A Multi-Service Train-to-Ground Bandwidth Allocation Strategy Based on Game Theory and Particle Swarm Optimization

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***Abstract*— The rapid development of high-speed trains renders more information exchange between the train and ground. However, the bandwidth resources for various service communications are limited. The bandwidth should be allocated effectively to ensure that the vital information related to safety and efficiency can be transmitted in prior with better use of the residual bandwidth. This paper presents a multi-task train-to-ground bandwidth allocation strategy for wireless communication systems of high-speed trains. First, by analyzing the bandwidth demand and data characteristics of each service, the utility and weighting functions are formulated. The optimization model is established by using the asymmetric cooperate Nash game theory. Second, the Particle Swarm Optimization (PSO) is adopted to realize the nonlinear bandwidth allocation optimization described as a Non-Deterministic Polynomial (NP) problem. Finally, the novel bandwidth allocation scheme is verified with comparative simulations. It is shown that the scheme allocates the bandwidth dynamically according to the weighting factor of each service, and maximizes the bandwidth utility with satisfying the real-time demands of the running train. It optimizes the train-to-ground bandwidth allocation, and thus improves the operation safety, efficiency, and bandwidth usage of high speed trains.**

***Index Terms*—Bandwidth allocation, Nash game theory, Non-deterministic polynomial (NP), Particle swarm optimization (PSO), Train-to-ground communication (TGC)**

I. INTRODUCTION

Recent years have seen rapid development in high-speed train networks around the world, including the mileage, running speed and carrying capacity. Copious amounts of information are exchanged between the train and ground [1], such as the information of operation control, passenger information service, online entertainment services, and other monitoring data [2-4]. However, the bandwidth available is limited in current train-to-ground communication systems (TGCSs) such as GSM-R, LTE-R, etc. [5,6]. For high speed trains, GSM-R and LTE-R are unsuitable due to the frequent handover. Some novel methods have been presented to reduce the handover, such as moving frequency concept [7], MIMO-OFDM channel model [8], and broadband wireless communications [9]. But they can hardly to meet the needs simultaneously. Some bandwidth allocation schemes have been applied to manage the valuable bandwidth and improve the quality of service (QoS) [10].

In high-speed TGCSs, multiple services are sharing the limited bandwidth, while the system bandwidth and the bandwidth demand for each service are varying. Therefore, we need a system utility function to reflect the asymmetry and cooperation amongst services, and facilitate the allocation for both individual bandwidth needs and system bandwidth usage. An optimization method is vital as well to meet the real-time demands of the high-speed TGCSs. For example, game theories are useful to manage and allocate the telecommunication resources [11-19], including the 3G operators resource allocation, cloud-computing resource allocation, wireless network coverage, et al.

Motivated by this observation and inheriting from the fact that the bandwidth allocation mechanism has similar pattern to that of Game theories, we propose a novel system utility function based on the asymmetric cooperate Nash game theory. Most existing studies focus on the static bandwidth allocation [20-23], and very limited results are related to TGCS whose bandwidth resources vary rapidly caused by the Doppler shift of the running high-speed train. Thus, the static bandwidth allocation strategies no longer fit into the resources fluctuating circumstances. Moreover, few papers focus on both the cooperation and asymmetry between the services simultaneously. For example, the cooperation Nash Game theories use the sum of service utilities as the system utility function, but maximizing the system utility function may invalidate some services, and the effect of linearly designed individual utility function on the total system utility function is ignored [24-25]. As for the unique characters of various services in TGCS, the asymmetric Nash Game theories are preferable solutions, but existing methods use static weighting factors, which can hardly meet the real demands of system services [26-31].

This paper presents a multi-service train-to-ground bandwidth allocation strategy for wireless communication systems of high-speed trains based on cooperation asymmetric Nash game theory and PSO, with optimized objectives for different roles of services. The salient features of the strategy are four-fold. 1) The critical information is transmitted in terms of various priorities; 2) the basic bandwidth needs are ensured for various services; 3) the bandwidth allocation is realized dynamically according to the weighting factor of each service; 4) the system bandwidth utility is maximized with satisfying the real-time demands.

The rest of this paper is organized as follows. Sec. II introduces the typical services and bandwidth requirements of the high-speed TGCS, and depicts the overall scheme. In Sec. III, the allocation model is described in detail. The bandwidth allocation method based on PSO is presented. In Sec. IV, simulations are conducted to validate the proposed bandwidth allocation scheme. Comparative studies are carried out on the scheme based on Asymmetric Nash Bargaining Solution using Distributed Coordination Function (ADCF) [23]. The conclusions and some research issues are discussed in Sec. V.

II. Overall Scheme of Bandwidth Allocation

The stability and rapidity of the high-speed TGCSs are crucial to ensure the operational safety and passenger demands. This requires sufficient bandwidth to ensure the information transmission for various services. However, two key issues are to be addressed for the limited bandwidth usage. First, the real-time requirement and priority of each service is different and should be considered during the bandwidth allocation. Second, the mathematical relationship of bandwidth allocation for each service is difficult to express analytically, so intelligent optimization methods are preferable. Thus, this paper blends the asymmetric cooperation Nash game theory with PSO algorithm to allocate the bandwidth dynamically, and this helps optimize the bandwidth usage and improve the QoS of high-speed TGCS.

As shown in Fig.1, the system is composed of three layers: the input data layer, the bandwidth allocation strategy layer, and the output data layer.

A. Input Data Layer

Four typical services are included: *Operation Control Information (OCI)*, *Passenger Information Service* (*PIS*), *Passenger Data Service* (*PDS*), and *Train Monitoring Service.*

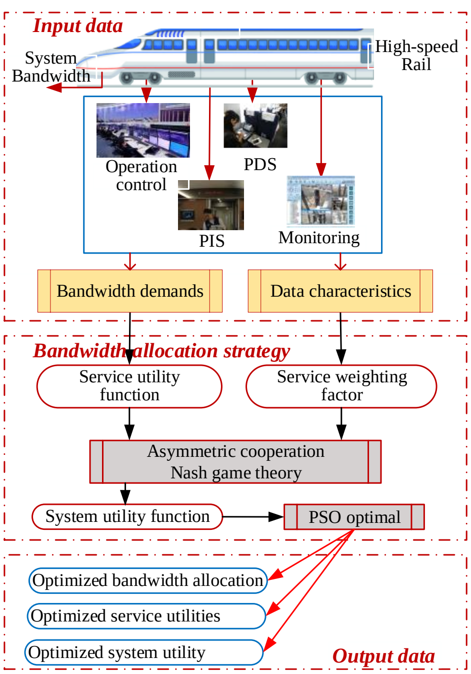


Fig.1. Overall scheme of high-speed TGCS bandwidth allocation

The input data coming from the operating train include three aspects: 1) the system bandwidth of TGCS varying with the changing positions and speeds of the train; 2) the minimum and maximum bandwidth requirements for each service; 3) the data characteristics, that is, the parameters describing the real-time requirement and importance of each service. The bandwidth requirements and characters of the four typical services come from [21] and the "High-speed train to ground communication simulation platform" as shown in Fig.2. As the increase of the bandwidth demands in High-Speed Railway Communication System, the communication protocol with more bandwidth such as LTE-R is applied in the field [22]. The simulation data are listed in Table 1.

TABLE 1
Bandwidth Requirements and Characters of Four Typical Services

Service Type	Real-time	Importance	Minimum bandwidth	Maximum bandwidth
Operation Control Information (OCI)	high	high	1Mbps	4Mbps
Passenger Information Service (PIS)	medium	medium	2Mbps	15Mbps
Passenger Data Service (PDS)	low	low	9Mbps	32Mbps
Train Monitoring Information (TMI)	medium	high	1.5Mbps	6Mbps

Fig.2 High-speed Train-Ground Communication simulation platform

B. Bandwidth Allocation Strategy Layer

The bandwidth allocation is conducted in terms of the system bandwidth of the TGCS, the service bandwidth requirement, and the data characteristics. After analyzing the data characteristics, including the dynamics of system bandwidth, the asymmetry of transmitted data, and the nonlinearity of the optimization process, we define the service utility function and weighting factor, and then formulate the system utility function by using the asymmetric cooperation Nash game theory and optimize the nonlinear allocation mechanism with the PSO algorithm. The service and system utility represent the degree of satisfaction with bandwidth allocation results. That is, the service utility increases with the increasing bandwidth allocation for itself, while the system utility can be improved using a reasonable strategy to balance the bandwidth allocation among all services. So, a hybrid scheme by blending the asymmetric cooperation Nash game theory with particle swarm optimization, i.e., N-PSO, is developed to address the bandwidth allocation problem.

As shown in Fig.1, the basic allocation strategy includes three steps. 1) The service utility function is built in light of the bandwidth requirement and the service data characteristics; 2) The service weighting function is built in a way that corresponds to the service data characteristics and the bandwidth allocated at the last instant; 3) the to yield the output data.

C. Output Data Layer

The output data includes: 1) the optimized bandwidth allocation, to ensure the minimum bandwidth demand for each service; 2) the optimized service utilities, to satisfy the bandwidth allocation demands for all services after the bandwidth allocation; 3) the system utility, i.e., the key indexes for evaluating the total utility of system bandwidth.

III. Modeling and Methodology of Bandwidth Allocation

In this section, we model the system utility function and conduct the bandwidth allocation based on the N-PSO method. The basic structure of this novel method is shown in Fig.3.

A. Modeling and Bandwidth Allocation

In Nash game theory, there are n players participating the resources allocation, and each player holds their own strategy and utility. All players strive to maximize their own utility. Meantime, the players cooperate with each other to improve the system utility. Due to the limited system bandwidth, the cooperation among each service is required to maximize the system utility, which is called the cooperation game. Denote the service utility function $u_i(x_i, \mu_i)$ as the service transmission utility of the allocated bandwidth. According to the Nash game theory, the system utility function U^* is defined as:

$$U^* = \arg\max_{x} \prod_{i=1}^{n} (u_i(x_i, \mu_i)) \quad (1)$$

Each service has equal contribution to the system utility. But this is unrealistic in the train-to-ground bandwidth allocation because the transmitted information for each service is actually asymmetric. So, we update the system utility function with the asymmetric Nash game theory, in terms of the service characteristics such as the bandwidth requirements, the real-time demands and importance of transmitted data. The system utility is updated as:

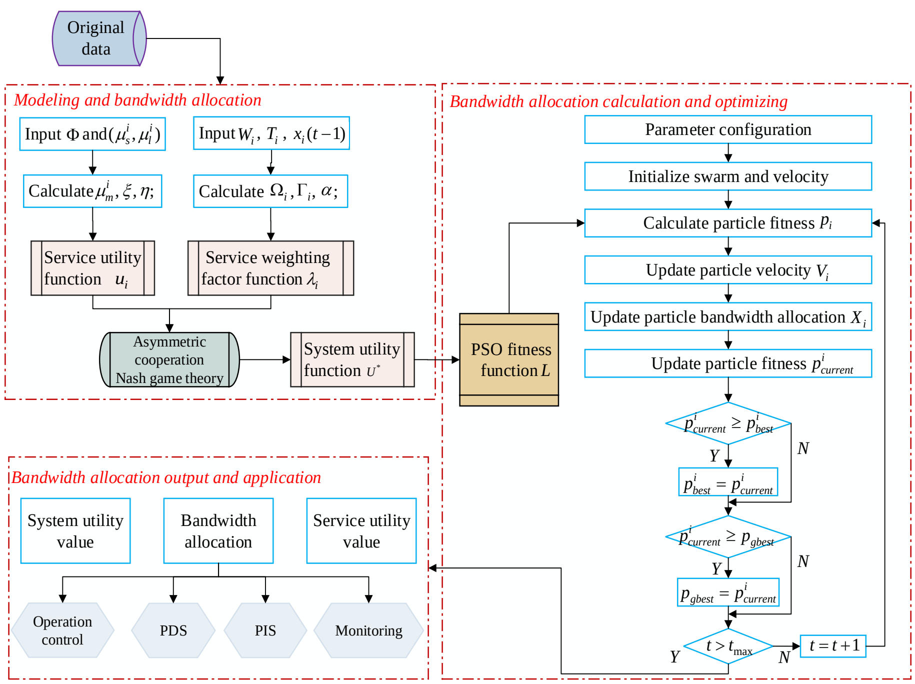


Fig.3. Bandwidth allocation scheme based on N-PSO

$$U^* = \arg\max_{x} \prod_{i=1}^{n} (u_i(x_i, \mu_i))^{\lambda_i} \quad (2)$$

where λ_i represents the weighting factor for each service in the asymmetric Nash game model. It determines the effect of each service utility on the system utility. The asymmetric mechanism enables better allocation mode and optimizes the usage of the total utility bandwidth.

- *Service Utility Function*

Before adopting the asymmetric Nash game algorithm to allocate the bandwidth, the service utility function should be formulated. According to the minimum and maximum service bandwidth demands, the service utility function is given as:

$$u_i(x_i, \mu_i) = \begin{cases} 0 & x_i \leq \mu_i \\ \dfrac{1}{e^{\frac{\xi(x_{mi} - x_i)}{(x_{ai} - x_{mi})}} + 1} & \mu_i \leq x_i \leq x_{mi} \\ 1 - \dfrac{1}{e^{\frac{\eta(x_i - x_{mi})}{(x_{ai} - x_{mi})}} + 1} & x_{mi} \leq x_i \leq x_{ai} \\ 1 & x_{mi} \leq x_i \end{cases} \quad (3)$$

Here, $u_i(x_i, \mu_i)$ denotes the $i-th$ service utility function, which is a monotonic increasing function in terms of the allocated bandwidth x_i and the minimum bandwidth demand μ_i. x_{ai} is the maximum bandwidth demand of the $i-th$ service; x_{mi} is the medium bandwidth when the utility is 0.5; ξ and η

represent the effect of allocated bandwidth on the service utility, that is, the steepness of the utility curve.

In practical, there exist various bandwidth demands from different services. Allocating the same bandwidth to different services may lead to different effects. So we define the service utility function based on the demands. As shown in Fig.4, the growth trends of service utility curves for different services are obvious different. In practice situations, if the total bandwidth is limited, it would be allocated to the services whose bandwidth demands are low, so as to ensure that these services are active.

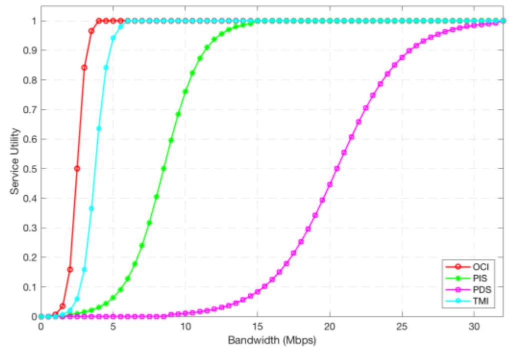


Fig.4 Service utilities of different services with N-PSO

In reality, the bandwidth allocation should be balanced among all services. It can be seen from Fig.5 that in order to avoid the arbitrary allocation with ADCF (Asymmetric Nash Bargaining Solution based on Distributed Coordination Function) [23], whose service utility increasing linearly between the minimum and maximum bandwidth demand, ignoring others demands and system utility, we propose N-PSO allocation scheme to enable practice applications in TGCS. The service utility increases slightly at the beginning which enables the service to gain more resources, so as to improve the service utility and ensure the basic information communication successfully. Then, the service utility increases rapidly. When it comes near to 1, the service utility increases slightly again, which enables the system to allocate bandwidth resources to other services whose bandwidth demands are more urgent. This obviously helps improve the total system utility.

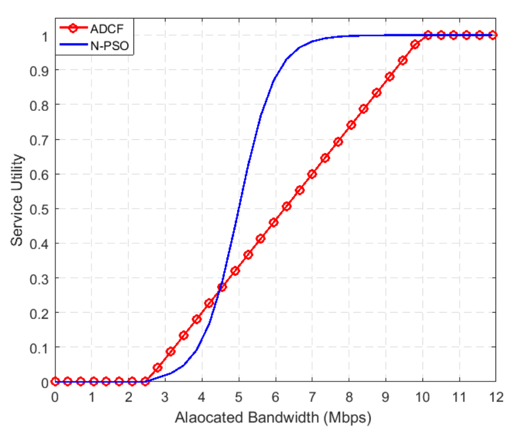


Fig.5 Comparison of ADCF with N-PSO in terms of service utility

- *Service Weighting Factor*

The service weighting factor $\Lambda = \{\lambda_i \,|\, i = 1,...,n, \lambda_i \geq 0\}$ is very important to modulate the system utility function by using the asymmetric Nash game theory. It depends on the service bandwidth requirement, the real-time bandwidth requirement, and the importance of the transmitted data. Thus, we define it as:

$$\lambda_i^{'} = \alpha * \Omega_i + (1-\alpha)\Gamma_i, i = 1,2,...,n \tag{4}$$

It is normalized as:

$$\lambda_i = \frac{\lambda_i^{'}}{\sum_{i=1}^{N} \lambda_i^{'}}, i = 1,2,...,n \tag{5}$$

where, $\sum_{i=1}^{n} \lambda_i = 1,\ 0 \leq \alpha \leq 1$.

Herein, Ω_i represents the bandwidth satisfaction factor, defined as:

$$\Omega_i = 1 - \frac{x_i}{x_{ai}}, i = 1,2,...,n \tag{6}$$

where, $0 \leq \Omega_i \leq 1, i = 1,2,...,n$.

Γ_i represents the data characteristics, given as:

$$\Gamma_i = \beta * T_i + (1-\beta) * W_i, i = 1,2,...,n \tag{7}$$

where $\sum_{i=1}^{N} T_i = 1,\ \sum_{i=1}^{N} W_i = 1,\ 0 \leq \beta \leq 1$, T_i depicts the real time requirement, and W_i is importance of service transmitted data. Thus, α denotes the adaptive parameter to balance Ω_i and Γ_i. Similarly, β is the adaptive coefficient to balance T_i and W_i.

- *System Utility*

The system utility function is used to guide bandwidth allocation through maximum the utility value. It is composed of service utility and weighting factor based on the cooperation asymmetric Nash game theory. We suppose there are n classes of services in high-speed TGCS participating in the bandwidth allocation, so the system utility function is defined as:

$$\begin{aligned} U^* &= \max_x \sum_{i=1}^{n} \lambda_i * \ln(u_i(x_i, \mu_i)) \\ s.t. \quad & \sum_{i=1}^{n} x_i = \Phi \\ & \sum_{i=1}^{n} \lambda_i = 1 \\ & x_i \geq \mu_i, i = 1,2,...,n \\ & x_i \geq 0,\ i = 1,2,...,n \end{aligned} \tag{8}$$

where, Φ is the system total bandwidth. The first condition represents that the total bandwidth is fully utilized. The second condition is that the sum of the service weight factors is 1. The third condition satisfies that the bandwidth allocated to each service is bigger than the minimum bandwidth demand, and this ensures the transmission of the basic vital data. The forth condition guarantees the bandwidth allocation is nonnegative.

B. Bandwidth Allocation Calculation and Optimization

The system utility is a nonlinear function, and the procedure of bandwidth allocation is a nonlinear optimization issue. Compared with those optimization methods like Neural Networks, SVM, Genetic Algorithms, etc, PSO is a preferable method for multi-service bandwidth allocation in this work. Firstly, the problem to be addressed in this paper is a multi-dimensional optimization problem, which can be solved with PSO adequately. Secondly, as a heuristic method, the rules of PSO are more straightforward than those of Neural Networks and Genetic Algorithms, while the optimization precision and convergence speed are satisfactory.

Assuming there are n classes of services, and m particles involved in the bandwidth allocation optimizing. The bandwidth allocation for each service is an n-dimensional vector $X_i = (x_{i1}, x_{i2}, ..., x_{in})$, where x_{ij} represents the allocated bandwidth of the $i-th$ particle in the process of optimization of the $j-th$ service. Herein, we suppose $i \le m$ and $j \le n$.

- *Fitness Function*

For bandwidth allocation with PSO, each particle represents a set of bandwidth allocation results. The optimization uses the particle swarm moving continuously to search for the optimal bandwidth allocation for the TGCS. Therefore, a fitness function is needed to evaluate and restrain the optimization process. By adjusting the particle swarm moving speed and direction, the optimal bandwidth allocation results of the services are found after a certain optimization times.

Obviously, $u_i(x_i, \mu_i)$ is a concave function as shown in formula (3), and the strategy set defined by the constraint condition is a nonempty compact convex set. Moreover, $u_i(x_i, \mu_i)$ is monotonically increasing and has a 1-order continuous partial derivative to meet the Kuhn-Tucker condition. The Lagrange polynomial $L(x_i, \varphi, \delta_i)$ is defined as follows:

$$\begin{aligned} L(x_i, \varphi, \delta_i) = & \sum_{i=1}^{n} \lambda_i * \ln(u_i(x_i, \mu_i)) + \varphi * (\sum_{i=1}^{n} x_i - \Phi) \\ & + \sum_{i=1}^{n} \delta_i * (x_i - \mu_i) \end{aligned} \tag{9}$$

where $\varphi \le 0, \delta_i \le 0, i = 1, ..., n$.

- *PSO Bandwidth Allocation and Optimization*

Suppose $x_{ij}(t) \in [L, U]$ where L and U represent the lower and upper limits of the allocated service bandwidth, respectively. $V_i = (v_{i1}, v_{i2}, ..., v_{in},)$ represents the optimization speed for the $i-th$ particle, and $v_{ij}(t) \in [v_{\min,j}, v_{\max,j}]$, where $v_{\min,j}$ add $v_{\max,j}$ are the minimum and maximum optimization speed for the $j-th$ service. In each optimization process, the particles track the two extreme values. One is p_{best}^{i} , the present optimal solution for the $i-th$ particle, and the other is p_{gbest} , the global optimal solution for the particle swarm. Then the position and the optimization speed of the particle at $t+1$ can be updated as shown in *Algorithm.*

The proposed N-PSO based bandwidth allocation algorithm is achieved with the following eight steps.

Algorithm: The N-PSO bandwidth allocation

***Step* 1.** Formulate the service utility function $u_i(x_i, \mu_i)$: confirm the number of services n in the train-to-ground communication; preset the minimum and maximum bandwidth need of each service; and set the coefficients of the utility function.

***Step* 2.** Obtain the current system bandwidth Φ according to the location and speed of the train.

***Step* 3.** Formulate the service weighting factor function λ_i : calculate the real-time requirement, importance of each service, and bandwidth satisfaction factor for the current allocated bandwidth.

***Step* 4.** Formulate the system utility function U^* based on the asymmetric cooperation Nash Game theory.

***Step* 5.** Preset the N-PSO parameters, such as: the number of service n , the range of bandwidth allocation $[L, U]$, the learning factors c_1 and c_2 , the number of iteration $t_{\max}$ and the range of search velocity $[v_{\min}, v_{\max}]$. Initialize the particle swarm bandwidth $X = (X_1, ..., X_m)$ and velocity $V = (V_1, ..., V_m)$ randomly; set the current system utility of each particle as p_{best}^{i} , and choose the maximum p_{best}^{i} as p_{gbest} .

***Step* 6.** Calculate the current utility of each particle (denoted as $p_{current}^{i}$), if it is larger than p_{best}^{i} , update p_{best}^{i} with this current value. Update p_{gbest} in the similar way.

***Step* 7.** Update the velocity and bandwidth allocation of each particle as (13) and (14). If $v_i > v_{max}$, set $v_i = v_{max}$; if $v_i < v_{min}$, set $v_i = v_{min}$, otherwise, v_i remains unchanged.

***Step* 8:** Loop until $t = t_{max}$, and then output the allocation result to each service; otherwise, go back to ***Step* 6.**

IV. Simulation Validation and Analysis

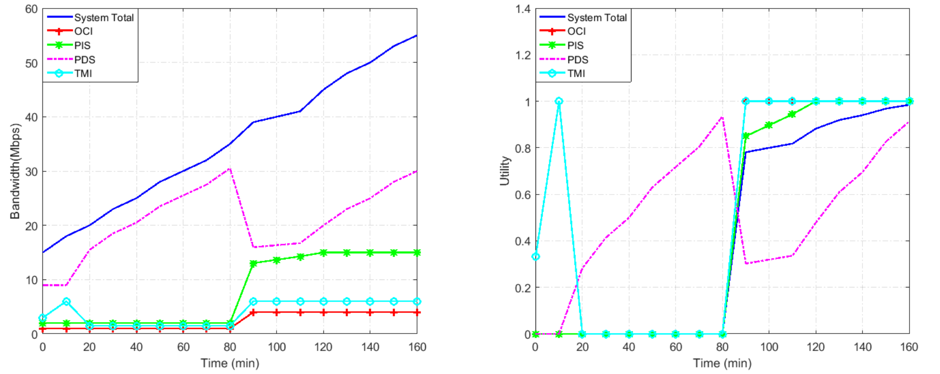
In order to validate the effect of the changing bandwidth on the bandwidth allocation, the system bandwidth is rearranged to vary from the small value to the large value along the horizontal axis. Simulations are conducted with comparison to the traditional ADCF method [23] regarding to the bandwidth allocation utility function.

C. Parameter Configuration of the N-PSO Method

The parameters for the N-PSO method are chosen as Table 2. In this case study, four services are considered. The optimal parameters of PSO are tuned via trail-and-error tests to make a trade-off between the optimization speed and accuracy. The bandwidth demands are determined according to the statistical analysis on the historical Chinese high-speed TGCS data sets. The system factors are tuned by considering the constraints of transmission services.

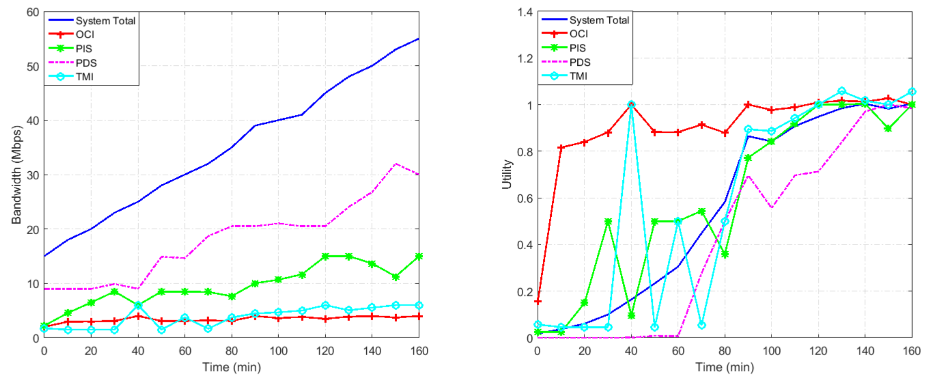
TABLE 2
Parameters for the N-PSO method

No.	Parameter	Value
1	Service number n	4
2	Particle number m	80
3	Learning coefficients c_1, c_2	2, 2
4	Inertia weight ω_{start} , ω_{end}	0.9, 0.4
5	The maximum optimal times $t_{\max}$	1500
6	Allocation area $[x_{\min}, x_{\max}]$	$[0, \Phi]$
7	Update velocity $[v_{\min}, v_{\max}]$	[-5,5]
8	Minimum bandwidth demands $[\mu_1, \mu_2, \mu_3, \mu_4]$	[1,2,9,1.5]
9	Bandwidth demands when utility is 0.5 $[x_{m1}, x_{m2}, x_{m3}, x_{m4}]$	[2.5,8.5,20.5,3.75]
10	Maximum bandwidth demands $[x_{a1}, x_{a2}, x_{a3}, x_{a4}]$	[4,15,32,6]
11	Service utility factors ξ, η	5,5
12	Service weighting factors α, β	0.5,0.5
13	Importance factors $[W_1, W_2, W_3, W_4]$	[0.43,0.18,0.1,0.29]
14	Real-time requirement factors $[T_1, T_2, T_3, T_4]$	[0.38,0.25,0.18,0.19]



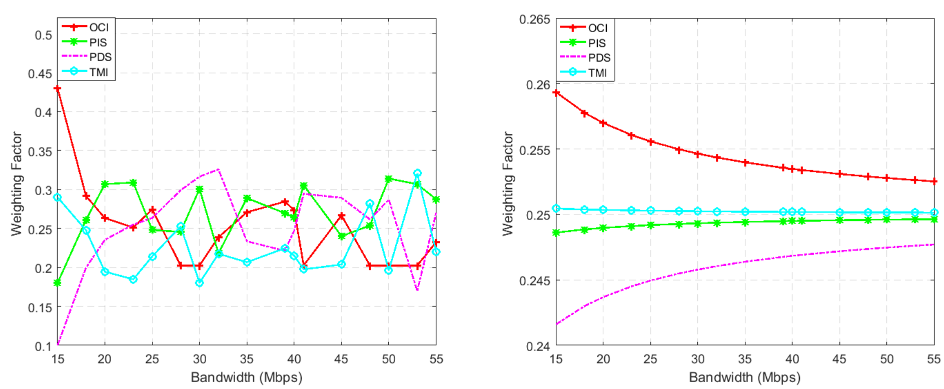
(a) Bandwidth allocation results using N-PSO (b) System and service utility values using N-PSO

Fig.6 Bandwidth allocation results and utility values based on N-PSO



(a) Bandwidth allocation results using ADCF (b) System and service utility values using ADCF

Fig.7 Bandwidth allocation results and utility values based on ADCF



(a) Weighting Factor of N-PSO (b) Weighting Factor of ADCF

Fig.8 Comparison of ADCF with N-PSO in terms of service utility Weighting Factor

TABLE 3

Bandwidth allocation results and utility values based on N-PSO

No.	U^*	Φ	x_1	u_1	x_2	u_2	x_3	u_3	x_4	u_4
0	0.019	15	2.019	0.156	2.234	0.025	9.000	0.000	1.747	0.057
1	0.037	18	2.947	0.816	4.553	0.024	9.000	0.000	1.500	0.045
2	0.061	20	2.997	0.840	6.503	0.150	9.000	0.000	1.500	0.045
3	0.100	23	3.102	0.881	8.500	0.500	9.898	0.000	1.500	0.045
4	0.164	25	4.000	1.000	6.000	0.096	9.000	0.001	6.000	1.000
5	0.233	28	3.105	0.882	8.500	0.500	14.895	0.008	1.500	0.045
6	0.305	30	3.104	0.882	8.500	0.500	14.646	0.007	3.750	0.500
7	0.448	32	3.210	0.914	8.415	0.544	18.703	0.276	1.672	0.053

8	0.582	35	3.095	0.879	7.655	0.358	20.500	0.500	3.750	0.500
9	0.865	39	4.000	1.000	10.032	0.773	20.500	0.697	4.468	0.894
10	0.842	40	3.626	0.977	10.677	0.842	21.022	0.556	4.675	0.887
11	0.908	41	3.831	0.988	11.664	0.919	20.500	0.697	5.005	0.942
12	0.948	45	3.500	1.010	15.000	1.000	20.500	0.713	6.000	1.000
13	0.985	48	3.889	1.016	15.000	1.000	24.049	0.839	5.062	1.058
14	1.004	50	4.000	1.013	13.662	1.004	26.804	0.970	5.535	1.016
15	0.982	53	3.735	1.027	11.265	0.897	32.000	1.000	6.000	1.000
16	1.004	55	4.000	1.000	15.000	1.000	30.000	0.984	6.000	1.055

TABLE 4
Bandwidth allocation results and utility values based on ADCF

No.	U^*	Φ	x_1	u_1	x_2	u_2	x_3	u_3	x_4	u_4
0	0.000	15	1.000	0.000	2.000	0.000	9.000	0.000	3.000	0.333
1	0.000	18	1.000	0.000	2.000	0.000	9.000	0.000	6.000	1.000
2	0.000	20	1.000	0.000	2.000	0.000	15.500	0.283	1.500	0.000
3	0.000	23	1.000	0.000	2.000	0.000	18.500	0.413	1.500	0.000
4	0.000	25	1.000	0.000	2.000	0.000	20.500	0.500	1.500	0.000
5	0.000	28	1.000	0.000	2.000	0.000	23.500	0.630	1.500	0.000
6	0.000	30	1.000	0.000	2.000	0.000	25.500	0.717	1.500	0.000
7	0.000	32	1.000	0.000	2.000	0.000	27.500	0.804	1.500	0.000
8	0.000	35	1.000	0.000	2.000	0.000	30.500	0.935	1.500	0.000
9	0.781	39	4.000	1.000	13.045	0.850	15.955	0.302	6.000	1.000
10	0.800	40	4.000	1.000	13.659	0.897	16.341	0.319	6.000	1.000
11	0.818	41	4.000	1.000	14.273	0.944	16.727	0.336	6.000	1.000
12	0.882	45	4.000	1.000	15.000	1.000	20.000	0.478	6.000	1.000
13	0.919	48	4.000	1.000	15.000	1.000	23.000	0.609	6.000	1.000
14	0.940	50	4.000	1.000	15.000	1.000	25.000	0.696	6.000	1.000
15	0.968	53	4.000	1.000	15.000	1.000	28.000	0.826	6.000	1.000
16	0.985	55	4.000	1.000	15.000	1.000	30.000	0.913	6.000	1.000

D. Bandwidth Allocation Results and Analysis

The bandwidth allocation results and utility functions are compared and shown as Fig.6 and Fig.7, by using the proposed N-PSO method and traditional ADCF method, respectively. Table 3 and Table 4 list the data of allocation information and utility results in detail, so that the allocation principles and optimization results can be analyzed in a quantitative way.

It is seen in Fig.6 (a) that the allocated bandwidth for each service is changing dynamically with the varying given system bandwidth. The minimum bandwidth demand of each service is satisfied in terms of priority, while the remaining bandwidth is dynamically allocated to services according to the requirements. In the scenario of this paper, the weighting factor of OCI is the highest (which is associated with train operation safety), and the bandwidth demand is relatively low. Therefore, OCI is given the highest priority of bandwidth allocation. In contrast, the weighting factor of TMI is the lowest, but the bandwidth requirement is smaller than that of PIS and PDS. Consequently, when the system bandwidth is not enough to satisfy the requirement of PIS and PDS, a higher priority of bandwidth allocation is given to TMI, so that more efficient use of bandwidth resources is ensured.

Figure 6(b) shows that with the increasing system bandwidth, the system utility is increasing continuously and gradually. For OCI with a higher weighting factor but a lower bandwidth demand, the utility remains larger than 0.8 after the bandwidth allocation. During the process of the bandwidth changing from 20Mbps to 23Mbps, the allocated bandwidth of PIS goes down slightly, while the allocated bandwidth of PDS goes up slightly. Meantime, the system utility is increasing, so that the goal of bandwidth allocation is achieved. Besides, the variation trend of the system utility is more consistent to the system bandwidth.

Comparatively, the optimization results using traditional ADCF method [23] are shown in Fig. 7. It is seen that during the period when the system bandwidth is relatively small, the minimum bandwidth requirement of each service is satisfied in terms of priority, while the remaining bandwidth is mainly allocated to PDS whose weighting factor is medium but bandwidth requirement is the largest. When the system bandwidth is larger than 32Mbps, the maximum bandwidth demands of OCI, PIS, and TMI are satisfied, while the remaining bandwidth is allocated to PDS. The system utility increases sharply from zero to 0.8 when the system bandwidth is near to 32Mbps. Then, the value gradually increases to 1. In other words, the ADCF based bandwidth allocation method places insufficient priority on the weighting factors of the services. Consequently, the bandwidth allocation scheme is “unfair” for various services, and the system utility vary abruptly even though the system bandwidth is increasing smoothly. This may bring heavy pressure on the stability of the high-speed TGCS.

As shown in Fig.8, the N-PSO strategies proposed in the paper focus on the bandwidth allocation dynamically based on the bandwidth demands of each service. The weighting factor in N-PSO is related to not only the system total bandwidth but also bandwidth allocated to each service, however, in ADCF just the total bandwidth variable is considered. The dynamic allocation method is more effective to improve the system utility and make full use of the limit resources of TGCS.

V. Conclusion

For different services of high-speed TGCS, the information transmission needs to be optimized to ensure the operational safety of train and data service of passengers. However, in a real running train, the bandwidth resource of TGCS is limited and variable, and thus it is impossible to provide every service with satisfactory bandwidth allocation. To make better use of the limited system bandwidth, we proposed an effective and efficient bandwidth allocation model based on the cooperation asymmetric Nash game theory, and optimized the bandwidth allocation mechanism with particle swarm optimization (PSO) algorithm. The system utility involves the importance of the service transmission data, the real-time demand, the bandwidth requirement, and the total system bandwidth. The maximum system utility is treated as the ultimate objective of the bandwidth allocation. We calculated the optimal bandwidth allocation results for each service, with simulation validation to reveal the effectiveness and efficiency of the proposed scheme. It is concluded that the system utility is superior to that of ADCF with better response capacity for the dynamic bandwidth allocation.

The simulations based on real train data sets demonstrate the four vital advantages of the proposed strategy.

1) The critical services concerning to the operation safety are given the highest priority in bandwidth allocation, whose utility value is maintaining above 0.8 and arrives at 1 gradually with the increasing allocated bandwidth.

2) After satisfying the minimum bandwidth demands of all services, the remaining bandwidth is allocated using the proposed N-PSO scheme.

3) The bandwidth allocation is realized dynamically, and this renders a “fair with respect to criticality” scheme of resource attribution.

4) The scheme enables more efficient bandwidth allocation and higher system overall utility.

5) The scheme proposed in the paper balances the bandwidth allocation between the users and control channels, so that both sides may utilize the limited bandwidth in a more efficient way.

Multi-service TGCS bandwidth allocation has been regarded as a vital factor to the railway operation. The rapid development of high-speed railway requires more communication services between train and ground, so an efficient bandwidth allocation algorithm is vital to the usage of the limited bandwidth resources and this helps ensure the operation safety of the railway systems. But rare studies have focused on the allocation of TGCS, so this work may be valuable to developing future bandwidth allocation schemes of TGCS.

VI. Future Work

Three potential topics deserve further research. First, we may consider the situation that the system bandwidth is less than the sum of minimum bandwidth needs of all services. That is, there will be some services that have no bandwidth resource to complete the basic information transmission. In this paper, we assign a bigger weighting factor to the vital service and let the system allocate the limit bandwidth resources autonomously. In the future work, variable structure would be applied to cope with different system bandwidth issues. Second, the allocation scheme could be validated and improved by using the real operation data sets of high speed trains. Finally, the utility function could be involved for evaluating the optimization process and results, while the formulation and effect of the function need to be considered further.

Future more, it is found that the N-PSO method shows favorable engineering potentialities in TGCS. It is true that there are many services in TGCS, but most of them could be categorized into groups. First, all these services are divided into several groups, and we use the N-PSO to allocate the bandwidth for these groups. Then, in each group the N-PSO is applied again to allocate the bandwidth for all services. In this way, the iteration number will not increase considerably with the increasing services due to the limited groups and service numbers in each round. The feasibility of the proposed N-PSO scheme is ensured and the iteration complexity for increasing services is acceptable as well.

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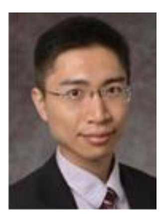

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