR_dB.
- Scaling the input data bitsnr1 into an array with interval [0,1] and storing it in variable SNR_dB_1.
- Scaling the input data bitsnr2 into an array with interval [0,1] and storing it in variable SNR_dB_2.
- Declaring a matrix of zeros having length of the dimension, SNR_dB in the variable BER_Rx for transmitter to relay.
- Declaring a matrix of zeros having length of the dimension, SNR_dB_1 in the variable BER_Ry for relay to receiver.
- Declaring a matrix of zeros having length of the dimension, SNR_dB_2 in the variable BER_Rd for direct line of sight.
- Declaring a for loop variable, a to iterate from 1 to bitsnr.
- Storing SNR_dB_(a) in the variable SNR.
- Declaring another variable, snr as 10 raised to power of (SNR/10).
- Declaring a variable, N0 as noise spectral density having the value of Eb/snr.
- Initializing the variable Error as 0.
- Declaring another loop variable k inside the main loop, to iterate from 1 to num_bit.
- Initializing variable data to store the round of integer values of the random numbers given by computer.
- Declaring variable s as (2*data – 1).
- Generating noise, N as the product of square root values of No/2 and random values from computer.
- Checking in if conditional statement whether error is present in the signal by (Y>0 && data == 0) || (Y<0 && data == 1).
- Incrementing the value of error by 1 if the proposition mentioned is true.
- End of if conditional statement.
- End of inner for loop statement.
- Now calculating the Bit error rate (BER) for BPSK modulation scheme, of transmitter to relay channel using the formula ½ error function of the square root value of snr and storing it in variable BER_Rx(a).
- End of the main loop statement.
- Similarly, declaring for loop variable b to iterate from 1 to bitsnr1.
- Using similar formulas mentioned above, we calculate the variables SNR, snr, N0 and error where symbols have their usual meaning.
- Similarly, we generate the signal Y which is the summation of s and n and checking whether error is present or not by if conditional statement.
- Incrementing the value of error by 1 if the proposition mentioned is true.
- We finally calculate the Bit error rate (BER) for BPSK modulation scheme, of transmitter to relay channel using the formula ½ error function of the square root value of snr and storing it in variable BER_Ry(b).
- Again using similar formulas mentioned above, we calculate the variables SNR, snr, N0 and error where symbols have their usual meaning.
- Now, we generate the signal Y which is the summation of s and n and checking whether error is present or not by if conditional statement.
- Incrementing the value of error by 1 if the proposition mentioned is true.
- Thus we finally calculate the Bit error rate (BER) for BPSK modulation scheme, of transmitter to relay channel using the formula ½ error function of the square root value of snr and storing it in variable BER_Rd(u).
- Calculating the capacity of the channel using the Shannon-Hartley law and storing it in variable Cap.
- Displaying the value of Bit error rate from transmitter to relay channel to the user by variable BER_Rx(a).
- Displaying the value of Bit error rate from relay to receiver channel to the user by variable BER_Ry(b).
- Plotting the first curve of SNR_dB vs BER_Rx for transmitter to relay channel using semilogy and subplot function.
- Marking the respective xlabel, ylabel and legend of the following mentioned plot.
- Plotting the second curve of SNR_dB_1 vs BER_Ry for relay to receiver channel using semilogy and subplot function.
- Marking the respective xlabel, ylabel and legend of the following mentioned plot.
- Plotting the third curve of SNR_dB_2 vs BER_Rd for direct line of sight channel using semilogy and subplot function.
- Marking the respective xlabel, ylabel and legend of the following mentioned plot.

- Plotting the fourth curve of SNR_db_2 vs Cap for Capacity of the selected channel at the receiver end using semilogy and subplot function.
- Marking the respective xlabel, ylabel and legend of the following mentioned plot.
- Now checking for maximum error either from transmitter to relay channel or relay to receiver channel using if conditional statement.
- Printing the maximum bit error rate to the user using the appropriate channel obtained.
- Storing the maximum value of the transmitter to relay channel Bit Error Rate (BER) in the variable max .
- Checking for maximum error either from transmitter to relay channel or relay to receiver channel using else conditional statement.
- Printing the maximum bit error rate to the user using the appropriate channel obtained.
- Storing the maximum value of the relay to receiver channel Bit Error Rate (BER) in the variable max .
- Now comparing whether max is greater than the direct line of sight channel Bit Error Rate(BER) using if conditional statement.
- If proposition found true, printing to the user the appropriate channel for propagation of signal having minimum Bit Error Rate (BER) is the line of sight channel.
- Else is proposition is found false, printing to the user the appropriate channel for propagation of signal having minimum Bit Error Rate (BER) is the relay network channel.
- End of if-else conditional block.
- Printing to the user the channel capacity by the Shannon-Hartley law using the variable Cap.
- End of the MATLAB simulation source code.

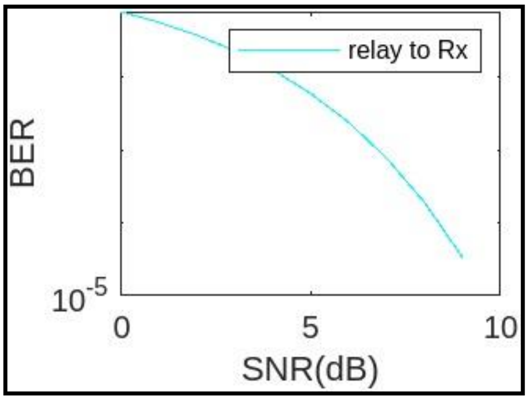
The simulation graphs are shown below:



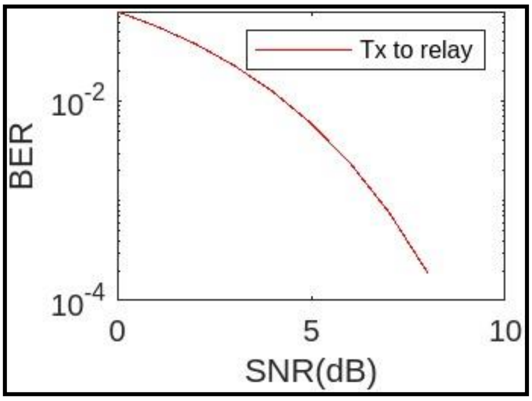
Capacity of channel vs SNR in dB plot



Bit Error Rate (BER) vs SNR in dB for direct line of sight network plot



Bit Error Rate (BER) vs SNR in dB for relay to receiver plot



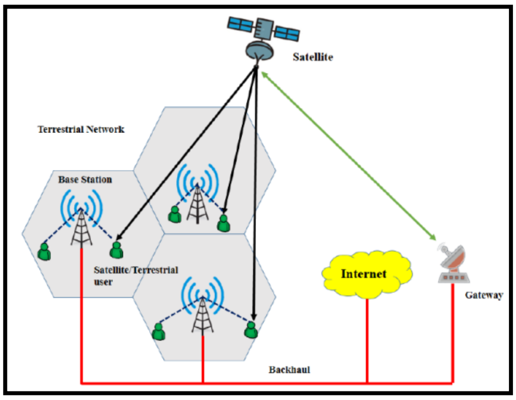
Bit Error Rate (BER) vs SNR in dB for transmitter to relay plot

3.e. Cooperative Relays and Cognitive Relays:

For a more detailed study of Hybrid Satellite-Terrestrial Network (HSTN), cooperative relays and cognitive relays are two key topics that play a major role in improving the overall performance, reliability and efficiency of the network system.

i.Cooperative Relays:

Cooperative relays refer to the utilization of intermediate nodes to facilitate communication between a source and destination node. In a hybrid satellite-terrestrial network, cooperative relays can be terrestrial nodes or satellite nodes strategically placed to enhance coverage, capacity, and reliability. These relays can assist in extending the network reach, overcoming fading effects, and mitigating signal attenuation in challenging environments.



Cooperative Relay System

The cooperative relay system operates by having the source transmit its information to relay node, which then retransmits the received signal to the destination node. This technique offers several advantages, including:

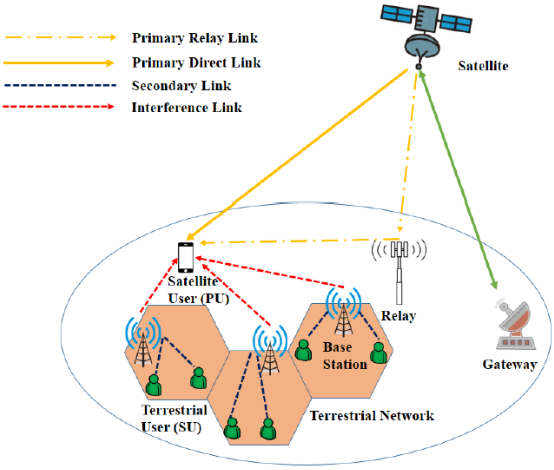
a) **Extended Coverage:** Cooperative relays enable signal transmission over longer distances, as they bridge the gap between the source and destination nodes. They can help overcome signal degradation and improve coverage in areas where direct communication is hindered due to obstacles or long distances.

b) **Increased Reliability:** By using cooperative relays, the network can achieve diversity gain, which helps combat fading and improves the overall reliability of the communication link. If one relay encounters signal degradation, another relay can take over the transmission, enhancing system resilience.

c) **Enhanced Capacity:** Cooperative relays can increase network capacity by effectively utilizing the available network resources. They can assist in offloading traffic from heavily loaded nodes, reducing congestion and improving overall system performance.

ii.Cognitive Relays:

Cognitive relays, also known as intelligent relays, are relays equipped with cognitive capabilities, such as sensing, learning, and decision-making. These relays are capable of adapting their behavior based on the changing network conditions and can optimize their operation to maximize performance and resource utilization.



Cognitive Relay Network

In a hybrid satellite-terrestrial network, cognitive relays can perform various functions:

a) **Spectrum Sensing:** Cognitive relays can sense the spectrum to identify available frequencies and detect unused or underutilized spectrum bands. By intelligently selecting the best frequency bands, they can improve spectrum efficiency and mitigate interference.

b) **Dynamic Spectrum Access:** Cognitive relays can dynamically access available spectrum resources and utilize them efficiently. They can opportunistically access idle or lightly utilized spectrum bands to improve network capacity and overall performance.

c) **Intelligent Routing:** Cognitive relays can make intelligent decisions about the routing of data packets within the network. They can evaluate network conditions, such as link quality, congestion levels, and available resources, to locate the minimum error path for transmission of information and data.

d) **Adaptive Power Control:** Cognitive relays can dynamically adjust their transmit power levels based on the channel conditions and network requirements. By optimizing the transmit power, they can conserve energy and improve spectral efficiency.

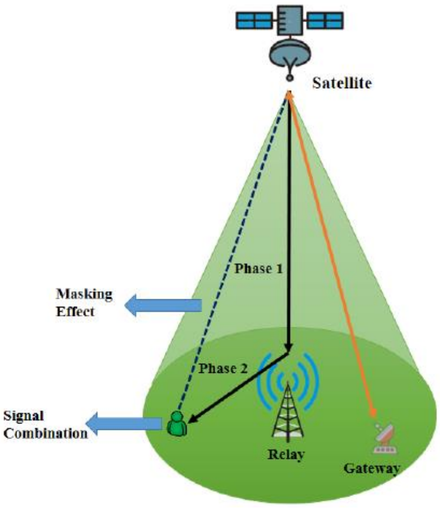
By incorporating cognitive capabilities into relays within a Hybrid Satellite-Terrestrial Network (HSTN), the overall network performance can be enhanced through improved spectrum utilization, adaptive routing, and intelligent decision-making. This leads to increased efficiency, better quality of service, and improved user experience.

A comprehensive comparison between Cooperative and Cognitive HSTRNs is shown below:

Criteria	Cooperative HSTRN	Cognitive Relay HSTRN
Relaying Technique	Cooperative relaying between nodes	Relaying nodes equipped with cognitive capabilities
Network Intelligence	No cognitive capabilities	Cognitive nodes adaptively adjust parameters based on network conditions
Relay Node Decision Making	Based on predefined cooperation protocols	Based on cognitive abilities and intelligent decision making
Resource Allocation	Cooperative distribution of resources	Cognitive nodes dynamically allocate resources based on demand
Knowledge of Network Parameters	Nodes have limited knowledge of network parameters	Nodes possess knowledge of network parameters for decision making
Flexibility and Adaptability	Limited adaptability to changing conditions	Adaptive and flexible operation based on cognitive abilities
Interference Management	Limited interference management capabilities	Cognitive nodes can manage interference intelligently
Energy Efficiency	Relatively higher energy consumption due to cooperative relaying	Cognitive relays optimize energy consumption based on network conditions
Complexity and Implementation	Relatively simpler implementation	More complex implementation due to cognitive functionalities
Spectrum Efficiency	Relatively lower spectrum efficiency	Cognitive relays optimize spectrum utilization and improve efficiency
QoS Improvement	Cooperative relaying can improve QoS	Cognitive relaying can intelligently enhance QoS based on network conditions

4. HSTRN (Hybrid Satellite Terrestrial Relay Network): Usage Of Relay Satellites:

HSTRN stands for Hybrid Satellite-Terrestrial Relay Network. It is a network architecture that combines both satellite and terrestrial communication technologies to provide seamless connectivity and enhanced coverage in various environments. In an HSTRN, the satellite component utilizes geostationary satellites or low Earth orbit (LEO) satellites to establish communication links with ground stations and user terminals. Satellites offer wide-area coverage and can reach distant or underserved areas where terrestrial communication infrastructure is limited or absent. The terrestrial component of HSTRN involves the deployment of relay nodes or base stations on the ground. These relays serve as intermediate communication points between the satellite and end-user devices. They can be strategically located to optimize coverage, overcome signal blockages, and improve overall network performance. To propel the performance and stability of HSTNs, satellite signals should be relayed independently towards users. Thus, the users of an HSTN can receive signals simultaneously from the satellites and relays to take advantage of this spatial diversity from hybrid multiple systems and to overcome the masking effect in satellite networks. This leads to a HSTN relay network, as shown in the figure.



HSTN with relaying structure

Relay satellites play a pivotal role in the hybrid satellite-terrestrial relay network (HSTRN) by facilitating communication between the satellite and terrestrial components. Here are some key applications of relay satellites within HSTRNs:

i. **Extending Terrestrial Coverage:** In areas with limited terrestrial infrastructure or challenging terrain, relay satellites act as intermediaries to extend the coverage of terrestrial networks. These satellites receive signals from terrestrial base stations and relay them to users in remote or underserved regions, ensuring connectivity where direct terrestrial coverage is not feasible.

ii. **Seamless Handovers:** Relay satellites enable seamless handovers as users transit between terrestrial and satellite coverage areas. When a user moves from a terrestrial network's coverage range to an area served by satellites, or vice versa, relay satellites ensure uninterrupted communication by facilitating the handover process. This allows users to maintain connectivity without experiencing service disruptions.

iii. **Disaster Recovery and Emergency Communications:** During natural disasters or emergencies, terrestrial networks may become damaged or overloaded. Relay satellites in HSTRNs can provide backup communication channels, ensuring that critical information can be transmitted reliably even in challenging circumstances. They help establish temporary or emergency communication links, facilitating disaster response efforts and providing essential communication services to affected areas.

iv. **Remote and Rural Connectivity:** Relay satellites are instrumental in connecting remote and rural areas that lack reliable terrestrial infrastructure. They bridge the connectivity gap by relaying signals between terrestrial base stations and users in isolated locations. This application is particularly valuable for providing internet access, telecommunication services, and other vital connectivity to underserved communities.

v. **Maritime and Aeronautical Communication:** Relay satellites are deployed to provide communication services for maritime and aeronautical applications. They enable reliable and continuous communication for ships at sea, aircraft in flight, and other mobile platforms. These satellites ensure seamless connectivity over vast oceanic or aerial areas where terrestrial networks are limited or unavailable.

vi. **Military and Defense Operations:** Relay satellites are extensively used in military and defense operations. They enable secure and resilient communication networks for military personnel in remote or hostile environments. Relay satellites enhance situational awareness, command and control capabilities, and coordination among military units by providing reliable communication links.

vii. **IoT Connectivity:** The Internet of Things (IoT) is a relatively new domain consisting of a network of interconnected physical devices, vehicles, appliances, and other objects embedded with sensors, software, and connectivity, enabling them to collect and exchange data. It relies on robust connectivity for its widespread deployment. Relay satellites within HSTRNs play a vital role in providing IoT connectivity, particularly in areas where terrestrial networks have coverage limitations. They enable IoT devices to transmit data to the cloud and facilitate communication between IoT devices across vast geographical regions.

Relay satellites are a critical component of HSTRNs, ensuring seamless communication and expanding the reach of terrestrial networks. Their applications span various sectors, including telecommunications, disaster management, rural connectivity, transportation, and defense, among others, enabling reliable and ubiquitous connectivity in diverse scenarios.

5. Physical Layer Security of HSTRNs:

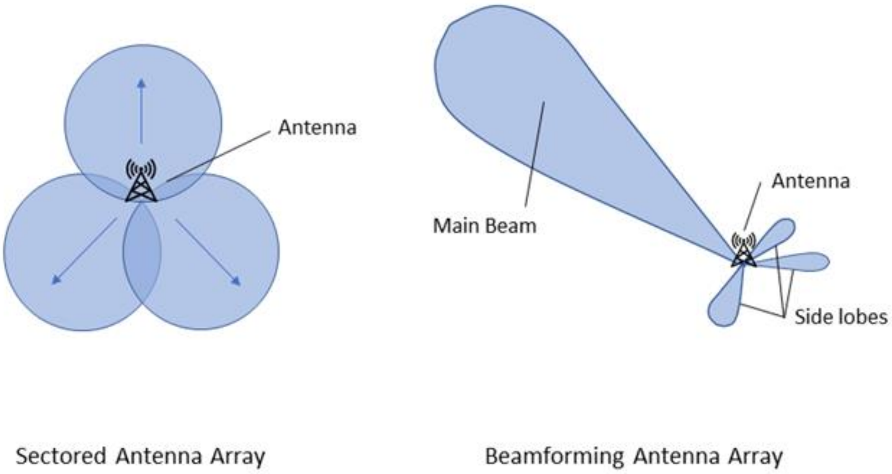
As a complex communication infrastructure comprising satellites in different orbits,
UAVs, and other low-and high-altitude aerial platforms and terrestrial networks, an HSTN may have security risks. Thus, methods of confidentiality must be employed to prevent unauthorized data disclosure, as all the interconnected devices could suffer from

this vulnerable threat. The secure transmission of sensitive data via HSTNs continues to be a severe problem due to the broadcast nature of wireless communications. Secure communication has historically been ensured by cryptographic algorithms at upper layers of the protocol stack based on the assumed psychology that eavesdroppers have limited computational capabilities. Communications can be guarded at the subsequent layers by making use of wireless channel characteristics and advanced signal processing techniques, which has generated a lot of interest in the electronics field recently.

Physical layer security refers to the use of physical properties of communication channels to enhance the security of data transmission. In the context of Hybrid Satellite-Terrestrial Relay networks (HSTRNs), physical layer security techniques can be implemented to protect the confidentiality and integrity of data transmitted over the channel. Some of the physical layer security techniques commonly used in Hybrid Satellite-Terrestrial Relay Networks (HSTRNs) are enlisted as follows:

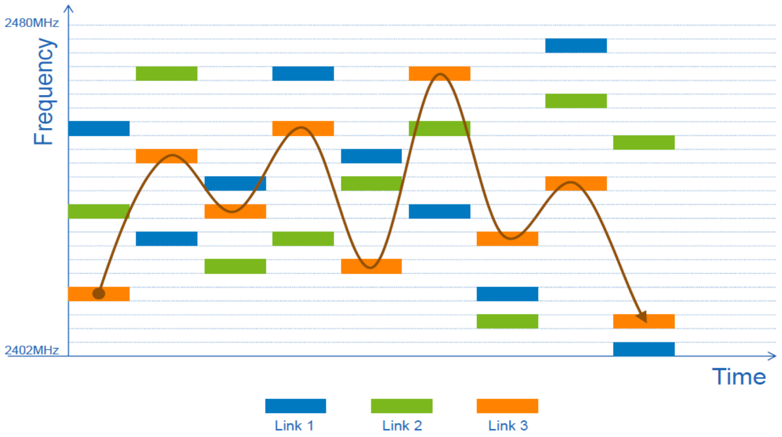
i. **Signal Power Control:** By controlling the transmit power levels at the satellite and terrestrial relay stations; it is possible to limit the coverage area and reduce the chances of eavesdropping. The power control can be optimized to provide sufficient signal quality at the intended destination while keeping the signal strength low at unauthorized receivers.

ii. **Beamforming:** Beamforming is a technique that focuses the transmitted signal towards the intended receiver, thus reducing the signal leakage to unauthorized users. By adjusting the antenna patterns at the satellite and terrestrial relays, the transmitted signal can be directed towards the desired direction, improving both security and efficiency.



Beamforming

iii. **Frequency Hopping:** Frequency hopping involves rapidly changing the frequency of transmission over a wide range of frequencies. This technique makes it difficult for eavesdroppers to capture the entire signal and extract useful information. The hopping pattern can be pre-determined or dynamically adapted based on the channel conditions.



Frequency Hopping

iv. **Artificial Noise Injection:** Artificial noise can be intentionally added to the transmitted signal to confuse eavesdroppers. The noise can be generated using special techniques and is designed to degrade the signal quality at unauthorized receivers without affecting the legitimate communication.

v. **MIMO Techniques:** Multiple-Input Multiple-Output (MIMO) techniques can be employed in hybrid satellite-terrestrial relay networks to enhance security. By utilizing multiple antennas at the transmitter and receiver, it is possible to create multiple independent signal paths, which can be combined to improve the signal quality at the intended receiver while making it difficult for eavesdroppers to decode the transmitted information.

vi. **Physical Layer Key Generation:** Physical layer security can also be achieved by exploiting the randomness inherent in communication channels to generate secret keys for encryption. Channel characteristics, such as channel fading, can be used to generate unique keys that are known only to the legitimate transmitter and receiver.

These physical layer security techniques can be combined and tailored to the specific requirements and characteristics of hybrid satellite-terrestrial relay networks to provide robust protection against eavesdropping and unauthorized access to the transmitted information.

6. Performance Analysis of HSTRNs using NOMA:

6.a. Introduction-

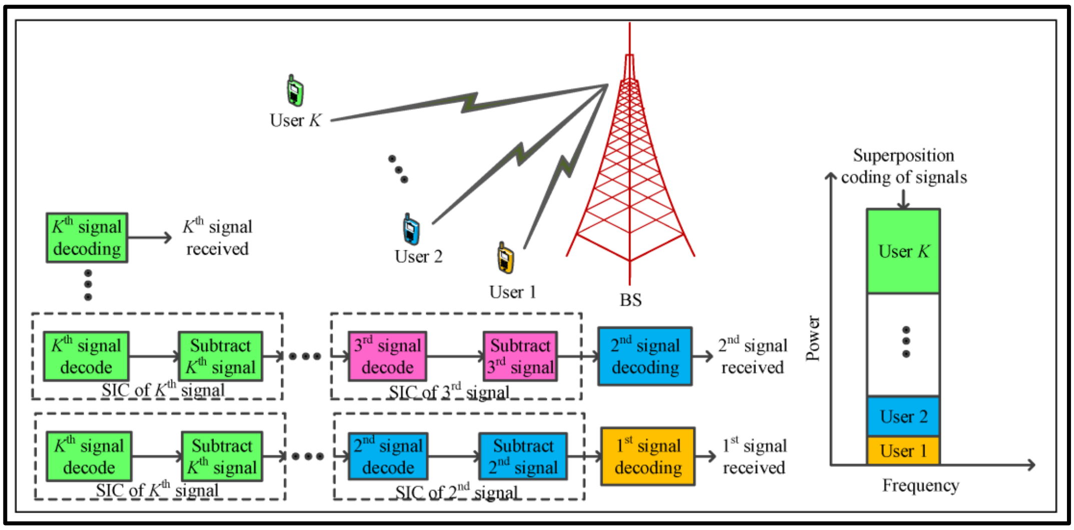
Non-orthogonal multiple access (NOMA) is a multiple access technique used in wireless communication systems to improve spectral efficiency and accommodate a large number of users. Unlike traditional orthogonal multiple access (OMA) techniques like frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA), NOMA allows multiple users for sharing the same time-frequency signals simultaneously.
In NOMA, users are separated in the power domain rather than in the orthogonal time or frequency domains. This means that multiple users can transmit their signals at the same time and frequency domain, but with different power levels. The receiver is then able to decode the signals from different users by exploiting the power differences among them.

There are two main approaches to implement NOMA:

i. **Superposition Coding (SC):** In this approach, users are allocated different power levels, and their signals are superimposed at the transmitter. The receiver then performs successive interference cancellation (SIC) to decode the signals of individual users. The user with the strongest signal is decoded first, and its signal is subtracted from the received signal to decode the next user, and so on.

ii. **Multi-User Shared Access (MUSA):** MUSA is another approach to implement NOMA, where users are allocated different power levels, but their signals are not superimposed. Instead, the signals are separated in the receiver using advanced signal processing techniques such as linear precoding, successive interference cancellation, or maximum likelihood detection.

NOMA offers several advantages over traditional OMA techniques. It allows for a higher number of users to be served simultaneously, resulting in increased spectral efficiency. It also improves the fairness of resource allocation among users, as power allocation can be adjusted to give more resources to users with poor channel conditions. Furthermore, NOMA can be combined with other advanced technologies like multiple-input multiple-output (MIMO) to achieve even higher capacity gains. NOMA has been considered as a potential technique for future wireless communication systems, including 5G and beyond, as it offers significant improvements in spectral efficiency and system capacity.



Non-Orthogonal Multiple Access (NOMA)

6.b. Data Decoding Procedure used by NOMA-

SIC: SIC stands for Successive Interference Cancellation. It is a technique used in communication systems, particularly in multi-user scenarios, to separate and decode overlapping signals from multiple users.

- **Working-**

i. **Reception:** The receiver captures the combined signal comprising overlapping transmissions from multiple users.

ii. **Detection and Decoding:** The receiver initially identifies and decodes the strongest user signal within the combined received signal, typically based on factors like signal quality or allocated power.

iii. **Interference Cancellation:** Upon successful decoding of the strongest user signal, the receiver estimates its contribution to the overall received signal and subtracts it, reducing the interference caused by that specific signal.

iv. **Iterative Decoding:** The receiver iteratively repeats the process by detecting and decoding the next strongest user signal from the modified received signal after interference cancellation. This step continues until all user signals have been decoded.

v. **Final Decoding:** Once all user signals have been decoded iteratively and their interference has been cancelled, the receiver obtains the decoded symbols for each user, enabling further processing or delivery to the respective users.

Non-Orthogonal Multiple Access (NOMA) offers several benefits that make it an appealing access technique for modern wireless communication systems. Unlike traditional orthogonal multiple access schemes, such as Orthogonal Frequency Division Multiple Access (OFDMA) or Code Division Multiple Access (CDMA), NOMA enables simultaneous transmissions by allocating different power levels or codebooks to different users. The benefits are as follows:

- **High Spectral Efficiency:** NOMA achieves higher spectral efficiency when compared to orthogonal multiple access techniques. By permitting several users to share the same time-frequency channel, NOMA maximizes the utilization of available spectrum. It is done by multiplexing the power domain of users, enabling simultaneous transmissions and increasing the overall capacity of the system.

- **Low Latency:** NOMA reduces latency by enabling simultaneous transmissions. Traditional access techniques may require sequential access, leading to increased waiting time for users. With NOMA, multiple users can transmit at the same time, resulting in reduced access time and lower latency.

- **High Reliability:** NOMA improves reliability by dynamically allocating different power levels or codebooks to users based on their channel conditions. Users with poor channel conditions are allocated higher power, ensuring that their transmissions are more robust and reliable. This enables better connectivity in challenging environments, such as cell edges or areas with weak signals.

- **Massive Connectivity:** NOMA is well-suited for supporting massive connectivity, a crucial requirement for the Internet of Things (IoT). With NOMA, numerous IoT devices can share the same resources efficiently, allowing for seamless communication among a large number of devices. This scalability is essential for applications like smart cities, industrial IoT, and sensor networks.

- **Improved Fairness:** NOMA provides improved fairness in resource allocation among users. By dynamically allocating different power levels or codebooks, NOMA can prioritize users with poorer channel conditions. This fairness enhancement ensures that all users receive a reasonable share of network resources, regardless of their channel quality.

- **High Throughput:** NOMA's simultaneous transmission capability enhances throughput in wireless communication systems. Users can transmit and receive data concurrently, which leads to increased data rates and overall system throughput. This is particularly beneficial in scenarios with high demand for data-intensive applications, such as video streaming or files transfers.

6.d. Challenges of NOMA-

Each user needs to decode the data received of all other users with the worst channel gains before decoding its own data, leading to increased receiver complexity and energy consumption.
When an error occurs in SIC at a user node, the subsequent decoding of the other users' data will likely be carried out by the same error. This implies, keeping the number of users in each cluster layer considerably low we can reduce the effect of error propagation.

7. Performance Analysis-

In this section, we have provided detailed formulations of the expressions mentioning the outage probabilities and the ergodic capacities of a network system. Before that it is beneficial to understand the different parameters for which a wireless channel depends. The details of the channel models are hereby mentioned:

7.a. Channel Model

Let us assume a scenario where the channel conditions for each hop are independent and identically distributed (i.i.d.). In the case of Shadowed-Rician fading model, the probability density function (PDF) describing the squared amplitude of the channel coefficient, denoted by|hSR|2, between the satellite and the relay can be represented as follows:

$$\begin{aligned} f_{|h_{SR}|^2}(x) &= \alpha e^{-\beta x} {}_1F_1(m_{SR};1;\delta x), x > 0 \\ &= \alpha \sum_{k=0}^{m_{SR}-1} \zeta(k) x^k e^{-(\beta-\delta)x}, \end{aligned}$$

Here, the parameters are defined as:

- $\alpha = (2b_{SR}m_{SR}/(2b_{SR}m_{SR} + \Omega_{SR})^{m_{SR}}/2b_{SR}$
- $\beta = 0.5b_{SR}$
- $\delta = \Omega_{SR}/(2b_{SR})(2b_{SR}m_{SR} + \Omega_{SR})$
- Ω_{SR}, $2b_{SR}$ and m_{SR} represent the average power, multipath components, and the fading severity parameter, respectively.
- $\zeta(k) = \frac{(-1)^k(1-m_{SR})_k\delta^k}{(k!)^2}$ and $(\bullet)_k$ denotes the Pochhammer symbol.

Additionally, the PDF of the random variable $\bar{\gamma}_{SR}$ can be defined as:

$$f_{\bar{\gamma}_{SR}}(x) = \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \frac{\Theta(M)}{(\rho_S)^{\Delta}} x^{\Delta-1} e^{-\left(\frac{\beta-\delta}{\rho_S}\right)x}$$

Here, the parameters are defined as:

- $\Theta(M) = \alpha^M \prod_{\ell=1}^{M} \zeta(i_\ell) \prod_{j=1}^{M-1} \text{ß}(\sum_{l=1}^{j} i_l + j, i_{j+1} + 1)$, $\Delta = \sum_{q=1}^{M} i_q + M$
- $\Delta = \sum_{q=1}^{M} i_q + M$
- *β(., .)* denotes the Beta function.

Finally, the cumulative distribution function (CDF) of $\bar{\gamma}_{SR}$ can be expressed as:

$$F_{\bar{\gamma}_{SR}}(x) = 1 - \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \frac{\Theta(M)}{(\rho_S)^{\Delta}} \sum_{p=0}^{\Delta-1} \frac{(\Delta-1)!}{p!} \left(\frac{\beta-\delta}{\rho_S}\right)^{-\Delta+p} x^p e^{-\left(\frac{\beta-\delta}{\rho_S}\right)x}$$

These mathematical expressions describe the distribution and behavior of the channel coefficients and random variables in the given system.

7.b. Outage Probability-

Outage performance refers to the maximum guaranteed rate or capacity achievable in a given system. It is a critical measure for evaluating the effectiveness of emergency service. In essence, the minimum outage probability is closely linked to the system's capacity. Thus, it is essential to characterize the outage behavior of energy harvesting Hybrid Sensor-Transmitter Receiver Networks (HSTRNs) to understand their performance.

The outage behaviour of energy harvesting HSTRNs pertains to the likelihood of experiencing an outage, where the system fails to meet a predefined performance level. This situation occurs when the harvested energy is insufficient to support data transmission or reception, leading to degradation in system performance.

Characterizing the outage behavior provides insights into the reliability and performance limitations of energy harvesting HSTRNs. By analyzing the outage probability, researchers and engineers can assess the system's capacity and determine the minimum outage probability achievable. This knowledge is crucial for optimizing the design and operation of energy harvesting HSTRNs, thereby improving their performance and ensuring dependable emergency services.

7.c. Calculations-

➢ **DF Protocol-**

In case of DF relay system protocols, it first decodes the received information and then forwards it to the users. With the help of an energy harvesting-enabled relay, the end-to- end transmission happens in dual phases. To conserve the energy, the relay network uses one single antenna to receive the signal from satellite. It then uses a predefined number(N) of antennas for maximum ratio transmission (MRT) to users.

During the initial sub-block of data transmission, satellite S utilizes multiple antennas to transmit a superimposed information signal represented as:

$$x = \sqrt{\Xi_1} x_1 + \sqrt{\Xi_2} x_2$$

In the first phase, the received signal at the destination (R) is influenced by the channel vector $\boldsymbol{h}_{SR}$ (representing the channel gains from S to R) and can be expressed as:

$$y_R = \sqrt{P_S} \mathbf{h}_{SR}^{\dagger} \mathbf{w}_{SR} \left(\sqrt{\Xi_1} x_1 + \sqrt{\Xi_2} x_2 \right) + n_R,$$

To facilitate decoding using Non-Orthogonal Multiple Access (NOMA), the decoding order is determined based on the channel gains. Assuming $\Xi_1 > \Xi_2$, the signal-to-interference-and-noise ratio (SINR) for detecting Ξ_1 is given by:

$$\Gamma_{R \to x_1}^{DF} = \frac{\bar{\gamma}_{SR} \Xi_1}{\bar{\gamma}_{SR} \Xi_2 + 1}$$

Here, $\bar{\gamma}_{SR} = \rho_S \left\| \mathbf{h}_{SR} \right\|_F^2$ where $\|.\|_F$ denotes Frobenius form and $\rho_S = \frac{P_S}{N_0}$. After performing successive interference cancellation (SIC) at the relay, the signal-to-noise ratio (SNR) for detecting Ξ_2 can be expressed as:

$$\Gamma_{R \to x_2}^{DF} = \bar{\gamma}_{SR} \Xi_2$$

Subsequently, energy harvesting is employed at the relay, and the energy level achieved is denoted as follows, where ER represents the relay energy:

$$E_R = \eta P_S \left\| \mathbf{h}_{SR} \right\|_F^2 \chi T$$

Based on the relay's energy level, the transmit power at the relay (PR) can be computed as:

$$P_R = \frac{E_R}{(1-\chi)\, {}^{T}\!/_{2}} = \frac{2\eta P_S \left\| \mathbf{h}_{SR} \right\|_F^2 \chi}{(1-\chi)}$$

In the second phase, the maximum ratio transmission (MRT) is utilized with a beamforming vector, resulting in $\mathbf{w}_i = \frac{\mathbf{h}_i}{\|\mathbf{h}_i\|}$ where $\|.\|$ denotes the Euclidean norm of a matrix. The received signal at user D_i is given by:

$$y_{D_i}^{DF} = P_R \left\| \mathbf{h}_i \mathbf{w}_i \right\| \left(\sqrt{\Xi_1} x_1 + \sqrt{\Xi_2} x_2 \right) + n_{D_i}$$

To decode Ξ_1, the SINR at D_i can be expressed as below where $\phi = \frac{2\eta\chi}{(1-\chi)}$

$$\Gamma_{D_1 \to x_1}^{DF} = \frac{P_R \|\mathbf{h}_1\|^2 \Xi_1}{P_R \|\mathbf{h}_1\|^2 \Xi_2 + N_0} = \frac{\phi \bar{\gamma}_{SR} \|\mathbf{h}_1\|^2 \Xi_1}{\phi \bar{\gamma}_{SR} \|\mathbf{h}_{SR}\|^2 \Xi_2 + 1}$$

Similarly, before and after SIC is performed at user D_2, the SNR for detecting signals Ξ_1 and Ξ_2 are respectively given by:

$$\Gamma_{D_2 \to x_1}^{DF} = \frac{\phi \bar{\gamma}_{SR} \|\mathbf{h}_2\|^2 \Xi_1}{\phi \bar{\gamma}_{SR} \|\mathbf{h}_2\|^2 \Xi_2 + 1}, \quad \Gamma_{D_2 \to x_2}^{DF} = \phi \bar{\gamma}_{SR} \|\mathbf{h}_2\|^2 \Xi_2$$

The PDF and CDF of $\|\mathbf{h}_1\|^2$ are given as respectively:

$$f_{\|\mathbf{h}_i\|^2}(x) = \frac{x^{N_i m_i - 1}}{\Gamma(N_i m_j) \Lambda_i^{N_i m_j}} e^{-\frac{x}{\Lambda_j}}$$

$$F_{\|\mathbf{h}_i\|^2}(x) = 1 - e^{-\frac{x}{\Lambda_i}} \sum_{n_i=0}^{N_i m_i - 1} \frac{x^{n_i}}{\Lambda_i^{n_i} n_i!}$$

We introduce $\Psi_i = 2^{\frac{2R_i}{1-\chi}} - 1$ as the threshold signal-to-noise ratios (SNRs) for the *i*-th user to decode the transmitted signal x_i. The outage probability of D_1 is determined by the probability that the minimum of the decoding SNRs of R, D_1, and D_2 is below Ψ_1. This can be expressed as:

$$\begin{aligned} \mathcal{P}_{out,D_1}^{DF} &= \Pr\left(\min\left(\Gamma_{R \to x_1}^{DF}, \Gamma_{D_1 \to x_1}^{DF}, \Gamma_{D_2 \to x_1}^{DF} \right) < \Psi_1 \right) \\ &= 1 - \Pr\left(\Gamma_{R \to x_1}^{DF} > \Psi_1, \Gamma_{D_1 \to x_1}^{DF} > \Psi_1, \Gamma_{D_2 \to x_1}^{DF} > \Psi_1 \right) \end{aligned}$$

The closed form outage probability of D_1 is given by:

$$\mathcal{P}_{out,D_1}^{DF} = 1 - \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{m_1N_1-1} \sum_{n_2=0}^{m_2N_2-1} \frac{(\beta-\delta)^{n_1+n_2-\Delta}}{n_1! n_2! \Lambda_1^{n_1} \Lambda_2^{n_2}} \left(\frac{\kappa_1}{\rho_S \phi}\right)^{n_1+n_2} \times \Gamma\left(\Delta - n_1 - n_2, \frac{\kappa_1(\beta-\delta)}{\rho_S}, \frac{(\Lambda_1+\Lambda_2)(\beta-\delta)\kappa_1}{\Lambda_1\Lambda_2\phi\rho_S}\right).$$

Similarly, the outage probability of D_2 is given by:

$$\begin{aligned}\mathcal{P}_{out,D_2}^{DF} &= \Pr\left(\min\left(\Gamma_{R\to x_2}^{DF}, \Gamma_{D_2\to x_2}^{DF}\right) < \Psi_2\right) \\ &= 1 - \Pr\left(\Gamma_{R\to x_2}^{DF} > \Psi_2, \Gamma_{D_2\to x_2}^{DF} > \Psi_2\right) \\ &= 1 - \Pr\left(\bar{\gamma}_{SR} > \kappa_2, \|\mathbf{h}_2\|^2 > \frac{\kappa_1}{\bar{\gamma}_{SR}\phi}\right)\end{aligned}$$

We can lead to a closed-form expression for the outage probability of D_2:

$$\mathcal{P}_{out,D_2}^{DF} = 1 - \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_2=0}^{m_2N_2-1} \frac{(\beta-\delta)^{n_2-\Delta}}{n_2!} \left(\frac{\kappa_2}{\Lambda_2\rho_S\phi}\right)^{n_2} \Gamma\left(\Delta - n_2, \frac{\kappa_2(\beta-\delta)}{\rho_S}, \frac{\kappa_2(\beta-\delta)}{\Lambda_2\phi\rho_S}\right)$$

- **AF Protocol:**

The AF relay protocol amplifies the received signal before transmitting it to the users. Therefore, we define variable gain (G) as:

$$G = \sqrt{\frac{P_R}{\|\mathbf{h}_{SR}\|_F^2 P_S + N_0}}.$$

In the second phase, the received signal can be expressed as-

$$\begin{aligned}y_{D_i}^{AF} &= \|\mathbf{h}_i\mathbf{w}_i\| G y_R + n_{D_i} \\ &= \|\mathbf{h}_i\mathbf{w}_i\| G\sqrt{P_S}\mathbf{h}_{SR}^{\dagger}\mathbf{w}_{SR}\left(\sqrt{\Xi_1}x_1 + \sqrt{\Xi_2}x_2\right) \\ &+ \|\mathbf{h}_i\mathbf{w}_i\| G n_R + n_{D_i}.\end{aligned}$$

Hence, the instantaneous received SINR for D_1 can be given by:

$$\begin{aligned}\Gamma_{D_1\to x_1}^{AF} &= \frac{G^2 P_S \|\mathbf{h}_1\|^2 \|\mathbf{h}_{SR}\|^2 \Xi_1}{G^2 P_S \|\mathbf{h}_1\|^2 \|\mathbf{h}_{SR}\|^2 \Xi_2 + \|\mathbf{h}_1\|^2 G^2 N_0 + N_0} \\ &\simeq \frac{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_1}{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_2 + \|\mathbf{h}_1\|^2\phi + 1}.\end{aligned}$$

As per the framework of NOMA, the approximate SINR expressions for D_1 and D_2 are expressed as:

$$\Gamma_{D_2\to x_1}^{AF} \simeq \frac{\phi\bar{\gamma}_{SR}\|\mathbf{h}_2\|^2\Xi_1}{\phi\bar{\gamma}_{SR}\|\mathbf{h}_2\|^2\Xi_2 + \|\mathbf{h}_2\|^2\phi + 1}$$

$$\Gamma_{D_2\to x_2}^{AF} \simeq \frac{\phi\|\mathbf{h}_2\|^2\bar{\gamma}_{SR}\Xi_2}{\|\mathbf{h}_2\|^2\phi + 1}.$$

The outage probability of D_1 (in case of AF relaying) can be expressed as:

$$\mathcal{P}_{out,D_1}^{AF} = \Pr\left(\Gamma_{D_1\to x_1}^{AF} < \Psi_1\right)$$

Thus, we can get the closed form outage probability of D_1 as below:

$$\mathcal{P}_{out,D_1}^{AF} = 1 - 2\sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{N_1 m_1 - 1} \sum_{q=0}^{\Delta-1} \binom{\Delta-1}{q} \frac{(\Lambda_1\phi)^q}{n_1!\,(\beta-\delta)^{\Delta}} \\ \times \left(\frac{\kappa_1(\beta-\delta)}{\Lambda_1\phi\rho_S}\right)^{\frac{\Delta+q+n_1}{2}} e^{-\frac{\kappa_1(\beta-\delta)}{\rho_S}} K_{\Delta-q-n_1}\left(2\sqrt{\frac{\kappa_1(\beta-\delta)}{\Lambda_1\phi\rho_S}}\right)$$

Similarly, the outage probability of *D₂* (in case of AF relaying) can be expressed as:

$$\mathcal{P}_{out,D_2}^{AF} = \Pr\left(\Gamma_{D_2\to x_2}^{AF} < \Psi_2\right) \\ = 1 - \Pr\left(\bar{\gamma}_{SR} > \frac{\kappa_2\left(\|\mathbf{h}_2\|^2\phi + 1\right)}{\phi\|\mathbf{h}_2\|^2}\right)$$

7.d. Ergodic Capacity:

We will now provide mathematical derivations of ergodic capacity for DF and AF relaying protocol systems. Theoretically it has been declared that ergodic capacity of a wireless network is an important parameter to determine the average link capacity of a channel.

- **Calculations:**

i.DF Protocol-

Let's derive the ergodic capacity for a relay using the Decode-and-Forward (DF) protocol. The achievable capacity at destination *D₁* can be computed as follows:

$$\mathcal{C}_{D_1}^{DF} = \frac{1-\chi}{2}\log_2\left(1 + \min\left(\Gamma_{R\to x_1}^{DF}, \Gamma_{D_1\to x_1}^{DF}\right)\right) \\ = \frac{1-\chi}{2}\log_2\left(1 + \min\left(\frac{P_S\|\mathbf{h}_{SR}\|_F^2\,\Xi_1}{P_S\|\mathbf{h}_{SR}\|_F^2\,\Xi_1 + N_0}, \frac{P_R\|\mathbf{h}_1\|^2\Xi_1}{P_R\|\mathbf{h}_1\|^2\Xi_2 + N_0}\right)\right)$$

In practice, the relay typically harvests a small amount of energy, resulting in a lower transmit power compared to the source. This implies that the Signal-to-Interference-plus-Noise Ratio (SINR) at the destinations is lower than at the relay. Thus, it is imperative to assume that:

$$\frac{P_S\|\mathbf{h}_{SR}\|_F^2\Xi_1}{P_S\|\mathbf{h}_{SR}\|_F^2\Xi_1 + N_0} > \frac{P_R\|\mathbf{h}_1\|^2\Xi_1}{P_R\|\mathbf{h}_1\|^2\Xi_2 + N_0}$$

Consequently, the capacity at *D₁* can be simplified as:

$$\mathcal{C}_{D_1}^{DF} = \frac{1-\chi}{2}\log_2\left(1 + \frac{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_1}{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_2 + 1}\right) \\ = \frac{1-\chi}{2}\log_2\left(\frac{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2 + 1}{\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_2 + 1}\right)$$

This leads to ergodic capacity for user D1 as below:

$$\bar{\mathcal{C}}_{D_1}^{DF} = E\left\{\frac{1-\chi}{2}\log_2\left(\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2 + 1\right)\right\} \\ - E\left\{\frac{1-\chi}{2}\log_2\left(\phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_2 + 1\right)\right\} \\ = \underbrace{\frac{1-\chi}{2\ln 2}\int_0^{\infty}\frac{1-F_{H_1}(x)}{1+x}dx}_{L_1} - \underbrace{\frac{1-\chi}{2}\int_0^{\infty}\frac{1-F_{H_2}(x)}{1+x}dx}_{L_2}$$

Here, $H_1 = \phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2$ and $H_2 = \phi\bar{\gamma}_{SR}\|\mathbf{h}_1\|^2\Xi_2$. By using previous research findings and algebraic manipulations, we can calculate $F_{H1}(x)$ as:

$$F_{H_1}(x) = 1 - \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{p=0}^{\Delta-1} \frac{(\Delta-1)!2^{-N_1 m_1 - p + 1}}{p!\Gamma(N_1 m_1)(\beta-\delta)^{\Delta}} \times \left(\sqrt{\frac{4x(\beta-\delta)}{\rho_S\phi\Lambda_1}}\right)^{N_1 m_1 + p} K_{N_1 m_1 - p}\left(\sqrt{\frac{4x(\beta-\delta)}{\rho_S\phi\Lambda_1}}\right).$$

Now, at D_2, the achievable capacity can be represented as:

$$C_{D_2}^{DF} = \frac{1-\chi}{2}\log_2\left(1 + \min\left(\Gamma_{R\to x_2}^{DF}, \Gamma_{D_2\to x_2}^{DF}\right)\right)$$

Thus, the ergodic capacity of D_2 is given by:

$$\bar{C}_{D_2}^{DF} = \frac{1-\chi}{2\ln 2} \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{p=0}^{\Delta-1} \frac{\Gamma(\Delta)}{\Gamma(N_2 m_2)\, p!(\beta-\delta)^{\Delta}} G_{1,3}^{3,1}\left(\frac{\beta-\delta}{\Lambda_2\phi\Xi_2\rho_S}\,\middle|\, \begin{matrix} 0 \\ 0, N_2 m_2, p \end{matrix}\right)$$

ii.AF Protocol-

The achievable capacity at destination Di in the Amplify-and-Forward (AF) relaying protocol is given by:

$$C_{D_i}^{AF} = \frac{1-\chi}{2}\log_2\left(1 + \Gamma_{D_i\to x_i}^{AF}\right)$$

Moreover, the ergodic capacity of user D_1 can be expressed as:

$$\bar{C}_{D_1}^{AF} = \frac{1-\chi}{2\ln 2} \int_0^{\Xi_2/\Xi_1} \frac{1 - F_{\Gamma_{D_1\to x_1}}(x_1)}{1 + x_1} dx_1$$

In the previous ergodic capacity formulation, the cumulative distribution function (CDF) of $\Gamma_{D_1\to x_1}$ can be defined as follows:

$$F_{\Gamma_{D_1\to x_1}}(x_1) = 1 - 2\sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{N_1 m_1 - 1} \sum_{q=0}^{\Delta-1} \begin{pmatrix} \Delta-1 \\ q \end{pmatrix} \frac{(|\Lambda_1\phi)^q}{n_1!(\beta-\delta)^{\Delta}} \times \left(\frac{x_1(\beta-\delta)}{(\Xi_1 - \Xi_2 x_1)\Lambda_1\phi\rho_S}\right)^{\frac{\Delta+q+n_1}{2}} e^{-\frac{x_1(\beta-\delta)}{(\Xi_1-\Xi_2 x_1)\rho_S}} K_{\Delta-q-n_1}\left(\frac{x_1(\beta-\delta)}{(\Xi_1 - \Xi_2 x_1)\Lambda_1\phi\rho_S}\right)$$

To compute $\bar{C}_{D_1}^{AF}$, we use Gaussian-Chebyshev with $\phi_n = \cos\left(\frac{2n-1}{2N}\pi\right)$, and then solving the integral, the expression for $\bar{C}_{D_1}^{AF}$ becomes:

$$\bar{C}_{D_1}^{AF} \approx \frac{1-\chi}{\ln 2} \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{N_1 m_1 - 1} \sum_{q=0}^{\Delta-1} \begin{pmatrix} \Delta-1 \\ q \end{pmatrix} \frac{(\Lambda_1\phi)^q}{n_1!(\beta-\delta)^{\Delta}} \frac{\pi}{N} \sum_{n=1}^{N} \frac{\Xi_1\sqrt{1-\phi_n^2}}{2 - \Xi_1(1-\phi_n)} \times e^{-\frac{(1+t)}{\Xi_2\rho_S(1-t)}(\beta-\delta)} \left(\frac{(\beta-\delta)(1+\phi_n)}{\Lambda_1\phi\rho_S\Xi_2(1-\phi_n)}\right)^{\frac{\Delta+q+n_1}{2}} K_{\Delta-q-n_1}\left(2\sqrt{\frac{(\beta-\delta)(1+\phi_n)}{\Lambda_1\phi\rho_S\Xi_2(1-\phi_n)}}\right)$$

Similarly, the ergodic capacity of D_2, denoted by $\bar{C}_{D_2}^{AF}$, can be computed as:

$$\bar{\mathcal{C}}_{D_2}^{AF} = \frac{1-\chi}{\ln 2} \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{N_1 m_1-1} \sum_{q=0}^{\Delta-1} \binom{\Delta-1}{q} \frac{(\Lambda_1\phi)^q}{n_1!(\beta-\delta)^{\Delta} 2^{\Delta+q+n_1}} \times \int_0^{\infty} \frac{e^{-\frac{x_2(\beta-\delta)}{\Xi_2\rho_S}}}{1+x_2} \left(\sqrt{\frac{4x_2(\beta-\delta)}{\Xi_2\Lambda_1\phi\rho_S}}\right)^{\Delta+q+n_1} K_{\Delta-q-n_1}\left(\sqrt{\frac{4x_2(\beta-\delta)}{\Xi_2\Lambda_1\phi\rho_S}}\right) dx_2$$

Subjecting to mathematical manipulations and usage of previous results, we can hence formulate the closed form expression for ergodic capacity of D_2 as:

$$\bar{\mathcal{C}}_{D_2}^{AF} = \frac{1-\chi}{2\ln 2} \sum_{i_1=0}^{m_{SR}-1} \cdots \sum_{i_M=0}^{m_{SR}-1} \Theta(M) \sum_{n_1=0}^{N_1 m_1-1} \sum_{q=0}^{\Delta-1} \binom{\Delta-1}{q} \frac{(\Lambda_1\phi)^q}{n_1!(\beta-\delta)^{\Delta}} \times G_{1,[1:0],0,[1:2]}^{1,1,0,1,2}\left(\begin{array}{c|c} \frac{\Xi_2\rho_S}{(\beta-\delta)} & 1 \\ & 0;- \\ \frac{1}{\Lambda_1\varphi} & - \\ & 0;\Delta,q+n_1 \end{array} \right).$$

8. CONCLUSION:

Thus, we have provided a detailed explanation of the current state-of-the-art in the field of Hybrid Satellite Terrestrial Network (HSTNs). We have displayed the HSTN network architecture and provided an overview of modern working techniques in cooperative and cognitive HSTN network models. We have shown how Relay Satellites can be effective in HSTRNs for long-term applications and how HSTRN technology can be preserved with utmost physical layer security. Moreover, we have simulated the optimization of SNR in Relay Based Technology using MATLAB and reviewed Shannon-Hartley Law. Finally, advanced technologies like NOMA and SIC which can be incorporated in HSTRNs have also been reviewed, along with emphasis on its pros, cons as well as mathematical analysis. Ultimately, all these technologies can culminate to the initiation of 6G technology in the long run.

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