Spatio-Temporal Schedulers in IEEE 802.16

Sara Motahari, Ehsan Haghani, Shahrokh Valaee
Department of Electrical and Computer Engineering, University of Toronto
Email: {Sara, Ehsan, Valaee}@comm.utoronto.ca

***Abstract*— With the growing interest in Broadband Wireless Access (BWA) and demand for mobile high-speed connection, there is a need to extend wireless connectivity to passengers travelling in highspeed vehicles. In this paper, we use the IEEE 802.16 standard as a backhaul communication technology for broadband wireless access to railway systems. The proposed architecture uses relay elements located in the vicinity of train track to repeat the signal between the base station and the mobile vehicle. The signal transmitted from the base station is received by repeaters and relayed to the train, and vice versa. We propose spatio-temporal scheduling as a means to increase downlink throughput. The proposed spatio-temporal scheduler distributes data traffic among the repeaters in the vicinity of the train and on the route of the train. Simulation results show that a substantial improvement can be obtained when data are scheduled in both temporal and spatial dimensions.**

I. INTRODUCTION

Ho and Valaee [1] [2] have recently proposed a link-layer solution for wireless communications to mass transportation systems such as trains, subways, and busses. In their architecture, a number of relay elements are placed along the track of the railway system acting as the repeaters between the base station and the train. They decompose data into smaller fragments transmitted towards train via multiple repeaters. They use erasure coding to secure data to fragment loss. They call this method *information raining* at which fragments of data are rained upon the moving vehicle from adjacent repeaters. Unfortunately, they only concentrate on the transmission link between the repeaters and the vehicle and do not investigate the backhaul link operating between the base station and the repeaters. In this paper, we use the IEEE 802.16 in the backhaul link.

The wireless MAN standard, IEEE 802.16 [3], was originally developed as a point to multipoint protocol to provide broadband connectivity for a large number of wireless users. Because of its adaptive physical and MAC layer characteristics and its superior performance, IEEE 802.16 promises robust and flexible high speed wireless communications [4]. However, the details of switching among different modulation and coding schemes are left open for the vendors. In this paper, we will use the IEEE 802.16 standard to facilitate backhaul communication between the base station and relay elements located along the track. We will also use the adaptation algorithm of [5] to switch among the available modulations.

The present paper proposes scheduling algorithms for downlink communication that can be used in base station to maximize total system throughput, defined as the number of bits received by the train. In particular, we will introduce the concept of *spatio-temporal scheduling* for downlink communication between the base station and the repeaters. A spatio-temporal scheduler transmits data in both temporal and spatial dimensions. If the direction and the speed of the mobile vehicle is known, the scheduler can transmit data to a repeater on the route of the vehicle. In Section III, we will introduce a novel scheduling algorithm to increase the system throughput and will show that in a highly loaded network, the proposed scheduler substantially decreases the total delay while increasing the throughput.

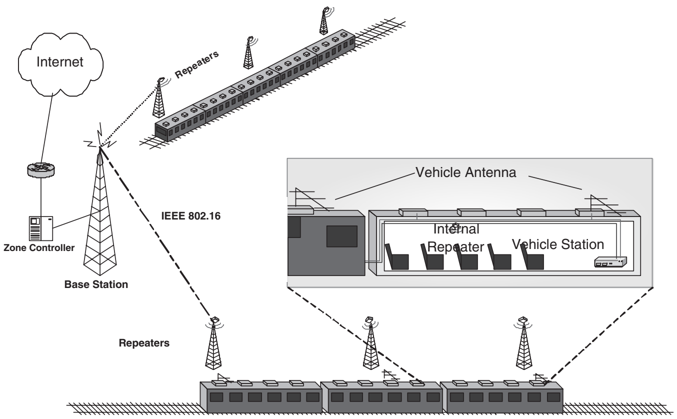

Fig. 1. Network Structure

II. SYSTEM ARCHITECTURE

Mass transportation vehicles, such as trains, subways, and busses, usually have large physical size that allows them to carry complex equipment for networking without significant space or power restriction. The system architecture proposed in [2] for wireless communication to such vehicles is illustrated in Fig. 1. It is assumed that simple, cost-effective relay elements—called *repeaters*—are located along the trackside of trains, routes of busses, or inside subway tunnels. The relay elements repeat the signal arriving from the base station to the train, and vice versa. It is also assumed that multiple antennas are mounted on the exterior of the vehicle as illustrated in the figure. These antennas can be powerful antennas that provide line-of-sight between the mobile vehicle and adjacent repeaters. The antennas and repeaters located in the vicinity of the vehicle create a bipartite graph. A proper matching can be used to tune each antenna to a corresponding repeater. Several heuristics for such matchings have been proposed in [2].

The architecture proposed in [2] comprises two main components: zone controller (ZC) and vehicle station (VS). The ZC resides at the base station and is responsible for traffic dissemination within a geographical sector that can be a street, a highway or a train route. The VS resides in the vehicle and sends the traffic to an in-car WLAN. The VS is also responsible for tuning each antenna to a peer repeater. We also assume that the base station and the repeaters have large buffers that make them capable of storing and forwarding data as needed.

The system architecture in Fig. 1 decomposes the wireless link between the ZC and the vehicle into two segments. The first segment connects the ZC to the repeaters and the second segment operates between the repeaters and the vehicle. Line-of-sight and the close distance between repeaters and antennas combat fading and can provide a high bandwidth wireless link. The link between the ZC and the repeaters may be implemented with wired or wireless technologies depending on the application for which the architecture is being used. The above scenario is applicable to both urban and rural areas, but the location of the repeaters and the distance among them depend on the wireless channel (environment), type of antennas and other factors.

In this paper, we focus on the link between the ZC and the repeaters that was not studied in [2]. Since downlink traffic has usually higher bandwidth than the uplink, we will only study downlink traffic. We will assume that the backhaul link uses the IEEE 802.16 protocol. IEEE 802.16 has originally been proposed for point-to-multipoint communication among stationary terminals. An ongoing standardization activity is underway to extend IEEE 802.16 for mobile users (IEEE 802.16e). In this paper, since both the base station and the repeaters are stationary, we will use the IEEE 802.16a standard.

We assume that the exact location of the train and its direction and speed is known at the ZC. This information can be easily collected by using a tagging system [6]. Each vehicle is assigned a tag when it enters the region controlled by a ZC. The tag is redeemed when the train leaves the region. We assume that the base station may be serving several trains simultaneously with a unique tag assigned to each train. Each train transmits its tag along its route to destination. All repeaters that hear the tag are awakened and can be used as relay points for data traffic communication between the ZC and the repeaters. The ZC can locate the train by observing the awakened repeaters.

III. SPATIO-TEMPORAL SCHEDULING

In this section, we introduce the concept of *spatio-temporal scheduling*. We assume that each active repeater estimates the downlink channel between the ZC and itself in each time slot and reports the results back to the ZC. In a conventional wireless application, this information is used to design a *temporal scheduler* to allocate proper bandwidth to each receiver to maximize the total downlink throughput. These techniques have been successfully used in cellular networks [7] [8]. However, the proposed spatio-temporal scheduling distributes data both in temporal and spatial domains to increase the total bandwidth.

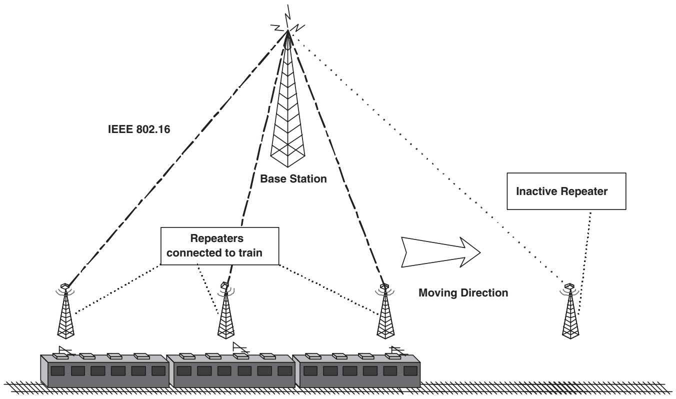

Fig. 2. Spatio-temporal scheduling

Using the tagging system [6], the ZC will be aware of the location of the train and its direction. We show an instance of this case in Fig. 2. In this figure, the three left repeaters are in the vicinity of the train and are awakened by the train. These three repeaters can directly communicate with the train. Our backhaul point-to-multipoint link should distribute data traffic on these three repeaters. The right most repeater is out of range of the train and is inactive. Now consider a case at which the aggregated downlink bandwidth between the BS and the three active repeaters is smaller than the total input traffic arriving at the BS from the Internet. In such conditions, the traffic should be buffered in the ZC and be transmitted in a later time when the downlink channel becomes available. The spatio-temporal scheduler will allow the ZC to transmit the excess traffic to the fourth repeater in Fig. 2 if the corresponding link can support a high bandwidth. The stored data at the fourth repeater are to be transmitted to the train when it enters the coverage area of that repeater. Indeed, the spatio-temporal moves the buffer from the ZC to a repeater along the route of the train.

Transmitting the traffic to an inactive repeater on the route of the vehicle can be visualized as adding a constant deterministic delay (assuming that the speed of the vehicle is constant) to the traffic and moving it quickly out of the ZC buffer. As we will see, this will increase the total throughput arriving at the train and substantially reduce the average delay in the system. An obvious question would be under what conditions an inactive repeater should be used and how much of the buffered traffic in the BS should be forwarded to that repeater.

It was shown in [9] that mobility can increase the throughput. In [9], the transmitter sends its packet to a mobile relay element that moves to the neighborhood of the receiver. The relay element then delivers the packet when it enters the coverage area of the receiver. Here, we use a different approach. In our scheme, the train moves to the vicinity of the repeater that is holding a packet for it. Therefore, we expect that the throughput will increase if the location of the mobile unit and its direction are used in the spatio-temporal scheduler. We will show this fact in the following sections.

IV. HEURISTIC SCHEDULING ALGORITHMS

We assume that the ZC supports data traffic of several trains. The proposed scheduler operates in two time scales. In a large time scale (1 sec), the ZC allocates a fraction of the IEEE 802.16 frame (5 msec) to each train in proportion to the amount of data buffered at the ZC for that train. Therefore, the total fraction of the frame assigned for each train is constant over 200 frames. If the i^{th} train has a data queue size of F_i at the base station, its allotted fraction, α_i will satisfy:

$$\begin{cases} \frac{F_i}{\alpha_i} = \frac{F_j}{\alpha_j} & \forall j \neq i \\ \sum\limits_i \alpha_i = 1 \end{cases}$$

In a smaller time scale of 5 msec, the allocated subframe for each train should be used to distribute data among repeaters. The ZC uses downlink channel capacity estimation to assign appropriate burst profiles for each repeater every 5 msec. The data are then distributed to all such repeaters in the decreasing order of their channel bandwidth.

In this section, we propose our heuristic scheduling algorithms to divide the allocated subframe of each train between the repeaters.

A. Temporal Scheduling

In this scheduling approach, the BS sends data only to the repeaters that are in the vicinity of the train and directly connected to it. Since each repeater communicates with the train for a limited time, the data remaining in its buffer must be retransmitted after disconnecting from the train. Any data left in the buffer of each repeater should be sent back to the ZC, on uplink channel, for retransmission towards the train via other repeaters. Since overfilling a repeater can increase the probability of retransmission, the ZC should consider the amount of data left in the buffer of each repeater while distributing data in each new cycle. We define a buffer threshold, B_{th}, to limit the maximum queue size in each repeater. If the queue size in a repeater is equal to B_{th}, it will not receive any data from the ZC. A proper value for B_{th} can be found by considering the velocity of the train, the distance and the channel condition between the repeaters and the train. Due to lack of space, the relationship between these parameters is not presented in this paper.

B. Spatio-Temporal Scheduling

In the heuristic spatio-temporal scheduler, the downlink data will be transmitted to a repeater along the route of the train if the channel condition of that repeater is much better than the channels of the active repeaters. To avoid large delays, we only allow the scheduler to use the next immediate inactive repeater on the route of the train as shown in Fig. 2.

We further note that only delay-tolerant (elastic) data are transmitted to inactive repeaters. Delay-sensitive (real-time) traffic is only distributed among active repeaters. Therefore, when the next immediate inactive repeater has a downlink channel better than the active repeaters, the scheduler first distributes real-time traffic among the active repeaters and then transmits delay-tolerant traffic to the inactive repeater. Our simulation studies show that the proposed spatio-temporal scheduler has higher throughput and smaller average delay than the temporal scheduler.

V. THROUGHPUT MAXIMIZATION

In this section, we proposed an optimum technique to maximize the total downlink throughput delivered to the train. In the optimization, the following parameters are defined for the j^{th} repeater at the t^{th} time slot for all $t < T$ and $j < M$, where T is the observation window, and M is the number of repeaters:

- C_{tj} : The maximum number of raw bits that can be sent from the repeater to the train in the t^{th} time slot (5 msec). To model switching between the repeaters, we assume that C_{tj} is zero for those repeaters which are not connected to the train at the t^{th} time slot.
- B_{tj} : Data queue size, buffered in the repeater at the beginning of the t^{th} time slot.
- L_{tj} : The number of raw data bits that can be sent from the ZC to the j^{th} repeater if the repeater uses the entire subframe dedicated to the train for the t^{th} time slot. L_{tj} depends not only on the length of the allocated subframe, but also on the channel conditions between the ZC and the repeater.
- A_{tj} : The fraction of the subframe allocated to the repeater. Hence, $A_{tj} \leq 1$, and the number of bits sent from the ZC to the repeater at that time slot equals $A_{tj}L_{tj}$.
- X_{tj} : The number of data bits sent from the repeater to the train.

From these defintions, we can show that B_{tj} satisfies the following equation:

$$\mathrm{B}_{tj} = \sum_{i=1}^{t-1} (A_{ij}L_{ij} - X_{ij}) \tag{1}$$

We assume that the distance between the train antennas are sufficiently large and the distance between the repeaters and the train antennas are short. Therefore, the interference can be neglected and X_{tj} can be assumed to be independent of X_{tk}; $k \neq j$.

If a repeater has enough data in its buffer, it will use the entire defined channel capacity to send it, but if it doesn't have a buffer size large enough to utilize C_{tj}, it only sends as much data as it has. In the other words:

$$X_{tj} = min(B_{tj}, C_{tj}) \tag{2}$$

Throughput, Γ, is the average data bits sent to the train by all repeaters during the observation interval T:

$$\begin{aligned} \Gamma &= \frac{1}{T}\sum_{j=1}^{M}\sum_{t=1}^{T} X_{tj} & (3) \\ &= \frac{1}{T}\sum_{j=1}^{M}\sum_{t=1}^{T} \min(B_{tj}, C_{tj}) & (4) \end{aligned}$$

Let us assume that C_{tj} and L_{tj} are known for all $t \leq T$. We can optimize throughput by:

$$\text{maximize:} \quad \Gamma = \frac{1}{T} \sum_{j=1}^{M} \sum_{t=1}^{T} \min(B_{tj}, C_{tj}) \tag{5}$$

subject to:

$$B_{tj} = B_{t-1,j} \; - X_{t-1,j} + A_{tj}.L_{tj} \tag{6}$$

$$\forall t < T : \qquad \sum_{j=1}^{M} A_{tj} = 1 \tag{7}$$

$$\forall t < T : \quad \sum_{j=1}^{M} A_{tj} L_{tj} \leq R_t \tag{8}$$

where, R_t is the queue size in the ZC buffer. This is a non-linear optimization problem and can be solved with numerical methods.

Note that the assumptions we made on C_{tj} and L_{tj} are unrealistic. We only use this optimization problem to evaluate our spatio-temporal scheduler. We will show that our proposed spatio-temporal scheduler performs very close to the scheduler found from (5).

VI. SIMULATIONS

We simulate a scenario with three trains using a single ZC. Trains are 100 meters long and have three antennas, with a distance of 50 meters between them. Repeaters also have a distance of 50 meters from each other. Each train is moving with the speed of 90 km/h. We assume that the IEEE 802.11g protocol is used for downlink communication between repeaters and the train. The maximum Doppler Shift in the channels of the repeaters to antennas is $f_m = \frac{v}{\lambda}$ and for 802.11 with $\lambda = 0.125m$ and for a train speed of 90 km/h, we have $f_m = \frac{25^{m/s}}{0.125^{m}} = 200$ Hz. So, the coherence time can be calculated as $T_c = \sqrt{\frac{9}{16.\pi.f_m^2}} = 2ms$. Since each train is 100 meters long and carries 3 antennas, the average duration of time that each antenna uses the 802.16 downlink frame is less than the coherence time. Therefore, good channel estimates can be found for downlink transmission. The channel between the base station estimates and each repeater is estimated every 5 msec. The coherence time of this channel is 0.4 second [10]. Therefore, the channel is very correlated during each transmission.

We consider three classes of traffic for downlink. The first type of traffic has the highest priority and is suitable for real-time applications. The second type is appropriate for applications such as FTP and web browsing, and the third type is delay tolerant (elastic). The ZC and the repeaters have separate buffers for each type of traffic and send the data from the buffers with respect to their priority.

Simulations were performed for 2100 seconds (or 420000 time slots of 5 msec). Throughput of each train is sum of all the data bits received during this period. The delay of each traffic type is computed separately.

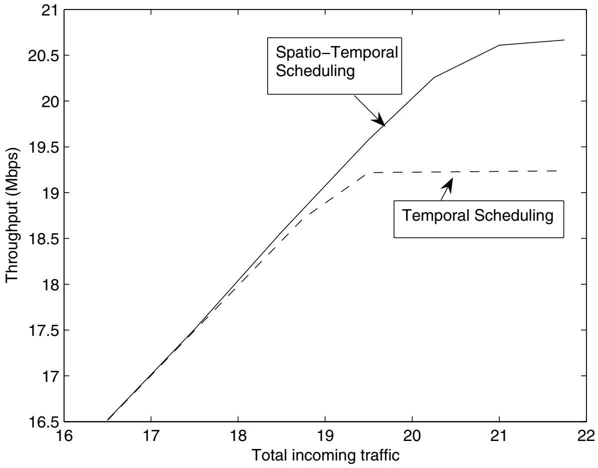

Fig. 3. Throughput Comparison

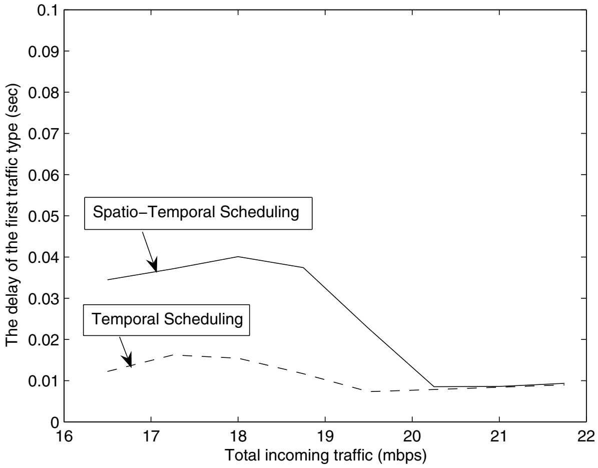

Fig. 4. Delay Comparison

In the simulation of the heuristic spatio-temporal algorithm the next immediate inactive repeater on the route of the train receives elastic traffic when it has the best channel among all repeaters. We have found that the highest throughput with acceptable delays were achieved when more than 4/5 of the frame was dedicated to the inactive repeater. The first and second classes of traffic are always sent to the active repeaters.

Fig. 3 illustrates how the throughput of spatio-temporal algorithm exceeds that of temporal algorithm as the incoming traffic increases. Fig. 4 and Fig. 5 show the delays of system for the first and second types of traffic. As shown in Fig. 6, the delay of the third traffic, rapidly growing in temporal scheduling, substantially decreases in spatio-temporal scheduling.

There is a trade off between the throughput and the delay of the first and second types of traffic. Although the total throughput increases with the spatio-temporal scheduling, the delays of the first and second traffic types also increase for low traffic loads. However, simulations show that these delays

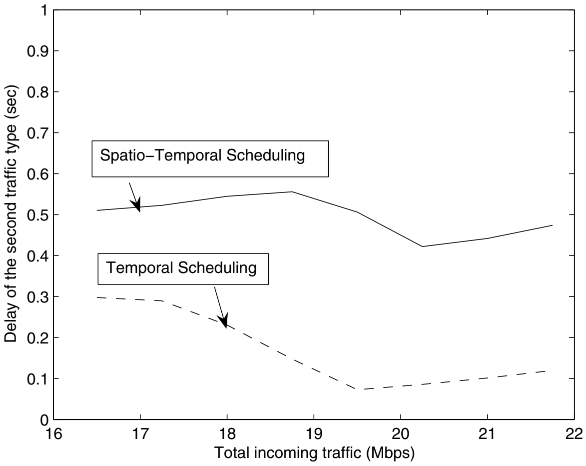

Fig. 5. Delay Comparison

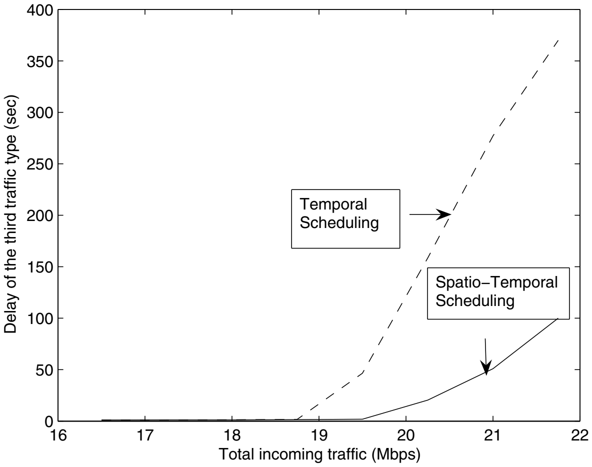

Fig. 6. Delay Comparison

are tolerable. The delay of the first traffic type is less than 40 msec in the worst case, and that of the second class is less than 0.6 sec as shown in Fig. 4 and Fig. 5.

Global optimization was solved when different classes of traffic were not considered, which means the whole data may be sent to the fourth repeater. It is because in throughput maximization, we only aim at maximizing the throughput, and not decreasing the delay. Because of the above freedom and as we assumed C_{tj} and L_{tj} were known for all $t < T$, this optimization result might seem to be better than the simulation results for heuristic spatio-temporal scheduler. However, As illustrated in Fig. 7, the spatio-temporal algorithm achieves a throughput of about 80% of that of the optimized technique.

VII. CONCLUSION

In this paper, we have used the IEEE 802.16 standard as a backhaul communication technology for broadband wireless access to railway systems. The proposed architecture uses relay elements located in the vicinity of train track to repeat the signal between the base station and the mobile vehicle. The signal transmitted from the base station is received by repeaters and relayed to the train, and vice versa. We have proposed a novel scheduling algorithm that distributes data in both temporal and spatial domains. We use the spatio-temporal scheduling as a means to increase downlink throughput. We have introduced a heuristic and an optimal spatio-temporal scheduler. Simulation results show that a substantial improvement can be obtained when data traffic are scheduled in both temporal and spatial dimensions.

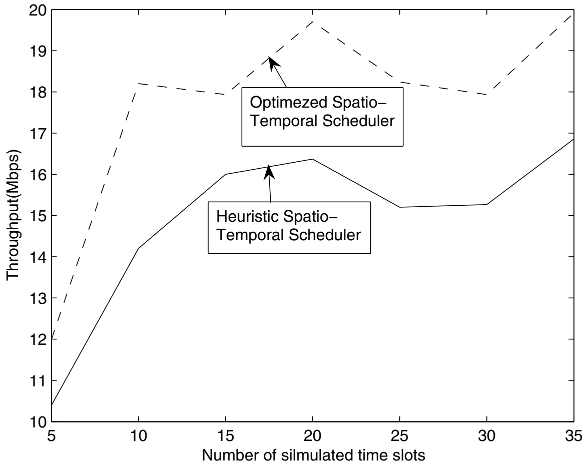

Fig. 7. Optimization and Simulation Results

REFERENCES

[1] D. Ho and S. Valaee, "Mobile hot spot in railway systems," in *proceedings of 22nd Biennial Symposium in Communications*, 2004.

[2] ——, "Information raining for link-layer design of mobile hotspots," *IEEE Trans. on Mobile Computing*, vol. 4, no. 3, pp. 271–284, May/June 2005.

[3] *IEEE 802.16-2004 WirelessMAN Standard for Wireless Metropolitan Area Networks*, IEEE Std. 802.16, 2004.

[4] C. Eklund, R. Marks, K. Stanwood, and S. Wang, "IEEE standard 802.16: a technical overview of the wirelessman air interface for broadband wireless access," *IEEE Communications Magazine*, vol. 40, no. 6, pp. 98–107, 2002.

[5] S. Ramachandran, "Link adaptation algorithm and metric for IEEE standard 802.16," Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, 2004.

[6] A. W. Anpalagan and E. S. Sousa, "A tagging-based medium access scheme for wireless data applications in CDMA/TDM networks," in *Proc. IEEE International symp. on personal, Indoor and Mobile Radio Communications*, San Diego, CA, USA, 2001, pp. E–152–E156.

[7] A. Jalali, R. Padovani, and R. Pankaj, "Data throughput of a CDMA/HDR a high efficiency high data rate personal communication wireless system," *IEEE VTC00*, pp. 1854–1858, 2000.

[8] X. Liu, E. Chong, and N. Shroff, "Optimal opportunistic scheduling in wireless networks," in *Proc. IEEE 58th Vehicular Technology Conference (VTC'2003)*, vol. 3, Oct. 2003, pp. 1417 – 1421.

[9] M. Grossglauser and D. Tse, "Mobility increases the capacity of adhoc wireless networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 4, pp. 477–486, 2002.

[10] V. Erceg, K. V. S. Hari, M. Smith, and D. S. Baum, "Channel models for fixed wireless applications," *Contribution to IEEE 802.16.3*, 2001.