Satellite Communication System adopts OFDM-MIMO Technology with High Speed Connectivity

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Abstract. The space communication development has strong urgent requirement for technology upgrading and evolution. The satellite communication capacity can be advanced by the application of a higher data transmission efficiency. It will be contented with diversified High Throughput Satellite (HTS) communication application requirements. A satellite communication system architecture design featured by higher transmission efficiency using Multi-Input & Multi-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) technology which has been wildly used in next generation of terrestrial wireless communications has been presented. It is proposed to solving problems on multiplexing data transmission, receiving signal’s anti-interference, and supporting various multi-user terminals. The throughput and application analysis was done to evaluate system performance in terms of diverse HTSs. A comprehensive evaluation and simulation analysis of space communication application efficiency are carried out to verify the feasibility of basic space application under the diverse simulation conditions. The total throughput of the communication system can reach up to 259Gbps as extremely high speed connectivity, and the maximum spectrum efficiency is close to the ultimate performance of 100bits/s/Hz.

Keywords: OFDM-MIMO; HTS communication; Space application.

1. Introduction

The hotspot study on the novel method and system has been delivering for developing of the next generation of terrestrial wireless communication. It is represented by several new techniques such as the Multi-Input & Multi-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM), which are progressively developing in progress [1]. These new technologies featured by taking full advantage of the channel characteristics of wireless transmission, as well as a combination of the resources of frequency, timeslot, coding, and space beam diversity and multiplexing, make a result of great improvement on the system performance. It has realized that transmitting signal on different channels by distributed array antenna could be modulated to one carrier frequency at the same time with common shared channel bandwidth, which significantly enhanced the data transmission efficiency. The wireless communication fields have been boosted by the application of these hotspot techniques for a long term evolution and sustainable development [2][3].

Space communication development, however has been influenced since long time ago, by many restrained factors like electronic devices, materials, craftworks, etc. The technologies adopted in space communication generically dropped behind those in modern terrestrial wireless communication. With the expansion of the scope and objects of human activities, it has strong urgent requirement for the upgrading and evolution of the current technology system. The satellite communication capacity can be advanced by the application of a higher data transmission efficiency in together with a wide-band...
resource. It will be contented with diversified High Throughput Satellite (HTS) communication application requirements. As an act of exploiting potential application of satellite communication and promoting technical integration between space segment and ground segment, it is essential to make investigation in novel technologies used in terrestrial wireless communications.

In this paper a satellite communication system architecture design featured by higher transmission efficiency using Multi-Input & Multi-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) technology has been presented. It is proposed to solving problems on multiplexing data transmission, receiving signal’s anti-interference, and supporting various ground terminals (multi-user, portable, mobile vehicle).

Hereinafter, the detailed system architecture design with mathematic module was introduced. Then a throughput and application analysis is established to evaluate system performance. The throughput on each single channel, throughput overall and frequency efficiency will be increased in terms of the variation of system parameters configuration. A comprehensive evaluation and simulation analysis of space communication application efficiency are carried out to verify the feasibility of basic space application under the diverse simulation conditions. Finally, the development analysis is made as further study to prospect for its future application scenarios. The project will be applied towards satisfying multiple space data transmission extensions for satellite-to-ground, satellite-to-satellite inner space constellation, and space long distance communication.

2. System Architecture Design with Higher Efficiency Data Transmission

The system architecture consists of two parts, transmitting subsystem and reception subsystem, as shown in figure 1.

In transmitting subsystem, the transmitting data is firstly converted from serial to parallel (S/P). For a \(N_{TX}\) multi-output system, each sub-channel from No.1 to No.\(N_{TX}\) is equally with the same architecture. Taking No.1 sub-channel on the upper branch in figure 1(a) as an example, data source is coded via an optional channel coding method, such as LDPC or Turbo coding. Afterwards, it is modulated through M-QAM modulation constellation scheme, where data source is transformed from binary stream to symbol stream, the ratio between binary stream and symbol stream is \(\log_2 M\) \([4]\).

Next, symbols are formed into an OFDM frame format, among which is inserted and mixed with pilot symbol in terms of several patterning. The OFDM signal is multiplexed by an IFFT algorithm. Each sub-channel could be equally deployed with same amount of sub-carriers. Assume that the OFDM sub-carrier quantity is totally \(N_{SC}\), equally divided into \(N_{TX}\) group, i.e., each sub-channel is equally deployed \(N_{SC}/N_{TX}\) sub-carriers, providing that \(N_{SC}\) can be divided by \(N_{TX}\) exactly with no remainder. Each sub-carrier is modulated by single data or pilot symbol. Suppose M-QAM modulated symbol on each sub-channel is \(d_{k,m}\), where subscript “\(k\)” denotes the \(k\) th \((0 \leq k \leq N_{SC}/N_{TX}-1)\) sub-carrier of each group on the \(m\) th \((0 \leq m \leq N_{TX}-1)\) sub-channel, the generated OFDM signal \(S_m(t)\) for the \(m\) th sub-channel can be parsed as given below \([5]\):

\[
S_m(t) = \sum_{k=1}^{N_{SC}/N_{TX}} d_{k,m} \times \exp\left(j \cdot 2\pi f_k t\right)
\]

where \(m = 0, 1, 2, \cdots, N_{TX} - 1\)

Thus the signal on each sub-channel are orthogonal and avoid interference with each other while being capable of transmitting all signal from various sub-channel and antennas at the same time, with same center RF frequency, as well as sharing same RF bandwidth.
In reception subsystem, for a NRX multi-input system, each sub-channel from No.1 to No.NRX is equally transmitted by TX antenna on each sub-channel.

After OFDM framed, signal is through D/A conversion, up-converter and HPA (High Power Amplifier), then transmitted by TX antenna on each sub-channel.

For FFT and quadrature detector, a basic processing algorithm is given below:

\[ R_n(t) = \sum_{\alpha=0}^{N_{TX}-1} S_{\alpha}(t) = \sum_{\alpha=0}^{N_{TX}-1} \sum_{k=1}^{N_{RX}} d_{k,\alpha} \times \exp(j \times 2\pi f_{\alpha} t) \]  
where \( n = 0, 1, 2, \ldots, N_{RX} - 1 \)

For FFT and quadrature detector, a basic processing algorithm is given below:

\[ \exp(j \times 2\pi f_{\alpha} t) = \cos(2\pi f_{\alpha} t) + j \times \sin(2\pi f_{\alpha} t) \]  

For FFT and quadrature detector, a basic processing algorithm is given below:

\[ R_n(t) = \frac{T_s}{k=1} \sum_{l=0}^{N_{TX}} R_{l,k}(t) \times \exp(-j \times 2\pi f_{l,k} t) \]

\[ = \frac{T_s}{k=1} \sum_{l=0}^{N_{TX}} S_{l,k}(t) \times \exp(-j \times 2\pi f_{l,k} t) \]

\[ = \frac{T_s}{k=1} \sum_{l=0}^{N_{TX}} \sum_{k=1}^{N_{RX}} d_{k,\alpha} \times \exp(j \times 2\pi f_{l,k} t) \times \exp(-j \times 2\pi f_{l,k} t) \]

\[ = \begin{cases} d_{k,\alpha} & n = m \quad \text{and} \quad k = l \\ 0 & n \neq m \quad \text{or} \quad k \neq l \end{cases} \]

where \( n = 0, 1, 2, \ldots, N_{RX} - 1 \)

Figure 1. Satellite Communication System Architecture with NTX-by-NRX Antennas and Transceivers. After OFDM framed, signal is through D/A conversion, up-converter and HPA (High Power Amplifier), then transmitted by TX antenna on each sub-channel.

In reception subsystem, for a NRX multi-input system, each sub-channel from No.1 to No.NRX is equally transmitted by TX antenna on each sub-channel.

Take No.1 sub-channel on the upper branch in Figure 1(b) as an example, received RF signal is firstly sent to LNA, down-converter and BPF (Band-Pass Filter). Then the signal is through an A/D conversion and OFDM de-framed. The OFDM signal is de-multiplexed by a FFT algorithm with quadrature detection (“”). Where signal on No.1 sub-channel is purified from the mixed signal that on any other sub-channel. As for each sub-channel on reception antenna RX, the received RF signal is mixed with all the transmitted signal from each single TX antenna. The received signal \( R_n(t) \) on the \( n \) th sub-channel can be parsed as given below, despite channel noise (AWGN) and other interference.
It is proven that the $r_{i,n}$ equals to the $d_{k,m}$ only when both sub-carrier and sub-channel are exactly identical, despite channel noise and other interference.

Next, pilot symbol is separated from data stream, which is applied for performing channel estimation and compensation on M-QAM demodulation. Data symbol is retrieved to binary stream and decoded in accordance with an optional channel coding method, then converted from parallel to serial (P/S) finally to the terminal user.

The pilots are inserted through a 3-D pattern. For antenna (TX or RX) No.1, a pilot is deployed at the first position every each group of certain amount of data symbols (sub-carrier) for first OFDM symbol, for second OFDM symbol within one same timeslot, pilots are deployed at every second position. For antenna (TX or RX) No.2, all pilots are backwards moved by one position along sub-carrier direction. The rest can be deduced by analogy.

![Figure 2. 3-D Pilot Patterning (Partial Profile)](image)

This patterning is designed in an integrated consideration with those realistic complicated channel transmission characteristics (time/phase delay, frequency shift, etc.) among subcarriers, timeslots and space array antennas.

The channel estimation approach adopts a conventional grouping linear interpolation [6]; received data symbol is firstly compensated by the Channel Characteristic Integrated Estimation unit; then compensated by the estimated channel characteristics of pilot adjacent to that symbol through each Sub-Channel Estimation unit. It can be implemented to impair any multiplicative channel interference to data symbol.

3. Throughput and Application analysis

Communication System total throughput is directly in proportion with the data transmission efficiency. The transmission efficiency is influenced by modulation scheme, channel coding, MIMO antenna patterning, and so on.

As for HTS telecommunication satellite system, generally the Ka-band power amplifier (Traveling Wave Tube Amplifier (TWTA) or Solid State Power Amplifier (SSPA) ) are configured as RF signal retransmitting and power-amplifying, whose average bandwidth is approx. 400MHz, thus the original data rate is 400Mbps. The data rate on each single channel shall be increasingly speeding along with the extending of the system architecture and parameters configuration. Providing that totally fifty (50) channels of power amplifier (TWTA or SSPA) are configured on the HTS communication satellite model.

On table 1 below, for each single channel of power amplifier (TWTA or SSPA) on-board, modulation scheme is set as the one selectable among BPSK, QPSK, 16-QAM, 64-QAM, respectively. Channel coding scheme is selected among 1/2-LDPC, 3/4-LDPC, and 8/9-Turbo, respectively. MIMO antenna is patterned by 2-by-2, 4-by-4, 8-by-8, and 16-by-16, respectively.

Table 1 below presents the Throughput per channel, Throughput Aggregate, as well as Frequency Efficiency.
Table 1. Throughput and Application Scene Parameters

| Scene | Modulation scheme | Channel Coding | MIMO XX-by-YY | Throughput /channel (Gbps) | Throughput Aggregate (Gbps) | Frequency Efficiency (bit/s/Hz) |
|-------|-------------------|----------------|--------------|---------------------------|-----------------------------|-------------------------------|
| 1     | BPSK              | 1/2-LDPC       | 2-by-2       | 0.8                       | 40                          | 2                             |
| 2     | BPSK              | 3/4-LDPC       | 2-by-2       | 0.8                       | 40                          | 2                             |
| 3     | QPSK              | 1/2-LDPC       | 2-by-2       | 1.6                       | 80                          | 4                             |
| 4     | QPSK              | 3/4-LDPC       | 2-by-2       | 1.6                       | 80                          | 4                             |
| 5     | QPSK              | 8/9-Turbo      | 2-by-2       | 1.6                       | 80                          | 4                             |
| 6     | QPSK              | 1/2-LDPC       | 4-by-4       | 3.2                       | 160                         | 8                             |
| 7     | QPSK              | 3/4-LDPC       | 4-by-4       | 3.2                       | 160                         | 8                             |
| 8     | QPSK              | 8/9-Turbo      | 4-by-4       | 3.2                       | 160                         | 8                             |
| 9     | 16-QAM            | 1/2-LDPC       | 2-by-2       | 3.2                       | 160                         | 8                             |
| 10    | 16-QAM            | 3/4-LDPC       | 2-by-2       | 3.2                       | 160                         | 8                             |
| 11    | 16-QAM            | 3/4-LDPC       | 4-by-4       | 6.4                       | 320                         | 16                            |
| 12    | 16-QAM            | 8/9-Turbo      | 4-by-4       | 6.4                       | 320                         | 16                            |
| 13    | 64-QAM            | 1/2-LDPC       | 4-by-4       | 9.6                       | 480                         | 24                            |
| 14    | 64-QAM            | 3/4-LDPC       | 4-by-4       | 9.6                       | 480                         | 24                            |
| 15    | 64-QAM            | 1/2-LDPC       | 8-by-8       | 19.2                      | 960                         | 48                            |
| 16    | 64-QAM            | 3/4-LDPC       | 8-by-8       | 19.2                      | 960                         | 48                            |
| 17    | 64-QAM            | 8/9-Turbo      | 8-by-8       | 19.2                      | 960                         | 48                            |
| 18    | 64-QAM            | 3/4-LDPC       | 16-by-16     | 38.4                      | 1920                        | 96                            |
| 19    | 64-QAM            | 8/9-Turbo      | 16-by-16     | 38.4                      | 1920                        | 96                            |

Note: throughput statistic does not consider the channel coding.

The above 19 scenes present system throughput variation in terms of the miscellaneous combined system parameters of modulation scheme, channel coding, and MIMO antenna patterning. The throughput on each single channel, throughput aggregate and frequency efficiency will be increased in terms of the variation of system parameters (modulation scheme, channel coding, and MIMO antenna patterning) configuration.

For scene 1#~5#, they could be used as a standard HTS communication satellite application system, with 40~80Gbps of total throughput; it is able to support most generic multimedia and broadcasting services [7]. The frequency efficiency is 2~4 bits/s/Hz.

For scene 6#~10#, they would be applied as a Very HTS (VHTS) communication satellite application system, with up to 160Gbps of total throughput; it can support communication among each other of several thousands (1,000s) people, where includes such as shopping mall, cinema, vocal concert hall. The frequency efficiency is 8 bits/s/Hz.

For scene 11#~14#, they would be applied as an Extreme HTS (EHTS) communication satellite application system, with up to 480Gbps of total throughput; it can support communication among each other of tens of thousands (10,000s) people, where includes such as gymnasium, venue [8]. The frequency efficiency is 16~24 bits/s/Hz.

For scene 15#~17#, they would be applied as a Supreme HTS (SHTS) communication satellite application system, with up to 960Gbps (almost 1TB) of total throughput; it can support communication among each other of hundreds of thousands (100,000s) people, where includes like stadium with worldwide football game and alike rendezvous. The frequency efficiency is up to 48 bits/s/Hz.

For scene 18#~19#, they would be applied as an Ultimate HTS (UHTS) communication satellite application system, with up to 1.92Tbps of total throughput; it can support communication among each other of millions (1,000,000s) people, probably cover a majority area of the entire urban city. The frequency efficiency can reach next to 100 bits/s/Hz level.

4. Experimental Work

The experimental work is performed under simulation environment with help of MATLAB SIMULINK toolkit. Several of communication modules within the toolkit are applied to build up the simulation
transmitting and reception subsystems respectively as shown in figure 1. The simulation environment has been fully run on a laptop PC with a 3.4GHz CPU, 4GB RAM and 500GB SSD. Select scene 6#, 11#, 19# on table 1 as simulation experimental work.

For scene 6#, satellite C-band frequency range is set as 3.4~4.5GHz with 1GHz bandwidth, 50 channels (25 HP and 25 VP) and 40MHz bandwidth for each channel.

**Table 2. C-band SATCOM Emulation Parameters**

| Input          | Unit Value | Output       | Unit Value |
|----------------|------------|--------------|------------|
| MIMO           | k-by-k     | BW each      | MHz        |
| OFDM           | 4096       | Rate each    | Mbps       |
| Modulation     | QPSK       | Channels     |            |
| Coding         | 1/2 LDPC   | Throughput   | Gbps       |
| Constellation  | $\beta$    | Frequency Efficiency | bit/s/Hz |

Data rate for single channel is up to 80Mbps, system capacity is multiplexed by 4 times. Thus, total throughput reaches to 16Gbps, where the frequency efficiency is 8 bit/s/Hz.

For scene 11#, satellite Ku-band frequency range is set as 11.45~12.75GHz with 1.3GHz bandwidth, 40 channels (20 HP and 20 VP) and 60MHz bandwidth for each channel.

**Table 3. Ku-band SATCOM Emulation Parameters**

| Input          | Unit Value | Output       | Unit Value |
|----------------|------------|--------------|------------|
| MIMO           | k-by-k     | BW each      | MHz        |
| OFDM           | 8192       | Rate each    | Mbps       |
| Modulation     | 16-QAM     | Channels     |            |
| Coding         | 3/4 LDPC   | Throughput   | Gbps       |
| Constellation  | $\beta$    | Frequency Efficiency | bit/s/Hz |

Data rate for single channel is up to 240Mbps, system capacity is multiplexed by 8 times. Thus, total throughput reaches to 76.8Gbps, where the frequency efficiency is 32 bit/s/Hz.

For scene 19#, satellite Ka-band frequency range is set as 18.7~20.2GHz with 1.5GHz bandwidth, 12 channels (6 HP and 6 VP) and 225MHz bandwidth for each channel.

**Table 4. Ka-band SATCOM Emulation Parameters**

| Input          | Unit Value | Output       | Unit Value |
|----------------|------------|--------------|------------|
| MIMO           | k-by-k     | BW each      | MHz        |
| OFDM           | 16384      | Rate each    | Mbps       |
| Modulation     | 64-QAM     | Channels     |            |
| Coding         | 8/9-Turbo  | Throughput   | Gbps       |
| Constellation  | $\beta$    | Frequency Efficiency | bit/s/Hz |

Data rate for single channel is up to 1350Mbps (1.35Gbps), system capacity is multiplexed by 16 times. Thus, total throughput reaches to 259Gbps, where the frequency efficiency is 96 bit/s/Hz.

As shown in figure 3(a), for simulation scenario 6#, QPSK modulation is adopted, the signal-to-noise ratio (SNR) is in the range of 10~20dB, and sampling is conducted at 1dB step interval. When the SNR is 13dB, the bit error rate (BER) is lower than $10^{-3}$, which is about 0.000819. When the SNR is 18db,
the BER is lower than $10^{-4}$, which is about 0.000083. If the SNR is further improved, the BER can be further reduced. For audio and video multimedia service transmission, the BER of $10^{-5}$ can guarantee its basic application feasibility.

As shown in figure 3(b), for simulation scenario 11#; 16-QAM modulation is adopted, and the SNR is in the range of 15~25dB, and sampling is conducted according to the step interval of 1dB. When the SNR is 19dB, the BER is lower than $10^{-3}$, which is about 0.000747. When the SNR is 25dB, the BER is slightly lower than $10^{-4}$, which is about 0.000094. Further improve the SNR; the BER reduction is still relatively slow. For high-speed data transmission services, the BER of $10^{-3}$ can guarantee its basic application feasibility.

As shown in figure 3(c), for simulation scenario 19#, 64-QAM modulation is adopted, the SNR is in the range of 20~30dB, and the sampling is conducted at the step interval of 1dB. When the SNR is 25dB, the BER is lower than $10^{-3}$, which is about 0.000813. Even if the SNR is 30dB, the BER is still higher than $10^{-4}$. Due to the influence of complex modulation mode and complex transmission channel environment, it is difficult to improve the BER. For massive high-speed data transmission services, the bit error rate of $10^{-3}$ can guarantee its basic application feasibility as well.

5. Conclusion
The system with MIMO-OFDM and higher efficiency data transmission technology for HTS is feasible. The transmission error rate of the system can meet the basic space communication requirements. As MIMO and OFDM signal has been widely applied in terrestrial communication network, the HTS communication system using MIMO-OFDM can be simply and feasibly access through gateway and mobile/fixed user terminal. Moreover, it can be introduced into the inter-satellite-link transmission in a GEO and LEO satellite constellation communication system, as inter-space transmission environment may possess less channel interference than that of satellite-to-terrestrial links, which might be a more popular, interesting and significant hot issue to further study.

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