Mobile Hotspot in Railway System

Daniel Ho, *Student Member, IEEE,* and Shahrokh Valaee, *Senior Member, IEEE*

***Abstract*— With the ever-growing need for mobile high-speed access, there is an apparent demand to extend access towards mass transportation vehicles such as trains. In this paper, we propose a novel networking paradigm for railway system. The architecture realizes spatial diversity, and transparency to mobile devices. We further investigate the link layer design approach of the architecture, with the use of erasure coding. The concept of information raining is explained, with simulations illustrating system throughput cyclicity due to positioning of vehicle.**

I. Introduction

In recent years, the Hotspot technology has gained tremendous popularity with the demand of mobile Internet access. In public areas such as airports, bus terminals and train stations, travellers may use their laptops and handheld devices to access the Internet while waiting for their departure. As more locations are becoming Hotspots, there is an apparent demand to extend high-speed Internet access towards mass transportation vehicles such as long-haul trains and metropolitan subways. In these vehicles, passengers are often idle and bored in a confined space. Organizations that enable mobile Hotspots in their mass transportation systems offer much appreciated convenience to their customers, and may ultimately experience an increase in ridership.

It is challenging to facilitate Internet access using traditional wireless local area network (WLAN) technology. The naive approach would be to place numerous access points (AP) along the transportation route to provide coverage to mobile users. However, this setup is highly unscalable with typical APs that cover small radii of 50m to 200m. This is especially true with long-haul railways where hundreds of kilometers of coverage is required. Whenever a vehicle travels across AP boundaries, WLAN must perform handoff operations to large number of users. For instance, a vehicle travelling at 72km/h demands handoff every 10s with AP coverage of 100m radius. These frequent handoffs must be performed without significant delay and packet loss, yet these handoff rates are infeasible with the current Mobile IP architecture.

Likewise, the cellular wireless industry thrusts towards enabling high data-rate services with 3G cellular networks. The challenges with cellular systems are similar to WLANs. For instance, there is an issue with cellular planning. Terrain obstacles such as hills, buildings and tunnels may cause shadowing and large delay spread of several microseconds to certain sections of these routes, which impair transmission quality in terms of bit-error-rate (BER) and achievable bandwidth. These factors justify the use of microcells along the transportation route, however these microcells result in frequent handoffs due to high mobility, and may generate interference to existing macrocells in the vicinity.

The Edward S. Rogers Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, ON, M5S 3G4 Phone: (416) 946-8032, Fax: (416) 978-4425 email: {dhtho,valaee}@comm.utoronto.ca

In this paper, we propose a novel system architecture to facilitate mobile Hotspots that is applicable to both WLAN and cellular systems. This is coherent with the recent development in the convergence of these two technologies. We then consider design issues when implementing our architecture at link layer, followed by simulation results. For the rest of this paper, we shall illustrate our discussion on downlink traffic forwarding due to the emergence of asymmetric data applications in mobile devices.

II. System Architecture

All handheld devices possess critical constraints in hardware component size, computation power and battery power. Consequently, they can only process relatively simple procedures, and only one small antenna can be installed in most devices. Conversely, one common feature among trains is their large physical size. More powerful networking equipment can be installed inside vehicles without practical space and battery power limitations. It is also ideal to install multiple antennas around the vehicles, connecting them to the networking equipment.

Furthermore, unlike generic mobile users, trains have a network of defined paths to travel. By installing repeaters at close vicinity along the network of paths, line-of-sight (LOS) can be guaranteed between repeaters and vehicles that move along the network.

We propose a system architecture for providing mobile Hotspot in railway system. The system diagram is shown in Figure 1. Similar to backbone networks and mobile switching centers of cellular systems, the mass transportation system communications network is a cloud of networking equipment that is responsible for routing traffic between the Internet and local information distribution centers we refer to as *zone controllers* (ZC). Zone controllers are responsible for traffic dissemination within their local region, such as a railway section of several kilometers. They are also responsible for detecting the presence of vehicles and their mobile users. Stationary repeaters are positioned along the responsible path. Repeaters and ZC may be connected via fiber cables, or via daisy chaining of wireless links with intermediate repeaters. These repeaters then relay traffic of ZC to multiple antennas that are installed on top of moving vehicles. Inside each vehicle locates a *vehicle station* (VS) that gathers traffic from vehicle antennas, and relays them to internal repeaters. The internal repeaters may be access points or cellular repeaters that provide service to mobile users, if the concerned technology is WLAN or cellular system respectively. Thus, passengers

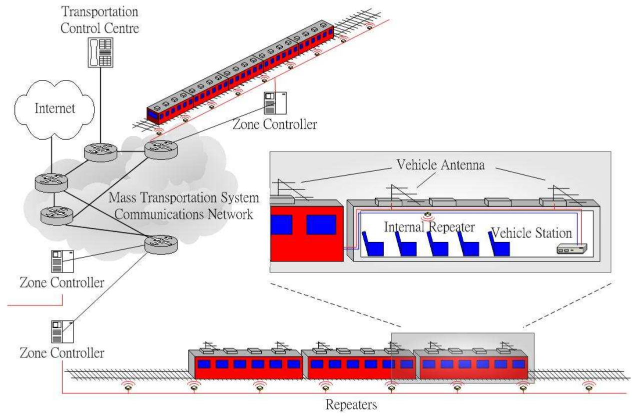

Fig. 1. Proposed architecture for mobile high-speed access in railway system

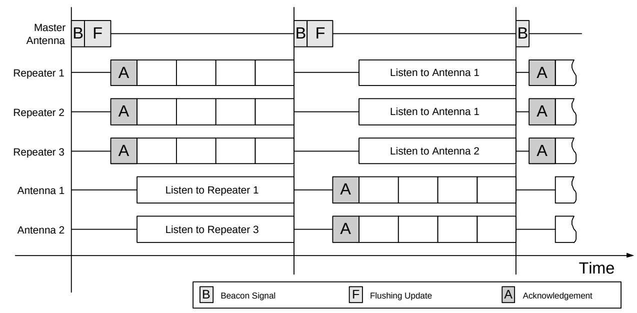

Fig. 2. MAC layer frame format for information raining

enjoy seamless mobile Hotspot service with no adjustment at the mobile terminal.

Repeaters may be placed on the ground near the railroads, with antennas on top of trains shifted to the side to allow line-of-sight, or in the case of underground subway systems, repeaters may be placed at the top of the tunnel. In any case, the paradigm is applicable to both urban and rural environments.

The separation distances among repeaters, between repeaters and antennas, and among antennas on the vehicles depend on many factors such as the type of antennas employed and their transmission range. We foresee separation distances in most systems do not exceed 100m, and may be as few as several meters.

III. Link Layer Design Considerations

In link layer design viewpoint, the ZC receives downlink data from system network and disseminates data to multiple repeaters at the vicinity of the vehicle. Each repeater forms a one-to-one wireless channel to each vehicle antenna and transmits such data via the channel. The VS at the vehicle receives the packets and forwards them accordingly.

Similar to multipath routing techniques [1], it is possible to improve system reliability with erasure coding on packets [2], [3]. Instead of error detection and correction, erasure codes are added to provide fault tolerance if a segment of data is lost, or “erased”, during transmission. By decomposing the encoded data into segments of equal length, these segments can be disseminated to the repeaters, which act as dumb terminals that repeat segments to the air interface. Since each wireless link may temporarily lose link due to fading and interference, not every segment may be received by the corresponding antenna. However, the decoder at VS can reconstruct the original data if a certain number of segments arrive successfully, regardless of the specific subset of segment arrivals. Effectively, erasure coding enhances robustness to the inherently unreliable wireless channels. From a network layer standpoint, the traffic flow between ZC and the vehicle is viewed as a single transparent link.

Notice that many links may possibly be established among vehicle antennas and nearby repeaters. One simple approach is to allow repeaters to blindly “rain” segments of information upon the vehicle, and allows each vehicle antenna to acquire any transmission link and receive partial information, so that hopefully enough data segments are received by the VS to recover the original information. We metaphorically describe this approach as *information raining*. Thus, handoff of wireless links within the zone is implicitly handled by link acquirement renewals.

The link layer design allows minimal intelligence from the repeaters, and the possibility to build them with relatively cheap, standards-ready components. A standard wireless link protocol should be employed to establish individual links. This is important for deployment cost because numerous repeaters must be installed along the transportation system.

We propose a general MAC layer structure, as shown in Figure 2. One *master antenna* is employed at the vehicle to broadcast a beacon signal to repeaters in the vicinity. Repeaters that detect the presence of this signal “awaken”, and broadcast their unique identification signals as acknowledgment. Each antenna detects their existence, and performs subchannel estimation on each awakened repeater, and tune to the repeater that yields the strongest link gain. All repeaters then broadcast segments during the frame payload, of constant length in time. A similar procedure occurs in uplink frames, but with repeaters and vehicle antennas in reversed-role.

At the end of each frame, some packets are successfully recovered. It would be redundant for repeaters to transmit segments of packets that are successfully recovered in previous frames. Consequently, we recommend a redundant-segment flushing process. The master antenna broadcasts a *packet recovery update record* after the beacon signal. Repeaters then discard all segments of the corresponding packets that remain in their buffer. This scheme effectively increases throughput of the system, and is particularly important when the system employs erasure coding with high protection ratio. The redundant-segment flushing update occurs only after a downlink frame, because in uplink, ZC is unlikely able to quickly feedback packet recovery updates to repeaters at the next frame header, and there is no equivalency of the master antenna to broadcast to the vehicle even if such information is available. Regardless of traffic direction, a complimentary segment-timeout mechanism must be implemented at both VS and repeaters to discard lingering segments.

Information raining has several implementation advantages. First, link establishment decisions are decentralized to the

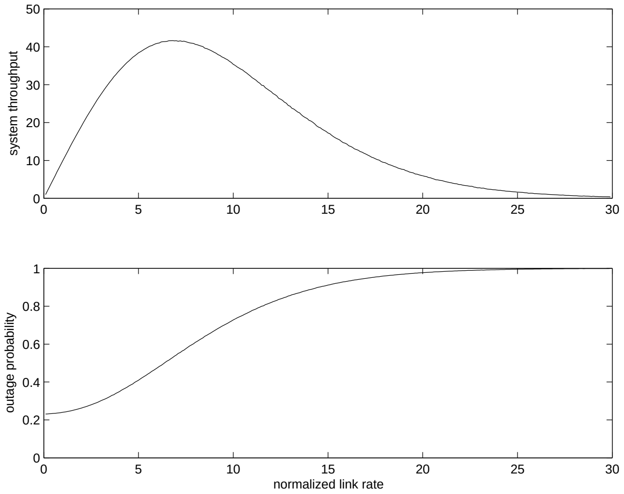

Fig. 3. System throughput and outage probability versus normalized link rate

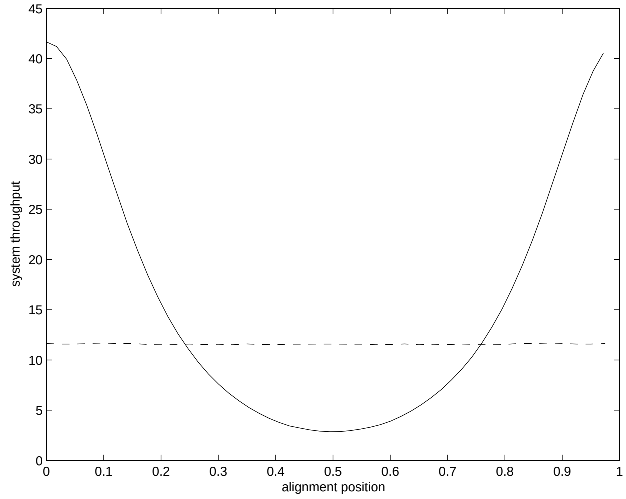

Fig. 4. Optimal system throughput versus repeater-antenna alignment

antennas. With off-the-shelf wireless components, it may be infeasible to pass channel estimation data to VS in real-time (i.e. with respect to channel coherence time) to generate a centralized decision. Second, there is no need for explicit MAC layer control. The repeaters and antennas are not required to "communicate" with each other in terms of per-link synchronization and addressing; repeaters only need to blindly transmit, and antennas only need to listen.

IV. Simulations

We have mathematically modelled our link layer architecture with information travelling from ZC to VS [4]. Our goal here is to share some insights through information raining simulations based on our system model.

Figure 3 plots the system throughput fluctuations with respect to data rate of individual links. (Both system throughput and link rates are normalized by system bandwidth and SINR threshold value to yield a fair comparison of different systems.) Intuitively, if link rate is set too low, then the aggregate rate, or system throughput, falls below its capability. If link rate is set too high, however, then many links lose their connectivity, and system throughput again falls below its capability. The outage probability in this case is defined as the probability that a segment transmitted from any repeater is not successfully received by any antenna. In information raining, there are two reasons of outage: 1) the transmitting repeater is not listened by any antennas during a frame, or 2) none of the listening antennas satisfy the SINR criteria. Simulation plots such as Figure 3 help system designers to set an optimal link rate.

When the separation distance between adjacent repeaters equals separation distance between adjacent antennas, a cyclical phenomenon in system throughput is observed as the train shifts forward, as shown in solid lines of Figure 4. The alignment position is the displacement, normalized by separation distance, of an antenna with respect to the nearest repeater behind it. The optimal system throughput reaches its maximum when repeaters and antennas are perfectly aligned, and falls to its minimum when repeaters and antennas are half-way between each other. This is expected as link gain diminishes with distance, but not desired, as the communication service becomes fluctuational. Moreover, the optimal link rate also fluctuates with alignment position, which may become a problem to the system.

A simple approach to significantly reduce cyclicity is to vary separation distances. For instance, we may increase repeater separation distance by a small amount such that some repeaters are aligned with the nearest antennas, while others are misaligned. The dashed line of Figure 4 plots the scenario that the repeater separation distance is $N/(N-1)$ times the antenna separation distance, where N is the number of antennas on the train. Clearly, the fluctuation in system throughput is mostly eliminated.

V. Conclusions

In this paper, we have investigated a novel system architecture that enables high-speed access in mass transportation vehicles. Spatial diversity is achieved through the installation of repeaters and vehicle antennas. The architecture is transparent to mobile users in the vehicle. We further investigate the link layer design approach of the architecture. The concept of information raining is also described, and simulated to illustrate cyclicity phenomenon.

References

[1] P. Djukic, "Optimum resource allocation in multipath ad hoc networks," MASc thesis, University of Toronto, Toronto, Canada, Aug. 2003.

[2] M. O. Rabin, "Efficient dispersal of information for security, load balancing, and fault tolerance," *Journal of the ACM*, vol. 36, pp. 335–348, Apr. 1989.

[3] E. Ayanoğlu, C.-L. I, R. D. Gitlin, and J. E. Mazo, "Diversity coding for transparent self-healing and fault-tolerant communication networks," *IEEE Trans. Commun.*, vol. 41, pp. 1677–1686, Nov. 1993.

[4] D. Ho, "Link layer design and throughput optimizatin of mobile hotspot in railway system," MASc thesis, University of Toronto, Toronto, Canada, to be published.