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An Overview of Internet Broadband Services in High Speed Trains

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ABSTRACT: High speed train (HST) passengers demand uninterrupted multimedia services throughout the journey. Rapidly fading radio channels, Doppler frequency shift and fast handover problem are a few challenges which the existing mobile communication systems encounter, while supporting the mobile user in high speed trains (around 350 km/h). In this article we briefly overview the solutions proposed for provisioning high quality internet broadband services to the travelers. These solutions are based on the available access network technologies. We have also discussed the drawbacks and technical difficulties involved for implementing the respective solutions. Lastly, we have briefed about the newly proposed C-HSTC architecture and the RADIATE architecture derived from the existing solutions, aimed to provide a cost-effective and high-quality communications solution for provisioning broadband Internet services in HSTs.

KEYWORDS: Global System for Mobile for Rail (GSM-R), Long Term Evolution (LTE), Distributed Antenna System (DAS), Remote Antenna Unit (RAU), Common public radio interface (CPRI).

I. INTRODUCTION

All developing countries envisage the implementation of high speed rail projects (250-350 km/h) aiming to take thousands of people from one place to another safely, comfortably and fast. Quality of services in terms of access to internet services, need to be upgraded, as people relying on internet are growing rapidly. Based on the available access technologies, the proposed solutions for enabling high quality broadband Internet services to commuters travelling in high speed trains can be categorised as:

A. Cellular- network based solutions;
B. Radio over frequency based solutions (RoF);
C. Leaky Coaxial cable based network access; and
D. Satellite communication based solutions.

This paper discusses the architecture, merits and drawbacks of each of these solutions. Lastly, an overview of newly proposed architectures which combine the merits of the above mentioned solutions, are introduced:

1. Baseband cloud (C-HSTC) system [14]; and
2. Radio over fibre as an antenna extender (RADIATE) [1].

II. LITERATURE REVIEW

The research work done by authors of ”Leaky Coaxial Cable for communication in high speed railway transportation”, May 1975 [13] briefs the structure and basics of the leaky coaxial cables and how the electrical characteristics like transmission loss and coupling loss of these cables change according to the surroundings such as place of installations, rain and snow. In “Study for Various Array Antenna Assisted Doppler Spread Compensator with MRC Diversity of ISDB-T Receiver,” 2006 [7], the authors have explained how antenna arrays are helpful in compensating Doppler spread. The article, “Bullet-Train Network Architecture for Broadband and Real-Time Access,” 2007 [10], explains the LCX architecture for Bullet trains. In” Radio-over-Fiber based Solution to Provide Broadband

Internet Access to Train Passengers," 2007 [9], the authors have briefed about the moving cell concept. The articles "Distributed Antenna Systems for Mobile Communications in High Speed Trains," 2012 [3], "A CoMP Soft Handover Scheme for LTE Systems in High Speed Railway,"2012 [4] and "Seamless Wireless Connectivity for Multimedia Services in High Speed Trains," 2012 [5], have discussed about the cellular based networks. The radio over fibre concept was comprehended from the articles "Radio over Fiber Link Design for Next Generation Wireless Systems,"2010, [8] and "On OFDMA Resource Allocation and Wavelength Assignment in OFDMA-Based WDM Radio-over-Fiber Picocellular Networks,"2011 [11]. In "RADIATE: Radio Over Fiber As An AnTenna Extender for High-Speed Train Communications,"2015 [1], and in "Reliable broadband wireless communication for high speed trains using baseband cloud", 2012 [14], the authors have proposed new architectures for broadband access in HSTs.

III. AVAILABLE SOLUTIONS

A. CELLULAR-NETWORK BASED SOLUTION

The cellular-network-based solution is a fine choice for provisioning broadband Internet services to mobile users because cellular networks are almost seamlessly deployed. Currently, a 2nd generation mobile communication technique, i.e. the Global System for Mobile for Rail (GSM-R) [3] is implemented in railways which can provide data rate only upto 200 kb/s to mobile users. The International Union of Railways (UIC) has chosen Long Term Evolution (LTE) as the next generation railway communications system for provisioning broadband Internet services [4].

Although the LTE system enhances the spectrum and power efficiency and provides higher data rates to mobile users, it is not optimized for fast moving users (with a speed of 300–500 km/h).

Cellular networks encounter two major technical difficulties specifically, the drastically changing channel condition and overly frequent handovers [5]. Orthogonal frequency-division multiplexing (OFDM) is the adopted transmission scheme by LTE as it is robust to frequency-selective fading. However, severe inter-channel interference (ICI) is caused due to the Doppler spread which deteriorates the orthogonality among the subcarriers. This Doppler spread is a result of fast channel changing conditions. To mitigate this performance deterioration, several approaches have been proposed. The 1st approach is to estimate and remove the frequency offset. The 2nd approach is to apply signal processing and frequency domain coding to reduce the sensitivity of the OFDM system to the frequency offset [6]. The 3rd approach utilizes antenna array to compensate for the Doppler spread [7]. Another challenge encountered by LTE is the overly frequent handovers. The handover process may fail as the users in the train traverse the overlapping coverage area in a very short time hence the users will be out of service with a large handover delay when the train is moving very fast. Also, tens of passengers from a single cabin of the train may request handover at almost the same time which may lead to signal congestion. To address this challenge, Karimi et al. [5] proposed a cell array solution that organizes LTE cells along a railway and sets up a femtocell in the train cabin to aggregate traffic demands.

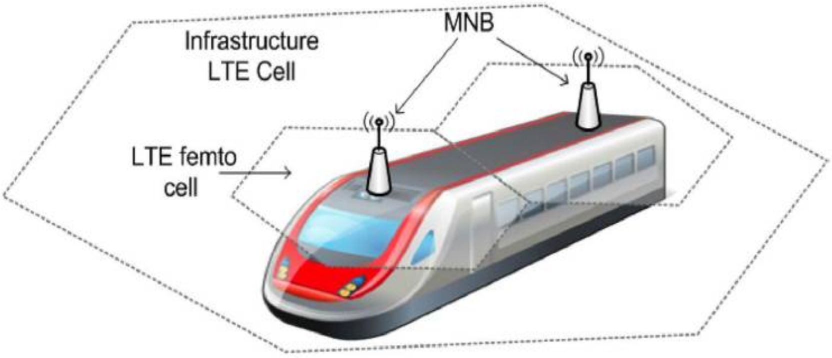


Fig.1: Long Term Evolution –Cell infrastructure [5]

Fig.1 illustrates the LTE cell infrastructure. A number of LTE femtocells can be used to cover each train cabin. The cell array solution as seen in Fig.2 enables seamless handover by predicting the upcoming LTE cells based on the movement of the train.

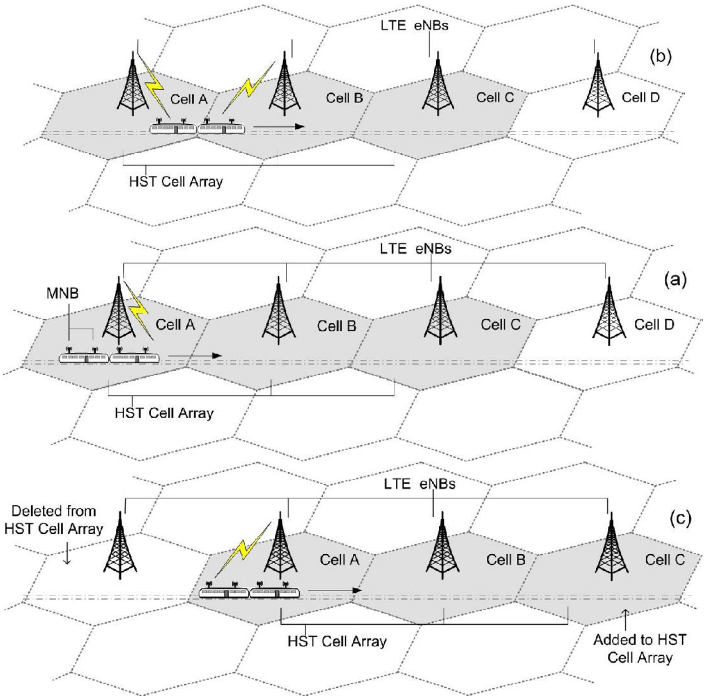


Fig. 2. Cell Array reconfiguration along the railway path [5]

B. RADIO OVER FIBER

For distributing wireless communication signals, Radio over fiber (RoF) is a well established technique [8]. One of the major applications of the RoF technique is the distributed antenna system (DAS). In a DAS, multiple remote antenna units (RAUs) are connected to a central unit via RoF transmission links. The RAUs are able to provide excellent coverage and dedicated capacity for short-range communications. The “moving cell” concept was proposed to mitigate the handover difficulty for high-speed trains by taking advantage of the RoF-based DAS [9]. The design of the “moving cell” concept is such that the base stations (BSs) track the movement of the trains and reconfigure their operating frequency accordingly to maintain the communication links with the passengers instead of requiring the passengers to adapt frequency during the handover process,. To realize the moving cell concept, RAUs are deployed along the rails to provide seamless coverage for the train. These RAUs are connected via fiber links with the central control station (CCS) unit, as shown in Fig.3, which tracks the movement of the train and reconfigures the operating frequency of these RAUs. The cell reconfiguration is easily synchronized with the movement of the train due to the low latency of fiber links. In the train, several wireless access points with radio interfaces of multiple access technologies are set up to aggregate traffic from the passengers. These wireless access points relay traffic between users and the RAU along the rail.

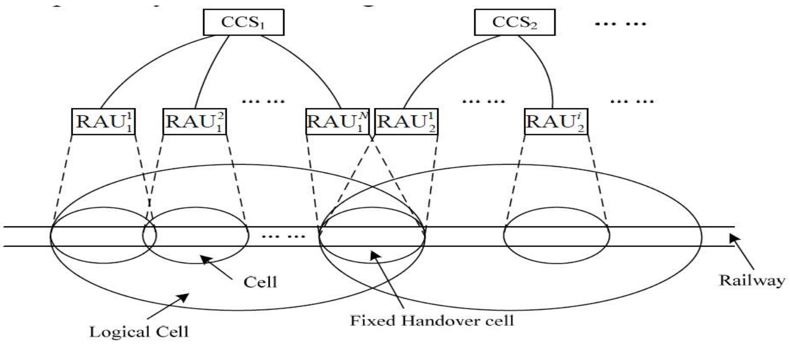


Fig.3. Distributed Antenna System architecture for high speed railway [12]

One major limitation in implementing the moving cell concept is the huge cost in deploying the fiber connected RAUs along the rails. For example, countries with railway transportation as their major transportation method for residents, deploying RAUs along the rails is extremely costly. In addition, it is even impossible to deploy RoF-based DAS in some mountainous terrains.

C. LEAKY -COAXIAL-CABLE-BASED NETWORK ACCESS

Leaky coaxial cable (LCX) is used as an antenna for data transmission and reception. The cable is slotted as seen in Fig 4 on its outer conductor to enable signal transmission and electromagnetic wave radiation [10]. LCX is arranged along the railway lines in Japan for radio communications on the trains. LCX can be utilized as backhaul connections for provisioning Internet services to passengers in the trains. Ishizu et al. [10] proposed Mobile- LCX architecture for Internet service on "Bullet- Train." In each train, a mobile bridge, which consists of radio interfaces for different types of access technologies such as IEEE 802.11, WiMax, and LCX, is deployed to aggregate data traffic in the train and communicate with the LCX-based stations.

The maximum data rate of the LCX based communication is 768 kb/s, which cannot satisfy the bandwidth requirement for broadband Internet services.

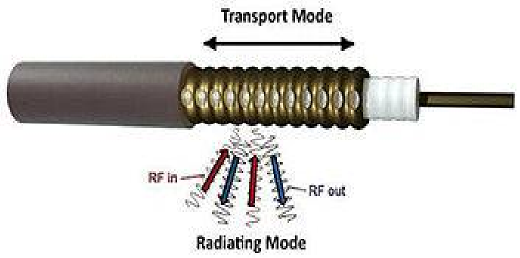
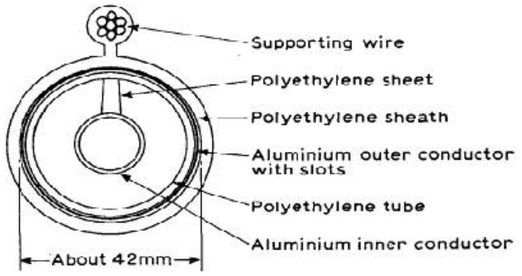


Fig. 4.a. Leaky coaxial cable



4.b. Cross sectional view of LCX [13]

D. SATELLITE COMMUNICATIONS

Satellites can be utilized to provide Internet services to the passengers on a train as they cover a vast area [2]. In order to connect with satellites, a pointing system, as seen in Fig.5, which performs the satellite acquisition and tracking, is set up on the train. In addition, a communication subsystem is deployed to aggregate data traffic within the train.

Providing broadband Internet services via satellite links has several drawbacks [9]. First, the delay of satellite communications, which is about 500–600 ms, is not suitable for real-time Internet applications. Second, the bandwidth of satellite links is limited and cannot satisfy the explosive traffic demands from hundreds of passengers on the train. Third, satellite communications highly depend on weather conditions and terrain, as seen in Fig.5. On rainy days, satellite signals are severely attenuated, resulting in significant capacity decrease. In addition, the satellite coverage in urban areas and hilly areas is very poor, and satellite signals cannot reach into tunnels.

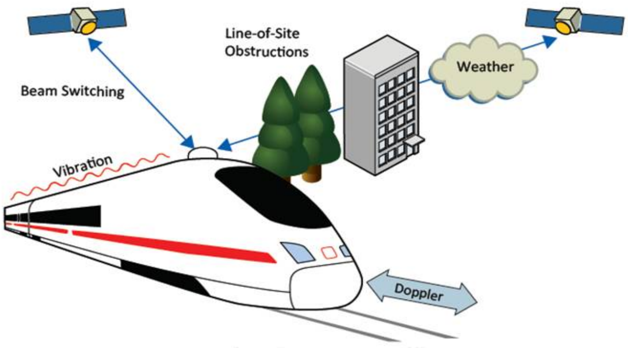


Fig. 5. Satellite communication

III. NEWLY PROPOSED SYSTEMS

1. C-HSTC SYSTEM ARCHITECTURE

[14] Qinglin Luo, Wei Fang, Jinsong Wu and Qingchun Chen proposed a new cloud-based High Speed Train Communication (C-HSTC) architecture which is as shown in Fig.6. The system consists of onboard Train Access Units (TAU), trackside Remote Radio Heads (RRHs), and a Baseband Unit (BBU) cloud.

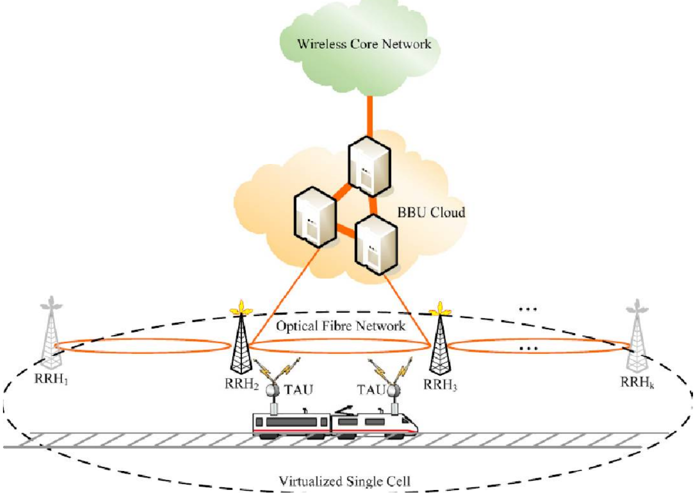


Fig. 6. Cloud-based High-Speed Train Communication system architecture. [14]

The TAU is equivalent to a mobile relay, responsible for gathering user traffic from/to the access points deployed in the carriages. The TAU communicates with the trackside RRHs via the air-interface channel. The number of TAUs equipped on a train depends on the user traffic volume and the train-to-ground transmission bandwidth. Two TAUs deployed- one on the front and the other at the end reduces the opportunity of interference between TAUs, while providing sufficient spatial diversity for the trackside RRHs to exploit advanced multiple-in-multiple-out (MIMO) transmission technologies. Optical fiber is used to connect the TAUs and the in-train access points so as to provide bandwidth for broadband services and keep the latency low.

Each RRH can have up to 8 transmit and receive channels for a Time-Division Long Term Evolution (TD-LTE) RRH. They are connected to BBUs via optical fiber interfaces such as common public radio interface (CPRI).

In a conventional HSTC system the BSs are deployed distributively along the track and connected via a low speed interface. In the new architecture a pool of collocated BBUs are connected by fast data links and are under the control of a common resource scheduler. Example of a BBU cloud is shown in Fig.7.

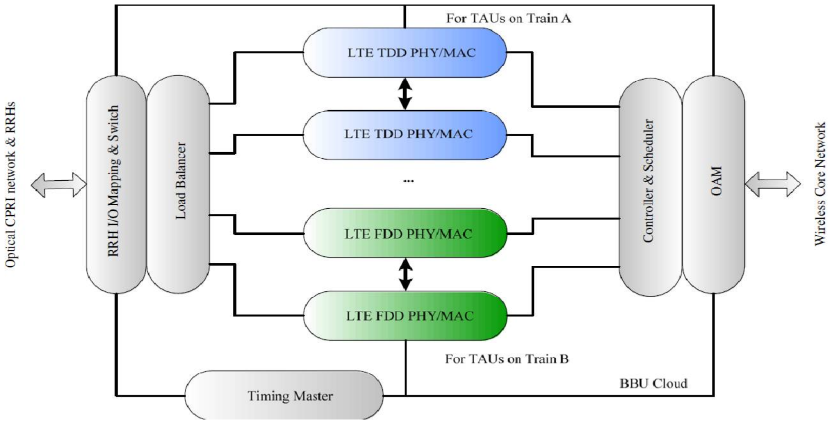


Fig.7.Example of a BBU cloud [14]

In the cloud, BBUs can support different communication protocols such as GSM, UMTS, LTE Time Division Duplex (TDD), LTE Frequency Division Duplex (FDD), etc. Their computing resources are under the supervision of a global scheduler/controller, thus can be dynamically allocated to different TAUs according to their instantaneous requirements. Furthermore, there is a unified input/output (I/O) interface between the BBU cloud and the RRH network, which is responsible for addressing and switching signals between the RRHs and BBUs. The addressing and switching is configurable not only statically via the operation and management (OAM) interface, but also dynamically by a load balancer which is monitoring the BBU computation resources. The entire cloud has a common timing source which helps to reduce the interferences in the C-HSTC network due to timing misalignments.

A fast RRH selection scheme which is Geo-aided is enabled by the cloud-HSTC architecture. Since all RRHs are centrally controlled by a BBU cloud, the train's geographical information (location and speed) is traceable in nearly real time. Only the RRHs that the train is approaching need to be selected and powered up for transmission. Other RRHs can be powered down for energy saving and interference reduction.

In addition to the fast RRH selection, the authors propose to implement a virtualized single cell based on the C-HSTC architecture to avoid the signalling overhead and delay caused by frequent resource allocation and reallocation in a conventional system. The virtualized single cell design also enables an efficient joint transmit beamforming scheme capable of delivering significant link level performance gain and providing sufficient data rate even at high mobility.

This proposed framework may not only overcome the challenge of high call drop rate due to frequent handover failures at high mobility but also achieve quality broadband communications under strong ICI environment due to severe Doppler frequency shift in the scenario of high speed train communications.

2. The RADIATE (Radio over fibre as an antenna extender) Architecture

[1]Tao Han and Nirwan Ansari proposed a novel broadband communication solution named RADIATE for high-speed trains by exploring and marrying the merits of cellular networks and the moving cell concept. RADIATE utilizes the fiber links to form an antenna system on the roof of the train, which virtually extends the antennas of individual users. As shown in Fig.8.a. RADIATE consists of in-cabin wireless access points, an on-roof antenna system, and the RADIATE control system (RCS). The in-cabin wireless access points have radio interfaces of multiple access technologies such as LTE, WiMAX, and WiFi. The passengers in the cabin access Internet services via these access points. The on-roof antenna system communicates with cellular networks, and relays the data traffic between the users and the cellular networks. The on-roof antenna system camouflages/shields the rapid channel variation and frequent handovers from the users.

The RCS performs two functions: (i) to schedule passengers' traffic to maintain fairness among users and fully explore the capacity of the on-roof antenna system; and (ii) to optimize and control the antenna system to maximize network capacity.

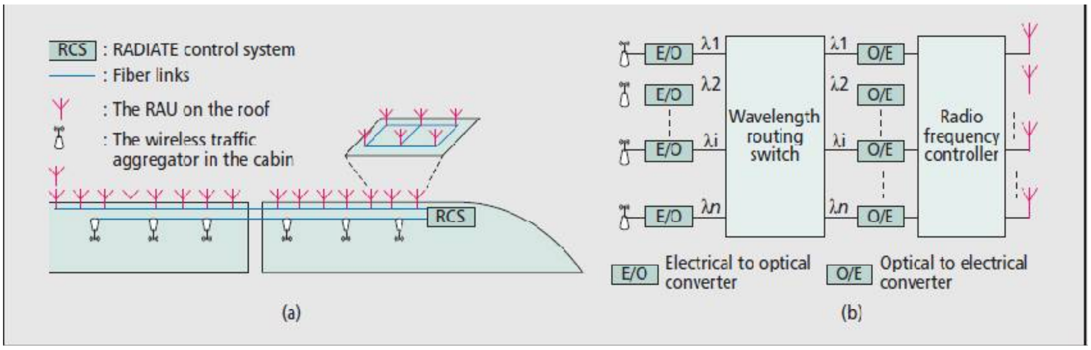


Fig. 8: An illustration of the RADIATE architecture and control system: a) the RADIATE architecture b) The RADIATE control system.

A simple implementation of RCS is shown in Fig. 8.b. A wavelength routing switch balances the traffic among different antennas. Various time-delay modules can be introduced to RCS [3, 11] to solve the problem of reduced channel capacity caused by the delays incurred by the signal propagation in optic fibres and the delays incurred due to the electrical-to-optical (E/O) and optical-to-electrical (O/E) converters. A radio frequency controller (RFC) is used to process the signals received from the antennas or transmitted to the antennas. The RFC also tracks the speed of the train and the round-trip time (RTT) of connecting the cellular network, and adapts its signal processing processes accordingly.

RADIATE enables a relatively stationary channel between the antennas and the serving Base Stations (BSs), making it easier for the receivers to apply Doppler shift compensation caused by the fast motion of train. The inter channel interference (ICI) caused by Doppler spread is reduced in turn. Also, the channel condition when the passengers receive the acknowledgment for the serving BS may change dramatically as compared to the channel condition reported to the BS. When relative stationarity is achieved, the channel condition may not change dramatically.

Fig.9.a shows the original communication scheme where the fast movement of train not only leads to severe Doppler spread but also deactivates the channel quality indication reported by the user. RADIATE exploits the on-roof antenna system to mask the channel variation from the users, as shown in Fig. 9.b. When a user initiates an access request, the user communicates with the BS via antenna terminal, AT 1. When the acknowledgment for the request sends back from the BS, AT 1 is already 10 m away from its original location. The RCS tracks the movement of the train and the RTT of the network, and selects the antenna that has the best performance in receiving the signal transmitted to AT 1. Since AT 2 is located at AT 1’s original location, AT 2 is supposed to experience the same channel condition as that of AT 1 reporting to the BS when AT 1 initiates the request.

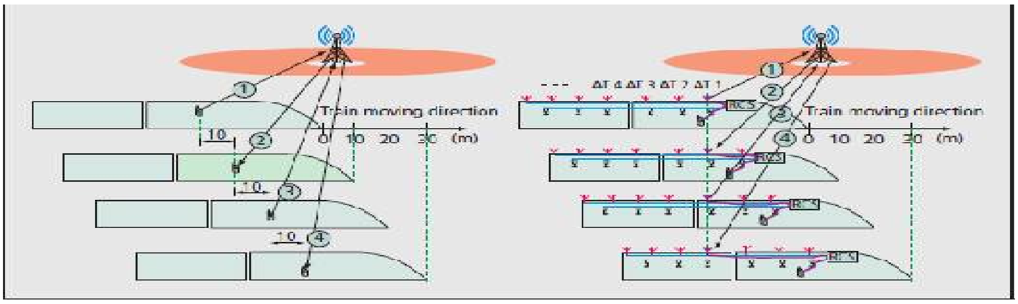


Fig. 9: The advantages of RADIATE for addressing rapid channel variations: a) the original communications scheme; b) the RADIATE communications scheme. [1]

Thus, from the BS’s point of view, it seems that the receiving node does not move at all, whereas the rapid channel condition variations are hidden from the viewpoint of the users. Since the antennas are deployed along the roof of the train, by proper antenna selection, the RCS is able to maintain roughly stable wireless communication links between the BS and the train for a considerably long time equalling tens of RTTs.

RADIATE masks the handover delay from the passengers and balances the traffic load among the antennas to avoid handover congestion by exploiting the on-roof antenna system. As seen in Fig.10, user equipment (UE) 1 initiates network access when the UE is located in the red cell. When the train is moving into the green cell, instead of handing over UE 1 to the green cell immediately, the RCS selects the antennas that are still in the red cell (e.g., AT 5) to serve the UE’s traffic demands. After the train has established communication links with the green cell, UE 1’s traffic demands can be switched to the green cell. In this way, the passengers in the train will not experience handover delay.

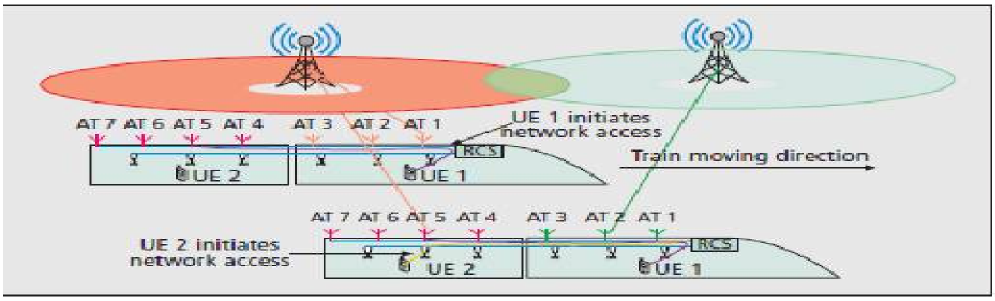


Fig.10. The RADIATE handover process. [1]

To avoid handover congestion, RADIATE redistributes the passengers' traffic demand among the antennas. In the example shown in Fig.8, when UE 2 initiates the network access, the UE is located in the red cell. The RCS predicts that UE 2 will eventually hand over to the green cell according to the movement of the train. Thus, the RCS hands over UE 2's traffic load to the green cell in advance. Although UE 2 is still in the red cell, the RCS directs UE 2's traffic to AT 2. As a result, UE 2's traffic demands are handed over to the green cell. When the train is within the coverage of multiple cells, the RCS determines the traffic demands distribution among these cells and selects proper timing for handing over these traffic demands. The RCS can delay the handover of certain users' traffic demands (e.g., UE 1) while bringing forward the handover of other users (e.g., UE 2). The traffic demand distribution and handover timing are optimized by the RCS to maximize the performance of RADIATE.

RADIATE is able to ensure quality of service even during handover processes. The system capacity may drop dramatically when the train moves away from a BS. By leveraging its antenna system, RADIATE selects the antenna with the best channel condition as the serving antenna and enables the system to maintain its peak capacity for a longer time. Also RADIATE reduces the capacity drops during the handover process. If all the antennas are utilized simultaneously, the aggregated system capacity is significantly enhanced.

V. CONCLUSION

In this article, we have briefly overviewed the existing broadband communication solutions for high-speed train communications. We have also discussed the limitations of each solution. The system architectures of two new architectures namely C-HSTC and RADIATE are overviewed. Hence for provisioning broadband Internet services in high-speed trains with seamless handover, low latency, we need to deal with factors such as zero call drops, meeting the traffic demands, maintaining system's capacity, avoiding handover congestion, etc. We conclude that, marrying the merits of the available access network technologies and framing strong algorithms may lead us to more efficient, cost effective and high quality communications solutions.

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