Light-trains: An Integrated Optical-Wireless Solution for High Bandwidth Applications in High-Speed Metro-Trains

Ashwin Gumaste, Akhil Lodha, Jianping Wang, Nasir Ghani and Si Qing Zheng

Abstract: Moving trains represent a voluminous mass of users moving at high velocities that require bandwidth (on demand). Existing solutions typically based on wireless technology alone cannot scale efficiently to provide for bandwidth to such fast-moving voluminous users. A new approach is proposed that facilitates dynamic provisioning, good scalability and efficient use of available bandwidth. The proposed approach called light-trains seamlessly integrates optical and wireless networking techniques to provide an ideal broadband Internet access solution to users in moving trains. We identify the set of requirements that a solution would require -- such as fast hand-off, low-cost of deployment, mature technology and ability to provide dynamic bandwidth provisioning (and hence low experienced delay). The requirements mentioned influence our choices of technologies for different domains in the network: (1) For access to end-users that reside within the train we use an efficient wireless last-inch solution like WiFi in the Point Coordination Function (PCF) mode. (2) For providing access between the wired backbone network and the train we use a modified WiMax system that gives good throughput and efficient channel utilization capacity in a point-to-point configuration. (3) Finally, to be able to provision bandwidth between the core network and the WiMax base-stations we propose the use of light-trail technology at the optical layer. The light-trail technology allows for dynamic provisioning of bandwidth at the optical layer through a unique node architecture and out-of-band control protocol. It turns out that the light-trail control protocol is useful for assisting fast hand-offs. The hand-off time being drastically reduced enables efficient utilization of the wireless channel even at very high speeds. A protocol that enable end-to-end provisioning across the three domains of technology aka light-trails, WiMax and WiFi is also proposed. The proposed protocol is a cornerstone mechanism for providing inter-domain (technology) connectivity in a pragmatic way. Different aspects of the protocol are considered, amongst which delay and efficiency are computed. The protocol and system requirements juxtaposed are simulated extensively. Results pertaining to utilization, delay, efficiency and network wide performance are all showcased. Viability of the model in being able to provide bandwidth to moving users is shown.

Key words: light-trails, moving trains, bandwidth-on-demand, cross layer

I. INTRODUCTION

The growth and spread of the Internet and other web services into the wireless domain has facilitated ubiquity and mobility for end-users. High bandwidth and multimedia applications are now being distributed through access networks that could be wired or wireless. A significant number of the end-users that could make use of such bandwidth intensive applications reside in mass-transportation systems. In order to provide bandwidth to users within the domain of a mass transportation system, it is imperative to have a wireless access mechanism that is further bolstered by a high-speed and dynamic wired backbone solution. The metro train represents a popular form of mass-transportation system in either its underground or over-bridge manifestation. (1) There are a large number of bandwidth hungry users within the confinement of a metro train. (2) Such a train represents a single moving entity that requires dynamic bandwidth allocation as it moves through a wireless network. (3) Further, several trains can statistically co-exist on the same track. This makes the bandwidth allocation problem along a track complex in lieu of the limited bandwidth-distance product offered by wireless technology. These triple needs imply added levels of complexity in the design of hand-off mechanisms and in provisioning the underlying “core” network to facilitate multimedia and emerging broadband applications. We propose a mechanism that enables bandwidth-on-demand to trains over a cross-medium architecture comprising of a wireless overlay supported by a metro-core optical network.

The delivery mechanism of bandwidth to end-users in a train leads to a new type of hierarchy. End-users within the train receive and transmit data from access points in each coach, and hence are part of a wireless LAN (IEEE 802.11 type). The access points are further connected to an Ethernet aggregation switch in the train. The question then is how to enable delivery of large bandwidth “chunks” to and from the switch to the rest of the wired Internet (core network) while the train is moving at high-speeds. Provisioning the underlying physical layer which is typically an optical network taking into cognizance this moving entity poses a new design problem.

Novelty of the Light-train Solution:

The dual needs of coarse bandwidth requirement and high-speed movement of the train makes bandwidth provisioning difficult to satisfy using independent conventional solutions in the wireless and optical domain. The light-train approach intelligently combines the wireless and optical layers to create an efficient solution for bandwidth allocation in metro trains. To do so, the light-train solution uses a novel optical layer technology that is used in conjunction with customized wireless end-user technologies. The nexus formed by the optical layer and wireless technologies is solemnized through a novel protocol that facilitates efficient, scalable, reliable, and available bandwidth allocation. The resulting solution creates several new technologies which have potential application in other networking domains. Amongst these, of primary importance is the optical layer assisted wireless (WiMax) hand-off scheme that results in two orders of magnitude improvement over existing hand-off techniques. The approach proposed by us
takes into consideration end-user profile from both a service requirement as well as equipment asset perspective. The protocol proposed ensures seamless ubiquity while adhering to the norms set by emerging networking services. Further, our approach has practical assumptions – there is no need to upgrade equipment at the end-users (done by using WiFi). Equipment is required only to be upgraded at the network side, to which the voluminous end users are totally oblivious.

We propose the light-trains model as an engineering solution for providing bandwidth on demand to moving trains. In Section II we discuss the system design of the light-trains model. Section III focuses on the node architecture, while Sections IV showcases how the IP network reacts to our light-train model. Section V discusses the principles of the integrated protocol. Section VI provides for analysis of the protocol delay perspective. Section VII compares our model to other related works. Section VIII discusses simulation results while Section IX summarizes the paper.

Fig. 1. Conceptual layout of metro trains over a wireless network and underlying optical network.

II. LIGHT-TRAIN SYSTEM

Consider a train $u$ moving along a track. The problem then is to provide bandwidth (on-demand) to users within train $u$. The system is as shown in Fig. 1. As the train $u$ travels it communicates with the rest of the core network through wireless gateways (along the track) that are situated at periodic intervals. The wireless gateways are overlaid on a fiber network. The fiber network supports the gateways in terms of providing connectivity to the rest of the Internet. The wireless gateway is used as an interface for communication between the train and the underlying optical network. The gateways have a limited transmission range and a series of gateways provide bandwidth to a moving train in a concept that is similar to cellular communications. Gateways are positioned one-after the other separated by a distance that is computed by the transmission range (to maintain effective Signal-to-Noise Ratio – SNR). The distance of coverage of a particular wireless gateway is defined as the geographic range of that gateway. In addition to geographic range, we define the concept of provisioning zone as the overlap area between the geographic ranges of two adjacent wireless gateways. Trains move from one wireless gateway to another in a seamless manner thus maintaining ubiquitous communication. Power based hand-off is the typical technique used for maintaining ubiquity. Hand-off occurs in the provisioning zones. Hand-off and associated methods are defined and explained subsequently in Section V. B.

The underlying optical network: Since multiple trains share the same track we are compelled not to use the track as a medium for data transport. For example, it is possible to use the track as a copper based last mile solution whereby a moving train taps data from a live track. However, this method does not support statistical space-sharing of the track amongst multiple trains (as is required in typical metro environments) and is also distance limited. The other flaw of the copper based solution is the restriction on the bandwidth-delay product due to properties of the copper medium. Hence an underlying optical network serves as a natural choice for providing rapid and broadband connectivity to the gateways. Further, most railway operators tend to have Rights-Of-Way (ROW) to lay fiber along the tracks. In order to support the communication to moving trains, the underlying optical network needs to meet certain characteristics.

The principle requirement on the optical network is of dynamic provisioning of bandwidth to wireless gateways. Data paths must be provisioned to the wireless gateways through the optical network on an on-demand basis while meeting the constraints of multiple services that a user would be subscribed to. This time-sensitive requirement, coupled with the fact that multiple trains will be sharing the same track, implies that pre-provisioning will generally lead to an inefficient bandwidth solution. In addition, a pre-provisioned solution would also be difficult to adapt to the fast moving train that requires rapid hand-off between successive adjacent wireless gateways.

To enable ubiquity it is necessary that the combined optical + wireless network be able to provide fast hand-off. Hand-off typically requires the following steps: (1) information gathering (power level compliance) and hand-off decision making, (2) signaling (to the switching center) and (3) re-provisioning of the connection. Each of these steps is time consuming and hence potentially leads to inefficient (underutilized) solutions. For example cellular hand-off solutions require several 100s of milliseconds. Similarly concepts based on moving tunnel approach as shown in [15] require up to 100 milliseconds in addition to adapting a completely new approach (whereby the entire network has to adapt to the moving tunnel technology).

With our selection of light-trail optical technology – we are able to minimize the delay involved in the hand-off. This is imperative especially if we consider that trains move at a high speed (around 300 kmph) and the range of gateways is of the order 1 km. Hence a train is within the range of a gateway for approximately only 20 seconds. Hence, hand-offs must be very fast in order to maintain effective (ubiquitous) and efficient (with good utilization) communication.

We propose an optically-assisted method for hand-off. The underlying principle is based on the dual concepts of optical multicasting and out-of-band aided control (described later).
Another characteristic for cross-medium integration is signaling: wireless gateways must be able to signal to each other about ongoing communication activities when trains move through their geographic range. This is essential for provisioning of dynamic requests and meeting needs of end-users especially for facilitating multimedia type coarsely granular duplex communication. The signaling is particularly important between neighboring (adjacent) wireless gateways to provide fast hand-off.

To illustrate this, consider the example of a train that moves through the geographic range of one wireless gateway to the next (adjacent) gateway. Assume that a user in the train is trying to download a large file. Assume that the time required to download the file exceeds the geographic range of the wireless gateway; and hence it cannot be downloaded within the range of one wireless gateway. In such a case the file must be made available to the next adjacent wireless gateway, when the train moves into its geographic range, so that the user in the train can successfully download the entire file. The time lost between tearing down the connection between the train and the first wireless gateway and the setting up the connection (making the file available) at the second wireless gateway is of critical importance. Another factor that also leads to an efficient cross-medium solution is that the second wireless gateway must be aware of the fraction of the file that was successfully transmitted through the first wireless gateway, so that it has to only transmit the remaining fraction. This necessitates the need for good signaling both at the optical and the wireless layer amongst nodes as well as between the nodes and the train along the track.

An optical networking solution that enables dynamic provisioning, optical multicasting and provides for effective signaling is the light-trails approach originally proposed in [1-4]. As opposed to conventional end-to-end circuit or lightpath (optical wavelength circuit), a light-trail is a generalization of a lightpath [5] such that multiple nodes along the path can communicate with each other. A light-trail is analogous to an optical bus with the added advantage that communication and arbitration of the bus is carried out by an out-of-band (OOB) control channel. The OOB control channel is optically dropped, electronically processed and then optically reinserted into the network. The differentiation between the OEO control channel and the all-optical (OOO) bus based data channel is the key to some of the functionalities of light-trail based networks. Multiple light-trails, each on a unique wavelength, use a common control channel.

In order to create a light-trail, nodes must be based on an architecture that supports three functionalities: (1) The ability to drop-and-continue incoming optical signal. (2) To passively add optical signal and (3) To support the OOB control. The first two properties, that of drop and continue as well as passive addition lead to formation of the optical bus, while the third property enables efficient (dynamic) provisioning within the bus. A light-trail is defined between two extreme nodes (a start node called the convener node and a stop node called end-node) that regulate signal flow within the optical wavelength bus. Signal flow is in the direction from the convener to the end-node. Light-trail node architecture is shown in Fig. 2.

A fiber that carries composite WDM signal enters the node premises from the left-side. The composite signal is demultiplexed into constituent wavelengths by an optical de-multiplexer (typically an Arrayed Wave-Guide – AWG). The control channel is also extracted and electronically processed by a control card. The data channels that are de-multiplexed are fed individually to a local access section. This section enables the node to access (TX/RX) data on individual light-trails. To do so, the section consists of two passive couplers separated by an optical shutter. The two couplers are in 1x2 and 2x1 configurations respectively. The first coupler drops and continues incoming optical signal while the second coupler enables passive addition of the optical signal. The optical shutter is a slow moving switch that is in the OFF position at the convener and end nodes of a light-trail while is in the ON position for all the intermediate nodes. Switching is required only when light-trails are set up or torn down, which for the case of providing bandwidth to moving trains is a semi-permanent feature and seldom used.

Once a light-trail is setup, its respective nodes can communicate by setting up connections. Connection setup and tear-down over a light-trail requires no optical switching and is carried about purely by the OOB control channel using a protocol we define in Section IV.

II. A. High Level System Description:

We assume a metro/inter-city railway network that is supported by a converged communications framework using our choice of optical and wireless technologies. An optical infrastructure constituting of optical fiber is assumed to provide a communication support below the entire railway track-grid. The optical signal is made available for communication at regular intervals (along the track) at sites – nodes also called Gateways (GWs). The optical layer employs the recently proposed and above described light-trail technology. Light-trail technology enables sub-wavelength granular dynamic bandwidth provisioning to GWs facilitated through a low-cost node setup. In addition light-trail also provides for optical multicasting (due to a bus property) which is critical for fast-hand-off. Each GW taps some portion of the optical power that passes through the fiber (wavelength-bus/light-trail).
An IP/MPLS backbone network interacts with the railway-grid at select gateways to provide backbone connectivity with the rest of the Internet. Typically, the selection of IP/MPLS routers along the grid implies points at which a light-trail terminates or commences as shown in the Fig 3 and Fig. 4.

Each gateway communicates with a passing train through a wireless link. To do so, the gateway has the following features: (1) support for a hybrid converged cross-medium optical and wireless communications platform whose architecture we discuss in Section III; (2) seamless communication and mobility to passing users through a method described in Section V; (3) provision, bill, and maintain services desired by end-users in fast-moving trains.

We propose WiMax as a candidate technology for the wireless link between a GW and a moving train. The choice of IEEE 802.16 WiMax is due to the support of large distance-bandwidth product and ability to coexist with other wireless last inch technologies that users may in addition subscribe to (for e.g. cellular/GSM or WiFi).

Fig. 3 Connection establishment in light-trains.

Further, we choose WiMax technology as an interface between the optical layer and the train, and WiFi as a last-inch connectivity technology as opposed to all WiMax solution are: (1) With a single Base Station (BS) (at the GW) and a single Subscriber Station SS (on the train) the complexity of hand-off as the train moves rapidly between GWs is minimal; i.e. a single hand-off is all that is required to provision connectivity to the train. If however, we had a WiMax interface all the way to the end-users (denoting these as SSs), then the problem would entail multiple hand-offs leading to complex management and provisioning issues, (2) WiMax to the end-users is not yet an off-the-shelf or an economical technology. WiFi on the other hand is common for most portable devices and widely accepted.

Information sent by the GW to the train is collected at a single platform within the train (the WiMax SS). This platform has a dual role: in one direction of communication it is used for communicating with the GW and in the other direction of communication it acts as an Access Point (AP) used to communicate with the end-users (residing in the train). Without loss of generality we assume in this paper, a single AP per train through multiple APs interconnected through a wired LAN within a train are also possible.

II. B: Duplex Communication in the Light-train System:

Let us now consider how a real-time application is supported at an end-user. A duplex communication application operates using two communication modes – Forward Communication (FC) and Reverse Communication (RC) depending on the direction of communication from or to the end-user. Forward Communication implies the sending of data from the end-users in the train to the core network. Reverse Communication implies the sending of data from the core network (wired) to the end-users in the train through the integrated (optical + wireless) converged network.

We first describe how FC works. The application at the end-user sends information through the intra-train WiFi network to the access point. In our model, we assume that the WiFi network is configured to implement PCF mode of operation, so as to enhance throughput.

The AP/SS collects this data (in form of Ethernet frames) and attempts to send it to a gateway through whose geographic range the train is presently passing. A scheduling protocol in the WiMax domain and a fast hand-off mechanism is assumed (and described in Section V.B) that enables establishment of communication and ubiquity between the SS and the GW. The WiMax frequency allocation is described in Section V. The railway tracks are assumed to be divided into cells in succession, that are overlapped power-threshold defined regions of communication. When a train passes from the range of one cell to another cell, a hard hand-off is assumed to happen. Packets are sent from the SS on an uplink frame through a WiMax point-to-point protocol. The point-to-point WiMax protocol has the challenge of supporting duplex communication as well as enabling efficient access to a fast-moving train. This protocol will be described subsequently.

Fig 4. Light-trail Architecture : Data collection at the trailponder.

The packets that are sent to the GW, are now required to be transported to the core network. This is done through the optical (light-trail) solution. Since a light-trail is an all-optical time-shared medium (bus), the packets are buffered in light-trail trailponders (electronic queues with added fast ON/OFF using burst-mode capability) [16] until a successful connection (in the light-trail) is established. A connection in a light-trail is when two nodes communicate over a light-trail. This is a software (control plane) defined operation that involves no optical switch configuration and thus leads to dynamic bandwidth provisioning. Once a connection at a gateway is established, the information is sent
through the light-trail to the nearest IP/MPLS router that is subsequently assumed to be connected to the rest of the Internet (core network). It is possible that, the information may hop over multiple light-trails that are interconnected with OEO based Ethernet switches (as shown in Fig. 4). The IP network is manipulated to support the dual notion of fast moving trains and all optical unidirectional light-trails and this is shown in the subsection on IP support (Section IV).

In the reverse direction of communication (RC), i.e. from the IP/MPLS router to the end-users, information for a particular end-user in form of packets arrives at a specific IP/MPLS router. This router is connected to a light-trail, that contains a GW in whose range the train is moving. The choice of IP/MPLS router as the destination IP address is described through a mobile IP allocation mechanism in Section IV. The data to be sent to the users in the train is collated in a trailponder [16] at the IP/MPLS router (as shown in Fig 4). The trailponder is responsible for sending this data into the light-trail by forming a connection. Since the light-trail is a time-shared medium, the trailponder at the IP/MPLS router competes with trailponders at GWs in connection provisioning. Multiple trailponders may exist at an IP/MPLS router – each supporting a different light-trail (on one of the many WDM channels). A single trailponder at an IP/MPLS router supports communication to all the nodes in the light-trail using the optical multicast property.

The information is sent into an appropriate light-trail (the one that contains the GW that has in its range the train that further contains the end-user that requests information). The connection is optically multicast to all the nodes in the light-trail including the node (gateway) over which the train is passing.

*Gateway nomenclature:* The GW through whose range the train is presently passing is called a live gateway; while the GWs through whose range the train has already passed are called dead gateways (for that particular train); finally, the gateways in whose range a train would soon arrive (downstream of the live gateway) are called dormant gateways. The live and the dormant gateways collect the information that arrives through the (optically multicast) connection, while the dead gateways discard the arriving information. The information is collected at the trailponders of the live and dormant GWs. The live GW then attempts to send this information to the train through the WiMax downlink channel. The gateway does so using a protocol that attempts to maximize the throughput by taking into consideration the buffer status and service delay parameters at both the GW as well as the AP/SS.

It may happen that the entire information content (say a file) is not transmitted by the live gateway while the train was in its range. The train may have moved to the next (dormant) gateway and begun communicating with this gateway (turning its status to a live gateway). The status change in GWs is dependent on a hand-off mechanism that is principally based on a power-threshold algorithm as defined in the IEEE 802.16e WiMax mobility standard in conjunction with our optical out-of-band control-channel. Hence, when the train undergoes a hand-off and begins to communicate with the next GW, the remainder of the file (a portion of which may have been transmitted by the previous gateway) has to be transmitted by this new “live” GW. In such an event, the new live GW should know the exact fraction of the file that has already been transmitted and also have access/contain the remaining fraction that is to be transmitted into the wireless channel. Due to optical multicast property of the light-trail all the nodes have access to the data that was sent by the IP/MPLS router, and hence the problem of availability of data at the new live gateway does not arise. However to avoid replication of transmission and thereby conserve wireless bandwidth, it is necessary that the new live node begin transmission from the frame/packet (within the file), where the previous gateway ceased transmission. This information pertaining to fractional file transfer is sent from one GW to the next through the out-of-band Optical Supervisory Channel (OSC)/control channel. Data transmitted by a GW through the WiMax channel is collected by the AP in the train. In this way, RC is provisioned through our integrated (optical + wireless) mechanism.

The above discussion also highlights the need for a protocol that tightly binds the users in the fast moving train that communicate through a WiFi network with AP/SS on the train, which in turn communicate through a series of gateways, each hosted on a light-trail capable node, with the light-trail itself supporting dynamic bandwidth provisioning and optical multicasting that is necessary for fast hand off for seamless data transfer.

![Cross-layer node architecture supporting a WiMax BS and light-trail based optical network. Note that the 1x2 WSS conserves power and cost by processing only select WDM channels at a site.](image)

**Fig. 5.** Cross-layer node architecture supporting a WiMax BS and light-trail based optical network. Note that the 1x2 WSS conserves power and cost by processing only select WDM channels at a site.

### III. Node (Gateway) Architecture

In this section we describe the node (GW) architecture that supports integration of wireless (WiMax) and optical (light-trail) networks for providing bandwidth to a moving train.
Shown in Fig. 2 is the architecture of a GW node. A wireless gateway is connected to an optical light-trail infrastructure through a layer-2 switch and supporting electronic buffers (trailponder). The wireless gateway and the light-trail infrastructure are assumed to function independently with the light-trail network control channel binding the two technologies together to function as a single entity. The binding mechanism is done via the protocol which is described in Sections V and VI.

The light-trail infrastructure is modified from the one shown in [3, 7] to suit cross-medium communication. Select WDM channels (light-trails) are accessible to the node through a light-trail optical retrieval section (LORS) [7,8]. By allowing only a fraction of the WDM channels to be accessible at a node, we enable the remaining channels to pass-through with limited power-loss. To do so, we introduce a sub-system called the Wavelength Selectable Switch (WSS) [9] that allows switching of any combination of channels from the express path (bypassing the node altogether) to the LORS. The LORS consists of two Arrayed Wave-Guides (AWGs) which de-multiplex and subsequently multiplex composite signal. Each constituent wavelength that is de-multiplexed is fed to a series of two passive optical couplers in 1x2 and 2x1 configurations which are defined as the drop coupler and the add coupler. The two couplers are separated by an ON/OFF optical switch as shown in the bubble in Fig. 5. The node accesses those light-trails that are switched into the bubble by the WSS. Typically, a node (GW) will have access to only one light-trail which is used for duplex communication (time-shared).

The dropped signal from the first coupler in the LORS is fed to an electronic buffer contained in a receive trailponder. Likewise, data arriving from the train through the WiMax channel is collected in a buffer in the transmit trailponder and subsequently sent into the light-trail through the (add) coupler. The trailponder [16] is a duplex interface device that enables communication between client side network equipment (WiMax BS in our case) and network-side light-trails. To do so, the trailponder consists of an electronic buffer in either direction and associated burst-mode transmitter and receiver for fast access to the light-trail. The burst-mode function of the TX and RX allows efficient sharing of the light-trail bandwidth amongst nodes by enabling fast provisioning (set up and tear down) of the connections.

Control Channel Processing Unit (CCPU): the OOB control channel is optically dropped and electronically processed at every node in the light-trail. This OEO function makes the control channel synchronous with respect to every node. Control packets are encapsulated within the control channel which is typically at 155 Mb/s and is standardized by the ITU as the Optical Supervisory Channel (OSC).

Type of control packets include buffer occupancy levels, fractional connection transmittance level (percentage of connection transmitted by a given gateway), and provisioning of the wireless gateway when a train arrives (or leaves).

IV. IP ROUTING WITH CONTROLLED OPTICAL MULTICASTING

In this subsection, we describe how the IP layer reacts to the moving train

When a train passes over a router, it registers itself at the router (which is at the convener node of a light-trail). The router advertises to the rest of the core network that the train is in its service domain. To support a large number of IP addresses we use Network Address Translation (NAT) at the AP.

Consider Fig. 6 in which an end-user in the train desires to communicate with a host in the core network. When the train crosses station 1 and moves towards station 2, the router at station 1 advertises the train to be in its range (first hop path). Correspondingly, the routing advertisements for the train, flow along the direction of the red lines (to the core network) and the data packets sent by a host in the core network flow along the direction of the blue lines (as shown in Fig. 7). It is here assumed that the train by itself is an edge router, and the router at station 1 is simply advertising a shortest route (of one hop) to this edge router.

In the next figure (Fig. 7), the train has moved to station 2, where it is assumed that a light-trail is terminated and a new light-trail begins (the terminating/end-node for the
previous light-trail is the convener node for the new light-trail. It is also assumed that between the previous and the next light-trail there is an IP router using the connection configuration as shown in Fig. 7. The train now registers itself with this IP-router at station 2. The router at station 2 begins to advertise the train to be in its one-hop range. The routing advertisements for the train flow along the direction of the red line in Fig. 7 and the data packets sent by a host in the core network follow the blue lines.

When the train registers at station 2, router 1 stops route advertisements, while router 2 starts route advertisements of the train being in its one-hop range. Router 1 is intimated of the new association (between the train and router 2) through the out-of-band control channel that connects routers 1 and 2. Data not transmitted by router 1 to the train, is then sent to router 2. The flow of data between router 1 and router 2 happens due to optical multicasting and this is shown in Fig. 8.

![Fig. 8. Populating buffers across interconnected light-trails.](image)

### V. Principles of Integrated Protocol Design

In this section we define the key principles of a protocol that integrates the optical and wireless layers. Consider a train on a track with our proposed (optical + wireless) protocol. Along the track there are gateways at fixed intervals. Each gateway has the architecture described in Section III. It supports light-trails with access trailponders, and also supports WiMax communication by connecting the trailpounder (input/output) to the WiMax BS feeders.

In particular, the protocol implements the following key tasks:
1. Management of hand-off leading to the concept of fast hand-off by using the dual property of optical multicasting and dynamic provisioning.
2. Signaling between gateways to enable seamless and efficient connection provisioning.
3. Setup and tear-down of optical connections between IP routers (at convener node/end-node) and the gateway.
4. Traffic engineering of connection data amongst GWs to provision real-time and data-centric services, thereby facilitating seamless communication and from the train as it moves along the track.

In the next two subsections we described how this protocol functions in detail. Note that the directions of optical signal propagation and train movement need not necessarily be the same.

### V. A. WiFi Protocol Functioning In The Train

When a user in a train sends a packet it does so in a WiFi network and this is the first source of delay. In our model, the access point in the train is assumed to use the Point Coordination Function (PCF) to communicate with the users inside the train. PCF enables good performance at high loads, as desired in a train with a large number of active users. The PCF access method is used in an infrastructure-mode whereby an AP (access point) is able to centrally control user access into the shared wireless medium. To do so, the AP polls users in a time-duration called contention-free-period (CFP). Users are then allocated slots by the AP on the basis of the polling scheme. Time is assumed to be in form of successive superframes, and each superframe is further composed of the CFP and a Contention Period (CP). Transmission in the CFP is the result of the polling mechanism initiated by the AP while transmission in the CP is assumed to be a Distributed Coordination Function (DCF). The central control provided by the AP enables a time-bounded network access to the end-users.

#### V. B. Protocol design: frequency allocation in WiMax channel

In this section we will discuss how the WiMax protocol functions in the light-train system. On account of the fast hand-off and associated optical layer dynamic provisioning/optical multicasting aids, the WiMax protocol is closely tied to the optical/physical infrastructure, in the sense that, the protocol is adapted to suit the light-train mode of operation. In particular two aspects need consideration: (1) WiMax frequency allocation and (2) WiMax hand-off. The first aspect will now be considered, while the second aspect of hand-off would be based on the frequency allocation in WiMax.

We assume that $f_{\text{WiMax}}$ be the set of OFDM channels available for use in the WiMax spectrum for providing communication between the GW (i.e. WiMax BS) and the train AP (WiMax SS). In typical wireless deployments, we would assume a cellular pattern with Base Stations and antennas launching wireless signal into cells, supported by a frequency allocation pattern that allows efficient reuse of frequencies by maintaining diversity. However, in the case of light-trains the frequency allocation differs significantly from regular cellular/WiMax networks. The difference in allocation of frequencies is due to the following reasons:

1. On a single track, two moving trains are separated by a minimum distance $d_{\text{min}}$ that is necessary for avoiding collision at some minimum cruising speed. Hence, if the cell width $C_W$ is greater than the train length (which is assumed to be true in our case), then it implies, to have non-colliding trains the relation $d_{\text{train}} > 2C_W$ must be valid, and hence there is no possibility of two trains being in adjacent cells as shown in Fig. 9. For example if the train cruising velocity is 200 Kmph and the deceleration rate is $.5 \text{ m/s}^2$ [20] then the distance required to decelerate including reaction time of the crew involved is close to 2 km which is typically greater than two cell widths in our model. Hence, we assume that two trains...
cruising in the same direction on the same track would not be in adjacent cells.

2. Under the assumption that (1) is valid, this means that the entire frequency band is reused in the adjacent cell as long as another train does not come in this cell’s range on an opposite/another track.

Fig. 9. Frequency allocation and its relation to cell-width (inter-GW distance), minimum distance to avoid collision and train size.

3. For the case when two trains cross each other in opposite tracks, we assume that through the network management system we are able to isolate the cell that would be live and contain both the trains. This live cell with two trains in its range is called a hyperlive cell. When a cell is hyperlive, the OFDM channels are divided based on FDM and all odd channels are allocated to the train moving in one direction while all even channels are allocated to the train moving in the opposite direction

Fig. 10a: Sync.

Fig. 10b: Ack.

Fig. 10c: Break

4. For the case when multiple \(Q\) trains are within the range of a single cell, then, the allocation of OFDM channels is done as per (3) except that the set of OFDM channels are now divided into \(Q\) disjoint subsets, one for each train. This situation is likely to happen at train stations.

Hand-off in WiMax is based on the principle of break before make and is assisted by light-trail properties. WiMax hand-off is done through the following steps:

(1) When a train enters the provisioning margin of a cell through which it has traversed, it indicates so to the GW through the UL Map of the WiMax uplink frame. The train gets this indication through a combination of distance traveled (since WiMax GWs are pre-allocated and static, thereby enabling the GW to tell the train its geographic range) as well as a power threshold. Once the train enters the provisioning margin it knows that it should now be invoking hand-off procedures.

(2) This indication through the UL map triggers a series of sync steps at the WiMax GW. The live WiMax GW now has to inform to the next GW (which is dormant) about the arrival of the train in its range and then has to sync with the buffer at the next dormant GW so that there is no redundancy in transmitted data (into the wireless channel). This step is pictorially represented in Fig. 10a.

(3) Sync between two adjacent GWs involves the live GW informing the adjacent dormant GW of the packet numbers that are being sent. This is done through the OOB control channel. In light-trails we have assumed that layer 2 frames are encoded with VLAN tags [16], these tags are useful in determining packet numbers. The dormant GW receives the same packets as the live GW through optical multicasting property of the light-trail – though it does not transmit the received packets into the wireless medium. The dormant GW then upon receiving the packet number information from the live GW sends an ACK-HAND-OFF frame. This ACK-HAND-OFF frame tells the live GW that the dormant GW has discarded all packets prior to the last packet number sent by the live GW. The live GW then sends (after some duration of time that corresponds to the end of a WiMax cycle) a final BREAK packet to the dormant GW and stops transmitting data into the wireless domain (as shown in Fig. 10b). By waiting for the duration of WiMax cycle to end, the live GW ensures that the train does not transmit any packets in the downlink during hand-off. The BREAK packet contains the packet number of the last packet that was transmitted by the live GW before it became dead. Once the dormant GW receives the BREAK packet it notes the last transmitted packet number and begins transmitting the packets in its buffer by setting its pointer to the last packet sent value (which it received from its adjacent/previous GW). The dormant GW has hence become a live GW, and hand-off has occurred (as shown in Fig. 10c).

(4) Note that in this hand-off the mobile train plays only a cursory role. It need not change frequency of reception/transmission. The used frequencies change only when the adjacent cell is a hyperlive cell. The train only triggers to the GW that it has reached the PM by traversing a distance corresponding to cell width and/or by noting that the power received value decreases below a certain threshold. It is possible to also have a differential power
algorithm whereby the adjacent (dormant) GW periodically (and hence conserving energy) transmits on a pilot OFDM frequency thus informing the train when the differential power level has changed.

(5) The delay in the WiMax hand-off i.e. the time of inactivity when no data is transmitted (by either of the two GWs or train) is the difference in time since the BREAK packet is sent by the live GW and the transmission by the dormant GW (thus making it a live GW). This delay is a function of control channel speed and distance between the two GWs (processing time, propagation delay). For cells that are up to 1.5 km in length, the delay is of the order 10 microseconds. Fig. 11 denotes the entire WiMax hand-off procedure using the optical layer for hand-off assistance.

![Flowchart: WiMax Hand-off](image)

**V.C. Light-trail Protocol Design**

In this section we describe the protocol that enables connection and light-trail setup and tear-down, taking into consideration the overlaid wireless network as well as the moving train. The light-trail protocol (for bandwidth provisioning) resides within the control channel of the light-trail.

This protocol works as follows: for every light-trail, the control channel is assumed to be synchronized with respect to each node. This assumption is valid since the control channel is optically dropped and electronically processed at every node in the light-trail; this OEO function facilitates synchronization amongst nodes in the light-trail. At the data layer, i.e. within the light-trail itself, we assume to have large duration (1-5 ms) time-slots (data-time-slots) for connection provisioning. Two adjacent time-slots are separated by a guard-band of about 10 ns that is necessary for physical establishment of a connection in a light-trail (resetting the receiver bias within a trailponder to enable burst-mode operation).

One of the light-trail nodes (typically either the convener or the end-node – collocated with an IP router) acts as an arbiter of bandwidth within the light-trail. This node would receive from each other node (within the light-trail) a bandwidth request in the \( t-1^{st} \) time-slot and then would arbitrate bandwidth to the highest deserving node for the \( t^{th} \) time-slot. The process of requesting bandwidth by nodes and the subsequent allocation (by the arbiter) is done through the out-of-band control channel. Also this process is done ahead in time, i.e. nodes request for bandwidth in the present time-slot and their request (if granted) is fulfilled in the next time-slot. This protocol is a derivative of the two-stage auction algorithm proposed in [19] and uses bids as requests for bandwidth allocation. The protocol uses bids within control packets to communicate between nodes and the arbiter.

**Light-trail Controller:** is a node that is given the responsibility of assigning connections to the light-trail. The controller is ideally situated in proximity of the IP router (i.e. at the convener/end-node).

We define the following control packet types for our proposed protocol:

* **Bid packet sent as packet_values:** these packets are used to inform the light-trail management system of the buffer status in a trailponder at a node. Buffer status is conveyed through a dual of buffer occupancy and service criticality that take into consideration both delay sensitivity and bandwidth intensity that a node would require. The former is an absolute measure of buffer occupancy whereas the latter is a time-out feature that enables latency sensitive services to be provisioned over shared medium light-trails (described in detail in Section VI). Computation of bids (and sending these as packet_value) is a key feature of our protocol. Since the bid in this case reflects the integrated optical and wireless cross-medium protocol, we term these as packet_value to differentiate from pure optical networking auctions shown in [19].

**V.D. Light-train protocol working**

The dynamic provisioning protocol works as follows: Each node in a light-trail sends a bid packet indicating the buffer status in the trailponder at a node to the light-trail controller. The light-trail controller then grants the node with the highest critical buffer status rights to form a connection in the next time-slot. The node could be an intermediate enode (thus forming a FC connection) or could be the IP/MPLS router (thus forming an RC connection). We first state the conventions used and then describe the protocol in operation.
Buffers $\text{Buff}_{GW}$ and $\text{Buff}'_{GW}$ have service differentiation capability, i.e. counters exists whose function is to compute packet statistics based on service differentiation as the packets are queued in the buffer. These counters are able to measure the time elapsed since packets for a particular service entered the buffer. This assumption is based on VLAN tagging of layer-2 frames as in light-trails [16] enabling service differentiation at layer-2 (VLAN-tag).

Let $B_{\text{max}}$ : size of the buffer at a node.

Let $T_{W\text{imax}}$ be the expected duration of a WiMax cycle. $T_{W\text{imax}}$ constitutes the following periods – uplink frame, downlink frame and associated guard-bands.

Let $t_{u}^{\text{max}}$ be the expected downlink time duration allocated to GW $i$ on the WiMax channel for transmission to train $u$.

Let $t_{u}^{\text{a}}$ be the expected uplink time duration allocated for transmission in the WiMax channel at the AP in train $u$ for transmission to GW $i$ in a cycle of duration $T_{W\text{imax}}$.

Then, $t_{u}^{\text{a}} + t_{u}^{\text{max}} \approx T_{W\text{imax}}$ is the WiMax cycle time, neglecting the guard-band between uplink and downlink frames. The expected values of $t_{u}^{\text{a}}$ and $t_{u}^{\text{max}}$ are computed as described in the next section.

**Bandwidth allocation policy:** We will now show how bandwidth (connection provisioning) is allocated within the light-trail.

Let $y_{a}(t)$ be the time elapsed since the first packet of service type $q$ entered the buffer $\text{Buff}_{GW}$ at GW $i$ destined for communication in the light-trail $k$ in the FC direction at time $t$.

Let $\gamma_{a}(t)$ be the time elapsed since the first packet of service type $q$ entered the buffer $\text{Buff}'_{GW}$ at GW $i$ destined for communication in the light-trail $k$ in the RC direction at time $t$.

Packet value computation at a GW $i$ for transmission on light-trail $k$ at time $t$ in FC direction is denoted by:

$$
\text{packet value}_{a}(t) = \max \left( \frac{\text{buffer}_{GW}(t)}{B_{\text{max}}}, \frac{\max(y_{a}(t))}{\max(y_{a}(t)) + \gamma_{a}(t)} \right)
$$

(1)

Where, $\gamma_{a}(t) = \min_{q \in L, h}(\Delta_{q} - y_{aq})$ : service statistics at GW $i$ in FC direction; where service statistics refers to the minimum delay tolerance limit for the buffer $\text{Buff}_{GW}$ at GW $i$ for communication in the light-trail $k$ in the FC direction at time $t$.

Subsequently $\bar{q}'_{i} = \arg \left( \min_{q \in L, h}(\Delta_{q} - y_{aq}) \right)$ denotes the service that corresponds to minimum tolerance value in the buffer at node $i$ in FC direction.

Let $\bar{q}_{i} = \arg \left( \min_{q \in L, h}(\Delta_{q} - y_{aq}) \right)$ be the service that corresponds to the tolerance value in the buffer at node $i$ in RC direction.

Let $\gamma_{i}(t) = \min_{q \in L, h}(\Delta_{q} - y_{aq})$ be the service statistics at node $i$ in RC direction for the buffer $\text{Buff}'_{GW}$; i.e. $\gamma_{i}(t)$.
Buffer status computation at GW $i$ (for packets received on light-trail $k$) for transmission on the WiMax channel at time $t$ in the RC direction is denoted by:

$$\text{packet\_value}_i(t) = \max \left[ \frac{\text{Buff}_{GW}^i(t) \cdot \max(y_{\text{delay}}(t))}{B_{\text{max}}} \cdot \max(y_{\text{delay}}(t)) + \gamma_i(t) \right]$$

(2)

In [19] we have observed that using a maximization of buffer utilization and service statistics as shown in (1), (2) i.e., packet value, leads to a proportionally fair [21] allocation of bandwidth resources. The explanation is that $\text{Buff}_{GW}^i(t)$ value is mapped to a combination of concave and sigmoidal function that ultimately leads to proportional fairness.

Dynamic provisioning protocol in a light-train

Stage 1:
- At every node in the light-train except IP router:
  - compute packet_value for each node
  - send packet_value to controller
- At IP router connected to convener of the light-trail $k$:
  - for every buffer
    - compute packet_value
    - send packet_value to controller (through control channel)
- At controller:
  - receive all packet_value
  - compute max(packet_value)
  - compute argmax(packet_value) suc(t)
  - send suc(t) information to all nodes

Stage 2:
- At all nodes in light-trail $k$ and at IP router at convener node:
  - if suc(t)=node index
    - wait till end of current time-slot
    - transmit for one time-slot duration or till buffer(t)=0
  - else
    - idle
  - endif

**Algorithm 1:** Communication between GW and IP Router (for both FC and RC)

V. D. Reverse Communication: A special case of connection provisioning:

The IP router sends data to the users in the train in reverse communication direction. The data sent depends on the user destination address and whether the train is in the domain of this IP router, i.e., the router supports a light-trail such that a GW on the light-trail contains the train in its geographic range. To send the data from the IP router to the GW, a connection is set up on the light-trail, established between the IP router and the GW that contains the train. This connection is also multicast to all the GWs downstream. Hence the GW that contains the train (live) and the GWs at which the train is expected to arrive (dormant) are privy to the information transmitted on the connection. The information is available to all GWs downstream and in the direction of the movement of the train. It does not matter if the train and the data flow (within the light-trail) are in opposite directions. The gateway or router in whose range the train resides, receives the data (on the connection) and attempts to send this to the AP (in the train) through the WiMax channel. Data that cannot be sent through the wireless channel because the train has left the range of a live GW is sent by the next (or series of next) GWs. Data received by the AP is then transmitted to the end-users over the PCF based WiFi connection.

Shown in algorithm 1 is the pseudo code for bandwidth assignment within the light-trail at both the GWs and at the IP router in both directions of communication, i.e., FC and RC.

VI. DELAY ANALYSIS IN THE LIGHT-TRAIN SYSTEM

The light-train system as shown earlier is an integrated optical-wireless communication methodology that provides access to fast-moving users in metro trains. The integrated solution consists of wireless access, wireless interconnection and optical infrastructure thereby requiring a unified approach to bandwidth provisioning. In terms of implementation, the variation in terms of provisioning methodologies seen between: the end-users and the AP (WiFi); the AP and the GW (WiMax); and between the GW and router (nodes of the light-trail) act as the three principle sources of delay, in the FC and RC directions.

We now compute each of these three delays i.e., at WiFi, within WiMax and accessing the light-trail and then present a unified delay model as a function of network load. We further extend this model to the RC case as well. The final delay is given by the following set of equations:

The delay experienced by a packet in the FC direction is given by:

$$\delta_{\text{final-FC}} = \delta_{\text{WiFi-FC}} + \delta_{\text{WiMax-FC}} + \delta_{\text{LT-FC}}$$

(3)

The delay experienced by a packet in the RC direction is given by:

$$\delta_{\text{final-RC}} = \delta_{\text{WiFi-RC}} + \delta_{\text{WiMax-RC}} + \delta_{\text{LT-RC}}$$

(4)

And average delay that a packet experiences through the network is:

$$\delta_{\text{final}} = \left[ \frac{\delta_{\text{final-FC}} + \delta_{\text{final-RC}}}{2} \right]$$

(5)

Where, $\delta_{\text{WiFi-FC}}$ is the delay in FC through WiFi; $\delta_{\text{WiFi-RC}}$ is the delay in RC through WiFi; $\delta_{\text{WiMax-FC}}$ is the delay in the FC through WiMax; $\delta_{\text{WiMax-RC}}$ is the corresponding delay in the RC through WiMax and finally, $\delta_{\text{LT-FC}}$ and $\delta_{\text{LT-RC}}$ are the delay in FC through the light-trail, while $\delta_{\text{LT-RC}}$ is the delay in the RC through the light-trail. We now compute each of the above six delay functions.

VI. A. WiFi Delay

To compute the delay we assume that there are $W(u)$ users in train $u$ that use the PCF mode for communication. The packet inter-arrival times at each user are assumed to be exponentially distributed with rate $\lambda$. Let the duration of a PCF mode superframe be denoted by $T_{\text{WiFi}}^u$ and the expected length of a packet at each user is $L$. The utilization of each
node is denoted by $\rho_{WiFi}$. We adapt from the model presented in [13] to compute the average queuing delay experienced by an arbitrary packet arriving at the $m^{th}$ user in the train $u$.

As shown in [13], since each polled user transmits exactly once in every superframe, the service rate of each user is $\mu_{WiFi} = 1/T_{WiFi}^S$, and the net-utilization is given by $\rho_{WiFi} = \lambda / \mu_{WiFi} = \lambda T_{WiFi}^S$. From the above, the delay experienced by a packet that passes through the WiFi network sent by end-user $m$ in the train $u$ is given by:

$$D_{WiFi}^m = \frac{1}{1 - \lambda T_{WiFi}^S} \left[ \frac{T_{WiFi}^S}{2} \left( \rho_{WiFi} L (2m - 1)(1 - \rho_{WiFi}) + L \right)(1 - \rho_{WiFi}) \right]$$

Let $\lambda^n_u$ be the departure rate at the end-user $m$ in train $u$. This implies that at user $m$, packets arrive (from client applications at a rate $\lambda^n_u$ and are sent out at an effective rate $\hat{\lambda}_m^n$, where the difference between $\lambda_n^u$ and $\hat{\lambda}_m^n$ is the result of the PCF bandwidth allocation strategy (due to control overhead). The net arrival rate at the AP ($\hat{\lambda}_m^n$) is given by:

$$\hat{\lambda}_m^n = \sum_{w \in W^m(u)} \lambda_w^n$$

Where $W^m(u)$ represents the set of users in train $u$. The departure rate at the end-users, in steady state, can be computed in terms of the arrival rate ($\hat{\lambda}_m^n$) and the average per-packet delay ($D_m^*$), that packets from user $m$ experience due to PCF allocation strategy. In steady state, the number of packets ($N_m^n$) that are buffered at the user $m$ is given by Little’s formula:

$$N_m^n = \hat{\lambda}_m^n D_m^*$$

Hence, we have:

$$\lambda_m^n D_m^* = \lambda_m^n T_{WiFi}^S - \lambda_m^n T_{WiFi}^S = N_m^n$$

$$\therefore \lambda_m^n = \lambda_m^n \left( 1 - D_m^* / T_{WiFi}^S \right)$$

Equation (9) gives the effective arrival rate at the AP due to user $m$ in train $u$.

**VI. B. WiMax Delay**

We now compute the average delay experienced by a packet over the WiMAX channel that connects the train to the gateway. The MAC frame structure consists of an uplink and a downlink sub-frame, whose durations are controlled depending on the provisioned services. The BS controls uplink and downlink bandwidth allocation. A SS requests for transmission opportunities on the uplink channel. The BS collects these requests and grants permissions to the SSs based on their service agreements. Allocation in WiMax is done through Downlink Map (DL Map) and Uplink Map (UL Map) that carries information of future allocations i.e. sub-frame assignment, and duration.

---

**Algorithm 2: Communication between AP and GW (both FC and RC) using WiMax communication**

Our model is similar to the model proposed in [14] with the primary exception that it is designed for communication with high-speed voluminous moving users. The characteristic of the model implies a single BS located at the gateway and a single SS located in the train. The BS polls to the SS and based on this polling allocates bandwidth in the UL-map (indicating size of uplink transmission). The BS (gateway) hence allocates bandwidth to the SS by sharing the entire bandwidth between itself (downlink) and the SS (uplink).

To compute the delay experienced by a packet in FC through the WiMax channel, we consider scenarios that are based on the time of arrival of a packet and state of the buffer at the AP. Let us define $t_{UL}$ to be the expected uplink time that train $u$ receives through the WiMax channel when moving through the GW $i$. Let $\mu$ be the service rate at the AP and $N_{buffer} = t_{UL} / \mu$ be the maximum permissible buffer occupancy (in terms of number of packets) that can be scheduled over the WiMax channel in the uplink (FC).

The communication through the WiMax channel consists of the two periods denoted by $t_{UL}$ and $t_{DL}$ for uplink and downlink respectively.

---

**At the GW $i$ (in RC)**

If train $u$ is in Range

1. In each slot of length $T_{WiMax}$
   - compute $j_{GW}^u$ (for $i = FC$ and $i = RC$)
   - send REQ to get $j_{AP}^u$ from the AP
   - compute $j_{UL}^u = j_{GW}^u - j_{AP}^u$ and $j_{DL}^u = T_{WiMax} - j_{UL}^u$
   - send $j_{UL}^u$ and $j_{DL}^u$ to AP (in UL, DL map)
   - receive data in $i_{UL}^u$ (UL)
   - transmit for the duration of $i_{UL}^u$
   - receive for the duration of $i_{DL}^u$
   - search for another train registers

**At the AP in train $u$ (in FC)**

If $GW$ is in Range

1. In each slot of length $T_{WiMax}$
   - compute $\lambda_{AP}^u$
   - send $\lambda_{AP}^u$ to GW as response to REQUEST
   - get $i_{UL}^u$ and $i_{DL}^u$ from $GW$
   - transmit for the time duration of $i_{UL}^u$
   - receive for the time duration of $i_{DL}^u$

---

**Algorithm 2: Communication between AP and GW (both FC and RC) using WiMax communication**


(FC) and downlink (RC) communication respectively between GW $i$ and train $u$. We also assume that the time a train spends communicating to a GW is denoted by $T_{WIMax}^{(u)} = T_{WIMax}^{u} = T_{WIMax}$ whereby we relax the constraint of velocity dependence (and hence Doppler effect), assuming measurements are made at a cruise velocity of 200 kmph. Then, the time the train spends communicating to a GW is denoted by $t_{i}^{u}$.

We also assume that the time a train spend communicating to a GW is denoted by $t_{i}^{u}$. We also assume that $\lambda_{GW}^{u}$ is the arrival rate at the AP (from the users in the train) and $\lambda_{GW}^{u}$ is the arrival rate at the gateway (from the light-trail).

For bandwidth allocation, the transmission time is divided into small slots and the AP as well as the GW are both given sub-slots to transmit within each slot (frames) proportional to their respective arrival rates.

We now compute the expected values of $t_{i_{UL}}^{u}$ and $t_{i_{DL}}^{u}$ that are critical in computation of the delay through the WiMax channel. The pdfs of $t_{i_{UL}}^{u}$ and $t_{i_{DL}}^{u}$ are computed as follows:

Assuming that the arrival processes $\lambda_{GW}^{u}$ and $\lambda_{AP}^{u}$ are independent at the train ($i$) and the gateway ($u$), the cycle time, $T_{WIMax}^{i} \approx T_{WIMax}^{u}$, can be decomposed into the following two sub-slots:

$$t_{i_{UL}}^{u} = \frac{1}{\lambda_{GW}^{u} + \lambda_{AP}^{u}} T_{WIMax}^{u} \quad \text{and} \quad t_{i_{DL}}^{u} = \frac{1}{\lambda_{GW}^{u} + \lambda_{AP}^{u}} T_{WIMax}^{u}$$

In (10) we divide the cycle time $T_{WIMax}^{u}$ proportional to the steady-state arrival rates $\lambda_{GW}^{u}$ and $\lambda_{AP}^{u}$. Their pdfs are computed as follows:

$$t_{i_{UL}}^{u} = \frac{1}{1 + \frac{\lambda_{GW}^{u}}{\lambda_{AP}^{u}}} T_{WIMax}^{u} \quad \text{and} \quad t_{i_{DL}}^{u} = \frac{1}{1 + \frac{\lambda_{GW}^{u}}{\lambda_{AP}^{u}}} T_{WIMax}^{u}$$

Let us now define $\lambda_{i}^{u} = \frac{\lambda_{GW}^{u}}{\lambda_{AP}^{u}}$ be the quotient of two independent random variables.

Let $g(\lambda_{GW}^{u})$ denote the pdf of $\lambda_{GW}^{u}$ and $h(\lambda_{AP}^{u})$ denote the pdf of $\lambda_{AP}^{u}$. Then the pdf of $\lambda_{i}^{u}$ is $f(\lambda_{i}^{u})$ and given by:

$$f(\lambda_{i}^{u}) = \int_{v=0}^{\infty} g(v \lambda_{i}^{u}) h(v) \, dv \cdot$$

From which we compute the expectation of $t_{i_{UL}}^{u}$ as:

$$E[t_{i_{UL}}^{u}] = \int_{0}^{T_{WIMax}} t_{i_{UL}}^{u} y(t_{i_{UL}}^{u} = t) \, dt$$

where $y(t_{i_{UL}}^{u} = t)$ is the pdf of $t_{i_{UL}}^{u}$ and can be computed from $f(\lambda_{i}^{u})$.

Our desire is to compute the delay experienced by packets that move in the FC as well as the delay experienced by packets moving in the RC directions assuming that the WiMax system has a net service rate of $\mu_{WIMax}$ packets per seconds. The communication cycle through WiMax is as shown in Fig. 13. To compute the average delay that a packet experiences in FC/RC direction through the WiMax channel we abstract three scenarios that a packet can experience and are described next. We assume that a packet arrives say at the AP (from the end-user) at time $t_{arr} \in [0, T_{WIMax}]$ and gets transmitted at $t_{dep} \in [0, T_{WIMax} + t_{UL}]$ in order to avoid an infinite queue system.
The scenarios below describe delay computation in the FC direction and the RC is just an extension of the FC delay which is shown subsequently.

**Scenario 1:** In this scenario the packet arrives while the AP is being serviced (through \( t_{iUL}^a \)) and departs in the same interval (uplink frame) as shown in Fig. 14a scenario 1. The condition is denoted by: \( t_{iUL} \in \left[0, t_{iUL}^a\right] \) and \( t_{dep} \in \left[0, t_{iUL}^a\right] \).

The average delay experienced by a packet in this case is: \( t_{iUL}^a / 2 \). The probability of occurrence of this scenario is given by the joint probability that the arrival occurs in the duration of the uplink frame and the departure also occurs within the same duration. This is given by:

\[
p_1 = p(t_{iUL} \in \left[0, t_{iUL}^a\right], t_{dep} \in \left[0, t_{iUL}^a\right])
\]

(13)

The two probabilities are computed as:

\[
p(t_{iUL} \in \left[0, t_{iUL}^a\right]) = \frac{t_{iUL}^a}{T_{WiMax}}
\]

(14)

\[
p(t_{dep} \in \left[0, t_{iUL}^a\right]) = p(Buff_{iUL}^a < N_{flash})
\]

(15)

Where, \( Buff_{iUL}^a \) as noted before denotes the occupancy of the buffer at the AP of train \( u \) while it passes through gateway \( i \) and \( N_{flash} \) denotes the maximum number of packets possible to be transmitted through the WiMax channel, with service rate \( \theta_{WiMax} \).

While the first probability \( p(t_{iUL} \in \left[0, t_{iUL}^a\right]) \) can be computed by examining the expected value of \( t_{iUL}^a \), to compute the second probability, we assume that at the AP, the buffer forms an M/M/1/c queue. Let us further assume that \( N_{flash} < c \) and hence we can compute the probability of the occupancy of the buffer as:

\[
p(Buff_{iUL}^a < N_{flash}) = \sum_{r=0}^{N_{flash}-1} \left( \frac{\lambda_{iUL}^a}{\mu_{WiMax}} \right)^r \left( 1 - \frac{\lambda_{iUL}^a}{\mu_{WiMax}} \right)
\]

(16)

\[
= \sum_{r=0}^{N_{flash}-1} \left( \rho_{iUL}^a \right)^r \left( 1 - \rho_{iUL}^a \right)
\]

Hence,

\[
p(Buff_{iUL}^a < N_{flash}) = 1 - \left( \rho_{iUL}^a \right)^{N_{flash}}
\]

(17)

Therefore,

\[
p_1 = \left( 1 - \left( \rho_{iUL}^a \right)^{N_{flash}} \right) \frac{t_{iUL}^a}{T_{WiMax}}
\]

(18)

**Scenario 2:** The second case denotes arrival of a packet when an uplink frame is being transmitted and the corresponding departure occurs during the next uplink frame, and this is shown in Fig. 14a scenario 1. In this case the packet has to wait for the duration of the current uplink frame (to complete transmission), as well as the next downlink frame, and then it is transmitted during the next (subsequent) uplink frame.

This condition is stated as: \( t_{iUL} \in \left[0, t_{iUL}^a\right] \) and \( t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right] \).

The average delay experienced by a packet in this second scenario is \( T_{WiMax} \). The probability of occurrence of this scenario is:

\[
p_2 = p(t_{iUL} \in \left[0, t_{iUL}^a\right], t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right])
\]

(19)

The two independent probabilities are computed as:

\[
p(t_{iUL} \in \left[0, t_{iUL}^a\right]) = \frac{t_{iUL}^a}{T_{WiMax}}
\]

(20)

\[
p(t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right]) = p(Buff_{iUL}^a \geq N_{flash})
\]

(21)

Simplifying and using result (17) we get:

\[
p_2 = \frac{t_{iUL}^a}{T_{WiMax}} \left( \rho_{iUL}^a \right)^{N_{flash}}
\]

(22)

**Scenario 3:** The last scenario represents when a packet arrives during the downlink frame and is transmitted in the next uplink frame as shown in Fig. 14a scenario 3. This scenario is stated as:

\( t_{iUL} \in \left[t_{iUL}^a, T_{WiMax}\right] \) and \( t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right] \)

The average delay experienced by a packet in this scenario is given by:

\[ T_{WiMax} - t_{iUL}^a / 2 = T_{WiMax} / 2 \] .

(23)

The probability of occurrence of this scenario is given by:

\[
p_3 = p(t_{iUL} \in \left[t_{iUL}^a, T_{WiMax}\right], t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right])
\]

(24)

The two independent probabilities are computed as:

\[
p(t_{iUL} \in \left[t_{iUL}^a, T_{WiMax}\right]) = 1 - \frac{t_{iUL}^a}{T_{WiMax}}
\]

(25)

\[
p(t_{dep} \in \left[T_{WiMax}, T_{WiMax} + t_{iUL}^a\right]) = p(Buff_{iUL}^a < N_{flash})
\]

Hence,

\[
p_3 = \left( 1 - \frac{t_{iUL}^a}{T_{WiMax}} \right) \left( 1 - \left( \rho_{iUL}^a \right)^{N_{flash}} \right)
\]

(26)

Therefore by combining (13)-(26), the expected delay a packet experiences through the WiMax channel in the FC direction is given by:

\[
\delta_{WiMax}^{FC}(i,u) = p_1 \frac{t_{iUL}^a}{2} + p_2 \left( \frac{T_{WiMax} - t_{iUL}^a}{2} \right) + p_3 \frac{T_{WiMax}}{2}
\]

(27)

Substituting and solving:

\[
\delta_{WiMax}^{FC}(i,u) = \frac{t_{iUL}^a}{2} + \frac{T_{WiMax} - t_{iUL}^a}{2} + \frac{t_{iUL}^a}{2} \frac{t_{iUL}^a}{2}
\]

(28)

Since the scenarios for RC are identical (as can be seen from Fig. 14b), the expected delay a packet experiences through the WiMax channel (in the RC direction) is given by:

\[
\delta_{WiMax}^{RC}(i,u) = \frac{t_{iUL}^a}{2} + \frac{T_{WiMax} - t_{iUL}^a}{2} + \frac{t_{iUL}^a}{2} \frac{t_{iUL}^a}{2}
\]

(29)

**VI. C. Light-trail Delay**

The final aspect of delay that a packet experiences through the light-train system is at the optical layer – i.e. through the light-trail. We will hence analyze the delay through the light-trail for both FC and RC directions.

Let us assume a light-trail \( k \) that has \( n(k) \) nodes and is supported by two IP-routers at each end (as shown in Fig. 1).
The light-trail is time-shared by its \( n(k) \) constituent nodes for both FC and RC. Time-sharing is done by time-slotsting the light-trail as described in [19]. Since multiple nodes time-share the optical wavelength bus, we require a method for arbitration which was described in Section V. Arbitration of bandwidth (time-slots) between nodes of a light-trail is done as follows:

1. An arbitrary node is selected in the light-trail as the controller node.
2. In every time-slot, all the nodes send their packet_value to the controller node.
3. The controller node responds back to the proposing nodes with an ACK or a NACK depending on the proposing node’s packet_value with respect to that of the other nodes. The ACKing and NACKing is done in the duration of the same time-slot (in which the packet_value was sent).
4. The node that receives an ACK transmits its data through the duration of the next time-slot.

We now discuss how to compute delay experienced by a packet waiting to be transmitted over a light-trail \( k \) with \( n(k) \) nodes. The transmission rate of a light-trail is 1Gbps.

Multiple flows may be provisioned at a node (with different destination) in every light-trail. The packet_value is computed over all the flows provisioned at a single node.

**Bandwidth assignment:** The largest packet_value that the controller receives is denoted by:

\[
mpacket_value(t) = \max_{\gamma \in \text{nodes}} (\text{packet}_value(t))
\]

While the node that gets rights to form the next connection is denoted by:

\[
suc(t) = \arg \max_{\gamma \in \text{nodes}} (\text{packet}_value(t))
\]

The winning node (suc(t)) would transmit (establish a connection) in the next \((t+1)th\) time-slot.

However, it may happen that a flow at a GW may not be serviced within its permissible delay limit or a buffer may reach an overflow condition. Such a flow or such a buffer implies an event called recourse that requires the algorithm to re-evaluate the flow and provision it through another light-trail (wavelength) or create a new light-trail. Recourse occurs when:

\[
t_{\text{up}} < \gamma_{\text{d}}(t) < (t_{\text{up}} + T_g) \quad \text{or} \quad \left[ 1 - \frac{\text{Buffer}_{\text{in}}(t)}{B_{\text{max}}}(t_{\text{up}}) \right] > B_{\text{d}}(t) > \left[ 1 - \frac{\text{Buffer}_{\text{in}}(t)}{B_{\text{max}}}(t_{\text{up}} + T_g) \right]
\]

This condition requires new light-trails to be set up and is dealt with in [19].

To compute the delay we are interested in computation of the probability that a particular node gets transmission rights in a time-slot at steady state. This probability of success of a node \( i \) in light-trail \( k \) is now computed.

Let \( P_{\text{succ}}^{k, FC}(t) \) be the probability of success of node \( i \) in light-trail \( k \) in the FC direction.

Let \( P_{\text{succ}}^{\text{ing}, RC}(t) \) be the probability of success for the router at the converner of light-trail \( k \) in sending data into the light-trail (i.e. in the RC direction). The superscript ing represents the ingress port for the light-trail \( k \) which is at the IP router.

The delay in the FC direction by an arbitrary node \( i \) in light-trail \( k \) is given by:

\[
\delta_{LT}^{FC} = \frac{T_g}{P_{\text{succ}}^{k, FC}(t)}
\]

In an \( n(k) \)-node light-trail a node \( i \) has to contend with the other \( n(k)-1 \) nodes that also includes the router (at the converner node) for arbitration. Hence the probability that node \( i \) will successfully send data into the light-trail is the probability that the packet_value sent by node \( i \) is greater than the packet_value sent by any other nodes and the IP router interface at the converner node. This condition is denoted by:

\[
\prod_{j=1}^{n(k)} p(\text{packet}_value^{\text{FC}}(t) > \text{packet}_value^{\text{FC}}(t))
\]

The packet_value computation is denoted in [] and we compute the probability that the packet_value sent by node \( i \) is the largest as:

\[
P_{\text{succ}}^{k, FC}(t) = \left( 1 - p \left( \frac{\gamma_{\text{d}}(t)}{\max_{\gamma \in \text{nodes}} (\text{packet}_value(t))} < \frac{\gamma_{\text{d}}(t)}{\max_{\gamma \in \text{nodes}} (\text{packet}_value(t))} \right) \right)
\]

The above equation is simplified in [19] and we state the result duly modified for our case taking into consideration duplex communication over the simplex light-trails (time shared FC and RC) as:

\[
P_{\text{succ}}^{k, FC}(t) = \left( 1 - \sum_{\phi \in \text{nodes}} \delta(\phi) \right) \prod_{j=1}^{n(k)} \left( 1 - \sum_{\phi \in \text{nodes}} \delta(\phi) \right)
\]

where, \( \phi = \frac{\gamma_{\text{d}}(t)}{\max_{\gamma \in \text{nodes}} (\text{packet}_value(t))} \) and \( \phi = \frac{\gamma_{\text{d}}(t)}{\max_{\gamma \in \text{nodes}} (\text{packet}_value(t))} \)

\[
P_{\text{succ}}^{\text{ing}, RC}(t) = \left( 1 - \sum_{\phi \in \text{nodes}} \delta(\phi) \right) \prod_{j=1}^{n(k)} \left( 1 - \sum_{\phi \in \text{nodes}} \delta(\phi) \right)
\]

and

\[
\delta(Q) = \sum_{\phi \in \text{nodes}} p(\gamma_{\text{d}}(t) > \max_{\gamma \in \text{nodes}} (\text{packet}_value(t))) v Q, p(\gamma_{\text{d}}(t) > \max_{\gamma \in \text{nodes}} (\text{packet}_value(t))) = v \cdot v
\]

\[
\delta_{LT}^{FC} = \frac{T_g}{P_{\text{succ}}^{\text{ing}, FC}(t)}
\]
The average delay experienced by a packet in the RC direction is computed in a similar fashion as for the case of FC:

\[
P_{\text{succ}, \text{RC}}^k(t) = \prod_{j=1}^{n(k)} p(\text{packet_value}_{\text{RC}} > \text{packet_value}_{\Phi}(t))
\]

\[
P_{\text{succ}, \text{RC}}^k(t) = \prod_{j=1}^{n(k)} \left[ 1 - p \left( \frac{\gamma_{\text{RC}}}{\max\{y_{\text{RC}}\}} \leq \frac{\gamma(t)}{\max\{y_q(t)\}} \right) \right]
\]

\[
P_{\text{succ}, \text{RC}}^k(t) = \prod_{j=1}^{n(k)} \left( 1 - \sum_{q \neq 0} \delta(\phi(t)) \right) = \prod_{j=1}^{n(k)} \left( 1 - \int_{0}^{t} \delta(\phi(t)) \, dt \right)
\]

Where, \( \phi = \frac{\gamma(t)/\max\{y_q(t)\}}{\gamma_{\text{RC}}/\max\{y_{\text{RC}}(t)\}} \)

The delay in the RC direction is given by:

\[
\delta_{\text{RC}} = \frac{T_e}{P_{\text{succ}, \text{RC}}^k(t)}
\]

VII. RELATED WORK

The concept of providing broadband connectivity to moving users especially fast moving users has been studied in [15], [17], [18], of which the [17] is our own preliminary work.

The approach in [17] was based on basic architecture definitions – using the light-trail node to serve as an element to provide dynamic provisioning and optical multicasting. This work however did not outline the technology used at the wireless layer nor did it analyze the system for delay and utilization.

The work in [15, 18] mentions two approaches – the mobile cell concept in [18] and the moving tunnel concept in [15]. While this fundamental work provides a prelude to the problem as well as outlines two solutions, our work differs from the aforementioned two approaches in terms of defining a technology solution. We present a complete end-to-end optical + wireless solution that spans across the network, data and physical layers using contemporary or available technology. In [15, 18] a radio-over-fiber solution is presented – which does not delve into the specifics in terms of architecture, protocol or working. In contrast, our solution defines the node architecture, protocol as well as how to provision bandwidth from user to the network. The solution in [15, 18] uses switching which is detrimental to providing bandwidth to fast moving users. The requirement of optical switching in [15, 18] means either that hand-off would suffer (due to infancy of optical technology) or that we require futuristic high-speed optical switches. The light-train scheme relies on existing available, mature technologies, and is glued together by an out-of-band protocol designed to provision (without optical switching) as well as facilitate hand-off at the wireless layer. This integration of optical and wireless technologies, enabling a symbiotic relationship is the key differentiator between the light-train solution and other existing solutions.

VII.A. Qualitative argument for Light-trails as opposed to conventional solutions:

In this subsection we outline the differences and advantages of light-trails as opposed to conventional point-to-point circuit technology.

1. The 2-layer light-trail enables dynamic sub-wavelength provisioning of bandwidth by fostering a unique node architecture that supports an optical bus, while using the standard ITU defined OOB control channel to dynamically arbitrate bandwidth within the bus. The dual layered approach allows fast configuration (provisioning) of bandwidth, while also providing optical multicasting.

2. Dynamic provisioning is an essential requirement for fast-hand offs – typically those envisioned for such applications like fast moving trains. The fast hand-off concept stems from two critical requirements: (a) reduction of time allocated for hand-off to maintain seamless and efficient communication under a large ratio of train size to cell-width, and (b) due to the high velocity of the train itself – requiring dynamic provisioning of bandwidth to efficiently utilize the wireless channel (if the time required for hand-off is large, then time lost in provisioning the connection when a train moves from one cell to its adjacent neighbor is also large and hence the efficiency of the system degrades).

3. The light-trail provides optical multicasting support. In conjunction with the dynamic provisioning property, this feature acts as a further enabler for seamless communication. With optical multicasting support, when a train moves from the range of an ingress cell site to the adjacent egress cell site (GW), the data is readily available at the egress GW. This means that there is no requirement for further signaling to set up a new connection between the network core router and the new GW, and this eliminates the need for pre-fetching. In the conventional case, i.e. using an Ethernet network like the one proposed in [15, 18] or using a backbone SONET/SDH network, we would require layer 3 termination [18] and further provisioning of a moving tunnel type concept. The time required would result in loss of bandwidth and hence degrading efficiency of the system.

Our model based on three factors namely, (a) absence of pre-fetching due to optical multicasting (b) dynamic provisioning of bandwidth within the light-trail bus and (c) the presence of an OOB control that allows an egress GW to accurately estimate the starting and ending times of the train within its range (and hence schedule data accordingly), are key to a low-latency high-efficiency and evolutionary approach to integrated optical-wireless design for support of fast moving and bandwidth intensive users.

VIII. SIMULATION AND RESULTS

To demonstrate the working of our protocol for light-trains, we developed a discrete event simulation (DES) model in C#. The topology simulated is based on the European landscape (Fig. 15) with sixteen major cities with distances not assumed to scale. The train contained end-users that supported
applications on their mobile devices (laptops etc.). These applications included voice, data and video (multimedia) services, each of which assumed Ethernet frame generation at layer-2. Ethernet frame arrival at a user followed a Poisson arrival process.

The basic event-size for DES model was 1 millisecond and is the time required by the system to transmit 6 full-size (1500 bytes) Ethernet frames at 70 Mbps over the WiMax channel. Light-trail line-rate was assumed at 1 Gbps. A typical light-trail had between 20 and 25 GWs (with reduced attenuation due to WSS support). Train velocity was pegged 200 km per hour. The DES was based on a C# class library as shown in Fig. 16.

The average distance between two gateways was assumed to be 1.5 km. Each Ethernet frame object belonged to a service class (voice, video and data) that also specified the maximum allowable delay. In the simulation, users boarded the train at different stations along the train routes. Simulation was performed under different values of cumulative network load. Load was computed as the ratio of total number of bits per-second that entered the network to the maximum number of bits that the network could support.

In Fig. 17 we show utilization versus load. Two cases are considered in which the average file size is 100 kb and 200 kb respectively. The load for both the cases is varied from 0.1 to 0.9. We observe that in case 1 as the load varies from 0.1 to 0.9 the utilization varies from 10% to 65% while for case 2 the utilization varies from 10% to 60%. The curves in both the cases increase almost linearly as the load increases and is the order of 2 ms. Average response time is defined as the time required for the system to fetch the first packet in a file after a request has been made.

In both directions of communication the average per packet delay is of the order of 100 ms. We observed that the FC delay is lower than the RC delay (Fig.19). This is explained by the fact that the end-users in the train proactively send data into the core thus occupying a larger percentage of the WiMax transmission slot.

Fig 20 shows the average response time per file requested by the end-user; the average response time increases almost linearly as the load increases and is the order of 2 ms.

Fig. 18 shows the average response time per file requested by the end-user; the average response time increases almost linearly as the load increases and is the order of 2 ms.

Average response time is defined as the time required for the system to fetch the first packet in a file after a request has been made.

0.1 to 0.9. In both directions of communication the average per packet delay is of the order of 100 ms. We observed that the FC delay is lower than the RC delay (Fig.19). This is explained by the fact that the end-users in the train proactively send data into the core thus occupying a larger percentage of the WiMax transmission slot.

Fig 20 shows the average response time per file requested by the end-user; the average response time increases almost linearly as the load increases and is the order of 2 ms. Average response time is defined as the time required for the system to fetch the first packet in a file after a request has been made.
presented to numerically gauge delay as a function of load for perspective. Finally, a sample simulation study is also functional. This protocol is analyzed from a delay medium, detailing message types and hand-off functionalities. To do so, we also propose a protocol that enables hand-off that is absolutely essential in provisioning of this bandwidth to a fast-moving train. The light-trail optical layer aware WiMax system that facilitates provisioning of gateway. The wireless GW supports a point-to-point service on demand to nodes with each node supporting a wireless gateway. The wireless GW supports a point-to-point service aware WiMax system that facilitates provisioning of bandwidth to a fast-moving train. The light-trail optical layer and WiMax wireless layer are conjoined to support ultra-fast hand-off that is absolutely essential in provisioning of this bandwidth. To do so, we also propose a protocol that enables dynamic bandwidth provisioning across the multiple physical mediums, detailing message types and hand-off functionalities. This protocol is analyzed from a delay perspective. Finally, a sample simulation study is also presented to numerically gauge delay as a function of load for different services and also comparison with legacy SONET/SDH networks is shown.

IX. CONCLUSION

In this paper we have proposed an efficient framework to provide bandwidth-on-demand to moving metro trains in a hybrid (integrated) wireless-optical environment called light-trains. In particular, we introduce a new node architecture that provides for cross-medium design between wireless and optical domains. Namely, at the optical layer we use modified light-trail technology that provides bandwidth-on-demand to nodes with each node supporting a wireless gateway. The wireless GW supports a point-to-point service aware WiMax system that facilitates provisioning of bandwidth to a fast-moving train. The light-trail optical layer and WiMax wireless layer are conjoined to support ultra-fast hand-off that is absolutely essential in provisioning of this bandwidth. To do so, we also propose a protocol that enables dynamic bandwidth provisioning across the multiple physical mediums, detailing message types and hand-off functionalities. This protocol is analyzed from a delay perspective. Finally, a sample simulation study is also presented to numerically gauge delay as a function of load for different services and also comparison with legacy SONET/SDH networks is shown.

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