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

(Invited Paper)

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Abstract: Moving trains represent a voluminous mass of users moving at high velocities that require bandwidth (on demand). A new solution is proposed that facilitates dynamic provisioning, good scalability and efficient use of available bandwidth. The proposed solution *(light-trains)* seamlessly integrates optical and wireless networking to provide broadband access to users in moving trains. The solution identifies the set of requirements – such as fast hand-off, low-cost of deployment, mature technology and ability to provide dynamic bandwidth provisioning. A protocol that enables 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 analyzed and 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 medium communications.

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. A significant number of the end-users that make use of bandwidth intensive applications are 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. These 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.

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. Provisioning the underlying physical layer which is typically an optical network taking into cognizance this moving entity poses a new design problem.

The light-train approach combines the wireless and optical layers to create an efficient solution for bandwidth allocation in trains. To do so, the light-train solution uses a novel optical technology used in conjunction with wireless end-user technologies. 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. Our approach has practical assumptions – there is no need to upgrade equipment at the end-users (who continue to use well-disseminated WiFi technology). Equipment is only upgraded at the network side.

This work is an extension of [12] – where we proposed the concept of bandwidth to moving trains. This work further enhances that concept providing a detailed stochastic model in addition to rigorous simulations. 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 showcases how the legacy IP network reacts/interfaces to our light-train model. Section IV discusses the principles of the proposed integrated protocol. Section V provides for delay analysis. Section VI compares our model to other related works. Section VII discusses simulation results while Section VIII summarizes the paper.
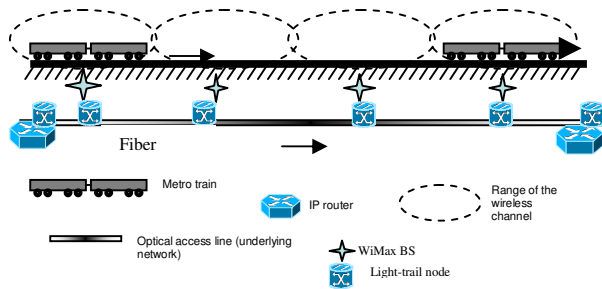
Fig. 1. Conceptual layout of metro trains over a wireless network and
underlying optical network.

II. LIGHT-TRAIN SYSTEM AND DEFINITIONS

Consider a train u moving along a track. The system is as
shown in Fig. 1.

Wireless Gateways: As the train u travels, it communicates
with the rest of the core network through *wireless gateways*
(GW) situated at intervals along the track. 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
another separated by a distance that is computed by the
transmission range (to prevent Signal-to-Noise Ratio – SNR
from degrading below a certain threshold). 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
GWs. Trains move from one GW 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 IV. B.

The principle requirement on the optical network is
of *dynamic provisioning of bandwidth* to wireless GWs. Data
paths must be provisioned to the wireless GWs through the
optical network on an on-demand basis to meet the BW and
delay constraints of services. 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. To enable ubiquity it is
necessary that the combined optical + wireless network be
able to provide *fast hand-off*.

For example cellular hand-off solutions require up to
several 100s of milliseconds. Similarly concepts based on
moving tunnel approach as shown in [8] require up to 100
milliseconds.

We propose an optically-assisted method for hand-
off. The underlying principle utilizes the dual concepts of
optical multicasting and out-of-band control (described later).

Another characteristic for cross-medium integration
is *signaling*: wireless GWs must be able to signal to each other

about ongoing communication activities when trains move
through their geographic range.

To illustrate this, consider the example of a train that
moves through the geographic range of one GW to the next
(adjacent) GW. 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 GW;
and hence it cannot be downloaded within the range of one
GW. In such a case, the file must be made available to the
next adjacent GW, when the train arrives in 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 GW and the setting
up the connection (making the file available) at the second
GW is of critical importance. Another factor that also leads to
an efficient cross-medium solution is that the second GW
must be aware of the fraction of the file that was successfully
transmitted by the first GW, so that it has to only transmit the
remaining fraction. While TCP sequencing would take care of
this issue, we do require a more robust and far more
dynamically adjustable solution. This necessitates the need for
efficient signaling both at the optical and the wireless layer
amongst nodes as well as between the nodes and the train.

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 done through an *out-of-band* (OOB)
control channel. The OOB control channel is optically
dropped, electronically processed and then 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)
Ability 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 de-
multiplexed 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. The first coupler (called Drop Coupler – DC) drops and continues incoming optical signal while the second coupler (called Add Coupler – AC) 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.

Nodes along a light-trail communicate with each other by setting up *connections*. Connection setup and teardown over a light-trail requires no optical switching and is done entirely through signaling in the OOB control channel using a protocol that we define in Section III.
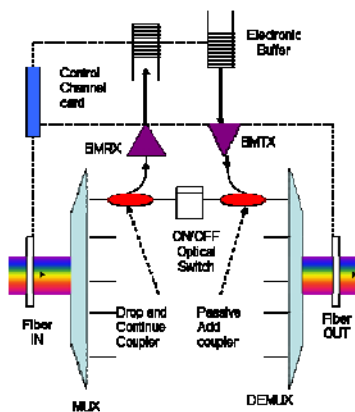

Fig. 2. Light-trail node specifics.

II. A. High Level System Description:

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. Each gateway communicates with a passing train through a wireless link.

We propose WiMax as a wireless 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 the 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).
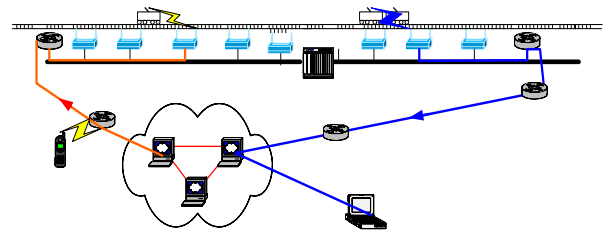

Fig. 3 Connection establishment in light-trains.

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).

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 through our system using two communication modes – Forward Communication (FC) and Reverse Communication (RC) depending on the direction of communication *from* or *to* the end-user. 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 passing. A scheduling protocol in the WiMax domain and a fast hand-off mechanism is assumed (and described in Section IV.B) that enables establishment of communication and ubiquity between the SS and the GW. The WiMax frequency allocation is described in Section IV. The railway tracks are assumed to be divided into cells in succession, that are partially overlapped power-threshold defined regions supporting wireless communication. When a train passes from the range of one cell to another cell, a *hard hand-off* is assumed to happen.
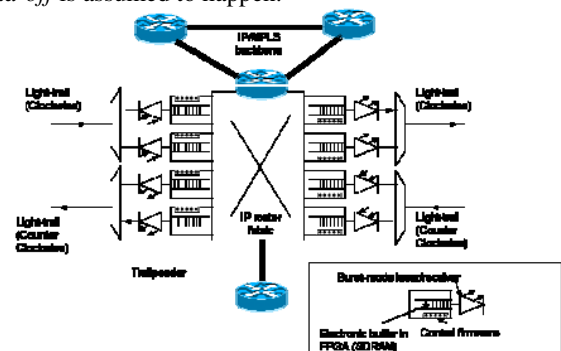

Fig. 4. Light-trail architecture : Data collection at the trailponder.

The packets that are sent to the GW, should now be transported into the core network. This is done by 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) [9] 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 resulting in 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).

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 data to be sent to the users in the train is collated in a *trailponder* [9] 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.(Fig. 4).

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 which requested for the information).
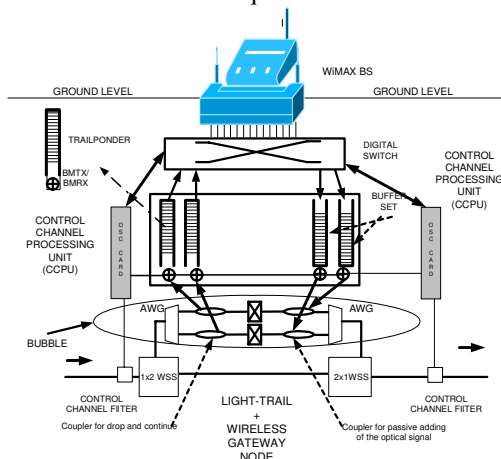

Fig. 5. Cross-medium node architecture supporting a WiMax BS and light-trail based optical network. Note that the 1x2 WSS conserves power and cost by processing only select WDM channels at a site.

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.

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 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 efficiently utilize the already scarce 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.
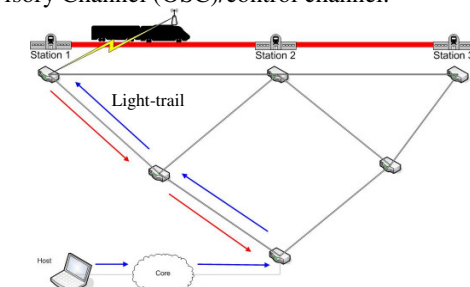

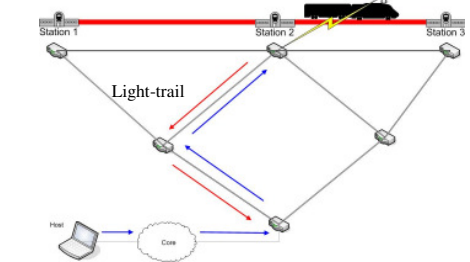Fig. 6. IP Routing when the train has registered at station 1.

Fig. 7. IP Routing when the train has registered at station 2.

III. 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 the convener node of a light-trail). The router advertises to the rest of the core network that the train is reachable through itself. 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 assumed that the train 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 Fig. 7, the train has moved to *station 2*, where 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 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 flow along 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 is due to optical multicasting and this is shown in Fig. 8.
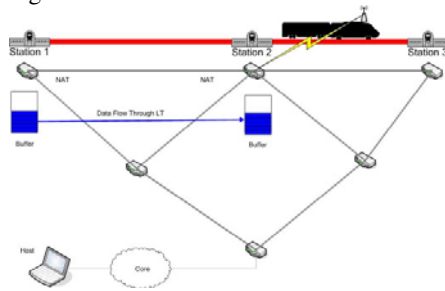

Fig. 8. Populating buffers across interconnected light-trails.

IV. PRINCIPLES OF THE 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.

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 connections amongst GWs to provision real-time and data-centric services facilitating seamless communication to and from the moving train.

IV. A. WiFi Protocol Functioning In The Train

The first source of delay for a user that sends a packet is within the WiFi network. 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 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 denoted as – *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).

IV. B. Frequency allocation in WiMax channel and hand-off using optical multicasting

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 features, 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.

We assume that f_{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 geographic 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. Conjecture: On a single track, two moving trains are separated by a *minimum distance* d_{train} 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 prevent collision between back-to-back trains, the relation $d_{train} > 2C_W$ should likely be valid, and hence two trains will not be in adjacent cells (as shown in Fig. 9).

2. Under the assumption that reason (1) above 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. However two trains moving in opposite directions can be in adjacent cells (just before crossing each other), and this implies a different allocation strategy considered next.
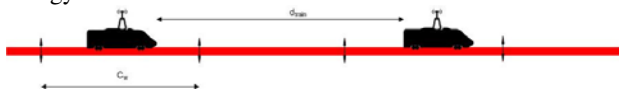

Fig. 9. Frequency allocation and its relation to cell-width (inter-GW distance), minimum distance to avoid collision and train size.

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(s) 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
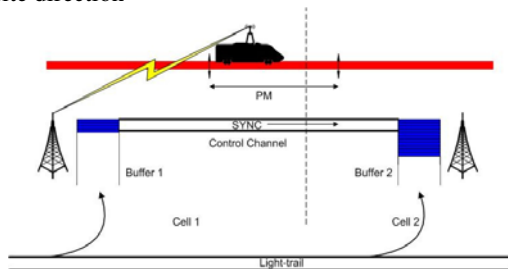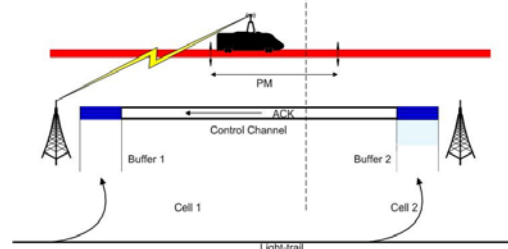

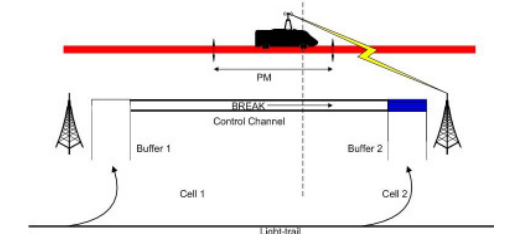
Fig. 10a: Sync.

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 of optical multicasting and dynamic provisioning. WiMax hand-off involves 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 GWs are pre-allocated and static, thereby enabling the GW to tell the train of its geographic range) as well as a power threshold. Upon entering the provisioning margin the train begins 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 duplication of 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 [9], these tags are useful in determining packet numbers. By stacking VLAN tags, we can have sequence numbering. The dormant GW receives the same packets as the live GW through optical multicasting property of the light-trial – though it does not transmit the received packets into the wireless medium. The dormant GW 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 a 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).

IV.C. Light-trail Protocol Design

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; the OEO function

facilitates synchronization amongst nodes in the light-trail. At the data layer, i.e. within the light-trail itself, we assume 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 us.

One of the light-trail nodes acts as an arbiter of bandwidth within the light-trail (and called light-trail controller). This node would receive from every other node (within the light-trail) a bandwidth request in the t-1st time-slot and then would arbitrate so as to give the highest deserving node the tth time-slot for transmission. 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 [10] and uses *bids* as requests for bandwidth allocation. The protocol uses bids within control packets to communicate between nodes and the arbiter.

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

IV. D. Light-trail 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 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 node (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.
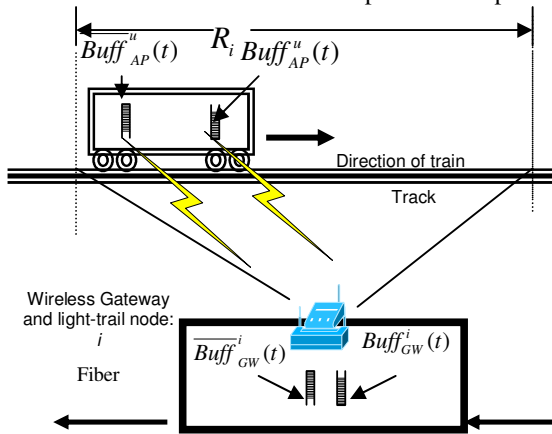

Fig. 11. Buffer representations at gateway and in train along with range of ith gateway.

Convention
a: number of trains in the system.
u: represents a particular train.
m: represents a particular user.
i: represent a particular Gateway (GW)
$R_i(t)$: range of the ith gateway at time t.

Let each user m generate data at a rate λ^m packets per second, where μ^m is the packet service rate.

Let us assume a set of h services be denoted by the set $S = \{S_1, S_2, \ldots, S_q, \ldots, S_h\}$

Then, let us define the maximum allowable latency for each of these h services to be represented by a set: $\Delta = \{\Delta_1, \Delta_2, \ldots, \Delta_q, \ldots, \Delta_h\}$.

The train u has an Access-Point (AP), and packets arrive at the AP from the users at a combined average arrival rate λ^u_{AP}.

Similarly packets arrive at the AP in train u from the underlying core network (through the WiMax channel) at an average rate of $\overline{\lambda}^u_{AP}$.

The buffer at the access point in train u that collects packets in FC direction (from the users) is denoted by $Buff^u_{AP}$ and whose instantaneous value is $Buff^u_{AP}(t)$.

In the FC direction, packets are sent by the AP that also functions as a WiMax SS, transmitting them to a WiMax BS that resides in conjunction with the GW, as shown in Fig. 11.

Let us assume GW i to be the communicating gateway for train u i.e. the train is passing through the geographic range of i. Then, the buffer for FC communication at GW i is $Buff^i_{GW}$, and it collects packets sent by the AP in train u. The instantaneous occupancy value of this buffer is denoted by $Buff^i_{GW}(t)$.

Similarly, at GW i we have in the RC direction buffer $\overline{Buff}^i_{GW}$ (with instantaneous value $\overline{Buff}^i_{GW}(t)$) that collects packets from the optical layer and transmits these packets into the WiMax channel (to the passing train).

Buffers $Buff^i_{GW}$ and $\overline{Buff}^i_{GW}$ have service differentiation capability, i.e. different counters exists for different services enabling service differentiation amongst the packets queued in the buffer. These counters are able to measure the time elapsed since packets for a particular service entered the buffer. Service differentiation is done by use of VLAN tagging on layer-2 frames in light-trails [9].

B_{max}: size of the buffer at a node.

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

$t^{i,u}_{DL}$ be the expected downlink time duration allocated to GW i on the WiMax channel for transmission to train u.

$t^{i,u}_{UL}$ 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_{WiMax}.

Then, $t^{i,u}_{DL} + t^{i,u}_{UL} \approx T_{WiMax}$ is the WiMax cycle time, neglecting the guard-band between uplink and downlink frames. The expected values of $t^{i,u}_{DL}$ and $t^{i,u}_{UL}$ are computed as described in the next section.

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Bandwidth allocation policy: We will now show how bandwidth (connection) provisioning happens in the light-trail. For bandwidth allocation consider Fig. 11.

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

Let $\overline{y}_{ikq}(t)$ be the time elapsed since the first packet of service type q entered the buffer $\overline{Buff}_{GW}^i$ 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:

$$packet\_value_{ik}(t) = \max\left[\frac{Buff_{GW}^i(t)}{B_{\max}}, \frac{\max(y_{ikq}(t))}{\max(y_{ikq}(t)) + \gamma_{ik}(t)}\right] \quad (1)$$

Where, $\gamma_{ik}(t) = \min\limits_{q=1,...h}(\Delta_q - y_{ikq})$: service statistics at GW i in FC direction; where service statistics refers to the minimum delay tolerance limit for the buffer $Buff_{GW}^i$ at GW i for communication in the light-trail k in the FC direction at time t. Subsequently $q'_i = \arg\left[\min\limits_{q=1,..h}(\Delta_q - y_{ikq})\right]$ denotes the service that corresponds to minimum tolerance value in the buffer at node i in FC direction.

Let $\overline{q'}_i = \arg\left[\min\limits_{q=1,..h}(\Delta - \overline{y}_{ikq})\right]$ be the service that contributes to the minimum delay tolerance in the buffer at node i in RC.

Let $\overline{\gamma}_{ik}(t) = \min\limits_{q=1,...h}(\Delta - \overline{y}_{ikq})$ be the allowable delay at node i (how long can a node i wait without being serviced) in RC direction for the buffer $\overline{Buff}_{GW}^i(t)$; i.e. $\overline{\gamma}_{ik}(t)$

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:

$$\overline{packet\_value}_{ik}(t) = \max\left[\frac{\overline{Buff}_{GW}^i(t)}{B_{\max}}, \frac{\max(\overline{y}_{ikq}(t))}{\max(\overline{y}_{ikq}(t)) + \overline{\gamma}_{ik}(t)}\right] \quad (2)$$

In [10] we have observed that using a maximization of buffer utilization and service statistics as shown in (1), (2), leads to a proportionally fair [11] allocation of bandwidth resources in a shared medium. The explanation is that $Buff_{GW}^i(t)$ value is mapped to a combination of concave and sigmoidal function that ultimately leads to proportional fairness.

Dynamic provisioning protocol in a light-trail

Stage 1:
At every node in the light-trail 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 $suc_k(t) = argmax(packet\_value)$
      send $suc_k(t)$ *information to all nodes*

Stage 2:
At all nodes in light-trail k and at IP router at convener node :
   if $suc_k(t)$=node index
      wait *till end_of_current_time-slot*
      transmit *for one time-slot duration or till buff$_{ik}$(t)=0*
   else
      idle
   endif

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

IV. D. Special Case: Reverse Communication

The IP router sends data to the users in the train in reverse communication direction. The data sent depends on the user IP-destination address and whether 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 (in the direction of the moving train). 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 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 GW. 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.

V. DELAY ANALYSIS IN THE LIGHT-TRAIN SYSTEM

The integrated optical-wireless solution that gives bandwidth to fast-moving users in trains, consists of wireless access, wireless interconnection and optical infrastructure thereby requiring a unified approach to bandwidth provisioning. In terms of implementation, the variation in provisioning methodologies seen between: the end-users and the AP (WiFi); the AP and the GW (WiMax); 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 represented by the following set of equations with the associated conventions described subsequently:

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

$$\delta_{final-FC} = \delta_{WiFi-FC} + \delta_{WiMax-FC} + \delta_{LT-FC} \qquad (3)$$

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

$$\delta_{final-RC} = \delta_{WiFi-RC} + \delta_{WiMax-RC} + \delta_{LT-RC} \qquad (4)$$

Finally, the average delay that a packet experiences through the network is:

$$\delta_{final} = \left[\delta_{final-FC} + \delta_{final-RC} \right] / 2 \qquad (5)$$

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

V. 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 λ. Let the duration of a superframe (used in the PCF mode) be denoted by T_S^{WiFi} and let L be the expected length of a packet at each user. The utilization of each node is denoted by ρ_{WiFi}. We adapt from the model presented in [6] to compute the average queuing delay experienced by an arbitrary packet arriving at the mth user in the train u.

As shown in [6], since each polled user transmits exactly once in every superframe, the service rate of each user is $\mu_{WiFi} = 1/T_S^{WiFi}$, and the net-utilization is given by $\rho_{WiFi} = \lambda / \mu_{WiFi} = \lambda T_S^{WiFi}$. 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:

$$D_{WiFi}^m = \frac{1}{1 - \lambda T_S^{WiFi}} \left[\frac{T_S^{WiFi}}{2} + \left(\frac{\rho_{WiFi} L^2 (2m-1)(1-\rho_{WiFi})}{T_S^{WiFi}} + L \right)(1-\rho_{WiFi}) \right] \qquad (6)$$

Let $\lambda_m^{'u}$ 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 λ_m^u and are sent out at an *effective* rate $\lambda_m^{'u}$, where the difference between $\lambda_m^{'u}$ and λ_m^u is the result of the

PCF bandwidth allocation strategy (due to control over-head). The net arrival rate at the AP (λ_{ap}^u) is given by:

$$\lambda_{ap}^u = \sum_{m \in W^m(u)} \lambda_m^{'u} \qquad (7)$$

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 (λ_m^u) and the average per-packet delay (D_m^u), that packets from user m experience due to PCF allocation strategy. In steady state, the number of packets (N_m^u) that are buffered at the user m is given by Little's formula: $N_m^u = \lambda_m^u D_m^u$. Hence we have:

$$\lambda_m^u D_m^u = \lambda_m^u T_S^{WFi} - \lambda_m^{'u} T_S^{WFi} = N_m^u \qquad (8)$$

$$\therefore \quad \lambda_m^{'u} = \lambda_m^u \left(1 - \frac{D_m^u}{T_S^{WFi}} \right) \qquad (9)$$

V. B. WiMax Delay

We now compute the average delay experienced by a packet over the WiMAX channel. The MAC frame structure consists of an uplink and a downlink sub-frame, whose durations are dependent on the provisioned services and are controlled by the BS. 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.

Our model is similar to the model proposed in [7] with the primary exception that it is designed for communication with high-speed voluminous moving users. This implies the model has a single BS located at the GW 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 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 denote $t_{UL}^{i,u}$ to be the expected uplink time that train u receives through the WiMax channel when moving through the GW i. Let μ be the service rate at the AP and $N_{flush} = t_{UL}^{i,u} / \mu$ be the maximum permissible buffer occupancy (in terms of number of packets) that can be scheduled over the WiMax channel in the uplink –FC).

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At the GW i (in RC)

---

if train u is in *Range*
    In each slot of length T_{WiMax}

      compute $\lambda_{GW}^{i,u}$

      send *REQ* to get $\lambda_{AP}^{i,u}$ from the *AP*

      compute $t_{UL}^{i,u} = \dfrac{\lambda_{AP}^{i,u}}{\lambda_{AP}^{i,u}+\lambda_{GW}^{i,u}}$ and $t_{DL}^{i,u}=T_{WiMax}-t_{UL}^{i,u}$

      send $t_{UL}^{i,u}$ and $t_{DL}^{i,u}$ to AP (in UL, DL map)

      receive data in $t_{UL}^{i,u}$

      on completion of $t_{UL}^{i,u}$, **transmit** for duration of $t_{DL}^{i,u}$
else
      sleep till another train *registers*
endif

At the AP in train u (in FC)

If GW i is in *Range*
    In each slot of length T_{WiMax}

      compute $\lambda_{AP}^{i,u}$

      send $\lambda_{AP}^{i,u}$ to GW *as response to REQ*

      get $t_{UL}^{i,u}$ and $t_{DL}^{i,u}$ from GW i

      transmit for the time duration of $t_{UL}^{i,u}$

      receive for the time duration of $t_{DL}^{i,u}$
else
      search for a *GW*
endif

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

The communication through the WiMax channel consists of the two periods denoted by $t_{UL}^{i,u}$ and $t_{DL}^{i,u}$ for uplink (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 $T_{WiMax}^{v(t),u,i} \approx T_{WiMax}^{u,i} \approx T_{WiMax}$ whereby we relax the constraint of velocity dependence (and hence Doppler effect), assuming measurements are made at a *cruise* velocity of in the region of 100~300 kmph. Then, the time the train spends in communicating with the gateway is given by an integral multiple of: $T_{WiMax}=\left(t_{UL}^{i,u}+t_{DL}^{i,u}\right)$. We also assume that $\lambda_{AP}^{i,u}$ is the arrival rate at the AP (from the users in the train) and $\lambda_{GW}^{i,u}$ is the arrival rate at the gateway (from the light-trail).

For bandwidth allocation, the transmission time is divided into small slots with the AP and the GW both allotted sub-slots to transmit within each slot, the size of which is proportional to their respective arrival rates.

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

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

$$t_{UL}^{i,u}=\frac{\lambda_{AP}^{i,u}}{\lambda_{AP}^{i,u}+\lambda_{GW}^{i,u}}T_{WiMax} \text{ and } t_{DL}^{i,u}=\frac{\lambda_{GW}^{i,u}}{\lambda_{AP}^{i,u}+\lambda_{GW}^{i,u}}T_{WiMax} \quad (10)$$

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

$$t_{UL}^{i,u}=\left(\frac{1}{1+\lambda_{GW}^{i,u}/\lambda_{AP}^{i,u}}\right)T_{WiMax} \text{ and denote, }\left(\frac{1}{1+\lambda_{GW}^{i,u}/\lambda_{AP}^{i,u}}\right)=X \text{ , then}$$

$$\frac{1-X}{X}=\lambda_{GW}^{i,u}/\lambda_{AP}^{i,u}. \quad (11)$$

Let us now define $\overline{\lambda}^{i,u}=\dfrac{\lambda_{GW}^{i,u}}{\lambda_{AP}^{i,u}}$ as the quotient of two independent random variables.

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

$$f(\overline{\lambda}^{i,u})=\int_{v=-\infty}^{\infty} g(v\overline{\lambda}^{i,u})h(v)\,|\,v\,|\,dv . \quad (12)$$

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

$$E\left[t_{UL}^{i,u}\right]=\int_{0}^{T_{WiMax}} t.y\left(t_{UL}^{i,u}=t\right)dt, \text{ where } y\left(t_{UL}^{i,u}=t\right)\text{ is the }pdf\text{ of }$$

$t_{UL}^{i,u}$ and can be computed from $f(\overline{\lambda}^{i,u})$.

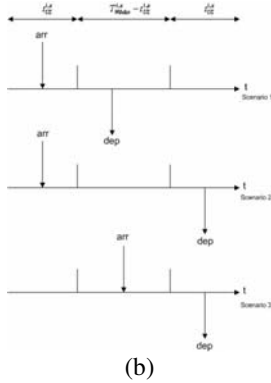Fig. 12. WiMax cycle (slot) time.

(a)
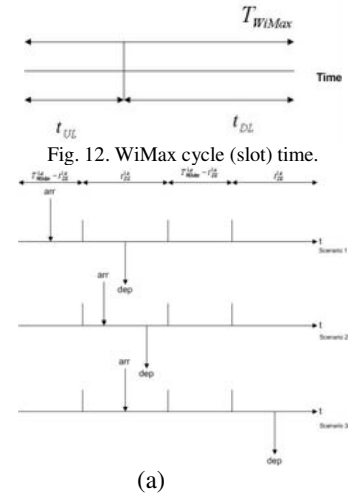
(b)
Fig. 13. WiMax communication: (a) shows the three scenarios for FCd (b)
shows the three scenarios for RC.

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 an effective service rate of μ_{WiMax} packets per seconds. The composition of the communication cycle in WiMax is as shown in Fig. 12. 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. The assumption is that a packet arrives at the AP (from the end-user) at time $t_{arr} \in [0, T_{WiMax}]$ and gets transmitted at $t_{dep} \in [0, T_{WiMax} + t_{UL}]$ which avoids an infinite queue system.

The scenarios below describe delay computation in the FC direction and the RC is an extension of the FC delay shown subsequently.

Scenario 1): In this scenario the packet arrives while the AP is being serviced (through $t_{UL}^{i,u}$) and departs in the same interval (uplink frame) as shown in Fig. 13a *scenario 1*.
The condition is denoted by: $t_{arr} \in [0, t_{UL}^{i,u}]$ and $t_{dep} \in [0, t_{UL}^{i,u}]$.

The average delay experienced by a packet in this case is: $t_{UL}^{i,u}/2$. 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:

$$p_1 = p(t_{arr} \in [0, t_{UL}^{i,u}]) . p(t_{dep} \in [0, t_{UL}^{i,u}]) \quad (13)$$

The two probabilities are computed as:

$$p(t_{arr} \in [0, t_{UL}^{i,u}]) = \frac{t_{UL}^{i,u}}{T_{WiMax}} \quad (14)$$

$$p(t_{dep} \in [0, t_{UL}]) = p(Buff_{AP}^{i,u} < N_{flush}) \quad (15)$$

Where, $Buff_{AP}^{i,u}$ as noted before denotes the occupancy of the buffer at the AP of train u while it passes through gateway i and N_{flush} denotes the maximum number of packets possible to be transmitted through the WiMax channel, with service rate μ_{WiMax}.

While the first probability ($p(t_{arr} \in [0, t_{UL}^{i,u}])$) can be computed by examining the expected value of $t_{UL}^{i,u}$, 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 $N_{flush} < c$ and hence we compute the probability of the occupancy as:

$$p(Buff_{AP}^{i,u} < N_{flush}) = \sum_{r=0}^{N_{flush}-1} \left(\frac{\lambda_{AP}^{i,u}}{\mu_{WiMax}} \right)^r \left(1 - \frac{\lambda_{AP}^{i,u}}{\mu_{WiMax}} \right) \quad (16)$$

$$= \sum_{r=0}^{N_{flush}-1} \left(\rho_{AP}^{i,u} \right)^r \left(1 - \rho_{AP}^{i,u} \right)$$

Hence, $\quad p(Buff_{AP}^{i,u} < N_{flush}) = 1 - \left(\rho_{AP}^{i,u} \right)^{N_{flush}} \quad (17)$

Therefore, $\quad p_1 = \left(1 - \left(\rho_{AP}^{i,u} \right)^{N_{flush}} \right) . \frac{t_{UL}^{i,u}}{T_{WiMax}} \quad (18)$

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. 13a *scenario 1*. In this case the packet has to wait for the duration of (1) the current uplink frame (to complete transmission) and (2) the next downlink frame. The packet is then transmitted during the subsequent uplink frame.

This condition is stated as: $t_{arr} \in [0, t_{UL}^{i,u}]$ and $t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]$.

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

$$p_2 = p(t_{arr} \in [0, t_{UL}^{i,u}]) . p(t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]), \quad (19)$$

The two independent probabilities are computed as:

$$p(t_{arr} \in [0, t_{UL}^{i,u}]) = \frac{t_{UL}^{i,u}}{T_{WiMax}} \quad (20)$$

$$p(t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]) = p(Buff_{AP}^{i,u} \geq N_{flush}) \quad (21)$$

Simplifying and using result (17) we get:

$$p_2 = \frac{t_{UL}^{i,u}}{T_{WiMax}} . p(Buff_{AP}^{i,u} \geq N_{flush}) = \frac{t_{UL}^{i,u}}{T_{WiMax}} \left(\rho_{AP}^{i,u} \right)^{N_{flush}} \quad (22)$$

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. 13a *scenario 3*. This scenario is stated as:

$$t_{arr} \in [t_{UL}^{i,u}, T_{WiMax}] \text{ and } t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]$$

The average delay experienced by a packet in this scenario is given by: $((T_{WiMax} - t_{UL}^{i,u}) + t_{UL}^{i,u})/2 = T_{WiMax}/2$. $\quad (23)$

The probability of occurrence of this scenario is given by:

$$p_3 = p(t_{arr} \in [t_{UL}^{i,u}, T_{WiMax}]) . p(t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]) \quad (24)$$

The two independent probabilities are computed as:

$$p(t_{arr} \in [t_{UL}^{i,u}, T_{WiMax}]) = 1 - \frac{t_{UL}^{i,u}}{T_{WiMax}}, \text{and}$$

$$p(t_{dep} \in [T_{WiMax}, T_{WiMax} + t_{UL}^{i,u}]) = p(Buff_{AP}^{i,u} < N_{flush}) \quad (25)$$

Hence,
$$p_3 = \left(1 - \frac{t_{UL}^{i,u}}{T_{WiMax}}\right) \cdot \left(1 - \left(\rho_{AP}^{i,u}\right)^{N_{flush}}\right) \qquad (26)$$

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

$$\delta_{WiMax}^{FC}(i,u) = p_1 \cdot \frac{t_{UL}^{i,u}}{2} + p_2 \cdot \left(T_{WiMax} - \frac{t_{UL}^{i,u}}{2}\right) + p_3 \cdot \frac{T_{WiMax}}{2} \qquad (27)$$

Substituting and solving we get:

$$\delta_{WiMax}^{FC}(i,u) = \left(\frac{\left(t_{UL}^{i,u}\right)^2 + \left(T_{WiMax}\right)^2 - 3t_{UL}^{i,u}.T_{WiMax}}{2T_{WiMax}}\right)\left(1 - \left(\rho^{i,u}\right)^{N_{flush}}\right) + t_{UL}^{i,u} \qquad (28)$$

Since the scenarios for RC are identical (as can be seen from Fig. 13b), the expected delay a packet experiences through the WiMax channel in the RC direction is given by:

$$\delta_{WiMax}^{RC}(i,u) = \left(\frac{\left(t_{DL}^{i,u}\right)^2 + \left(T_{WiMax}\right)^2 - 3t_{DL}^{i,u}.T_{WiMax}}{2T_{WiMax}}\right)\left(1 - \left(\rho^{i,u}\right)^{N_{flush}}\right) + t_{DL}^{i,u} \qquad (29)$$

V. 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.

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 through time-slotting the light-trail [10]. Since multiple nodes time-share the optical wavelength bus, we require a method for arbitration which was described in Section IV. 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 within 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 this light-trail.

Multiple flows may be provisioned at a node (each with different destinations). 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:

$$mpacket\_value_k(t) = \max_{\forall i:N_i \in k}(packet\_value_{ik}(t)) \qquad (30)$$

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

$$suc_k(t) = \arg\max_{i:N_i \in k}(packet\_value_{ik}(t)) \qquad (31)$$

The winning node ($suc_k(t)$) would transmit (establish a connection) in the next ($t+1^{st}$) time-slot.

Note: 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 either some other light-trail (wavelength) or create a new light-trail. Recourse occurs when:

$$t_{HP} < \gamma_{ik}(t) < \left(t_{HP} + T_S\right) \qquad \text{or}$$

$$\left[1 - \frac{Buff_{GW}^i(t)}{B_{max}}(t_{HP})\right] > B_{ik}(t) > \left[1 - \frac{Buff_{GW}^i(t)}{B_{max}}(t_{HP} + T_S)\right] \qquad (32)$$

This condition requires new light-trails to be set up.

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 T_s be the time-slot duration, and let T_g be the guard-band between two successive time-slots. We assume T_g to have a very small value and hence neglect the effect of T_g on the overall light-trail delay.

Let $P_{succ}^{ik,FC}(t)$ be the probability of success of node i in light-trail k in the FC direction. Let $P_{succ}^{k-ing,RC}(t)$ be the probability of success for the router at the convener 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 any arbitrary node i in light-trail k is given by:

$$\delta_{LT}^{FC} = \frac{T_S}{P_{succ}^{ik,FC}(t)} \qquad (33)$$

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 convener 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 convener node. This condition is denoted by:

$$P_{succ}^{ik,FC}(t) = p(packet\_value_{ik}^{FC}(t) > packet\_value_{k-ing}^{RC}(t)).$$
$$\prod_{\substack{j=1 \\ j \neq i}}^{n(k)} p(packet\_value_{ik}^{FC}(t) > packet\_value_{jk}^{FC}(t)) \qquad (34)$$

The *packet_value* computation is denoted in (1) and (2) from which we compute the probability that the *packet_value* sent by node i is the largest as:

$$P_{succ}^{ik,FC}(t) = \left(1 - p\left[\frac{\gamma_{ik}(t)}{\max_{\forall q}(y_{ikq}(t))} \leq \frac{\overline{\gamma_{k-ing}(t)}}{\max_{\forall q}\left(\overline{y_{k-ingq}(t)}\right)}\right]\right).$$
$$\prod_{\substack{j=1 \\ j \neq i}}^{n(k)}\left(1 - p\left[\frac{\gamma_{ik}(t)}{\max(y_{ikq}(t))} \leq \frac{\gamma_{jk}(t)}{\max_{\forall q}(y_{jkq}(t))}\right]\right) \qquad (35)$$

The above equation is simplified in [10] 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:

$$P_{succ}^{ik,FC}(t) = \left(1 - \sum_{\phi=0}^{1} \delta(\bar{\phi})\right) . \prod_{\substack{j=1 \\ j \neq i}}^{n(k)} \left(1 - \sum_{\phi=0}^{1} \delta(\phi)\right) \qquad (36)$$

where, $\bar{\phi} = \dfrac{\overline{\gamma_{k-ing}}(t) / \max\limits_{\forall q}\left(\overline{y_{k-ingq}}(t)\right)}{\gamma_{ik}(t) / \max\limits_{\forall q}(y_{ikq}(t))}$ and $\phi = \dfrac{\gamma_{jk}(t) / \max\limits_{\forall q}(y_{jkq}(t))}{\gamma_{ik}(t) / \max\limits_{\forall q}(y_{ikq}(t))}$

$$P_{succ}^{ik,FC}(t) = \left(1 - \sum_{\phi=0}^{1} \delta(\bar{\phi})\right) . \prod_{\substack{j=1 \\ j \neq i}}^{n(k)} \left(1 - \sum_{\phi=0}^{1} \delta(\phi)\right) = \left(1 - \int_{0}^{1} \delta(\phi')d\phi'\right) . \prod_{\substack{j=1 \\ j \neq i}}^{n(k)} \left(1 - \int_{0}^{1} \delta(\phi)d\phi\right)$$

$$(37)$$

and

$$\delta(Q) = \sum_{v=t_{HP}}^{\max_{q \in Buff_{GW}^t(t)} (\Delta_q)} p\left(\frac{\gamma_{ik}(t)}{\max\limits_{\forall q}(y_{ikq}(t))} = vQ\right) . p\left(\frac{\gamma_{jk}(t)}{\max\limits_{\forall q}(y_{jkq}(t))} = v\right) v$$

$$(38)$$

Leading to:

$$\delta_{LT}^{FC} = \frac{T_S}{P_{succ}^{k-ing,FC}(t)} \qquad (39)$$

The average delay experienced by a packet in the RC direction is computed in a similar fashion:

$$P_{succ}^{k-ing,RC}(t) = \prod_{j=1}^{n(k)} p(packet\_value_{k-ing}^{RC}(t) > packet\_value_{jk}^{FC}(t)) \quad (40)$$

$$P_{succ}^{k-ing,RC}(t) = \prod_{j=1}^{n(k)} \left(1 - p\left[\frac{\overline{\gamma_{k-ing}}(t)}{\max\limits_{\forall q}\left(\overline{y_{k-ingq}}(t)\right)} \leq \frac{\gamma_{jk}(t)}{\max\limits_{\forall q}(y_{jkq}(t))}\right]\right) \quad (41)$$

$$P_{succ}^{k-ing,RC}(t) = \prod_{j=1}^{n(k)} \left(1 - \sum_{\phi=0}^{1} \delta(\phi')\right) = \prod_{j=1}^{n(k)} \left(1 - \int_{0}^{1} \delta(\phi')d\phi'\right) \quad (42)$$

Where, $\phi' = \dfrac{\gamma_{jk}(t) / \max\limits_{\forall q}(y_{jkq}(t))}{\overline{\gamma_{k-ing}}(t) / \max\limits_{\forall q}\left(\overline{y_{k-ingq}}(t)\right)}$

The delay in the RC direction is given by:

$$\delta_{LT}^{RC} = \frac{T_S}{P_{succ}^{k-ing,RC}(t)} \qquad (43)$$

The delays computed in (28), (29) for WiMax, (33), (43) for light-trail are plugged in (3)-(5) to obtain final end-to-end delay, neglecting propagation delay.

VI. RELATED WORK

The concept of providing broadband connectivity to moving users especially fast moving users has been studied in [8], [12], [13], of which the [12] is our own preliminary work.

The approach in [12] proposed the basic architecture – 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. No protocol was presented for delivery of bandwidth to the end-user through the unified optical-wireless network.

The work in [8, 13] mentions two approaches – the mobile cell concept in [13] and the moving tunnel concept in [8]. 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 [8, 13] 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 [8, 13] uses switching which is detrimental (due to switching speed/uncertainty) in providing bandwidth to fast moving users. The requirement of optical switching in [8, 13] 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. Our method of integration of optical and wireless technologies, enabling a symbiotic relationship is the key differentiator between the light-train solution and other existing solutions.

VI.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 (data + control) 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 supporting 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). A fast hand-off concept is investigated by us in [14].

(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 in the overlaid wireless channel. 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 [8, 13] or using a backbone SONET/SDH network, we would require layer 3 termination [13] and further provisioning of a moving tunnel type concept. The time required would result in loss of bandwidth and hence degradation of system efficiency.

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.

VII. 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. 14) with sixteen major cities and distances not assumed to scale but assumed that the cities are within one huge metro region. The train contained end-users that supported applications on their mobile devices. 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-duration for the DES model was 1 millisecond and is the time required by the system to transmit 6 Ethernet frames (MTU=1500 bytes) 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 by deploying Wavelength Selectable Switch support). Train velocity was pegged 200 km per hour. The DES was based on a C# class library.

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 (through VLAN tags). 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 is 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. 15 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 effective utilization varies from 10% to 65% while for case 2 the utilization varies from 10% to 60%. The curves in both the cases increase with load, linearly for most parts but

are logarithmic at high loads. This implies that light-trains are not only able to cope well at low and medium loads but also achieve good utilization at high loads. Utilization is computed as the average time the system is busy.
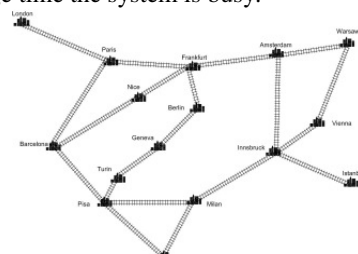

Fig. 14. European simulation topology.

Fig. 16 shows the delay experienced in FC and Fig. 17 shows the delay experienced in RC as the load varies from 0.1 to 0.9. In both directions of communication the average per packet delay is of the order of 100 us. We observed that the FC delay is lower than the RC delay (Fig. 17). This is explained by the fact that the end-users in the train instantaneously send generated data into the core thus occupying a larger percentage of the WiMax transmission slot as compared to the IP-router initiated communication (RC). This result is quite counter-intuitive as compared to typical TCP traffic and is explained by the manner in which bandwidth allocation is done in the WiMax channel, taking AP buffer values into consideration in conjunction with BS (GW) values. 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 2-3 ms. Average response time is defined as the time required for the system to fetch the first packet in a file since a request has been made.
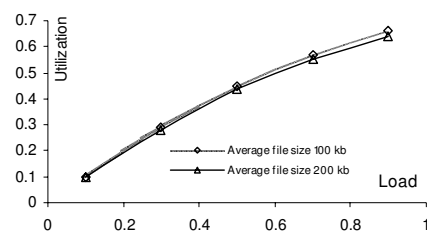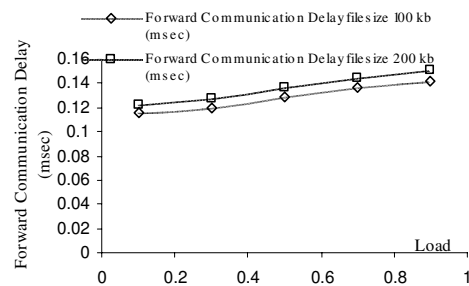

Fig. 15. Utilization versus load

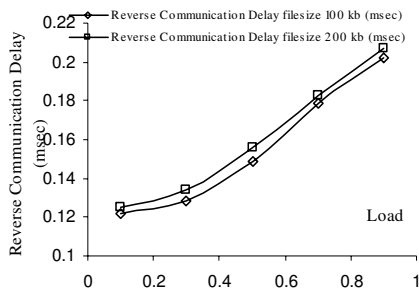Fig. 16: Forward Communication delay versus load

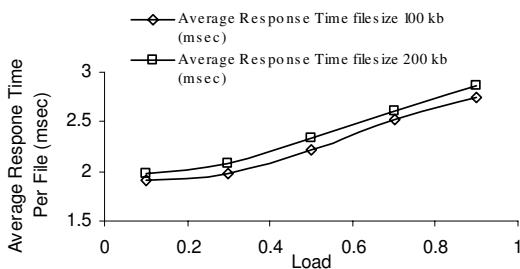Fig. 17. Reverse Communication delay versus load

Fig. 18. Average response time versus load

VIII. 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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