Intelligent Optimization of Modulation Indexes in Unified Tracking and Communication System

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Abstract. In the unified tracking and communication system, the ranging signal and the telemetry, communication signals are used in the same channel. In the link budget, it is necessary to allocate the power reasonably, so as to ensure the performance of system and reduce the cost. In this paper, the nonlinear optimization problem is studied using intelligent optimization method. Simulation analysis results show that the proposed method is effective.

1. Introduction
Unified tracking systems, such as USB (Unified S-Band), UCB (Unified C-band) are widely deployed in ground tracking stations to support space flight missions including spaceship, satellite, deep space explorer, etc. In unified tracking system, subcarriers for ranging, telemetry, command are modulated to one carrier by PM (Phase Modulation) or FM (Frequency Modulation) and the power allocation between them are determined by modulation indexes. Appropriate modulation indexes will lower the transmitted power, thus lower the cost while guaranteeing the specified system performance[1], so an optimization procedure is needed in the mission design. However, in this scenario, the optimization problem is nonlinear and quite complicated.

In this paper, we propose an approach based on Multimethod Collaborative Optimization (MCO) algorithm and verifies its effectiveness, efficiency by simulation.

2. Power Allocation Model of Downlink Signal
In the downlink of the communication between the satellite and the ground station, the link equation is usually expressed as [2]:

\[ \frac{S}{\Phi} = EIRP + G/T + 2\lambda - 2R - 20\lg(4\pi) - k - L_e - M \]  \hspace{1cm} (1)

Where S is the power of the signal, \( \Phi \) is the power spectral density of the noise, \( G/T \) is the quality factor of the ground receiving system, \( EIRP \) is the equivalent isotropic radiated power of the satellite transponder, \( \lambda \) is downlink carrier wavelength, \( R \) is the operation range, \( k \) is Boltzmann constant, \( L_e \) is other losses except feed line loss, and \( M \) is system design margin.

Angle modulation is adopted for each signal in the unified tracking and communication system. In downlink channel, phase modulation is used for all signals while the residual carrier is used as a tracking lock signal. In this paper, S-band system is taken for example, there are three sub-carriers in
downlink, which are major tone, minor tone, and the telemetry sub-carrier. Signal noise power spectral density ratios of residual carrier and each sub-carrier are as follows:

\[
\begin{align*}
\frac{S}{\Phi_c} &= \frac{S}{\Phi_E} \cdot \prod_{i=1}^{3} J_i^2(m_i) \\
\frac{S}{\Phi_j} &= \frac{S}{\Phi_E} \cdot 2 J_j^2(m_j) \cdot \prod_{i=j}^{3} J_i^2(m_i) \quad (j = 1, 2, 3)
\end{align*}
\]

(2)

where \(m_1, m_2, m_3\) are modulation indexes of each sub-carrier, \(J_0, J_1\) are zero-order and first-order Bessel function individually.

In the link budget, it is necessary to allocate the power of the various signals reasonably, so as to ensure the performance of the work, and to make the lowest emission power, in order to reduce the cost.

Taking into account the main constraints of power allocation, the optimization model is established as follows:

\[
\begin{align*}
\text{Find} & \quad m_1, m_2, m_3 \\
\text{Min} & \quad \text{EIRP} \\
\text{S.T.} & \quad \frac{S}{\Phi_c} \geq \frac{S}{\Phi_{c,th}} \\
& \quad \frac{S}{\Phi_j} \geq \frac{S}{\Phi_{j,th}} \quad (j = 1, 2, 3) \\
& \quad m_c = \sqrt{\frac{\sum_{j=1}^{3} m_j^2}{\pi}} < \frac{\pi}{2}
\end{align*}
\]

(3)

where \(\frac{S}{\Phi_{c,th}}\), \(\frac{S}{\Phi_{j,th}}\) are thresholds of carrier and each sub-carrier. \(m_c\) is the total modulation index.

3. Multimethod collaborative optimization algorithm

Multimethod Collaborative Optimization (MCO) algorithm is proposed based on comprehensive analysis of the optimization problem and a variety of optimization methods, which combines multiple effective and collaborative methods with a certain strategy to obtain better optimization performance.

The optimization information of one collaborative step is obtained by a certain number of iterations of each chosen methods, which is processed and used in next collaborative step. The algorithm is terminated when the collaborative optimization termination criterion is met. Using MCO algorithm to solve the optimization problem can get better results than the single optimization method.

In this paper, genetic algorithm, pattern search method and Powell method are chosen for collaborative optimization using parallel collaborative strategy. The genetic algorithm has better global optimality while the latter two are local search methods. Collaborative optimization with these three methods, can make use of their advantages to obtain good results.

4. Simulation Analysis

Assuming that the signal noise power spectrum density ratio of the residual carrier, the error rate of the telemetry signal and ranging accuracy are known, the threshold for carrier and each sub-carrier are calculated as follows:

(1) the residual carrier. \(\frac{S}{\Phi_{c,th}} = 43\, \text{dBHz}\);
(2) the ranging tone. major tone (100kHz) ranging accuracy ($R_0$) is required for 10m, the signal noise power spectrum density ratio required by ground terminal is:

$$\frac{S}{\Phi_{th}} = 20 \log \frac{c}{18 \times R_0 \times 10^7} + 10 \log 5 = 32 \text{dBHz}, \quad \frac{S}{\Phi_{th}} = 27 \text{dBHz};$$

(3) telemetry signal. the error rate $P_e = 1 \times 10^{-4}$ request signal to noise ratio $S/N = 7.4$ dB, taking into account the demodulation loss 2.5dB, bit rate is 1024 bit / s, so ground telemetry terminal signal to noise power spectrum density ratio is:

$$\frac{S}{\Phi_{th}} = 7.4 + 10 \log(1024) + 2.5 = 40 \text{dBHz};$$

The optimal power allocation is based on the detection threshold of the modulation signal, and make the ratio of the useful power to reach the maximum, so that the power component of the modulated signal reaches the maximum.

Total index modulation should be no more than 1.5, i.e. $m_c \leq 1.5$.

| Variables | unit | value | Variables | unit | value |
|-----------|------|-------|-----------|------|-------|
| $R$ | km | 1000 | $G/T$ | dB/K | 22.5 |
| $f$ | MHz | 2250 | $M$ | dB | 6 |
| $\frac{S}{\Phi_{th}}$ | dBHz | 43 | $\frac{S}{\Phi_{th}}$ | dBHz | 32 |
| $\frac{S}{\Phi_{th}}$ | dBHz | 27 | $\frac{S}{\Phi_{th}}$ | dBHz | 40 |

| Variables | carrier | Main side tone | The secondary tone | telemetry |
|-----------|---------|----------------|--------------------|----------|
| $m_c$ | rad | 0.391 | 0.223 | 0.898 |
| $m_c$ | rad | 1.0041 | | |
| $L_e$ | dB | -2.29 | -13.29 | -18.29 | -5.28 |
| $\eta$ (%) | 59.02 | 4.69 | 1.48 | 29.64 |
| $\eta$ (%) | | 94.83 | | |
| $\frac{S}{\Phi_{th}}$ | dBHz | 43 | 32 | 27 | 40 |
| $\frac{S}{\Phi_{th}}$ | dBHz | | | | 45.29 |
| EIRP | dBW | | | | -40.32 |

5. Conclusion
In this paper, the power allocation optimization model of downlink signal is established for the unified tracking and communication system. Multimethod collaborative optimization is proposed to solve this nonlinear optimization problem in order to obtain optimal modulation indexes, which can reduce the cost while guaranteeing the specified system performance. Simulation results show that the proposed method is effective and all the constraints are satisfied.

References
[1] L.Zhang, G. Li 2007 Optimized selection of modulation index of TTC system *Spacecraft Engineering* 16 38
[2] Yefu Zhao et al 2013 *Radio Tracking System* (Beijing, Defense Industry Press) p 391