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Optically Backhauled Moving Network for Local Trains: Architecture and Scheduling

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ABSTRACT The concept of moving cell in cellular systems has been discussed for 5G group mobility where rapidly moving platforms such as trains carry a large number of user terminals. It has been considered to employ wireless backhaul for moving cell, the problem of which is its limited and unstable bandwidth. To realize high bandwidth with wireless backhaul, a large number of base stations (BSs) are required along the railway. Therefore, this paper proposes the concept of optically backhauled moving network (OBMN) for local trains to efficiently provide backhaul links for local trains. In the OBMN, an autonomous BS (ABS) is set on the top of a train and is connected to a gateway via optical backhaul. While the user terminals onboard move, the ABS set on the train always satisfies the moving demands through high-bandwidth optical backhaul. The effectiveness of the proposed architecture and scheduling was confirmed by examining two case studies in the suburban and urban areas in Tokyo. The number of required BSs and deployment cost are reduced by half with the proposed OBMN compared with the existing static deployment.

INDEX TERMS Communication networks, mobile communication, optical fiber networks.

I. INTRODUCTION

Wireless telecommunication networks have evolved rapidly and mobile traffic is growing exponentially [1]. Toward 5G networks, it has attracted considerable attentions to support moving hot spots [2]. They are generated by the increasing data traffic of mobile users using smartphones, tablets, and laptops via mobile networks onboard. Since the number of mobile users onboard has increased dramatically these years, the moving traffic demands have been densely distributed on public transit vehicles such as buses, trams, and trains. It becomes a significant research topic for network operators to improve onboard mobile coverage and capacity to satisfy the moving demands.

There have been various technologies developed for satisfying moving demands in different scenarios. To deploy mobile/moving relay nodes (MRNs) on the vehicles is one of the most promising solution [3]–[7]. The MRNs consist of outdoor and indoor antenna units connected with cables. An MRN moves along with the mobile users within the vehicle, and communicates with the donor evolved nodeB (DeNB). The network connections for users onboard can be kept by properly placing DeNBs and MRNs. Mobile relay offers three advantages; high rate communications with good channel condition between users and the MRN, low transmit power of user equipments enabled by the spatial closeness to the MRN, and small signaling overhead for group handovers [5]. It was shown in [4] that the MRNs deployed on top of public transportation vehicles bring significant enhancement to the quality of service (QoS) experienced by the users in the case of moderate to high vehicular penetration loss (VPL) by comparing the performance of MRNs with that of the single-hop direct transmission and fixed relay nodes. The challenges for MRNs are pointed as the VPL, user mobility management, and handovers [3]. In particular for ultra-dense urban scenarios, the major challenge in deploying moving networks inside vehicles was the inter-cell interference, which is exacerbated by the urban canyon effects and can be reduced with interference management approaches such as multi-antenna interference suppression techniques [8], [9].

The moving small cell concept was presented in [10] and [11] regarding an efficient small cell deployment. Its performance was evaluated in [10] for the scenario where mobile small cells are mounted in public buses, aggregate user traffic, and communicate with macro cells through wireless backhaul links. In crowded streets, suppose small cells are deployed on the top of public transportation circulating, i.e. a bus or a taxi, it allows to carry traffic generated by the passengers in addition to the one coming from its vicinity [11]. Such scenario was indicated to be efficient for deploying small cells in crowded areas in the presence of stationary traffic hotspot inside a macro cell.

The mobile femtocell is another concept that has been suggested for moving demands [12]–[16]. This is a scenario for deploying heterogeneous and small cell networks (HetSNets) which provide a good throughput via small cells close to mobile users [17]. Thanks to its low-range and energy-efficient nature, femtocell base stations (BSs) is suitable for accommodating mobile traffic inside homes and buildings. The essence of mobile femtocell is to exploit such peculiarity inside vehicles. In addition to that, mobile femtocells can integrate user connectivity to core networks and can reduce frequent handovers between macro BSs and a number of users. In [12], implementation of mobile femtocells has been shown to reduce the signaling overhead and enhance system capacity. Some other investigations also proved that mobile femtocell users enjoyed better QoS than fixed femtocells users [13]–[15]. A related concept of a vehicular network with cellular infrastructure as a backbone was proposed in [16]. For this purpose, mobile femto access points are mounted on vehicles and supportively used as relays to macro BSs in order to improve the mobile connectivity. Better throughput and delay performances were provided than the conventional IEEE 802.11p vehicular networks.

This paper focuses on moving networks for local trains in urban and suburban areas. As stated above, there have been huge research efforts related to moving networks. Meanwhile, there remains a key challenge for backhauling from networks to MRNs. To provide broadband Internet access in trains has been significant research topics [18], and a major one of which is to adopt wireless communications technologies to high speed trains (HSTs) moving at speeds of up to 350 km/hr, 500 km/hr, or higher [19], [20]. Various configurations have been investigated such as cooperative MRN [21], [22], millimeter-wave beamforming [23] with multiple-input multiple-output (MIMO) channel modeling [24], and distributed antenna systems [25]. However, to the best of our knowledge there is no architecture specialized for local trains in urban and suburban areas. They go and return on railways that range from several kilometers to several tens of kilometers at speed up to around 120 km/hr. The moving network technologies for HSTs are relatively costly for local trains, because such technologies are optimized for high-speed moving objects. Thus, in this paper we propose a novel concept of moving networks optimized for local trains utilizing the characteristics of them.

This paper proposes the optically backhauled moving network (OBMN) architecture for local trains. The basic idea is published in [26]. The goal of the proposed OBMN architecture is to provide high and stable bandwidth for the moving demands. To this end, it employs optical backhaul links instead of wireless backhaul; a BS is set on the top of a train and connected to a gateway node through fiber optic networks. The traffic to and from moving demands is forwarded by the BS with a radio access technology (RAT). The BS can continuously communicate with the gateway through high-bandwidth optical fiber, while the demands onboard move with the train. This architecture is suitable for local trains, because the optical fibers can be laid along overhead lines without interruptions. The key technology for implementing the OBMN is to adjust the length of optical fiber between the BS and the gateway in order to follow the movement of the train. When the train arrives at certain points, the BS on it is autonomously unloaded and another BS is autonomously loaded. This process is called *transfer*, and the handover in the OBMN is executed with *transfer*. The OBMN can ensure the certain range of propagation delay by limiting the optical fiber length with this *transfer* sequence. The proposed architecture can efficiently provide higher bandwidth than the existing moving cell architectures that employ wireless backhaul.

The proposed network architecture is one of the deployment scenarios for the autonomous base stations with optical reflex backhaul (ABSORB) architecture [27]. The ABSORB architecture was proposed to adapt to fluctuations in mobile traffic. In the ABSORB architecture, the traffic at moving demands is forwarded to and from an autonomously moving BS, which is called an ABS. An ABS is connected to a gateway node through flexible optical networks, which is called optical reflex backhaul (ORB). The ABS follows the demand movement, and consequently the network is flexibly reconstructed according to the demand distribution. The ORB architecture proposed in this paper is based on the Harness type ABSORB, where ABSs are always connected to and communicates with gateways via optical networks; if an ABS is scheduled to move to another location, it autonomously moves to the specified location, dragging the connected fiber. In the following, a BS that provides autonomous movement functions is referred to as an ABS, and the adjustable optical backhaul for a moving ABS is called the ORB in the same way as the ABSORB. Although the movable range of an ABS is limited because of the connected fiber, this feature is not a limitation for the deployment in local trains since optical fibers can be laid along overhead lines without interruptions.

The rest of the paper is organized as follows. Section II describes related work and contribution of this paper in detail. Section III introduces the proposed OBMN architecture. In section IV, we explain the deployment and scheduling algorithm to efficiently place and move ABSs in the proposed OBMN. Section V describes the performance evaluation of the proposed architecture with case studies in two scenarios; the suburban and the urban scenario. The conclusion is provided in section VI.

II. RELATED WORK: MOVING CELL WIRELESS BACKHAUL

Wireless backhauling is an essential technology for flexible installation of small/femto cells [28]. It is also expected to be effective in movable BSs which are mounted on unmanned aerial vehicles (UAVs) such as drones [29]. Here summarizes challenges and solutions related to the wireless backhaul and emphasizes the contribution of this paper. Transmission capacity of the backhaul link is required to be much larger than that of the access network. Massive MIMO at the millimeter-wave band is one of the most promising solutions in terms of high capacity and energy efficiency [30]. Massive MIMO beamforming can compensate link budget shortfall due to the higher frequency band while improving system capacity via high order spatial multiplexing. Wireless backhaul in most cases is fixed scenario, i.e. channel environment is stable and thus the required transmission rate can be simply designed. As for the moving network, channel state drastically fluctuates and it deteriorates system capacity. Many challenges have been tackled to realize wireless backhaul for moving cells as well as capacity improvement. Although the channel environment can be expected to be line-of-sight (LoS) which provides frequency-flat fading, high mobility causes unacceptable Doppler frequency shift. Channel tracking scheme and employing high-directivity antenna can reduce Doppler effect [31]. Systematic approach introduced in [32] optimizes cell structure based on directive antenna BSs and channel allocation. Wireless backhaul structure enhancing the current LTE network was investigated [33]. Splitting control (C-) and user (U-) plane can suppress signaling overhead and thus transmission efficiency can be improved. It exemplified wireless link throughput of maximally 30 Gbps can be achieved in backhaul link via massive MIMO at 20 GHz band. However, it is also exposed that backhaul link capacity is largely fluctuates depending on distance between backhaul BS and moving BSs. In addition, moving BS must be capable of frequent handover between backhaul BSs. Reference [34] proposed seamless handover scheme by providing plurality of IP interfaces on the transmitter and receiver sides.

As reviewed above, there exists many challenges and problems to stably provide wireless backhaul link for moving cells. This paper attempts to resolve all these problems by a novel approach using wired lines.

III. OBMN ARCHITECTURE

A. CONCEPT

This section describes the concept for the proposed OBMN. The OBMN architecture is shown in Fig. 1. An ABS is set on the top of a train, and is connected to a gateway, which is installed in a central office, via optical backhaul. Access point to be connected to user equipments shall be equipped on ceiling inside the train. A high-speed reel is located on telecommunications facilities such as telegraph poles, or stations. The structure of the high-speed reel is similar to a fishing reel. It spins to reel up and send out the optical fiber to adjust the length of optical fiber between the ABS and the gateway to follow the movement of the train. Although MRNs can be used in the OBMN, we explain the proposed architecture taking the simple moving antenna as an example.

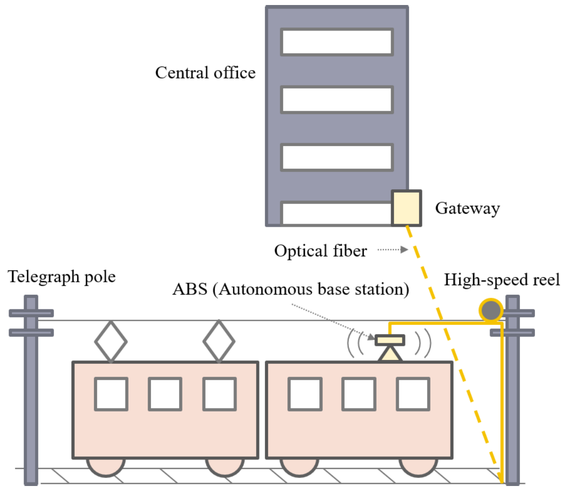


FIGURE 1. Concept of OBMN architecture.

The advantage of the proposed OBMN is introduced with Fig. 2 as regards the efficiency for demand satisfaction. Consider a scenario where the mobile traffic demands onboard move with the train. Fig. 2a shows the conventional moving cell architecture, which we call the static architecture. With this architecture, a moving antenna is set on the top of the train and static ground BSs are deployed along the railway. The moving antenna communicates with ground BSs via wireless backhaul. To achieve high throughput in this wireless backhaul connections comparable to optical fiber links, the cell coverage of each static ground BS is limited. For example, it was shown that the ground BS spacing cannot exceed certain distance, around 100 m [33]. Thus, the problem of this architecture was that the number of required static BSs increases in proportion to the length of railway lines. Fig. 2b shows the conceptual deployment model of the proposed OBMN architecture. An ABS is set on the top of the train, and moves with the train and traffic demands onboard. With this architecture, the demands onboard can always achieve high throughput, because they are always included in the cell coverage of the ABS which is directly connected to a gateway through optical backhaul. In this scenario, the number of required BSs is independent of the length of railway and is drastically reduced compared with the conventional static model.

B. SYSTEM ARCHITECTURE

The basic architecture of the proposed OBMN is the same as the original ABSORB proposed in [27]. Here we describe the different factors for the OBMN from [27].

1) OVERVIEW

An ABS is set on the top of the train and a gateway node is placed in a central office, as shown in Fig. 1. The ABS is connected to the gateway through ORB, which consists of fiber optic networks. The physical topology of the ORB network can be point to point (P2P) or a star such as passive optical network (PON). The traffic to and from moving

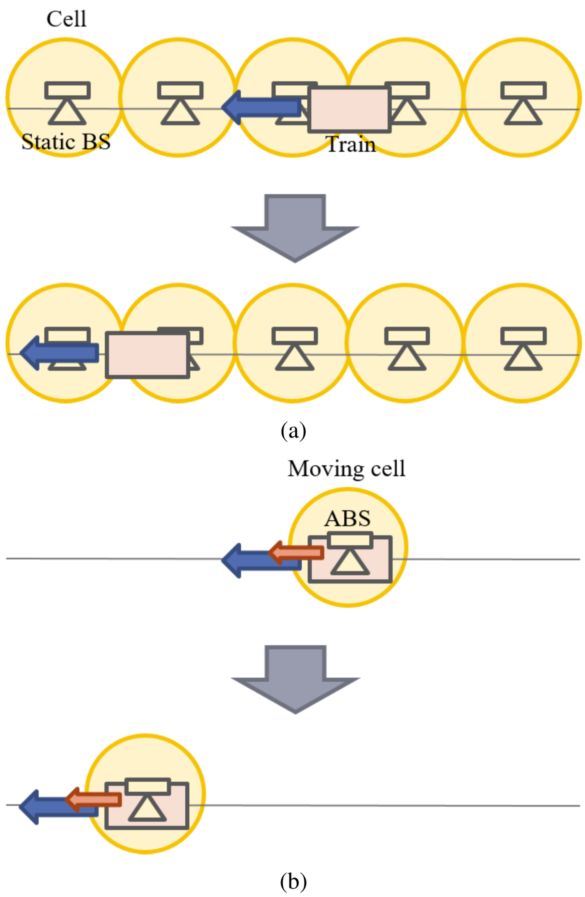


FIGURE 2. Demand satisfaction for railways. (a) Static architecture. (b) Proposed OBMN architecture.

demand onboard is forwarded by the ABS using an arbitrary RAT in the same way as a static BS. The ABS functions are introduced in III-B2.

Since the ABS is set on the train, the ABS can follow the demand movement as the train moves. While the ABS moves, the optical backhaul is always connected with the gateway; the optical fiber length between the ABS and the gateway is appropriately adjusted to follow the movement. The key ideas for realizing this concept are high-speed reels and fiber lanes, which are explained in III-B3 and III-B4. The optical fiber cable is held with fiber lanes and adjusted with high-speed reels. With this architecture, the ABS set on the top of the train always covers the traffic demands onboard via fiber optic networks during the movement. As a consequence, high-bandwidth and stable optical backhaul is always available for the moving demands.

2) ABS

An ABS moves to a new location according to a relocation schedule. The relocation schedule is computed by a controller, which is installed in a remote server. The ABS and the controller are connected via a control channel. The control channel can be established using ORB or macro-cell communication. The relocation is realized with autonomous robot vehicle technologies [35], e.g., sensing, navigation, and motion planning. In the OBMN, the autonomous movement functions required for an ABS is limited to the functions related to getting on and off a train, unlike the generic ABSORB. This is because the movement to a new location is executed by the train on which the ABS is set. The autonomous getting on and off function can be implemented in two ways: self-movement and supported-movement. The self-movement type ABS autonomously moves and rides on a train based on the schedule. This type can be implemented as a robot vehicle such as drone. The supported-movement type ABS is loaded on and unloaded from a train by other mechanical equipment, e.g. a robot arm grabs an ABS, moves it, and puts it on and off a train. Either type of BS is referred to as an ABS in the following description for simplicity.

3) HIGH-SPEED REEL

The key idea for deploying OBMN is a high-speed reel. It is placed along the railway on telecommunications facilities such as telegraph poles. The conceptual structure of the high-speed reel is similar to a fishing reel and is depicted in Fig. 3a. It spins to reel up and send out the optical fiber to adjust the fiber length between the ABS and the gateway. When the connected ABS is approaching, it rotates to reel up the fiber. When the ABS is going away, it spins to send out the fiber. The basic rotation schedule is programmed corresponding to the relocation schedule of the connected ABS, which is calculated by the controller. In addition, a high-speed reel should provide a sensing function to keep the tension of the fiber constant. If the tension becomes high, it decreases the tension by sending out the fiber.

4) FIBER LANE

Fig. 3b shows the fiber lanes and corresponding structure of an ABS. Fiber lanes are paired structure to hold the optical fiber cable. They are installed with a certain interval in parallel to the overhead contact wire of the railway. The purpose of installing them is to control the track of cable in the train movement. Without fiber lanes, the ABS and the high-speed reel are linearly connected irrespective of the railway track. Thus, more number of fiber lanes are required for curves and the interval can be set longer in straight tracks.

As shown in Fig. 3b, the fiber cable is outputted from the ABS via the upright. The ABS passes through fiber lanes using the hanger. When the hanger arrives at fiber lanes, they slide to smoothly pass the ABS. To realize smooth movement of the hanger and cable, it is essential to reduce the frictional resistance of the fiber lanes. In addition, fiber lanes helps the fiber cable movement by spinning to reduce the tension of the fiber.

C. TRANSFER

1) SEQUENCE

Transfer is a concept for executing handover in the proposed OBMN architecture. This is one of the key technologies

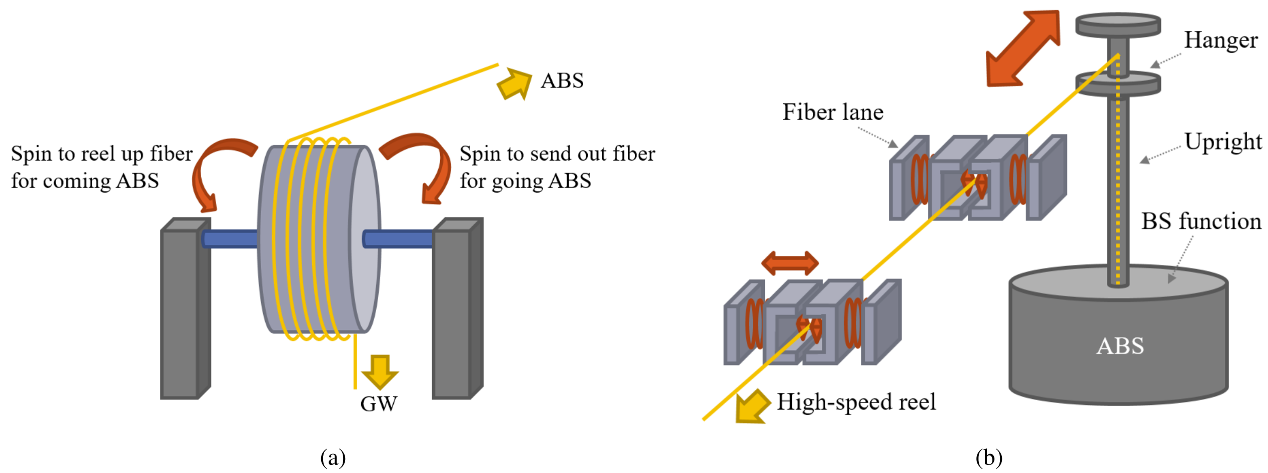


FIGURE 3. **Architecture for OBMN components. (a) High-speed reel. (b) Fiber lane.**

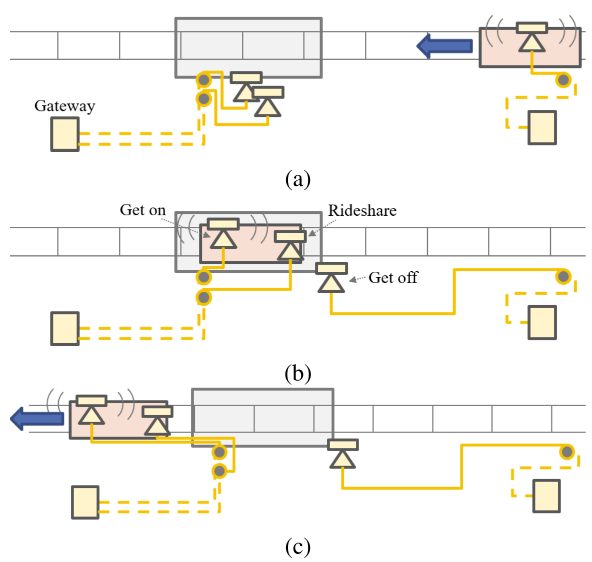


FIGURE 4. **Sequence of *transfer*. (a) Arrival. (b) Handover. (c) Departure.**

for the proposed OBMN, because the optical fiber length is physically limited, and it cannot be infinitely extended due to the propagation delay. *Transfer* is executed at a certain point, which is called a *transfer point*. The sequence of *transfer* is the following.

1. *Arrival*

   A train arrives at a *transfer point*. An ABS is set on the train and covers the traffic demand onboard (Fig. 4a).

2. *Handover*

   The ABS is unloaded from the train, and another ABS is loaded on the same train. The demand onboard is handovered to the newly set ABS (Fig. 4b).

3. *Departure*

   The train departs from the *transfer point* (Fig. 4c).

It is possible to perform the *transfer* when the train stops or moves at a low-speed, and thus the *transfer points* are mainly assumed to be stations.

The handover procedure in the OBMN is the same with conventional handover. The moving demand is automatically connected to another gateway when the transfer is executed and another ABS is loaded. Furthermore, the handover in the OBMN is even easier than the conventional one for moving networks where it is frequently performed while the train moves at a high-speed.

2) RIDESHARE

Rideshare is a concept of transporting ABSs to another *transfer point*, which is depicted in Fig. 4. Surplus ABSs are loaded on a train at a *transfer point*, and unloaded at another *transfer point*. *Rideshare* is executed to improve the utilization efficiency of ABSs. Accumulation of ABSs at a certain *transfer point* can be avoided, even if the train timetables are unsymmetrical, e.g. commuter trains between midtown and suburbs.

IV. OBMN SCHEDULING

The key challenges for the proposed OBMN architecture are how to efficiently place ABSs, move them, and perform *transfer*. This section describes the deployment and scheduling methodologies of the proposed architecture. The variables used in this section are summarized in Table 1, and their detailed explanations are provided in the following.

A. STATE TRANSITION

The state transition of an ABS is defined for the scheduling purpose. Considering the *transfer*, the state of an ABS is defined as the following.

Ready

Waiting for a train at a *transfer point*. A *Ready* ABS can be loaded on the next train.

Getting on

Getting on the arriving train at a *transfer point*.

Traffic forwarding

Forwarding mobile data on the train.

TABLE 1. Variables.

Variable	Definition
t	Time period identifier ($0 \leq t \leq T$)
p	*Transfer point* identifier
P	Section identifier
$\mathcal{E}$	Set of *events*
e	*Event* identifier, $e \in \mathcal{E}$
$\mathcal{I}_P$	Set of *ingress events*
i_e	*Ingress event* identifier, $i_e \in \mathcal{I}_P$
$\mathcal{O}_P$	Set of *egress events*
o_e	*Egress event* identifier, $o_e \in \mathcal{O}_P$
t_{i_e}	Occurrence time of i_e
c_{i_e}	Occurrence place of i_e
j	ABS identifier
$s_j(t)$	State of jth ABS at t
$\mathcal{X}_p(t)$	Set of ABSs that satisfies $s_j(t) = Ready$
$\mathcal{Y}_p(t)$	Set of ABSs loaded for i_eth *ingress event*
$Q_p(t)$	ABS queue
$\mathcal{F}_P$	Set of fiber lanes for Pth section
f	Fiber lane identifier, $f \in \mathcal{F}$
$u_f(t)$	Binary function for state of fth lane
t_p	Available time for *transfer* at pth point
τ_{on}	Time required for *Getting on*
τ_{off}	Time required for *Getting off*

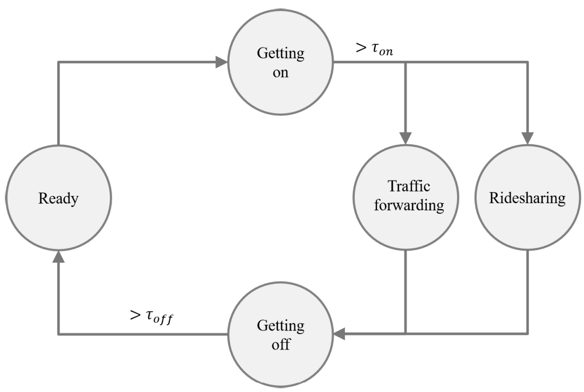


FIGURE 5. ABS state transition.

Ridesharing
Loaded on the train as a surplus ABS, not forwarding data.

Getting off
Getting off the train at a *transfer point*.

The state transition is described as shown in Fig. 5. Let τ_{on} and τ_{off} denote the constant time required for *Getting on* and *Getting off*, respectively.

B. SECTION

Here we introduce the concept of *section*, which is shown in Fig. 6. A *section* represents a range covered by a certain set of ABSs. A *transfer point* is set at a *section edge*, thus *transfer* is performed at a *section edge*. A high-speed reel is installed at any place in the *section* such as either *section edges*, and the ABS moves between the *section edges*. The location of the high-speed reel does not matter. Using the concept of *section*, we can consider the deployment of OBMN for each section separately.

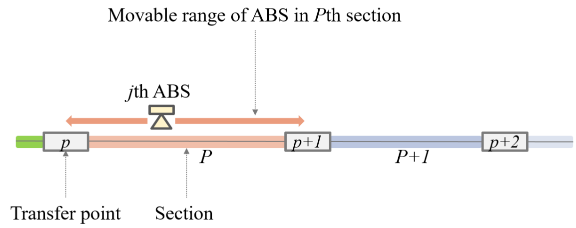


FIGURE 6. Concept of *section*.

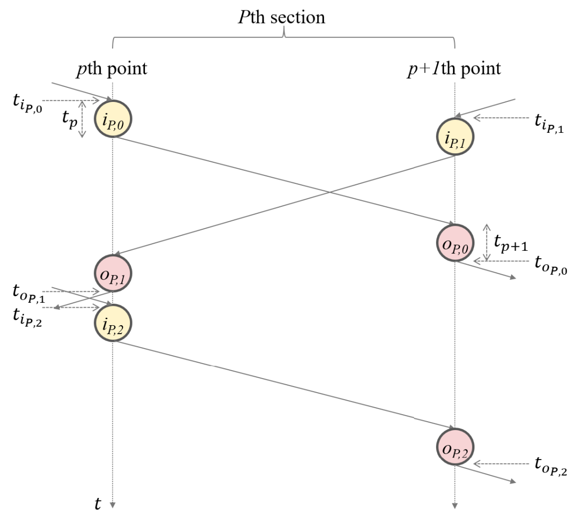


FIGURE 7. Concept of *events* in *P*th *section*.

Let p denote the identifier for a *transfer point*, and P denote the identifier for a *section*. We define the Pth *section* as a *section* whose *section edges* are the pth and $p+1$th *points*. Let t_p denote the available time for *transfer* at the pth *point*. $\tau_{on} < t_p$ and $\tau_{off} < t_p$ are required to perform a *transfer*.

C. EVENT

We explain the concept of *events*, which is depicted in Fig. 7. We define an incoming and outgoing event of a train at a *section* as an *ingress event* and *egress event*, respectively. Let $\mathcal{I}_P = \{i_0, i_1, \cdots, i_e, \cdots\}$ denote the set of *ingress events* in the Pth *section*, where e denote the identifier for each *event*. Likewise, let $\mathcal{O}_P = \{o_0, o_1, \cdots, o_e, \cdots\}$ denote the set of *egress events* in the Pth *section*, using the event identifier e. It is defined that i_e and o_e represent the *event* of the same train; i_e represents the arrival of the train at the Pth *section*, and o_e represents the departure of the same train from the Pth *section*. The *event* sets are generated from the train timetables. Let t_{i_e} and c_{i_e} denote the time and occurrence place of i_e, respectively. c_{i_e} is either the pth or $p+1$th *point*. In Fig. 7, three *ingress* and *egress events* in the Pth section are depicted. The $i_{P,0}$th *ingress event* occurs at the pth *point* when $t = t_{iP,0}$.

Then, the $o_{P,0}$th *egress event* occurs at the $p+1$th *point* when $t = t_{oP,0}$. The other *events* occur in the same way.

Let j denote the identifier for an ABS in the Pth *section*. The state of the jth ABS at period t is represented as $s_j(t)$. Let $\mathcal{X}_p(t)$ denote the set of ABSs that satisfies $s_j(t) = Ready$ at the pth *point* at period t. If $c_{i_e} = p$ is satisfied and jth ABS is selected to be loaded on a train, jth ABS is extracted from $\mathcal{X}_p(t_{i_e})$, and the state of jth ABS becomes $s_j(t_{i_e}) =$ *Getting on*. It starts to move at period $t_{i_e} + t_p$ and the state $s_j(t_{i_e} + t_p)$ becomes *Traffic forwarding* or *Ridesharing*. If $c_{o_e} = p$ is satisfied, jth ABS arrives at pth *point* at period $t_{o_e} - t_p$, and the state of jth ABS changes to *Getting off*. Then, the train departs at t_{o_e}. The state of jth ABS $s_j(t_{o_e})$ becomes *Ready* and it is added to $\mathcal{X}_p(t_{o_e})$.

D. ALGORITHM

Based on the notions described above, here we introduce the proposed ABS scheduling algorithm. The purpose of the proposed algorithm is to efficiently satisfy demand with the minimum number of ABS deployment. It determines the optimal movement of ABSs at each period based on the distribution of *ingress* and *egress events* of the *section*.

1) INGRESS EVENT

Let $\mathcal{Y}_{i_e}$ denote the set of ABSs that are loaded on the train for i_eth *ingress event*. At least one ABS is required for each *ingress event*. When multiple ABSs are loaded, one ABS is *Traffic forwarding* and other ABSs are *Ridesharing*. To ensure demand satisfaction, $\mathcal{Y}_{i_e}$ satisfies

$$|\mathcal{Y}_{i_e}| \geq 1 \quad \forall i_e \in \mathcal{I}_P. \tag{1}$$

To enable the ABS loading, available ABSs are required at the *transfer points* for all *ingress events*. This idea is formulated as:

$$|\mathcal{X}_{c_{i_e}}(t_{i_e})| \geq |\mathcal{Y}_{i_e}| \quad \forall i_e \in \mathcal{I}_P. \tag{2}$$

The variation of the ABS set at i_eth *ingress event* is formulated as:

$$\mathcal{X}_{c_{i_e}}(t_{i_e} + t_{c_{i_e}}) = \mathcal{X}_{c_{i_e}}(t_{i_e}) - \mathcal{Y}_{i_e}. \tag{3}$$

2) EGRESS EVENT

At o_eth *egress event*, the ABSs in $\mathcal{Y}_{i_e}$, which are loaded on the train at the corresponding i_eth *ingress event*, are unloaded and added to the set of *Ready* ABSs of the *transfer point*. The variation of the ABS set at o_eth *egress event* is formulated as:

$$\mathcal{X}_{c_{o_e}}(t_{o_e}) = \mathcal{X}_{c_{o_e}}(t_{o_e} - t_{c_{o_e}}) + \mathcal{Y}_{i_e}. \tag{4}$$

3) ABS SELECTION

To equalize the frequency of use for the deployed ABSs, the selected ABS at each *ingress event* is determined as the following. Let $Q_{c_{i_e}}(t)$ denote the first-in first-out (FIFO) queue for ABSs in $\mathcal{X}_{c_{i_e}}(t)$. At i_eth *ingress event*, the first $|\mathcal{Y}_{i_e}|$ ABSs are dequeued from $Q_{c_{i_e}}(t_{i_e})$. At o_eth *egress event*, the ABSs in $\mathcal{Y}_{i_e}$ are enqueued to the tail of $Q_{c_{o_e}}(t_{o_e})$.

4) FIBER LANE SELECTION

It is assumed that a fiber lane is occupied by an ABS during it is out of the ABS queues. When an ABS is dequeued, it takes the possession of a fiber lane, which is not in use. Then, the lane is released when the ABS is enqueued.

Let $\mathcal{F}_P$ denote the set of fiber lanes for Pth section, and $f \in \mathcal{F}$ denote the identifier for them. $u_f(t)$ is a binary function that denotes the state of the fth lane; $u_f(t) = 0$ represents the fth lane is occupied by an ABS at t, and $u_f(t) = 1$ represents it is not used. When an ABS is dequeued, the fth fiber lane that satisfies $u_f(t) = 1$ is selected from $\mathcal{F}$. Thus, the requirement for fiber lanes for each *ingress event* is formulated as:

$$\sum_f u_f(t_{i_e}) \geq |\mathcal{Y}_{i_e}| \quad \forall i_e \in \mathcal{I}_P. \tag{5}$$

5) PROCEED AND REWIND

The proposed scheduling algorithm determines the ABS movement for each *ingress* and *egress event* using (3) and (4) by incrementing t from 0 to T.

In the beginning, $\mathcal{X}_p(0)$ and $\mathcal{X}_{p+1}(0)$ are set as $\emptyset$. From (1), $|\mathcal{Y}_{i_e}| = 1$ is initially set for all i_e.

When i_eth *ingress event* occurs, if (2) is satisfied, $\mathcal{Y}_{i_e}$ is generated by dequeuing from queue $Q_{c_{i_e}}(t_{i_e})$. At the same time if (5) is satisfied, unused fiber lanes are allocated to the ABSs in $\mathcal{Y}_{i_e}$. If (5) is not satisfied, a fiber lane is added to $\mathcal{F}_P$. If (2) is not satisfied, *rewind* process is executed. In the *rewind* process, *rideshare* or increment of the number of ABSs is executed with deducted t. Let e' denote an *event* that satisfies $c_{i_{e'}} \neq c_{i_e}$ and $t_{o_{e'}} < t_{i_e}$. If there is such an e', which means there is a surplus ABS at a prior *event*, the size of $\mathcal{Y}_{i_{e'}}$ is incremented to execute *rideshare* and t is rewinded to $t_{i_{e'}}$. If there is not such an e', which means that there is no surplus ABS, t is rewinded to 0 and $\mathcal{X}_{c_{i_e}}(0)$ is incremented.

When o_eth *egress event* occurs, $\mathcal{X}_{c_{o_e}}(t_{o_e})$ is updated with (4), and the ABSs in $\mathcal{Y}_{i_e}$ are enqueued to the tail of $Q_{c_{o_e}}(t_{o_e})$.

The position and state of each ABS is decided with the scheduling scheme above. Consequently, traffic demand is satisfied with the proposed OBMN architecture by deploying and moving ABSs based on the determined schedule.

The proposed scheduling algorithm is described in pseudocode as Algorithm 1.

V. EVALUATION

The performance of the proposed OBMN architecture was confirmed with case studies. The optimal deployment and movement of ABSs were computed with the proposed scheduling scheme.

A. CONDITION

1) SCENARIO

We executed the case studies in two scenarios; the suburban scenario and the urban scenario.

Algorithm 1 Scheduling Algorithm

$\mathcal{X}_p(0) = \emptyset$
$\mathcal{X}_{p+1}(0) = \emptyset$
$|\mathcal{Y}_{i_e}| \leftarrow 1 \quad \forall i_e \in \mathcal{I}_P$
$t \leftarrow 0$
while $t < T$ **do**
  if $t = t_{o_e} \quad e \in \mathcal{E}$ **then**
    Enqueue $\mathcal{Y}_{i_e}$ to $Q_{c_{o_e}}(t_{o_e})$
    Update $\mathcal{X}_{c_{o_e}}(t_{o_e})$
  if $t = t_{i_e} \quad e \in \mathcal{E}$ **then**
    if $|\mathcal{X}_{c_{i_e}}(t_{i_e})| \geq |\mathcal{Y}_{i_e}|$ **then**
      if $\sum_f u_f(t_{i_e}) < |\mathcal{Y}_{i_e}$ **then**
        Add fiber lane to F_P
      Dequeue from $Q_{c_{i_e}}(t_{i_e})$ and generate $\mathcal{Y}_{i_e}$
      Update $\mathcal{X}_{c_{i_e}}(t_{i_e})$
    if $\exists e' \in \mathcal{E}, c_{i_{e'}} \neq c_{i_e} \wedge t_{o_{e'}} < t_{i_e}$ **then**
      $|\mathcal{Y}_{i_{e'}}| \leftarrow |\mathcal{Y}_{i_{e'}}| + 1$
      $t \leftarrow t_{i_{e'}} - 1$
    else
      $|\mathcal{X}_{c_{i_e}}(0)| \leftarrow |\mathcal{X}_{c_{i_e}}(0)| + 1$
      $t \leftarrow -1$
  $t \leftarrow t + 1$

a: SUBURBAN SCENARIO

The study area for the suburban scenario was Keikyu-Kuhihama Line in Kanagawa, Japan. Fig. 8a shows the geographical distribution of the study area. This is a residential area located in the south of Tokyo. We assumed that *transfer points* were set at each station. The logical topology is shown in Fig. 8b. There were nine stations and eight *sections*. The total length was 13.4 km, and there is no express train for this line.

b: URBAN SCENARIO

The study area for the urban scenario was Tokyu-Denentoshi Line in Tokyo, Japan. Here we focused on the section between Shibuya and Mizonokuchi shown in Fig. 9a. This line is one of the most crowded railways in Tokyo, the crowdedness of which is caused by the upstream commuter movement from the residential area to Shibuya which is one of the busiest terminal station. The logical topology is shown in Fig. 9b. There were ten stations and the total length was 11.4 km. We defined different *sections* for local and express trains; A0th to A8th *section* for local, and B0th to B2nd *section* for express.

The lengths of each section are under several kilometers in both scenarios. The propagation delay in optical fiber (5μs/km) satisfies the severe delay requirement for mobile fronthaul, 250μs [36], in addition to mobile backhaul.

2) EVENTS AND PARAMETERS

For the proposed scheduling scheme, the *event* sets were generated from the train timetables (January 2017 version). Table 2 shows an example timetable of the weekday evening at Shin-otsu station, which is the 1st *point* of the suburban scenario. We assumed for simplicity that the available time for *transfer* t_p was less than one minute and state transition time τ_{on} and τ_{off} were sufficiently short.

TABLE 2. Example timetable at Shin-otsu station (1st *point* of the suburban scenario), weekday evening.

Direction	Hour	Minute
Downstream	18	7 14 22 24 32 34 43 45 53 55
	19	3 5 13 15 22 25 32 34 42 44 52 54
	20	2 4 12 14 22 24 32 35 42 44 50 59
Upstream	18	1 11 21 31 41 51
	19	0 10 19 31 42 52
	20	2 12 22 32 42 52

We describe through this evaluation that the OBMN architecture can drastically reduce the number of BSs compared with the static BS deployment for moving cell [33]. We assumed that the static ground BS spacing was 100 m, which is the interval that can achieve high throughput equivalent to optical backhaul. For the static deployment, the number of required BSs was calculated with their intervals and the total length of the railway.

3) COST EVALUATION

Then, we evaluated the relative deployment cost C_{rlt} of the OBMN using:

$$C_{rlt} = \frac{\alpha N_{abs} + \beta N_{lane}}{N_{static}}, \tag{6}$$

where N_{abs} and N_{lane} denote the total number of ABSs and fiber lanes with the OBMN, N_{static} denotes the total number of BSs with the static deployment. α is the weight for the cost of ABS functions, such as a high-speed reel, an upright, and a hanger shown in Fig. 3. β is the weight for the cost of a fiber lane. The practical cost C_{prc} is also calculated as:

$$C_{prc} = (c_{abs} + c_{reel})N_{abs} \sum_P L_P(c_{fiber}N_{abs,P} + c_{lane}N_{lane,P}), \tag{7}$$

where c_{abs} and c_{reel} denotes the cost of an ABS, a high-speed reel, respectively. c_{fiber} and c_{lane} denotes the cost of an optical fiber and a fiber lane per unit distance, respectively. L_P denotes the total distance and $N_{lane,P}$ denotes the number of fiber lanes of the Pth section. Let c_{static} denote the cost of a static BS.

B. RESULT

1) DEPLOYED BSS AND FIBER LANES

Fig. 10 shows the number of required BSs. The proposed OBMN architecture can reduce the number of deployed BSs compared with the static deployment for both scenarios.

For the suburban scenario, the number of deployed BSs is reduced with the OBMN architecture in all the *sections*, and the total number of deployed BSs is reduced

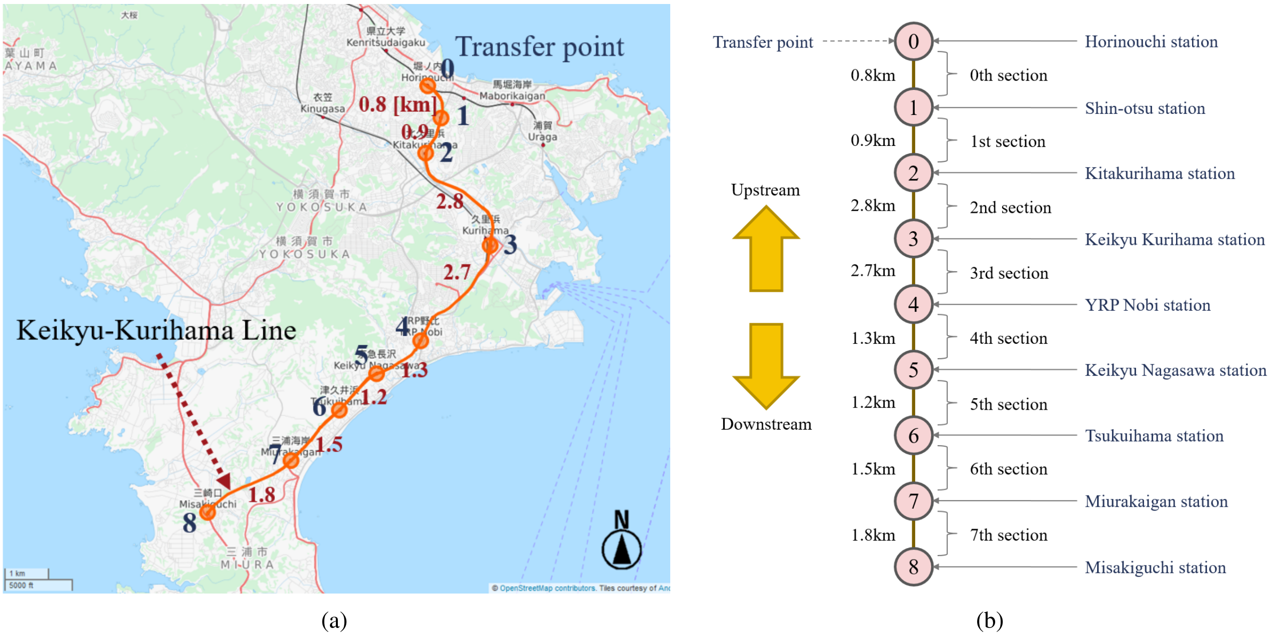


FIGURE 8. **Suburban scenario: Keikyu-Kurihama Line. (a) Geographical distribution. (b) Logical topology.**

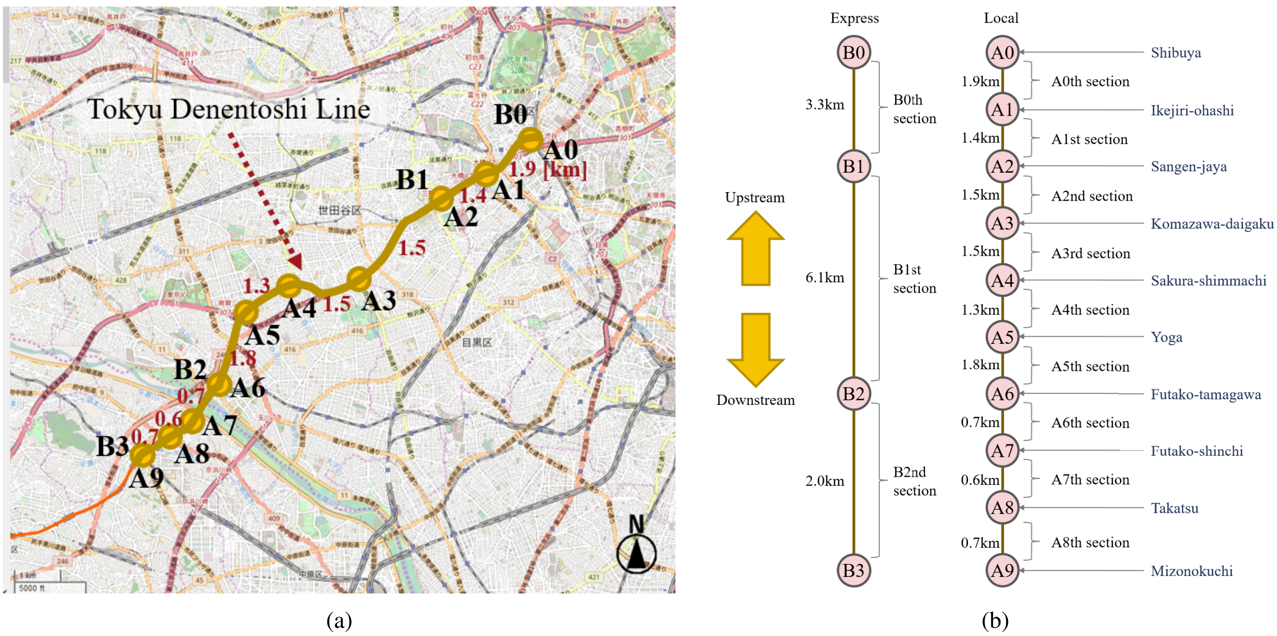
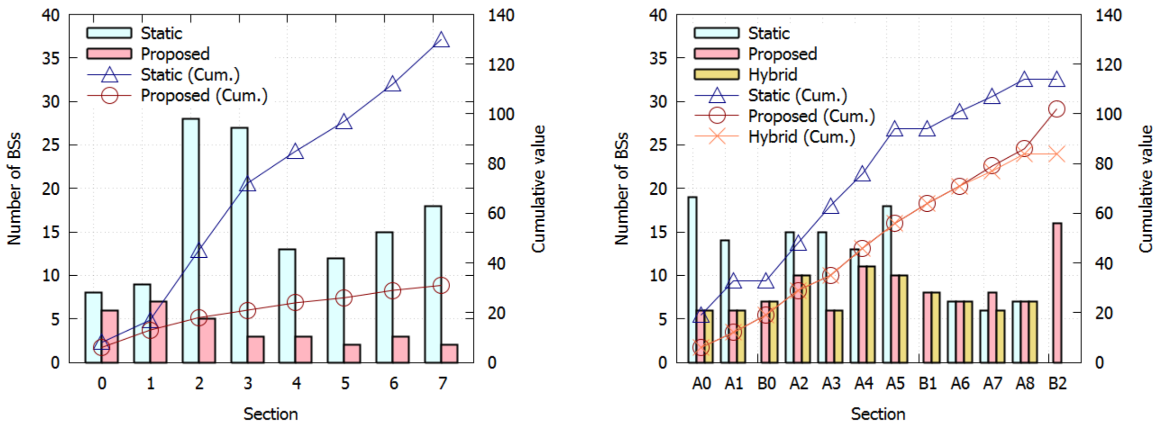


FIGURE 9. **Urban scenario: Tokyu-Denentoshi Line. (a) Geographical distribution. (b) Logical topology.**

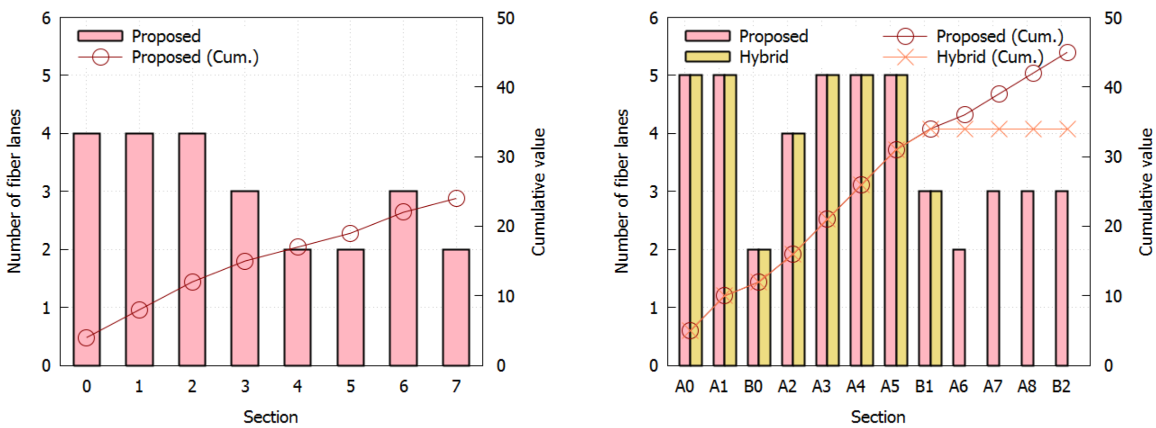
by 75% (Fig. 10a). With the OBMN, several ABSs are required for each *section*, and the number of ABSs are large at 0–2nd *sections*, because more trains are scheduled in the timetables. With the conventional static deployment, the number of BSs are in proportion to the length of the *section*. Thus, the OBMN is highly effective for long-distant *sections* with smaller number of trains, such as 3rd *section*.

For the urban scenario, although the total number of deployed BSs is reduced with the OBMN, the reduction effect is smaller than the suburban scenario (Fig. 10b). This is because more trains are scheduled in the time tables and different ABSs are required for the local (*A*0th – *A*8th *section*) and express (*B*0th – *B*2nd *section*) trains, whereas static BSs can support all the passing trains. In particular, the static architecture was efficient for the section between Futako-tamagawa and Mizonokuchi (*A*6th – *A*8th and *B*2nd *sections*) because of the short section lengths. In this case, the total number of deployed ABSs is minimized



(a) (b)

FIGURE 10. Number of deployed BSs. (a) Suburban scenario (Keikyu-Kurihama Line). (b) Urban scenario (Tokyu-Denentoshi Line).



(a) (b)

FIGURE 11. Number of deployed fiber lanes. (a) Suburban scenario (Keikyu-Kurihama Line). (b) Urban scenario (Tokyu-Denentoshi Line).

by the hybrid deployment, where the suitable one of the OBMN or the static architecture is selectively employed for each *section*. The OBMN is employed for the section between Shibuya and Futako-tamagawa ($A0$th – $A5$th and $B0$th – $B1$st *sections*) and the static BSs are deployed for the other sections ($A6$th – $A8$th and $B2$nd *sections*). The total number of deployed BSs is 26% smaller than the conventional static deployment as shown in Fig. 10b.

Fig. 11 shows the number of required fiber lanes. Several fiber lanes are needed for each *section* in both scenarios. In general, more fiber lanes are deployed for the *sections* with more number of ABSs. As shown in Fig. 10b the hybrid deployment can also reduce the fiber lanes because the static architecture is employed in $A6$th – $A8$th and $B2$nd *sections*.

From above results, the proposed OBMN is highly effective for suburban areas with smaller number of trains in long distance. In addition, we confirmed that it is efficient to selectively deploy the OBMN architecture along with the static architecture based on the computed scheduling results.

2) SCHEDULING RESULT

The following presents the scheduling result with the proposed algorithm using the suburban scenario as an example. Fig. 12 shows the dynamics of ABS queue length at each *section*. The results for the weekday evening (6pm – 9pm) are depicted as an example, where 6pm is represented as $t = 0$. The queue size at each *transfer point* decreases with *ingress events* and increases with *egress events*. Multiple ABSs are dequeued when *rideshare* is executed. Without *rideshare*, more ABSs are required because the train timetables are unsymmetrical in commuting time zones as shown in Table. 2. The movement of each ABS in the 4th *section* for the same time periods is shown in Fig. 13. The speed of trains between *transfer points* are approximated as constant. Each ABS trips around the 4th *point* and the 5th *point*. From these results, it was confirmed that the movement of each ABS is adequately scheduled with the proposed algorithm.

3) COST EVALUATION

The relative deployment cost C_{rlt} calculated with (6) using different weights is shown in Fig. 14. In the urban scenario,

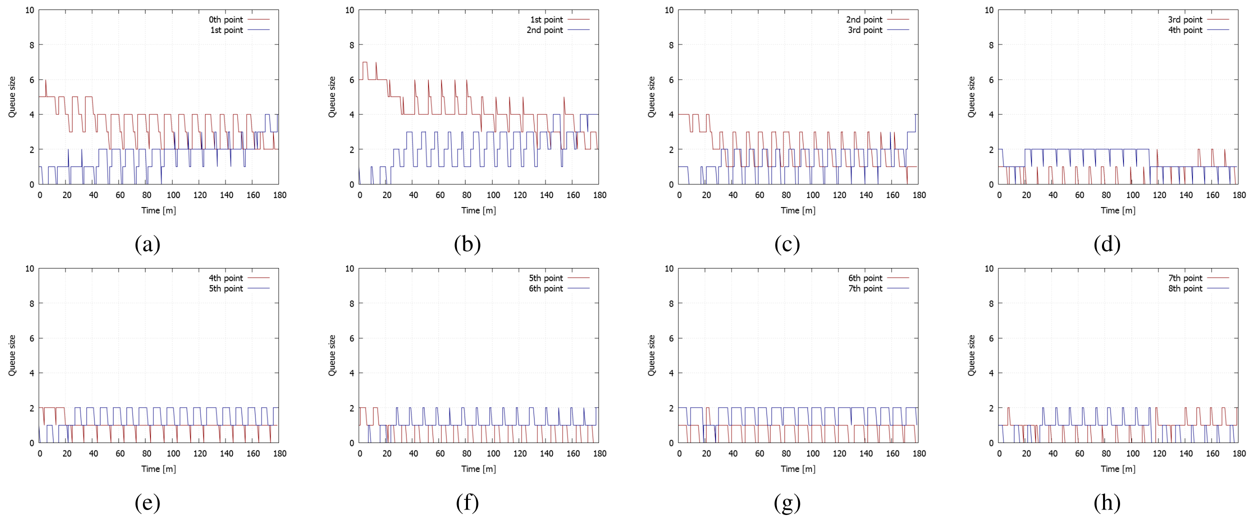


FIGURE 12. BS queue size in the suburban scenario. (a) 0th *section*. (b) 1st *section*. (c) 2nd *section*. (d) 3rd *section*. (e) 4th *section*. (f) 5th *section*. (g) 6th *section*. (h) 7th *section*.

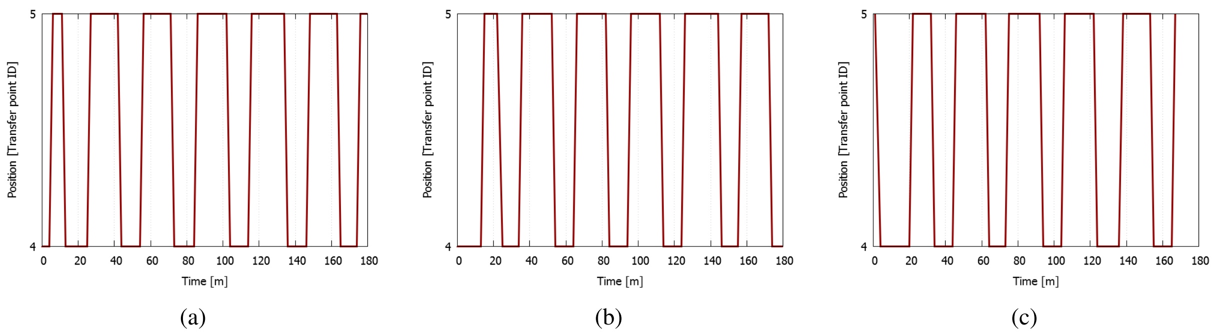


FIGURE 13. ABS movement of 4th *section* in the suburban scenario. (a) *0*th ABS. (b) *1*st ABS. (c) 2nd ABS.

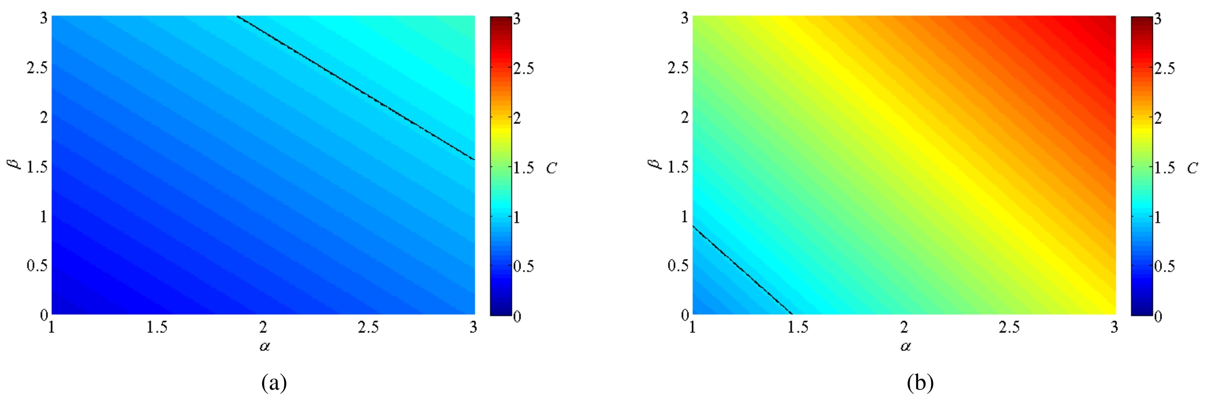


FIGURE 14. Relative deployment cost (OBMN vs static). (a) Suburban scenario (Keikyu-Kurihama Line). (b) Urban scenario (Tokyu-Denentoshi Line).

the hybrid architecture is compared with the static one. The relative cost increases with the weights α and β. When $C_{rlt} = 1$ is satisfied, the deployment cost of the OBMN is equal to that of the static deployment. The cost reduction range of the OBMN becomes larger as the BS reduction effect is large. For the suburban scenario, $C_{rlt} = 1$ is satisfied on the straight line passing through $(4.19, 0)$ and $(1, 4.13)$ in the $\alpha - \beta$ plane. Even if the cost of an ABS and a fiber lane is twice as high as that of a static BS, the OBMN architecture is cost-effective as regards the total deployment cost. For the urban scenario, $C_{rlt} = 1$ is satisfied on the line passing through (1.47, 0) and (1, 0.88). The OBMN is applicable for urban areas if the ABS functions and fiber lanes are implemented at sufficiently low cost.

Then, the practical deployment cost C_{prc} is calculated with (7). The cost in suburban scenario C^S_{prc} is formulated as:

$$C^S_{prc} = 31(c_{abs} + c_{reel}) + 47.6c_{fiber} + 39.2c_{lane}. \quad (8)$$

The cost in urban scenario C^U_{prc} is:

$$C^U_{prc} = 64(c_{abs} + c_{reel}) + 20c_{static} + 161.4_{fiber} + 70.4c_{lane}. \quad (9)$$

The deployment costs can be estimated if appropriate cost parameters are used in these equations. Here we do not solve these equations, because there are few publically available sources for product prices and actual prices largely depend on the vendor and order quantity.

C. DISCUSSION

Through the case studies, we confirmed the advantage of the proposed OBMN architecture in both urban and suburban scenarios: optimally adapting to the moving demand on local trains with high-throughput optical backhaul using small number of BSs. The reduction in the numbers of BSs results in corresponding reduction of deployment cost compared with the static deployment. If the cost of ABS functions and fiber lanes is small, total cost can be reduced by half. Although the OBMN is effective for both urban and suburban scenarios, it is highly effective for suburban areas with smaller number of trains in long distance. The application range of the OBMN is maximized in urban areas by employing the hybrid architecture with static deployment.

Next, we discuss the mechanical implementation of the proposed system. A high-speed reel is powered by a commercially available electric motor. A general commercial cable with high available tension can be used for an optical fiber that connects an ABS. The reel rotates for sending out the optical fiber at the acceleration of the train, and rotates for reeling up the optical fiber at the deceleration. The rotation frequency n is derived with

$$v = 2\pi na, \quad (10)$$

where v denotes the speed of the train and a denotes the diameter of the reel. The rotation speed is controlled to synchronize with the speed of the train so as to relieve the tension on the optical fiber. The relationship between the tension F, the torque T, and the output of the motor W is formulated as

$$T = aF \quad (11)$$

and

$$W = 2\pi nT. \quad (12)$$

For example, if we set $a = 50$ cm and $v = 120$ km/hr, the rotation frequency n is 1200 rpm. If we use a commercial motor with $W = 3$ kW as a reel, $F = 90$ N, which is a generally available value [37]. This output of the electric motor for the reel is determined to ensure the torque originated from the available tension and rotation frequency. Thus, the proposed system can be deployed with commercially available electric motors and optical fibers.

The contribution of the proposed OBMN is providing stable and high-bandwidth optical backhaul for the moving demands on local trains in urban and suburban areas, unlike any other moving cell architecture. Further advantages of the OBMN is reducing handovers and cell-edge users, because the small cells follow the moving demand and handovers only occur at *transfer points*. Although in the case studies above we set *transfer points* at each station, the interval of *transfer points* can be extended as long as the requirement for signal propagation delay allows. The novelty of the OBMN originates from the specialization for the local trains characteristics: fibers can be laid along overhead lines without interruptions, the movable range is limited from several kilometers to several tens of kilometers along railways, and the moving speed is up to around 120 km/hr. The main technical challenges for OBMN are constructing the high-speed reel and fiber lanes which can follow the train movement. We believe that the OBMN will be a promising architecture for the future mobile networks users on local trains, whose data traffic will continue to increase dramatically in the coming years.

VI. CONCLUSION

In this paper we proposed the concept of OBMN architecture for efficiently deploying moving cell for local trains. In the OBMN, an ABS which is connected to a gateway via optical backhaul is set on the top of a train. While the train moves, the ABS always forward traffic of moving demand onboard through high-bandwidth optical backhaul. The proposed architecture can efficiently provide high and stable bandwidth using small number of BSs, unlike existing moving cell architectures with wireless backhaul.

The OBMN is specialized architecture for local trains. The optical fibers are laid along overhead lines without interruptions. The movable range of an ABS is limited along railways. To follow the movement of the train, the length of optical fiber that connects an ABS and a gateway is adequately adjusted with a high-speed reel located along the railway. When the train arrives at a *transfer point*, *transfer* is performed for handover. In the *transfer* sequence, the ABS set on the train gets the train off and another ABS is set on the train. To satisfy demand with the minimum number of ABSs, we proposed the ABS scheduling scheme which determines the position and state of each ABS based on *ingress* and *egress events*.

The performance of the proposed architecture and scheduling was confirmed through two case studies in the suburban and urban area in the Tokyo area. With the OBMN, the moving demand on local trains can be optimally satisfied with high-throughput optical backhaul using small number of BSs in both scenarios. The number of required BSs and deployment cost are reduced by half with the proposed OBMN architecture, compared with the existing static BS deployment. The OBMN is highly effective in suburban areas with smaller number of trains in long distance. The effect can be improved in urban scenario by employing hybrid architecture with the existing scheme. We believe that the proposed OBMN architecture will be a promising architecture for the future moving cell deployment for local trains.

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