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Joint Resource Allocation and Power Control Algorithm for D2D Based Train to Train Communication

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Abstract. The next generation Communication based train control (CBTC) system has many new features, one of which is the introduction of train-to-train (T2T) communication. T2T communication can be realized by device-to-device (D2D) communication based on long-term evolution (LTE). However, D2D communications may generate interference in the system if not designed properly. In this paper, a joint resource allocation and power control algorithm is proposed to maximize the overall network throughput while guaranteeing the quality-of-service (QoS) requirements for both T2T links and cellular links. The algorithm has two steps. The first step is to allocate resources according to channel state information (CSI), the second step is to allocate power while maintaining system performance. Simulation results show that compared with random resource allocation, proposed approach provides a significant improvement in the system performance.

1. Introduction

Communication based train control (CBTC) system in urban rail transit realizes continuous automatic train control through high-precision train positioning, continuous train-ground data communication and vehicle-mounted and ground safety function processor [1]. With the development of communication technology, some scholars proposed to add the direct communication link between trains into the CBTC system to improve the train control system [2]. Train-to-train (T2T) communication has become the research focus of the next generation CBTC system [3]. In [4], the signal system and train control mode in CBTC system with T2T communication is studied. In [5], the feasibility of using Ad-Hoc network for T2T communication is demonstrated. In [6], a T2T communication scheme based on WLAN is proposed, and a train control system based on perceptive control is designed. However, in view of the disadvantages of WLAN, such as the lack of quality of service (QoS) and the vulnerability to interference [7], the wireless communication carrying of CBTC system is transiting from WLAN to long term evolution (LTE) which is more secure and stable [8]. At the same time, 3GPP added device to device communication (D2D) in LTE, which allows data to be transmitted directly between users, without base station (BS) relay [9]. This provides the technical basis for implement T2T communication in CBTC system. In [10], the feasibility of using D2D to realize T2T communication is demonstrated. In [11], the train control problem of T2T communication system is discussed, and the feasibility is verified by field test.

According to the existing research, a joint resource allocation and power control algorithm is proposed for T2T communication, which is based on D2D. The algorithm has two steps, resources is allocated according to CSI firstly, then the power is allocated according to the beetle antennae search (BAS) algorithm. The algorithm maximizes system throughput while ensuring QoS.



The rest of this paper is organized as follows. In section 2, the system model is discussed. The joint resource allocation and power control algorithm is proposed in Section 3. Section 4 discusses the simulation result and demonstrates comparative study. Section 5 is conclusion.

2. System model

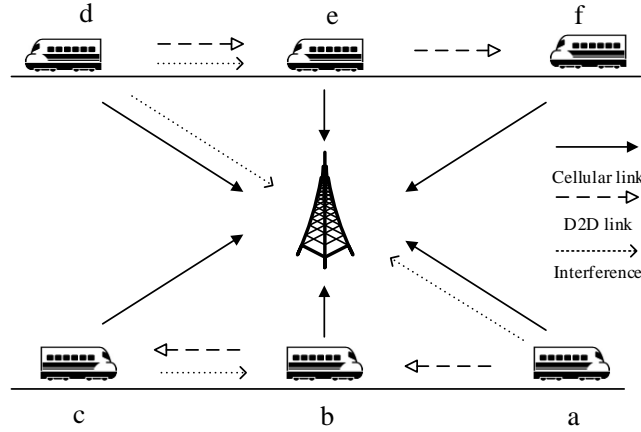


Figure 1. System model.

The single cell system model is shown in Figure 1 which shows T2T communication enabled CBTC system. Assume, there are N trains, all of them maintain communication with the BS through cellular network. T2T communication is conducted between the front and rear trains, which is based on D2D. So, there are two kinds of data links in the system, cellular link (or c-link) and T2T link. Corresponding to N c-links, N orthogonal channels are available. And the T2T links reuse the resources which belong to c-links. And uplink resources are used for reuse, not downlink resources in the system. Set of c-links and T2T links are $C=\{1,2,3,...,N\}$ and $D=\{1,2,3,...,M\}$, respectively. The BS is the core of the whole system, so suppose it has all the channel state information (CSI). The channel gain between the transmitter of c-link i and BS can be represented by g_i . Similarly, we can use g_j to represent the channel gain of T2T link j . When T2T link j reuse c-link i resource, interference channel gain between transmitter of T2T link j and BS is $h_{j,i}$ and interference channel gain between transmitter of c-link i and receiver of T2T link j is $h_{i,j}$. The sum throughput of the system optimization problem can be formulated in equation.

$$\max_{\rho_{i,j}, P_i, P_j} \left\{ \sum_{i \in C} \sum_{j \in D} \left[\log(1 + \xi_i) + \rho_{i,j} (1 + \xi_j) \right] \right\} \quad (1)$$

$$\text{s. t. } \xi_i = \frac{P_i g_i}{\sigma_N^2 + \sum_{j \in D} \rho_{i,j} P_j h_{j,i}} \geq \xi_{\min}^c, \forall i \in C \quad (2)$$

$$\xi_j = \frac{P_j g_j}{\sigma_N^2 + \sum_{i \in C} \rho_{i,j} P_i h_{i,j}} \geq \xi_{\min}^d, \forall j \in D \quad (3)$$

$$0 \leq P_i \leq P_{\max}^c, 0 \leq P_j \leq P_{\max}^d, \forall i \in C, \forall j \in D \quad (4)$$

Where, P_i and P_j represent the transmit power of c-link i and T2T link j respectively, and P_{\max}^c and P_{\max}^d is the maximum values of the them; ξ_i and ξ_j represent the signal to interference plus noise ratio (SINR) of c-link i and T2T link j , respectively, ξ_{\min}^c and ξ_{\min}^d represent the minimum SINR requirement of them. σ_N^2 is the additive white Gaussian noise power. $\rho_{i,j} \in \{0,1\}$ is an integer which is used to indicate whether T2T link reuses the resource of c-link, i.e., $\rho_{i,j}=1$; otherwise, $\rho_{i,j}=0$.

The problem mentioned in equation (1) is non-linear mixed integer problem. It is very difficult to solve directly. To solve this problem, it is divided into two parts, resource allocation and power

control. Resources is allocated according to CSI firstly, then the power is allocated according to the BAS algorithm.

3. Resource allocation and power control algorithm

3.1. Resource allocation algorithm

Resource scheduling is controlled by the BS with CSI. Higher values of ξ_i and ξ_j would aid in increased c-link and T2T link throughput respectively. It is obvious that lower channel gain $h_{i,j}$ between the transmitter of c-link i and the receiver of T2T link j will result in higher ξ_j i.e. will cause less interference to T2T link j . Therefore, any c-link with higher channel gain g_i can share resources assigned to them with the T2T link of which the receiver has lower channel gain between them. To avoid complex interference, T2T link can't reuse the resource assigned to its transmitter or receiver. As shown in figure 1 the T2T link between train d and e reuse the resource assigned to train d, this will cause co-channel interference.

Table 1. Resource allocation algorithm

Algorithm 1: Resource allocation algorithm

```

1 C: Sorted list of CQIs for c-links in decreasing order
2 D: List of T2T links yet to be assigned resources
3 begin
4    $i = 1$ ;
5   while  $D \neq \emptyset$  or  $i = N$  do
6     Pick resources with  $i$  th largest value;
7     Find the T2T link  $j$  for which  $h_{i,j}$  is minimum;
8     Calculate  $\xi_i$  and  $\xi_j$ ;
9     if  $\xi_i > \xi_{\min}^c$  and  $\xi_j > \xi_{\min}^d$  then
10      Share resources of c-link  $i$  with T2T link  $j$ ;
11       $D = D - \{j\}$ ;
12       $i = i + 1$ ;
13    else
14       $j = j + 1$ ;
15    end
16  end
17 end

```

3.2. Power control algorithm

After matching the c-link for T2T link to reuse resources, the power is allocated. Optimization problem is expressed below. The object is to optimize power for the D2D transmitter and its reuse partner.

$$(P_i^*, P_j^*) = \arg \max_{P_i, P_j} \{ \log_2(1 + \xi_i) + \log_2(1 + \xi_j) \} \quad (5)$$

$$\text{s.t. } \xi_i = \frac{P_i g_i}{\sigma_N^2 + P_j h_{j,i}} \geq \xi_{\min}^c \quad (6)$$

$$\xi_j = \frac{P_j g_j}{\sigma_N^2 + P_i h_{i,j}} \geq \xi_{\min}^d \quad (7)$$

$$0 \leq P_i \leq P_{\max}^c, \quad 0 \leq P_j \leq P_{\max}^d \quad (8)$$

To solve this problem, an optimization method based on BAS algorithm is proposed.

Beetle antennae search (BAS) algorithm is a meta-heuristic algorithm proposed in recent year with an excellent performance on optimization problems [12]. Its invention is inspired by the behaviour of beetles foraging. The beetles use its two antennae to explore the area randomly and tuning to the direction which has higher concentration of odour. The position of the beetle at t th time instant is represented by a vector \mathbf{x}_t ($t=1, 2, \dots$). The odour concentration at position \mathbf{x} is defined as $F(\mathbf{x})$. The maximum value of $F(\mathbf{x})$ is the source point of the odour. For optimization problems F is the fitness function and $\mathbf{x} \in \mathbb{R}^n$ denotes the function variable in n dimensions. BAS algorithm searches randomly to explore the solution space. The main formula contains two aspects: searching behaviour and detecting behaviour. The searching behaviour is expressed by a normalized random unit vector \mathbf{b} , a left side antennae \mathbf{x}_l and a right antennae \mathbf{x}_r :

$$\mathbf{b} = \frac{\text{rand}(n,1)}{\|\text{rand}(n,1)\|} \quad (9)$$

$$\begin{cases} \mathbf{x}_l = \mathbf{x}_t - d_t \mathbf{b} \\ \mathbf{x}_r = \mathbf{x}_t + d_t \mathbf{b} \end{cases} \quad (10)$$

where $\text{rand}(\cdot)$ is a random function; n signifies dimensions of variable; d denotes the length of antennae. The detecting behaviour is in an iterative form:

$$\mathbf{x}_{t+1} = \mathbf{x}_t + \delta_t \mathbf{b} \text{sign}(F(\mathbf{x}_l) - F(\mathbf{x}_r)) \quad (11)$$

where δ_t represents the step size of each iteration, $\text{sign}(\cdot)$ represents a sign function. The antennae length d_t and step size δ_t are recommended as follows: $d_{t+1} = z_1 d_t$, $\delta_{t+1} = z_2 \delta_t$. Where z_1 and z_2 are regulatory factors.

Before solving the problem defined in equation (9) with the BAS algorithm, the fitness function should be established. For the constraint (10) and (11), the penalty function can be introduced, so as to form the fitness function together with the objective function. The definition of penalty functions $f_1(P_i, P_j)$ and $f_2(P_i, P_j)$ are these:

$$f_1(P_i, P_j) = \begin{cases} 1, & \xi_i < \xi_{\min}^c \\ 0, & \xi_i \geq \xi_{\min}^c \end{cases} \quad (12)$$

$$f_2(P_i, P_j) = \begin{cases} 1, & \xi_j < \xi_{\min}^d \\ 0, & \xi_j \geq \xi_{\min}^d \end{cases} \quad (13)$$

Then the fitness function can be expressed as:

$$F(P_i, P_j) = \log_2(1 + \xi_i) + \log_2(1 + \xi_j) + \varphi_1 f_1(P_i, P_j) + \varphi_2 f_2(P_i, P_j) \quad (14)$$

Where φ_1 and φ_2 are penalty factors. Use \mathbf{x}_t and \mathbf{x}_{bst} represent $(P_{i,t}, P_{j,t})$ and (P_i^*, P_j^*) respectively. T is the maximum iteration number.

Table 2. Power control algorithm

Algorithm 2: Power control algorithm

- 1 **Initialization:** Initialize $\mathbf{x}_0, \delta_0, d_0, z_1, z_2$;
 - 2 **while** ($t < T$) **do**
 - 3 Generate the direction vector unit \mathbf{b} according to (9);
 - 4 Search in variable space according to (10);
 - 5 Update the state variable \mathbf{x}_t according to (11);
 - 6 **if** \mathbf{x}_t beyond the boundary defined by (8) **then**
 - 7 \mathbf{x}_t takes the boundary value;
-

```

8   end
9   if  $F(\mathbf{x}_i) > F_{\text{bst}}$  then
10   $F_{\text{bst}} = F(\mathbf{x}_i)$ ,  $\mathbf{x}_{\text{bst}} = \mathbf{x}_i$ ;
11  end
12  Update  $d_i$  and step size  $\delta_i$  respectively;
13 end
14 return  $\mathbf{x}_{\text{bst}}$ ,  $F_{\text{bst}}$ .

```

4. Results and discussion

In this section, simulation results for a cell has one BS at the centre is presented. $N = 8$, it is the number of trains which run on two tracks of which the directions is opposite. Corresponding to 8 trains there are 8 c-links and 6 T2T links at most. Cost231-hata is adopted as the wireless signal propagation model in the simulation experiment, and the specific parameters are shown in table 3.

Table 3. Simulation parameters

Parameter	Value
Bandwidth	10 MHz
Carrier frequency	1.8 GHz
Max cellular link Tx Power	23 dBm
Max T2T link Tx Power	23 dBm
Antenna height of BS	30 m
Cell radius	3 km
Antenna height of train	3 m
Speed of train	60 km/h

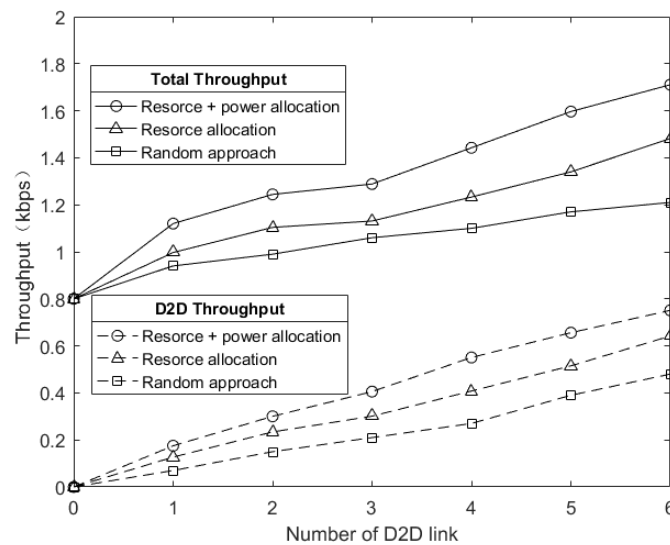


Figure 2. Relationship between throughput and D2D link quantity.

Figure 2 shows the system throughput and D2D throughput of the three schemes. The throughput is compared on the condition that the average distance between two trains is 200m. Results of joint algorithm is compared with other two approaches: random resource allocation with fixed power and proposed resource allocation with fixed power. Random approach randomly matches cellular link and T2T link, that causes intense interference within the system and reduced system throughput. As the number of trains increases, the interference becomes more complex. In random approach the average

throughput of one cellular link is 91.25kbps, and the average throughput of one T2T link is 82.03kbps. In proposed resource allocation approach minimum SINR requirement of different kinds of links in the system is considered. The approach uses the gain of each channel as the basis for resource allocation and resources are reused flexibly among T2T links and cellular links, that reduces the impact of interference in the system. The resource allocation approach has higher throughput as compare to random approach in the same situation. The average throughput of this approach for one cellular link is 105.03kbps and for one T2T link is 107.12kbps. The joint algorithm optimizes the power allocation after the resource allocation and further increases the throughput. In joint algorithm the average throughput of one cellular link is 121.78kbps, and the average throughput of one T2T link is 123.26kbps. The performance improvement is significant.

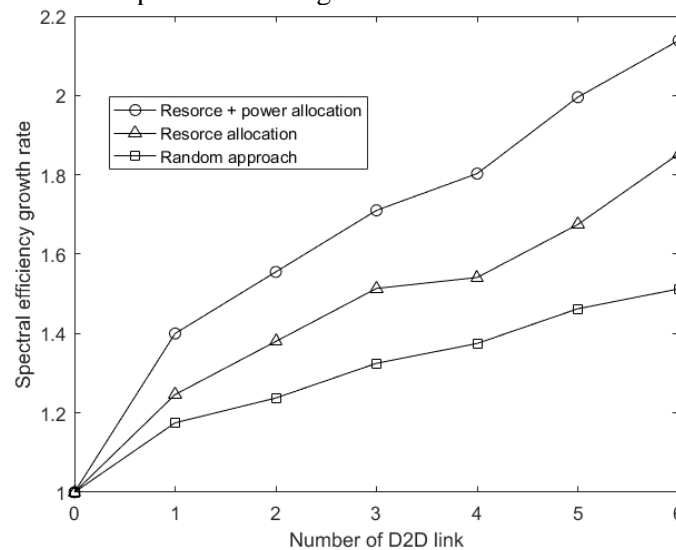


Figure 3. D2D link number and relative growth rate of spectral efficiency

Figure 3 shows the relative growth rate of spectral efficiency of D2D enabled network compared with the network without T2T link. The spectrum efficiency of joint algorithm increases more obviously than random approach and proposed resource allocation approach. The spectral efficiency increased by about 112% in the optimal condition. The main source of growth is D2D link throughput.

5. Conclusion

In this paper, we have introduced a joint resource allocation and power control algorithm to improve the cellular network performance for CBTC wireless communication system. The algorithm has two steps, resource allocation according to CSI and power control by BAS algorithm. Proposed joint algorithm solved the throughput optimization problem by incorporating the constraints while maintaining QoS of the system. Proposed approach is compared with two other techniques (resource allocation without power control and random resource allocation) and significant improvement is found in terms of system throughput. Simulation results show that network gives better performance after applying the algorithm and the utilization of spectrum is more efficient.

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