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Research on Resource Migration Based on Novel RRH-BBU Mapping in Cloud Radio Access Network for HSR Scenarios

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ABSTRACT Cloud radio access network (C-RAN) is considered as a promising architecture for 5G with advantages of green energy, convenient resources allocation. In this paper, we explore the feasibility of C-RAN for high-speed railway (HSR) scenarios. A novel phenomenon of group handover is defined in the extensively and densely distributed railway network and we present a resource migration cost with a closed-form expression to depict the group handover. To reduce the cost, we propose a novel connection relationship between the remote radio head (RRH) and the baseband unit (BBU) pool. Based on this, we establish a flexible network so as to allocate the resource dynamically and formulate a graph by abstracting the RRH-BBU and BBU-BBU mapping relationship. Then the minimization of resource migration cost along the high-speed train (HST) routine is converted into the shortest path problem (SPP). By using the modified Floyd-Warshall algorithm, the SPP can be solved with high efficiency compared with the conventional algorithm. Finally, the simulation result shows that the proposed mechanism can decrease the resources migration cost significantly.

INDEX TERMS Cloud radio access network, group handover, graph theory, high-speed railway communication, RRH-BBU mapping.

I. INTRODUCTION

The proliferation of China's high-speed railway (HSR) enhances the quality of rail services, yield greater customer satisfaction and help to create socioeconomically balanced societies [1]. Meanwhile, the ever-increasing requirements of new railway communication services, e.g., real-time monitoring, train multimedia dispatching, railway emergency communications, railway Internet of Things (IoT), and broadband wireless access for train passengers [2], bring more and more challenges to the railway communications system, drawing vast worldwide attention. To satisfy these requirements, a reliable communications system is essential to guarantee the safe operation of the trains.

A wide variety of studies have concentrated on HSR communication, involving wireless channel measurements and modeling, wireless access methods, wireless resources allocation, etc. In [3], Liu established the statistical position-based channel models to characterize the HSR channel by performing extensive measurements at 2.35 GHz in China. Zhou focused on a survey of channel modeling for the future HSR communication systems in [4]. Fokum presented a survey of the approaches for providing broadband Internet access to trains in [5], including the Leaky Coaxial Cable-based Architecture, Satellite-based Architectures, WiMax-based Architectures, etc. Zhong reviewed the state-of-art radio resource management methods in [6]. These works lay a great foundation for the research and design of HSR communication.

Currently, the Global System for Mobile Communications for Railway (GSM-R) is widely implemented for the dedicated railway communication. However, the shortcomings of the GSM-R, e.g., the limited narrow bandwidth, cannot cater to the demand of the future HSR [7]. Since 2014, the International Union of Railways (UIC) has started to assess the future of HSR mobile communications and identify the Long-Term

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Evolution for Railway (LTE-R) as a more suitable candidate technology [2]. Meanwhile, the high-speed train (HST), with a faster and faster speed, has been evolving greatly. China's Fuxing bullet train has been running at a speed of 350 km/h since 2017 and its maximum speed can reach 400 km/h [8]. What's more, vactrain (or vacuum tube high-speed flying train), as a novel means of transportation, which can run at an ultra-high speed (over 1000 km/h), is attracting more and more attention since the Hyperloop One company first fully tested the hyperloop propulsion system using a test line in the northern desert of Las Vegas on May 12, 2016 [9]. With quite a few other means of transportation being under construction or preparation, how to provide a reliable access for HST becomes a critical challenge when deploying wireless networks along the high speed railways.

The finalization of LTE-R in near future is expected to provide high-quality, cost-efficient railway communication. However, the high speed of HST highlights the problems of the severe Doppler effect and the frequent handover, which degrade the LTE's quality of service (QoS). To address the above challenges, cloud radio access network (C-RAN), with the centralized baseband units (BBU) and distributed remote radio heads (RRH), is regarded as a promising wireless network architecture which can reduce the energy consumption [10]. Some researchers have investigated the application of C-RAN in HSR scenarios and proposed some novel seamless handover schemes, e.g., the cell array scheme [11] and moving cell scheme [12]. Yet it is noteworthy that the HST travels at a vast large geographical range, indicating that more than one BBU pool is needed to serve the HST in relay. Consequently, a phenomenon of handover occurs as the HST travels across different BBU pools. This problem will be addressed in detail in this paper. The main contributions of this paper are summarized as follows:

1) We present a phenomenon of group handover when the HST passes across different BBU pools. Moreover, we propose a closed-form expression to depict the resource migration cost of the group handover.
2) We propose a novel RRH-BBU mapping relationship. Based on this, we abstract the network into a graph by using the graph theory.
3) We establish a optimization problem and convert it into a shortest path problem (SPP). A modified Floyd-Warshall algorithm with low computational complexity is proposed to address the above problem.

The remainder of this paper is organized as follows: Section II presents a review of the background and some related works. Some challenges are put forward after the discussion on the strengths and shortcomings of the state-of-art solutions. Section III discusses the application of C-RAN in HSR scenarios. In Section IV, a novel connection relationship between RRHs and BBU pools is proposed. Based on this, we establish a flexible network and formulate a graph theory problem. The problem is addressed by the modified Floyd-Warshall algorithm with a low time computational complexity in section V. Section VI presents the simulation results. The summarization of this paper as well as the future work will be described in the final section.

II. BACKGROUND AND RELATED WORKS

Currently, the prevailing wireless communication system for the railway is GSM-R, which can provide a limited narrow bandwidth and is specifically dedicated for train control system instead of passengers' in-journey communication [13]. Therefore, GSM-R cannot meet the growing communication demands for future HSR. Various schemes have been proposed to enhance the performance of the broadband wireless access on HST. Satellite communication has been proved a good solution for the long-distance railway communication. Since it is traditionally used for wireless access over vehicles moving across vast geographical areas [14]. In Europe, the Air Force Research Laboratory developed the multi-modal global mobile broadband communication (MOWGLY) technology, which adopted WiFi and satellite technologies for in-vehicle and train-to-ground communications to provide broadband Internet access, respectively [15], [16]. However, the performance of satellite communication would degrade dramatically when the HST runs in the tunnel or other non-light-of-sight (NLoS) scenarios. In addition, the long transmission latency between the ground and satellites cannot cater to the requirements of some mission-critical services, jeopardizing the stability of the HST. Moreover, the high equipment cost hinders the large-scale deployment of satellite communication technology.

In China, the dedicated LTE networks have been deployed densely along a vast HSR line with a total length of about 15, 000 km by 2014. Moreover, it is expected to exceed 30, 000 km in 2020. Based on this, numerous work has been investigated to improve the performance of HSR communication. However, many problems have not been solved perfectly in the applications of LTE, especially the frequent handover, which degrades the communication reliability seriously. In [16], a scheme based on the radio over fiber (RoF) technology is proposed to reduce the handover frequency to some degree. Based on the coordinated multiple point (CoMP) transmission technology, Luo proposed a soft handover scheme instead of the traditional hard handover of LTE in [17]. However, these schemes cannot eradicate the handover problem completely.

C-RAN, as a novel network architecture, has attracted much attention on the application in HSR scenarios since it was proposed by China Mobile in 2011 [18]. When employing C-RAN, some researchers began to realize that a single BBU pool cannot cater to the communication demand of the long-distance railway lines. In [19], a concept of virtual cell, which combines all RRHs connected to the same BBU pool, is proposed to reduced the frequent handover in the long-distance railway lines.

In conventional C-RAN architecture, one RRH is connected to a single BBU pool, whereas one BBU pool is connected to many RRHs as shown in Figure 1. Some works

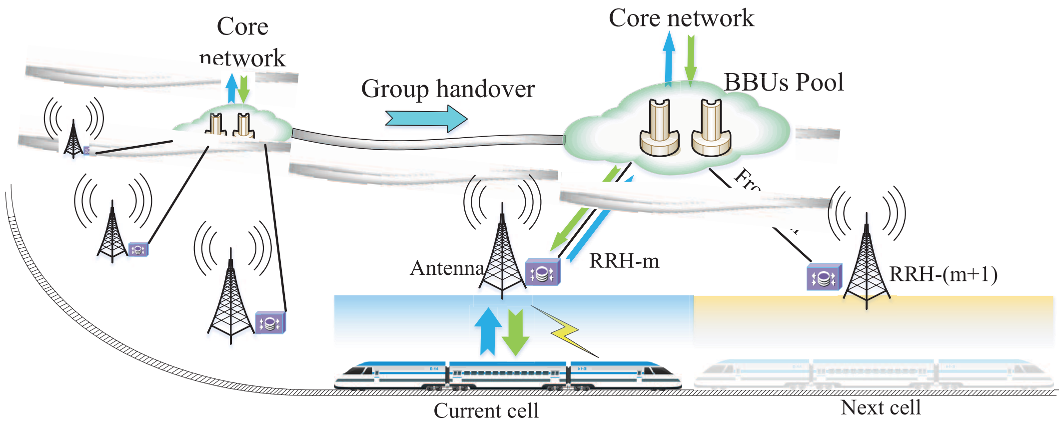

FIGURE 1. Diagram of C-RAN in HSR scenarios.

have been conducted to investigate the resource allocation or energy-saving problem by concentrating on the connection relationship between BBUs and RRHs in C-RAN. In [20], Boulos investigated the BBU-RRH mapping problem in C-RAN architecture so as to reduce network power consumption and formulate it as a bin packing problem. In [21], Chen redefined the resource allocation by proposing a dynamic BBU-RRH mapping scheme using a borrow-and-lend approach to dynamically allocate the resource. However, all these works are conducted based on the conventional RRH-BBU mapping relationship, i.e., one RRH can only be connected to a single BBU pool. Hence, we propose a novel mapping relationship in this paper and focus on the optimization of resource allocation during the handover. The HSR network model we established in this paper provides some new insights to the future research on HSR communication system.

III. CLOUD-RAN IN HSR SCENARIOS

In LTE, a typical wireless base station is comprised of the BBU and the RF processing unit (RRH). The BBU, with the advantage of modular design, small size, high integration, low power consumption, and easy deployment, is responsible for the baseband signal processing. The RRH refers to a remote radio transceiver that connects to an operator radio control panel via electrical or wireless interface [22]. The BBU is usually located near RRH and connected with the RRH via optical fiber. However, one of the primary shortcomings of this architecture is the high capital expenditure (CAPEX) and operating expenditure (OPEX) [10]. Therefore, the C-RAN architecture, with centralized BBUs at a near site, is proposed to cope with this problem.

Similarly, C-RAN mainly consists of three parts: the centralized BBUs, the distributed RRHs and fronthaul links. The multiple BBUs in C-RAN are pooled in a central cloud, i.e., BBU pool, which is able to provide powerful computation and storage resources, whereas RRHs are distributed across multiple sites to provide wireless access coverage and interact with terminal equipment. Figure 1 presents the deployment of C-RAN in HSR scenarios. The RRHs are distributed along the railway lines and the centralized BBUs are positioned at a certain place near the lines. The fronthaul links connect BBUs and RRHs via common public radio interface. RoF technology, which refers to a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link, is adopted in the fronthaul links. The real-time information of the HST such as the velocity, location, and the routine can be predetermined since the HST runs following the schedule strictly, which is different from the land mobile communication. In this paper, we assume the foreknowledge information of the HST can be obtained by quantities of transponders and sensors along the lines.

The combination of C-RAN and unique characteristic of HSR scenarios generates some novel communication solutions, e.g., the moving cell scheme. The moving cell scheme provides a continuous connection to the mobile network when the terminals are crossing among multiple cells at a high speed. In [12], Lannoo proposed a cellular trackside solution for providing broadband multimedia services to train passengers based on the RoF network in combination with the moving cells scheme. Moreover, Liu explored the feasibility of C-RAN-based communication system for ultra-high-speed flying train by utilizing moving cell scheme in [23] and [24], and proposed a promising prospect of C-RAN in high speed scenarios.

However, in order to guarantee the real-time transmission of the mission-critical services data, the length of the fronthaul link usually does not exceed 20 km. In other words, one single BBUs pool can only cover small part segment of the railway lines, approximately 40 km. Therefore, more than one BBU pool is needed to realized the seamless wireless access for HSR. When the HST passes through different BBU pools, the passengers in communication will disconnect with the previous BBU pool and establish a new connection with the next BBU pool. Meanwhile, the communication resources will migrate from one BBU pool to another. For example, as the HST moves from RRH1 to RRH2 in Figure 2(a), it will disconnect with the BBU pool1 first and establish a

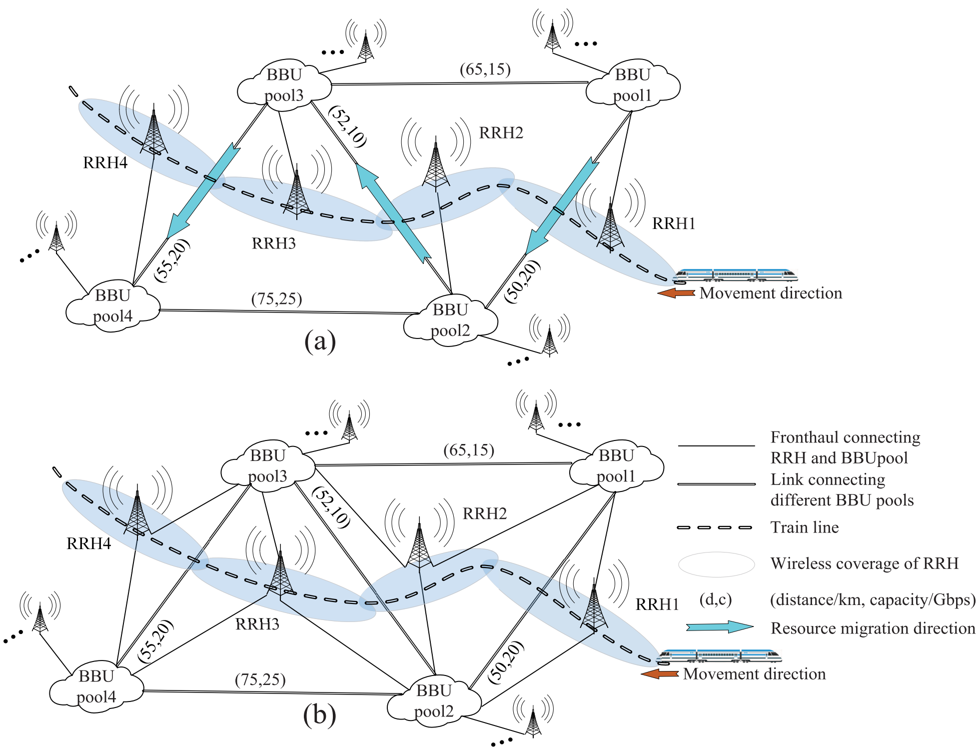

FIGURE 2. **Diagram of the C-RAN architecture in HSR scenarios. (a) The conventional architecture. (b) The proposed architecture.**

new connection with BBU pool2. The nature of this phenomenon is a kind of handover, namely, group handover, which degrades the performance of the system. This problem will be addressed in detail in the following section.

IV. SYSTEM MODEL

As shown Figure 2(a), the group handover yields a certain resource migration cost for long-distance railway lines. Hence, we make efforts to reduce the cost as much as possible by extending the connection relationship to a more flexible one. Moreover, a novel C-RAN architecture is proposed based on three assumptions listed as follows:

1) We establish a flexible RRH-BBU mapping relationship. To be more specific, each RRH is connected to several different BBU pools in the neighbor instead of one, which is illustrated in Figure 2(b).
2) When the HST runs within the wireless coverage of a single RRH, the RRH can only communicate with one BBU pool.
3) Group handover occurs when the HST moves between two adjacent RRHs that communicate with different BBU pools.

Figure 2(a) and Figure 2(b) show the diagrams of the conventional C-RAN architecture and our proposed C-RAN architecture in HSR scenarios, respectively. As shown in the figure, the double lines denote the links that connect two adjacent BBU pools. The solid lines represent the fronthaul links and the dotted double lines mean the railway lines. The sets of RRHs and BBU pools can be regarded as vertexes, whereas the links between them can be considered as edges. We will establish a graph model to describe the connection relationship abstractly. To start with, we list some important notations to facilitate further analysis.

1) The BBU pools set is denoted as $\{B_b \mid b \leq N_B\}$, where $N_B \in \mathbb{N}^*$ represents the number of all BBU pools. The BBU pools vector can be expressed as $\boldsymbol{B} = \left[B_1, \ldots, B_{N_B}\right]^{\mathrm{T}}$;
2) The RRHs set is denoted as $\{R_r \mid r \leq N_R\}$, where $N_R \in \mathbb{N}^*$ represents the number of all RRHs. The RRHs vector can be expressed as $\boldsymbol{R} = \left[R_1, \ldots, R_{N_R}\right]^{\mathrm{T}}$;
3) The train lines set is denoted as $\{l \mid l \leq L\}$, where $L \in \mathbb{N}^*$ represents the number of all lines.
4) $\omega_r \in \{0, 1\}$ means whether the train stays inside the coverage of RRH r or not (0 for no, 1 for yes). As for line l, the RRHs set that the train travels along line l can be expressed as

$$\boldsymbol{R_l} = \boldsymbol{\Omega_l} \odot \boldsymbol{R}, \tag{1}$$

where $\boldsymbol{\Omega_l} = [\omega_1^l, \ldots, \omega_{N_R}^l]^{\mathrm{T}}$ and symbol $\odot$ means the element-wise operation.
5) φ_{rb} denotes whether RRH r is linked to BBU pool b or not (0 for no, 1 for yes). Then the connection matrix

can be expressed as

$$\boldsymbol{\varphi} \triangleq \begin{bmatrix} \varphi_{11} & \cdots & \varphi_{1N_B} \\ \vdots & \ddots & \vdots \\ \varphi_{N_R1} & \cdots & \varphi_{N_RN_B} \end{bmatrix}_{N_R \times N_B}. \tag{2}$$

Hence, as the HST moves forward, the BBU pools that are connected to the RRHs distributed along the line l, namely, BBUs line matrix, can be expressed as

$$\boldsymbol{\Psi_l} = \underbrace{[\boldsymbol{R_l}, \cdots, \boldsymbol{R_l}]}_{N_B} \odot \boldsymbol{\varphi}. \tag{3}$$

Based on this, we establish a graph model $\mathcal{G} = (\mathcal{V}, \mathcal{E})$. The vertex set $\mathcal{V} = \mathcal{V}_R \cup \mathcal{V}_B$ consists of two subsets, that is, the RRH vertex set $\mathcal{V}_R = \{v_r \mid r \leq N_R\}$ and BBU pool set $\mathcal{V}_B = \{v_b \mid b \leq N_B\}$. Similarly, the edge set $\mathcal{E} = \mathcal{E}_{BB} \cup \mathcal{E}_{BR}$ is comprised of two subsets: edges that connect BBU pools $\mathcal{E}_{BB} = \{e_{bb'} \mid b, b' \leq N_B\}$ and edges that link BBU pools and RRHs $\mathcal{E}_{BR} = \{e_{br} \mid b \leq N_B, r \leq N_R\}$.

As for $\mathcal{E}$, each edge e_{ij} is assigned a weight h_{ij} referring to resources migration cost that takes when the train moves from one RRH to another. We assume that the weight of edge set $\mathcal{E}_{BR}$ is 0 since no handover occurs between them. As for edge $\mathcal{E}_{BB}$, the weight of those edges that two BBU pools are not connected by physical link, $b \nrightarrow b'$, is infinity, $h_{bb'} = +\infty$. For those edges that connect two vertexes $b \rightarrow b'$, the weight $h_{bb'}$ is determined by the distance between these two BBU pools $d_{bb'}$, the link capacity $C_{bb'}$, and the number of active passengers ηN_P (N_P denotes the total number of passengers and $\eta \in (0, 1)$ represents the ratio of active passengers). To be more specific, the weight $h_{bb'}$ can be expressed as

$$h_{bb'} = \begin{cases} 0, & b = b' \\ \eta N_P d'_{bb'}/C'_{bb'}, & b \rightarrow b' \\ +\infty, & b \nrightarrow b', \end{cases} \tag{4}$$

where $d'_{bb'} = d_{bb'}/max\,(d_{bb'})$ and $C'_{bb'} = C_{bb'}/max\,(C_{bb'})$ means the normalized distance and capacity, respectively. EQ. (4) implies that the weight is proportional to the normalized distance and inversely proportional to the normalized capacity. This can be explained that the long distance leads to high resource migration cost, whereas the high capacity results in the low cost. Then the resources migration cost matrix (cost matrix in brief) can be expressed as

$$\boldsymbol{H_{BB'}} = [h_{bb'}]_{N_B \times N_B}. \tag{5}$$

As the HST moves within the wireless coverage of RRH-m along the line l, only one BBU pool is allowed to communicate with the RRH based on the third assumption. In other words, the RRH-m ought to choose a connected BBU pool to communicate, which is denoted as

$$\boldsymbol{\chi^l_m} = \left[\chi^l_{m,n}\right]_{1 \times N_B}. \tag{6}$$

The constraints are described as

$$\sum_n \chi^l_{m,n} = 1, \tag{7}$$

$$\chi^l_{m,n} \in \{0, 1\}. \tag{8}$$

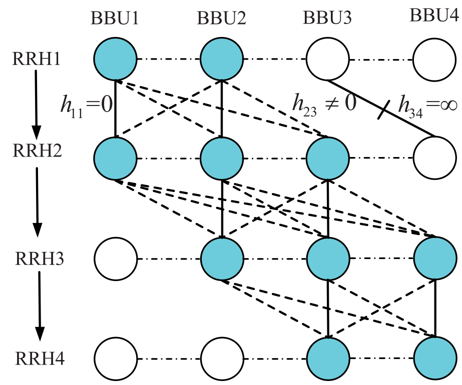

FIGURE 3. Schematic diagram of graph theory in HSR scenarios.

Then the selected communication BBU pools along line l can be deducted as

$$\boldsymbol{\chi^l} = \left[\boldsymbol{\chi^l_1}, \cdots, \boldsymbol{\chi^l_{N_R}}\right]^{\mathrm{T}}. \tag{9}$$

From EQ. (4), the total resources migration cost of line l can be expressed as

$$W_l = \sum_{m=1}^{N_R-1} \boldsymbol{H_{BB'}}(x_m, x_{m+1}) \tag{10}$$

$$\chi^l_m(x_m) = 1, x_m \in \{1, \cdots, N_B\}, \tag{11}$$

$$\chi^l_{m+1}(x_{m+1}) = 1, x_{m+1} \in \{1, \cdots, N_B\}, \tag{12}$$

$$\boldsymbol{\chi^l_m} \cdot \mathbf{1}^{\mathrm{T}} = 1, \tag{13}$$

$$\boldsymbol{\chi^l_{mC1}} \cdot \mathbf{1}^{\mathrm{T}} = 1, \tag{14}$$

where x_m represents the index of the selected BBU pool when the HST runs inside RRH-m, x_{m+1} means the selected BBU pool index of the next RRH. EQ. (11) indicates the current RRH-m is distributed along the line l and EQ. (13) infers that RRH-m can only communicate with one BBU pool from the connected BBU pools. As for RRH-(m+1), EQ. (12) and (14) have the same meaning with EQ. (11) and (13), respectively.

By using the graph theory, the communication network in Figure 2 can be modeled as a graph as shown in Figure 3. It can be learnt that the HST travels from RRH1 to RRH4 successively. The railway line involves 4 BBU pools, which can be expressed as RRU1→RRU2→RRU3→RRU4. In Figure 3, the vertical direction means the successive RRHs along the line l, whereas the horizontal direction represents all BBU pools. The deep color vertexes in the same row refer to the BBU pools connected to the same RRH. For instance, the first two deep color vertexes in the first row indicate that BBU pool1 and BBU pool2 are connected to RRH1. As the HST moves from RRH1 to RRH4, several BBU pools are needed to realize the seamless train-to-ground communication in relay. A possible arrangement of the BBU pools is considered as a path, and the corresponding resource migration cost can be obtained based on EQ. (10). Therefore, the goal of this paper is to find the optimal path of BBU pools so as to minimize the total resource migration cost, which can be expressed as

$$\min_{\chi^l}\{W_l\} \quad s.t.(11-14) \tag{15}$$

This is a NP hard problem and we will use some famous graph algorithms to deal with it in the next section.

V. PROBLEM ANALYSIS

To simplify the above problem and without loss of generality, we consider a single railway line in this paper. In this circumstance, the optimization problem (15) is regarded as the SPP. The goal to find an optimal BBU pool path can be solved by Floyd-Warshall algorithm, which can find the shortest routine between any two vertexes [25]. The basic idea of this algorithm is to update the distance between vertex i and j by traversing all vertexes, that is,

$$D(i,j) = \min_k\{D(i,k) + D(k,j), D(i,j)\}, \tag{16}$$

where k belongs to all vertex set. However, the time complexity of this algorithm is $\mathcal{O}(N^3)$, exerting great computational burden on BBU pools. Moreover, what we concern about is the shortest BBU pool path between the first and the last RRH in a single railway line. Therefore, the conventional Floyd-Warshall algorithm makes some effectless calculation, which is a great waste of computational resources.

Assume that the number of BBU pools connected to RRH-m is denoted as $N^m_{connect}$. Generally, $N^m_{connect}$ is relatively small since the dense distribution of multiple BBU pools leads to a high CAPEX and OPEX. The maximum $N^m_{connect}$ of all RRHs is marked as $N^{max}_{connect}$. We can regard the wireless coverage of a single BBU pool as an enormous cell. Therefore, the coverage shape of the BBU pool is kind of like a regular hexagon. Hence, it is reasonable to set $N^{max}_{connect} = 3$ in that three adjacent regular hexagons share a common RRH. As mentioned above, the direct use of the Floyd-Warshall algorithm brings unacceptable computational complexity if considering a vast range of railway lines. Hence, some modifications are proposed so as to search for the optimal path rapidly.

It is essential to denote some important notations to clarify following analysis. Vertex set $\mathcal{V}$ is the union of several subsets $\mathcal{V}_m$, which refers to the connected BBU pools when the HST moves in RRH-m. Vertex set $\mathcal{V}_1$ means the connected BBU pools of the first RRH along the line l. Vertex set S denotes the estimated vertex set of the shortest path that has been found, and U represents the all un-visited vertex of other undetermined shortest paths. $D(v)$ represents the estimated distance between vertex $\mathcal{V}_1$ and any vertex v. The modified Floyd-Warshall algorithm is described as follows:

1) Initialize $S = \{\mathcal{V}_1\}$, $U = \mathcal{V} - S$, the cost matrix $\boldsymbol{H_{BB'}}$ and $D(v)$ where $v \in S$,
2) Let $v \in \mathcal{V}_m (m \geq 1)$ and $u \in \mathcal{V}_{m+1}$, update the distance $D(u)$ by traversing all possible v, that is,

$$D(u) = \min_v\{D(v) + \boldsymbol{H_{BB'}}(v,u)\}. \tag{17}$$

Algorithm 1 Pseudocode of the Modified Floyd-Warshall Algorithm

Input $\mathcal{G}, \mathcal{V}, \mathcal{V}_1$
// Initializations
$S := \{\mathcal{V}_1\}$;
$U := \mathcal{V} - S$;
initialize $D[v]$;
while $1 \leq m \leq N^l_R - 1$ **do**
  // step 2
  for each vertext $u \in \mathcal{V}_{m+1}$ **do**
    for each vertext $v \in \mathcal{V}_m$ **do**
      if $D[v] + \boldsymbol{H_{BB'}}[v,u] < D[u]$ **then**
        $D[u] \leftarrow D[v] + \boldsymbol{H_{BB'}}[v,u]$
      end if
    end for
  end for
  // step 3
  $S = S \cup \mathcal{V}_m$;
  $U = U - \mathcal{V}_m$;
end while

3) Move $\mathcal{V}_m$ from U to S.
4) Repeat step 2-3 until the HST arrives at the last RRH in line l, which is denoted as N^l_R.

It can be found that the modified algorithm focuses on updating the vertexes from adjacent subsets instead of the vertex set $\mathcal{V}$. After the above procedures, the global optimal solution can be easily obtained by comparing these subsolutions, i.e., $D(u)$ where $u \in \mathcal{V}_{N^l_R}$, with low computational complexity.

The time complexity of the proposed algorithm is $\mathcal{O}(3^{N^l_R})$, which is much lower than the conventional Floyd-Warshall algorithm $\mathcal{O}(N^{N^l_R})$ where $N = N^l_R \times N_B$. Besides, the proposed algorithm can find the optimal solution more than suboptimum. The pseudocode of the above algorithm is expressed in Algorithm 1.

VI. SIMULATION

In this section, we will simulate the performance of the proposed network architecture considering a small network as shown in Figure 2(b). We assume that the HST carries $N_P = 1000$ passengers moving from RRH1 to RRH4 and half of the passengers are active in communication, i.e., $\eta = 50\%$. Based on EQ. (1-3), the BBU line matrix of this railway line can be expressed as

$$\boldsymbol{\Psi} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \end{pmatrix}. \tag{18}$$

The distance and capacity of each edge that connects two BBU pools is marked as $(distance/km, capacity/Gbps)$ in Figure 2. Therefore, from EQ. (5), the cost matrix can be

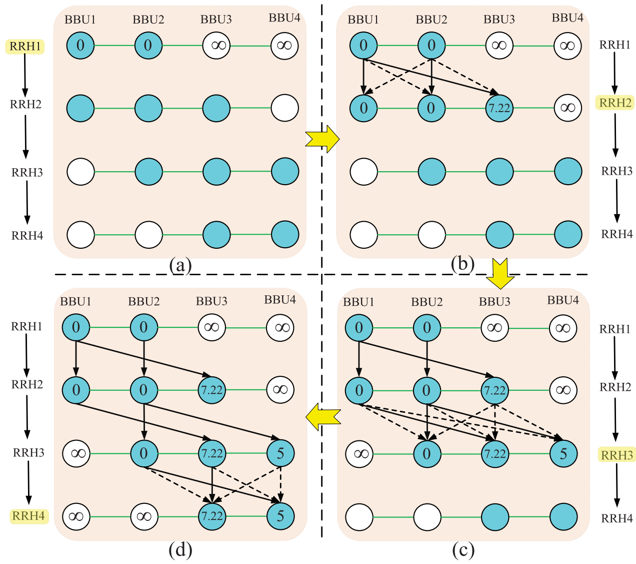

FIGURE 4. Steps of the solution procedure.

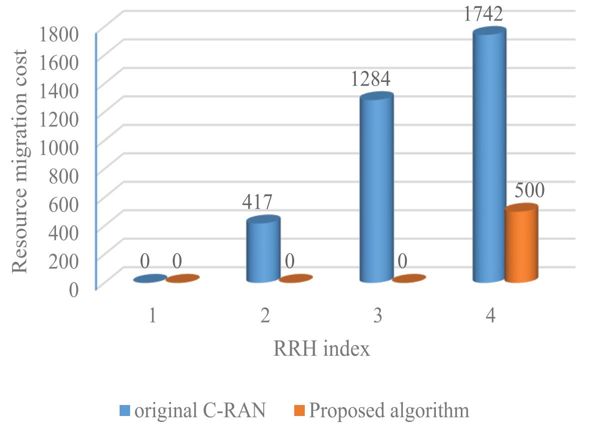

FIGURE 5. Resources migration cost at different position.

TABLE 1. Cost matrix and path matrix at different position.

Position	$\mathcal{C} \times 100$	$\mathcal{P}$
RRH1	$\begin{pmatrix} 0 & 0 & \infty & \infty \\ \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
RRH2	$\begin{pmatrix} 0 & 0 & \infty & \infty \\ 0 & 0 & 7.22 & \infty \\ \infty & \infty & \infty & \infty \\ \infty & \infty & \infty & \infty \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
RRH3	$\begin{pmatrix} 0 & 0 & \infty & \infty \\ 0 & 0 & 7.22 & \infty \\ \infty & 0 & 7.22 & 5 \\ \infty & \infty & \infty & \infty \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 0 & 2 & 1 & 2 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
RRH4	$\begin{pmatrix} 0 & 0 & \infty & \infty \\ 0 & \boxed{0} & 7.22 & \infty \\ \infty & \boxed{0} & 7.22 & 5 \\ \infty & \infty & 7.22 & \boxed{5} \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & \boxed{2} & 1 & 0 \\ 0 & \boxed{2} & 1 & 2 \\ 0 & 0 & 3 & \boxed{2} \end{pmatrix}$

obtained as

$$\boldsymbol{H_{BB'}} = \begin{pmatrix} 0 & 4.17 & 7.22 & \infty \\ 4.17 & 0 & 8.67 & 5 \\ 7.22 & 8.67 & 0 & 4.58 \\ \infty & 5 & 4.58 & 0 \end{pmatrix} \times 100. \quad (19)$$

Based on the modified Floyd-Warshall algorithm described in Section III, the solution procedure with detailed steps is presented in Figure 4 in a clockwise order. The corresponding cost matrix $\mathcal{C}$ and path matrix $\mathcal{P}$ of each step are listed in Tab. 1.

The HST starts to move from RRH1 which is connected to two adjacent BBU pools (BBU1 and BBU2) with a fill color of aqua shown in Figure 4. To incorporate EQ. (4), we assume that the resource migration cost is 0 when the HST runs inside a cell such as $\mathcal{C}(1, 1) = 0$ and the cost is ∞ when there is no HST, e.g., $\mathcal{C}(1, 4) = \infty$. Therefore, the first row of matrix $\mathcal{C}$ is $[0\ 0\ \infty\ \infty]$. As the HST moves to RRH2, which is connected to BBU1-3, there are several BBU pools paths, e.g., $BBU1 \rightarrow BBU2$. For each BBU pool in the second row, there are two paths from two BBUs in the first row. Hence we can calculate the resources migration cost based on EQ. (4) and select the optimal path with the lowest cost. All possible paths are presented in the second sub-figure in Figure 4, where the black lines denote the optimal path for each vertex. Based on this, the second row of $\mathcal{C}$ can be obtained and the corresponding parent BBU pool index is listed in the second row of path matrix $\mathcal{P}$. As the HST enters RRH3, each element u in the third row of $\mathcal{C}$ is updated by EQ. (17), where v means the element in the second row. Similar steps are performed until the train arrives at the last RRH. After the above procedure, the cost matrix is obtain as shown in Tab. 1 accompanied by the path matrix $\mathcal{P}$.

It is obvious that the minimum cost lies in the fourth element in the fourth row of $\mathcal{C}$, i.e., $\mathcal{P}(4, 4)$, which is inside the square frame. Element 2 in the same position of path matrix $\mathcal{P}$, inside the square frame, denotes the parent BBU pool with the lowest cost, that is, $\mathcal{P}(3, 2)$. Analogously, element 2 in $\mathcal{P}(3, 2)$ refers to the second BBU pool in the second row. Based on the above iterations, the optimal path can be obtained as $BBU2 \rightarrow BBU2 \rightarrow BBU2 \rightarrow BBU4$ with the lowest cost of 500.

Figure 5 demonstrates the total resource migration cost when the HST moves at different RRH. The blue cylinders denotes the cost of original C-RAN architecture as shown in Figure 2(a), whereas the orange cylinders represent the proposed architecture in Figure 2(b). It can be found that the value of the orange cylinders stays at 0 when the HST moves from RRH1-RRH3, whereas the blue one rises from 0 to 1284. The total cost of the original C-RAN is about 3.48 times that of the proposed C-RAN architecture, indicating that the proposed scheme can reduce the resource migration cost evidently. As for the time computational complexity, the proposed algorithm takes $2\times3+3\times3+3\times2 = 21$ steps to find the optimal path, whereas the conventional Floyd-Warshall takes $16^3 = 4096$ steps, which is much larger than the proposed one.

VII. CONCLUSION AND FUTURE WORK

In this paper, we investigated the feasibility of C-RAN in HSR scenarios and define a new group handover for long-distance railway communication. Moreover, we derived a closed-form expression of the resource migration cost to describe the group handover. To address this problem, we proposed a novel RRH-BBU mapping relationship and establish a flexible architecture. After abstracting the problem into the shortest path problem, we employed the modified Floyd-Warshall algorithm, which focuses on updating vertexes from the adjacent subsets instead of the vertex set, to minimize the resource migration cost more efficiently. Simulation results indicated that the proposed method can decrease the resource migration cost dramatically. The work we conducted is of much significance to the design of future HSR communication network.

Considering the flexibility of this proposed mapping relationship, we will further perform some extensive works to help expand and strengthen the results, which are listed as follows:

1) More than one railway line will be considered in future work, which puts forward some new constraints in this circumstance in terms of the intersection RRH of multiple lines.
2) We will investigate the feasibility of the proposed C-RAN architecture in ultra-high speed scenarios, e.g., the vactrain. This is because the high speed increases the handover frequency, which highlights the issue of resource migration. As a novel design for ultra-high-speed rail transportation, existing research on the vactrain mainly concentrates on the wireless channel [26], train-to-ground wireless access architecture [27] and the frequent handover [28]. However, little work has been conducted when it comes to the network architecture. Therefore, what we proposed in this paper provides some new insights in future research on the network architecture of the vactrain.

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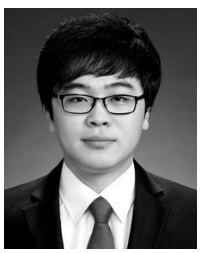

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