Europe's First 5G-Ready Railway Trial Utilizing Integrated Optical Passive WDM Access and Broadband Millimeter-Wave to Deliver Multi-Gbit/s Seamless Connectivity

Jim Zou(1), Peter Legg(2), Romeo Santiago(3), Valerio Bruschi(4), Richard Graham(2)*, Salvatore Pontarelli(4), Giacomo Belocchi(4), Luca Petrucci(4), Paula Ciria(5), Carles Terés(5), Juan Agusti(3), Manuel Alfageme(3)

(1) ADVA Optical Networking SE, 98617 Meiningen, Germany, jzou@adva.com
(2) Blu Wireless Technology Ltd., BS2 0BY Bristol, UK (* now with FirstGroup plc, UK)
(3) COMSA Corporación, 28037 Madrid, Spain
(4) CNIT, Research Unit of Roma Tor Vergata, 00133 Rome, Italy
(5) Ferrocarrils de la Generalitat de Catalunya, 08017 Barcelona, Spain

Abstract *We successfully carried out Europe's first 5G-ready railway trial in an operational environment by combining a passive wavelength-agnostic WDM for optical transport and 60 GHz millimeter-wave for wireless connectivity. The trial achieved multi-Gbit/s seamless connectivity from track-side access points to a fast-moving train.*

Introduction

The transformation of 5G aims not only to accommodate the mobile traffic growth, but also to support a large variety of dynamically varying applications and services. The 5G infrastructure is designed to bring new service capabilities to ensure user experience continuity in challenging vertical markets[1]. In particular, the train communication network (TCN) features mission critical services and high mobility in a heterogenous environment, where supporting the handovers required for consistent broadband connectivity on inter-city trains traveling at high speed is still a big challenge. Currently, the existing TCN supporting operational and passenger services relies on a complex mixture of different access technologies, including GSM-R/TETRA for train operation and LTE backhaul. This results in costly investment, complicated deployment, lack of versatility, and inefficient interoperability. Looking ahead, the Future Railway Mobile Communication System (FRMCS) initiated by International Railways Union (UIC) defines three service categories for transport digitalization, i.e. critical services related to operation safety, performance improvement services (e.g. telemetry and maintenance), and business services that provide the broadband mobile communication for train passengers. To have as fewer as possible the isolated TCNs, both the critical and non-critical services will benefit from sharing a single 5G infrastructure.

To this end, we propose and showcase a multi-tenant TCN for enabling 5G technologies in the railway sector. This first-of-its-kind solution uses an integrated high-capacity optical passive WDM and millimeter-wave (mm-wave) wireless transport. Though few trials on providing broadband communication for high-speed trains were reported recently[2],[3], to the best of our knowledge, we successfully demonstrated Europe's first 5G-ready deployment in a fully operational rail network. The trial achieved an end-to-end duplex throughput of more than 2 Gbit/s with an average one-way latency of 2.5 ms along a 2 km track.

Proposed Solution Architecture

Both 3GPP 5G-NR and the Telecom Infrastructure Project show considerable interest in moving to mm-wave frequencies. The extension to mm-wave resolves the issue of limited spectrum in the Sub-6 range, leading to a much higher bandwidth. Moreover, the shorter coverage makes the mm-wave ideal for the small cell deployment with the reduced antenna size and multipath spreads, which improves the spectrum reusability between the adjacent cells. According to our proposed architecture, we use two antenna modules mounted on the front and rear ends of the train roof, each facing forward and backward directions to maximize the handover coverage between two AP towers. The two host processor modules for these two antennas are installed inside two driver's cockpits (front and rear), respectively. Similarly, on the track side, each tower is equipped with two mm-wave APs, facing two directions of the rail. The mm-wave link uses single carrier modulation at 60 GHz (IEEE 802.11ad), capable of up to 4.6 Gb/s rate at the MAC-PHY interface. In addition, both the AP and the train exploit phase-array antennas that are highly directive to eliminate the spread of multipath interference, and use automatic beam forming to ensure optimal alignment at all train positions[4]. The CFO tracking mechanism is able to compensate for the Doppler shift.

Optical transport is ideal between the mm-wave APs and stations. However, fiber resource is scarce and, unlike a telco facility, is difficult to maintain given the vast amount of APs along the track and no onsite access when trains are running. We therefore propose a passive linear add/drop WDM link for the optical backhaul, of which the optical up- and downstream are multiplexed on the even and odd wavelengths in the C-band with 100 GHz spacing, respectively. This leads to a single trunk fiber between the antenna towers, and only the passive add/drop filter installed at each tower. Moreover, by implementing an out-of-band communication channel[5], the head-end/tail-end transceivers (HE/TE, in an SFP+ form factor) are capable of automatically tuning the exact WDM channel according to the connected port at on the filter, substantially reducing spare-part inventory and operational efforts. These tunable transceivers are temperature hardened for the outdoor use. A long-haul rail network can be segmented by multiple passive WDM links, which are further aggregated to a 100GbE core network.

Ethernet is used as the transport protocol, which aligns with the 5G RAN functional split. To ensure fast and reliable connection continuity while the train is moving at high speed between mm-wave APs, we implement a proprietary fast-data path solution[6], where two FPGA-based (NetFPGA SUME) FlowBlaze nodes terminate the aggregated traffic in the control center and the train, to dynamically route the traffic to the connected AP. The in-train FlowBlaze periodically sends probe packets towards the central FlowBlaze via the network. Each mm-wave AP tags the forwarded packets with a different VLAN ID, thus allowing the central FlowBlaze to detect from which AP the packet was received. Consequently, the central FlowBlaze is able to associate the MAC addresses of two train antennas to that specific VLAN and then return the requested traffic to the train via that connected AP. The central FlowBlaze keeps learning the VLAN tag of the packet, in order to determine which AP is associated with the moving train. More importantly, both FlowBlazes are implemented to discard any duplicated packets, in the case that the train front and rear antenna are associated to two adjacent APs in the coverage overlap. This fundamentally guarantees a seamless handover.

Field Trial and Results

An overview of the trial site is outlined in Fig. 1. Four rail towers between Martorell Central and Olesa in the FGC operational rail network in Barcelona were equipped with eight mm-wave AP backhauled by the passive WDM add/drop nodes. Based on the coverage of the mm-wave signal and the line of sight constraints, the separation distances between towers, as shown in Fig. 1 (inset table), were chosen to ensure that in cross-zone handover both train antenna units can simultaneously connect to two opposite APs on the adjacent towers.

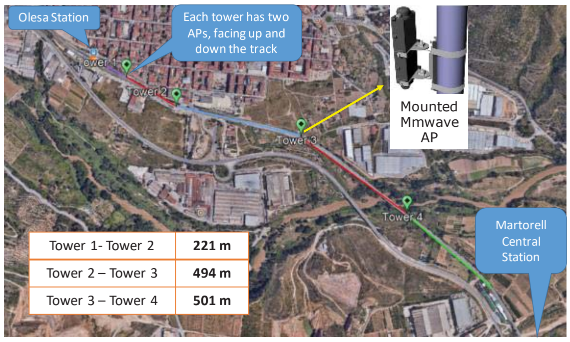

Fig. 1: Field trial overview and tower locations

Fig. 2 shows the complete trial setup and the onsite photos of installed equipment. Inside the train, two 10GbE switches were interconnected to terminate multiple on-board services on different VLAN slices. In the trial we considered the surveillance camera and LAN access representing the train performance service and the broadband passenger service, respectively. The FlowBlaze for mobility control duplicated the upstream to two train antennas, while removing duplicates on the downstream. On the track side, each add/drop filter dropped two downstream wavelengths on the odd grids, and multiplexed two neighboring wavelengths on the even grids for the upstream. In the station node, a low-latency transponder converted the optical interface between the tunable WDM and the grey client on the 100GbE aggregator. As such, each AP was linked up with an individual client port on the aggregator through a dedicated optical channel. In the control center, another 100GbE aggregator terminated the AP traffic associated with specific VLAN tags, which were forwarded first to the FlowBlaze for VLAN learning and then popped before reaching to the service terminals. The detected VLAN tag was then pushed to the current downstream.

Based on the measured passive WDM link loss, we can project the scalability as shown in Fig. 3(a). The link loss is linearly proportional to the number of APs. The margin between the link loss at the last AP and the transceiver receiving

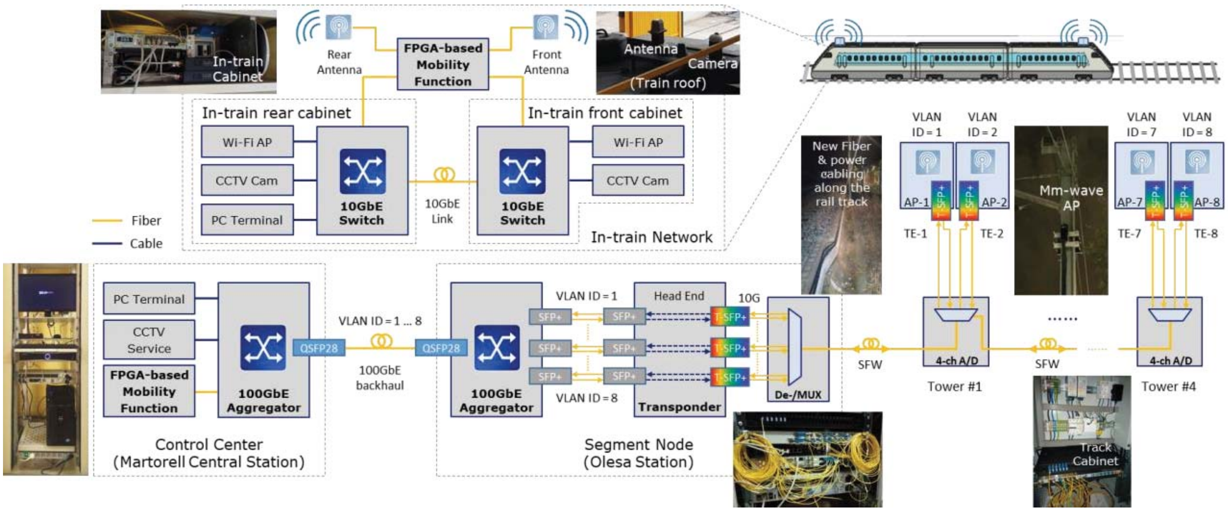

Fig. 2: Field trial setup composed of the control center, segment node, track-side network, and in-train network (inset photos)

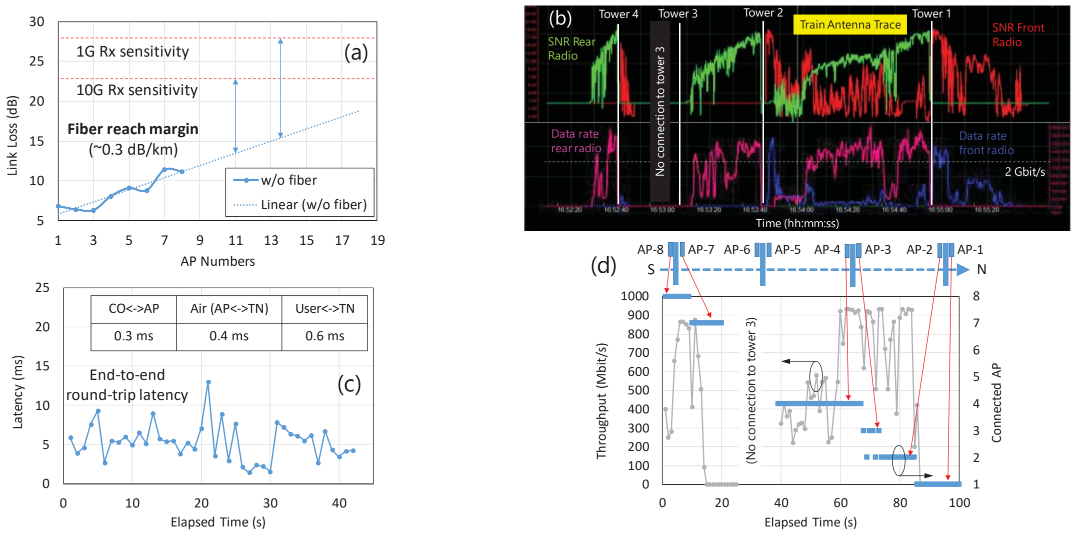

Fig. 3: (a) Link budget of passive add/drop WDM; (b) Mm-wave link telemetry; (c) End-to-end latency; (d) Handover analysis

sensitivity is the applicable transmission distance. Fig. 3(b) shows how the train front and rear antenna connected to APs alternately at a data rate of up to 2 Gbit/s, when passing through the trackside network. The two APs on the Tower-3 unfortunately could not work due to a technical issue. Fig. 3(c) shows the end-to-end round-trip latency measured by ICMP packets between the Control Center PC and the onboard PC, with the latency breakdown (inset table). The train moving direction (south to north) and the associated APs in the mobility test are depicted in Fig. 3(d), and we used the Iperf3 throughput analysis to evaluate the handover. The bidirectional throughput was increased when the train was closer to the AP, and decreased when leaving the coverage. Though multiple radio links might be established, only one link was actually used for data transmission, and the duplicated packets from other working links were dropped. The highest achieved end-to-end data rate of duplex 2 Gbit/s was in fact bounded by the 1GbE interface of the onboard PC as the Iperf3 server/client.

Conclusions

We demonstrated for the first time a multi-Gbit/s train access network with milliseconds latency in an operational environment, and showcased the future 5G network in the railway vertical.

Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement No. 762057 (5G-PICTURE).

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