Simultaneous Transmission and Reception Transponder for Nano-satellite

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Abstract. The feasibility of simultaneous transmission and reception (STAR) in the same frequency for space transponder in nano-satellite is discussed. The demand of the self-interference cancellation for the transponder is analysed by space-ground link budget, and a STAR superheterodyne architecture based transponder is also presented. Based on the conventional space TT&C frequency scheme, a feasible frequency scheme and digital signal processing process for the STAR transponder are expatiated. A FFT based carrier acquisition method is modified to adapt to such STAR transponder. The implementation of the STAR transponder is simulated. The simulation results show that with properly deploying the passive and active self-interference cancellation modules, the self-interference can be cancelled to meet with the demand of demodulation which also implies that the STAR transponder presented in this paper is feasible. The simulation results also show that the radio frequency self-interference cancellation (RF-SIC) does matter in such STAR transponder by realizing 29dB self-interference cancellation, and a total self-interference cancellation of about 68dB can be realized by the combination of passive suppression and RF-SIC. The numerical results show that the digital self-interference cancellation is not necessary for the transponder when the transmission power of ground-satellite uplink is high enough, and the phase noise power is increased by the digital self-interference module.

1. Introduction
The simultaneous transmission and reception (STAR) technology is based on the transceiver working at the same carrier frequency in the same time to achieve two-way data transmission. Compared with the traditional FDD, the communication capacity of the system can be doubled in theory, and the spectral resources can be relieved [1, 2]. As an alternative to 5G mobile communication technology, STAR has attracted wide attention in the field of civil and commercial applications.

The current research on STAR is mainly aimed at the wide-bandwidth self-interference cancellation and related performance based on OFDM modulation using the direct conversion transceiver architecture. The application scenes are mostly focused on indoor short distance wireless transmission. The research on STAR in satellite communication scene is less investigated. Ref [3] explored the military applications of STAR, and gives different modes of operation for listening and jamming. Ref [4] discussed the feasibility of STAR for the low orbit satellite communication system, but did not consider the space TT&C communication system. Ref [5] designed a test platform for narrow band STAR and validated its performance. Ref [6] discussed the application of STAR in personal communication in the satellite communication environment, but there was no specific discussion for...
TT&C system either. By far, there were no research results on STAR technology in the field of TT&C system. In this paper, based on the standard unified carrier TT&C system and the widely used transceiver architecture, a preliminary implementation scheme of the STAR TT&C transponder is given and simulated.

2. The Design of STAR Transponder

2.1. Feasibility Analysis

Whether the STAR is feasible for TT&C communication system is mainly determined by the high performance self interference algorithms which can cancel the self interference signal and its distortion under the receiver noise floor so as to ensure the demodulation performance of the receiver. The noise floor of the receiver can be expressed as:

\[
F_r (dBm) = -174 + NF + 10 \log B,
\]

where \(NF\) is the noise figure, \(B\) is the signal bandwidth.

Assuming that the bandwidth of a receiver is 2MHz and the noise figure is 3dB, the noise floor of the receiver can be calculated to be -108dBm. Assuming the transmit power is 27dBm, and then the self interference cancellation capability should be at least 135dB, which will satisfy the request of transponder demodulation. According to the research results of the self interference cancellation for 20MHz OFDM signal in [7], the RF self interference cancellation of 45dB and the digital self interference cancellation of 55dB were achieved, thus extra 35dB interference cancellation is required. If a three port network (circulator / duplex) with 20dB isolation is used to transmit and receive signal with single antenna in the RF front end of the transceiver, then the total interference cancellation can reach 120dB which still not meet the self interference suppression demand of 135dB. In addition, according to [5], the interference suppression ability and the signal bandwidth are closely related, i.e.

\[
SI_{RF,max} = 10 \log_{10} \frac{\Delta T}{T_s} = 10 \log_{10} B \Delta T,
\]

where \(B\) is the symbol rate, \(\Delta T\) is the time delay between two taps in the RFSIC. Therefore, using the analog domain interference cancellation method and the implementation structure in [7], when the signal bandwidth is reduced from 20MHz to 2MHz, an extra 10dB self interference cancellation can be obtained. Then the total interference suppression ability should be 20+45+10+55=130dB, and the self interference signal can theoretically cancelled to the noise floor of the receiver. The demodulation performance of the receiver is basically guaranteed.

A low orbit satellite with a height of 600km is taken as an example. Assuming that the spaceflight transponder for the satellite works in the S band, then the farthest transmission distance (the elevation angle of the ground antenna is 5 degree) is about 2330km, and the corresponding maximum path loss is 168dB. Suppose the ground station uses a parabolic antenna with 10m caliber to transmit signals,
and the transmit power is 100W. According to the link budget in Table 1, the minimum receiving power of the satellite receiver is -79dBm.

### Table 1. Link budget for a nano-satellite

| Frequency (MHz) | 2400 |
|-----------------|------|
| Transmit power (dBm) | 50.0 |
| Ground Station Gain (dB) | 45 |
| Ground Cable Loss (dB) | 3 |
| EIRP (dBm) | 92 |
| Ground Station Point Loss (dB) | 0.5 |
| Ground Station Polarization Loss (dB) | 0.5 |
| Ground Station Path Loss (dB) | 168 |
| Satellite Point Loss (dB) | 0.5 |
| Satellite Polarization Loss (dB) | 0.5 |
| Satellite Cable Loss dB | 1 |
| Satellite Gain (dB) | 0 |
| Minimum Received Power(dBm) | -79 |

According to this minimum received power, if the receiver bandwidth is 2MHz, the noise figure is 5dB, then according to

\[ P_{r_{\text{min}}} = -174 + NF + 10\log B + SNR_{\text{min}} \]  

the minimum signal to noise ratio of the receiver is obtained of 27dB. Based on the BPSK modulation, the demodulation signal-to-noise ratio of 10.5dB can achieve a bit error ratio of $10^{-6}$ theoretically.

Considering the demodulation loss, the signal to noise ratio for demodulating the uplink signal can set by 13dB, then there are still about 14dB allowance for degradation the self interference cancellation ability. Thus the self interference and noise power just needs to less than $-108+14 = -94$dBm to guarantee the demodulator work properly. Then, the demand of total interference suppression capability is 114dB, which reduces the requirement of 135dB self interference suppression capability of the system. To sum up, by designing appropriate suppression strategy and interfeference suppression algorithms with the actual application background, the STAR exploiting for space transponder is feasible.

### 2.2. The Implementation Scheme of STAR Transponder

Superheterodyne architecture is the most popular architecture used in the FDD transponder. In a superheterodyne transceiver, impacts of the leaked or reflected transmitted signal to the local oscillator are weakened by adopting twice frequency translation processes. However, additional filters are needed to filter out the unwanted sideband signals in the RF channel. The receiver can also reduce the requirement of high Q value filter in frequency selection, and assign the total gain of the entire receiving channel to radio frequency, intermediate frequency and baseband, and also increase the stability of high gain amplifier [8]. The disadvantage of superheterodyne architecture is that such transceiver can induce interference such as inter-module interference (parasitic interference), especially image interference. But this can be done by designing a high Q bandpass filter at the front end of the mixer to filter out the image frequency signal. Compared with the superheterodyne architecture, the direct conversion architecture does not have mirror frequency interference, and the receiver only contains high frequency LNA and mixer, which decrease the device quantity of the transceiver. However, there are some problems such as local oscillator leakage, DC bias and I/Q mismatch existing in the direct conversion architecture. Most of the literatures on STAR are focused on the performance and interference suppression ability with direct transformation architecture, such as the interference suppression ability of I/Q imbalance [9] or the leakage of local oscillator and so on.
Although the superheterodyne architecture is complex, there are no problems such as local oscillator leakage, DC bias and so on. In addition, combining the characteristics of the unified carrier TT&C, the carrier acquisition needs the upper and lower band information of the signal, and the transceiver assigns the gain to the baseband, the intermediate frequency and the radio frequency blocks, which can greatly guarantee the linear characteristic of the nonlinear components (power amplifier, mixer and so on). A superheterodyne architecture for STAR transponder is shown in Figure 1.

**Figure 1.** A superheterodyne architecture for STAR transponder implementation.

In Figure 1, the modulation signal firstly pass through DA converter, low pass filters, band-pass filters and mixers, VGA, driver amplifier and power amplifier, then the RF signal are coupled to two separate RF signals. One RF signal is sent to the RFSIC module, and the other is transmitted by the antenna. The received signal passed through the low noise, band-pass filter and VGA, down frequency conversions, and then accesses into the ADC for sampling. In Figure 1, the RFSIC is implemented as the scheme depicted in figure 2, in which the RFSIC contains N taps, and each tap includes a power splitter, a I/Q mixer, a vector modulator and ADC circuits[10]. The samples of the ADCs are used to calculate the control parameters of the vector modulator with LMS algorithms in MUC/FPGA. Assuming a sample of the PA output is \(d(k) = d_i(k) + id_q(k)\), N taps outputs are \(x(k) = [x_1, \ldots, x_n, \ldots, x_N]\) and the control parameters are \(w(k) = [w_1, \ldots, w_i, \ldots, w_N]\). Then based on the complex LMS algorithms in [11], the calculation procedure of \(w(k)\) can be expressed as follows:

**STEP1:** Initialized \(x(0) = w(0) = [0, 0, \ldots, 0]^T\);

**STEP2:** If \(k \geq 0\), calculate 
\[e(k) = d(k) - w^H(k)x(k); w(k+1) = w(k) + \mu e^*(k)x(k)\]

The real part and imaginary part of \(w(k)\) calculated by the LMS algorithm are used as the I/Q control input of the vector modulator after the DAC circuit, and then adjusting the amplitude and phase of the self interference signal in RFSIC[12, 13]. The specific adjustment process can refer to the data sheet of the selected vector modulator chip.

**Figure 2.** Implementation scheme of a RFISC.
In Figure 1, FPGA implements modulation and demodulation and digital domain interference cancellation algorithm. For low earth orbit nano-satellite systems, the Doppler frequency shift of S band transponder is generally less than 100kHz. In order to overcome the influence of telemetry tone to the demodulation of telecommand tone in the STAR transponder, the frequency of telemetry tone in the STAR transponder is selected as 250kHz with data rate 4096bps, the frequency of telecommand tone is 8kHz with data rate 2000bps. According to the frequency scheme, even considering the 100kHz Doppler shift, the telecommand tone and the telemetry tone still have a frequency interval of 150kHz, which provides convenience for design the demodulation filter in the digital signal processing procedure. In addition, the maximum frequency of the range tone is 100kHz, which still have 50kHz frequency interval to the telemetry tone even with 100kHz Doppler frequency shift. It is convenient for designing the digital FIR filters in demodulation of the range tone.

The digital processing flow within FPGA is shown in Figure 3. In Figure 3, the DSIC block is followed by a 256 order FIR bandpass filter to filter the telemetry tone and its harmonic components. The passband of the FIR filter is 100kHz. The implementation of the FFT capture block needs to eliminate the influence of the DC offset, which can be realized by setting the value of the DC offset to zero after the transformation. The order of FFT is 4096. Following the DDC1 block is a FIR filter with passband of the telecommand subcarrier and the filter order is 512. Then the real part or imaginary part of the FIR’s output are selected to mixing with local telecommand subcarrier in DDC2. The output of the DDC2 block is then filtered by a 2048 order FIR with passband of symbol rate.

\[ \theta_i(t) = \sum_{k=0}^{\infty} m_s d(t-kT) \cos(w_i t), \]

where \( m_s \) is the modulation index, \( d(t-kT) \) is the NRZ PCM symbol, \( w_0 \) is the angle frequency of the telemetry tone or telecommand tone. With two converters, the signal can be up-converted to the radio frequency, expressed as:

\[ x_{m2}(t) = \exp\{j((w_i + w_2)t + \theta_i(t) + \phi_1(t) + \phi_2(t))\} \]

where the \( \phi_1(t) \) and \( \phi_2(t) \) are the phase noises, \( w_i \) and \( w_2 \) are the angle frequency of the local oscillators. Then the signal is amplified by the power amplifier, which can be expressed as [14]

\[ x_{PA}(t) = a_x x_{m2}(t) + \sqrt{2a_x}x_{m2}(t)^2 - 3/2 a_x x_{m2}(t)x_{m2}(t)^2 \]

where \( a_x \) is the gain coefficients of the second and third order non-linear components. By using the path loss between the transceiver antennas as passive suppression, the self-interference signal enters into the receiver antenna is

\[ x_{SI}(t) = h_L(t) \ast x_{PA}(t-\tau) \]

where \( h_L(t) \) is the path loss. Then the received signal is

\[ y(t) = y_{SOI}(t) + x_{SI}(t) + n_{th}(t), \]

where \( y_{SOI}(t) \) is the signal of interested from the far end, \( n_{th}(t) \) is the thermal noise. Assuming the coupled signal of the PA output is \( x_{PA}(t) \), then the signal at the input port of the LNA is
\[ y_{RF}(t) = y(t) - \sum_{i=1}^{N} \omega_i \cdot x_{PA}(t - i\tau) \]
\[ = y_{SOI}(t) + \left[ x_{SI}(t) - \sum_{i=1}^{N} \omega_i \cdot x_{PA}(t - i\tau) \right] + n_{th}(t) \]
\[ = y_{SOI}(t) + x_{SI}^{\text{Res}}(t) + n_{th}(t) \tag{9} \]

where \( \omega_i \) is the control parameter, and \( x_{SI}^{\text{Res}}(t) \) is the residual self interference signal. Considering the LNA is a nonlinear device, the output of the LNA can be expressed as
\[ y_{LNA}(t) = \left( k_3 y_{RF}(t) + \sqrt{2} k_2 |y_{RF}(t)|^2 - \frac{3}{2} k_3 y_{RF}(t) |y_{RF}(t)|^2 \right) + n_{LNA}(t) \tag{10} \]

where \( k_2, k_3 \) are the gain coefficients of the second and third order non-linear components. Then with two converters, the signal frequency is down-converted to the baseband expressed as
\[ y_{m2}(t) = y_{LNA}(t) \exp(-j(w_2 t + w_1 t + \phi_1(t) + \phi_2(t))) \tag{11} \]

where \( w_1 \) and \( w_2 \) are the angle frequency of the local oscillator. Then the ADC converts the amplified baseband signals into digital signals for further processing in the digital base-band.

3. Simulation Results

Based on the above implementation scheme, the STAR transponder is simulated. The simulation parameters are set as follows: the local oscillator phase noise is modelled as a Gauss random variable with a mean of 0.45 degree, and the power amplifier is modelled based on the SSPA Sale model. For a complex baseband signal \( x(t) = a(t) \exp(j\phi(t)) \), the AM-PM effect can be expressed as \[ \text{AM}(a(t)) = \frac{\alpha_o |x(t)|}{1 + \beta_o |x(t)|^2}, \quad \text{PM}(a(t)) = \frac{\alpha_o |x(t)|}{1 + \beta_o |x(t)|^2}, \tag{12} \]

where \( \alpha_o = 1, \beta_o = 0.25, \alpha_o = 0.26, \beta_o = 0.25 \). In the simulation, the power amplifier chip selects HMC454 of AD Inc., its gain is 12.5dB and the 1dB compression point is 27.5dBm. The gain coefficient of the second and the third nonlinear components can be obtained by \[ \text{OIP}_m = G_1 + \text{IIP}_m, \quad \text{OIP}_m = G_m + m\text{IIP}_m, \tag{13} \]

where \( G_m \) is the \( m \)th gain coefficient. The low noise amplifier chip selects HMC669 of AD Inc., its gain is 17dB with the noise coefficient of 1.4dB, and the 1dB compression point is 12dBm. According to (13), the gain coefficients of the second and third non-linear components of the low noise amplifier can be obtained.

For RF interference cancellation module, vector modulator can choose MAX2045. It is assumed that the error in the phase and amplitude adjustment of the self interference signal can be ignored in the vector modulator, DAC and ADC circuits. The number of taps of the RFSIC is 32, and the baseband sampling frequency is 16,384MHz after frequency down conversion, then the sample time interval is 0.061us which means that each tap experienced a total time delay of 0.061us. The adaptive filter is set to 1024 iterations.

In the simulation, the satellite orbit height is 500km, the transmission power of the ground station is 17dBW, the antenna gain of the ground station is 45dB, and the path loss is 165dB when the antenna elevation is 5 degrees. The transmission power of the transponder is 500mW, the distance of the transceiver antennas of the transponder is 1 meters, the Doppler frequency shift is 40kHz, and the transmitter noise figure is assumed to be 10dB.
Figure 4 shows the powers comparison of transmitted and received signal. It is seen that the signal attenuates 39.7dB by the space isolation of the transceiver antennas. The telemeter tone and its harmonics are respectively at 250kHz and 500kHz etc. when the PCM-PM modulation is exploited. It can be seen that the received signal of interested (telecommand tone) is submerged in the received noise. Figure 5 shows the power comparison of the transmitted signal with received signal after RFSIC. It can be seen that after RFSIC, the power of the transmitted carrier signal is attenuated to -68.2dB, and RFSIC achieves the attenuation of about 29dB, while the harmonics and noises within bandwidth ±500kHz are also attenuated. It can be seen that the signal of interested is appeared at the 40kHz offset frequency of transmitted carrier with power of about -102dBW (-72dBm).

Figure 6 shows the signal power after the DSIC, in which the order of the adaptive filter is set to 128 with 1024 iterations. From the figure, the harmonics of the telemetry tone is further reduced about 10dB after the DSIC, but the power of the transmitted signal within bandwidth of carrier frequency±250kHz is raised about 8dB. This is because, after the RFSIC, the harmonics of the telemetry tone has larger power than the carrier, and the DFSIC mainly cancels the harmonics. It also depicts that the power of received signal are all amplified about 17dB which is accordant with the gain of LAN. Due to the raised power of in-band noise, the performance of demodulation is weakened.

Thus, we considered to remove the DSIC and filter and demodulate the received signal directly. Figure 7 gives the demodulation waveform of the telecommand symbols. In the simulation, the EbN0 is set to 15dB and the symbol rate is 2000bps. It can be seen from the graph that the telecommand PCM symbols are demodulated correctly.
4. Conclusion
In this paper, the feasibility of the STAR TT&C transponder is analyzed, and the transceiver architecture is presented. The scheme of the RFSIC and the process of digital signal processing are described. The key chips are selected and the system simulation is carried out. The simulation results show that the self interference cancellation of about 29dB can be realized by the RFSIC. The total self interference cancellation of about 68dB can be realized by the combination of the passive suppression and RFSIC. The simulation results also showed that the STAR implementation scheme is feasible and the demodulation of telecommunication PCM symbols can be realized. It is necessary to point out that the taps of the RFSIC scheme is 32, which leads to extra power consumption of the RF circuit compared with the traditional transponder, and the circuit is more complex, which needs to be solved in the future.

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