

Space Division Multiple Access (SDMA) for Robust Ad hoc Vehicle Communication Networks

Soheila V. Bana, Pravin Varaiya

Abstract— This paper proposes a novel robust and self-organizing architecture for mobile ad hoc networks. The proposed architecture, space division multiple access (SDMA), relies on user position information and provides users access to the communication channel based on their spatial locations. SDMA divides the geographical space, where the users are located, into smaller spaces. The key element of the design is a one-to-one map between the space divisions and the bandwidth divisions of time slots, frequency divisions, etc. Therefore, SDMA is compatible with any multiple access scheme such as TDMA, FDMA, CDMA, etc. The system requirement is the user information of its position and *a priori* knowledge of the one-to-one map between the space divisions and the bandwidth divisions. The scheme is self-starting and self-maintaining. It provides collision-free access to the communication medium for the users, and thereby, facilitates ad hoc communication address resolution amongst the users. In addition, SDMA guarantees delay-bounded communication in real-time. The paper presents the SDMA architecture and discusses its advantages and disadvantages. Moreover, enhanced SDMA is discussed for increased bandwidth efficiency.

Keywords— Vehicle Communication, Ad hoc Network, Medium Access Control, Address Resolution

I. INTRODUCTION

VEHICLE-TO-VEHICLE (V2V) communication can promote safety. Exchange of information regarding vehicle dynamics and road conditions among vehicles could play a crucial role in driver and passenger safety. A driver, provided with information about road conditions and velocities of the vehicles around it, is able to make better decisions with regards to vehicle control and travel path. As an example, consider driving in a bad weather condition such as heavy fog. When vehicles communicate their real-time velocity values, a driver can avoid accidents by adjusting her velocity according to neighboring vehicle velocities.

V2V communication is useful not only in enhancing safety but also in vehicle automation. V2V communication is a key element in vehicle automation. A vehicle in automated highway systems (AHS) [1] communicates with neighboring vehicles to exchange vehicle control data [2], [3], [4]. As a result, automated vehicles interact safely.

V2V communication is likely to be through ad hoc networks that do not rely on infrastructure because of the high-speed mobility of roadway communications and their dynamic topology.

Current wireless ad hoc network technologies are not

well-suited for V2V communication because they do not satisfy the following requirements. First, V2V communication for control needs to be in real-time and delay-bounded. Second, the communication addresses for the current wireless technologies are assumed to be resolved while in V2V communication addresses are not known *a priori*. Third, the technology must be scalable and provide access to a vast number of users. Fourth, the technology must take efficient use of the bandwidth. Finally, initializing an ad hoc network and maintaining its organization while different users constantly join and depart the network are major issues that need to be resolved. Initializing the network organization must be independent of the number of users and the network topology. If arrival or departure of a user disturbs the communication network, or introduces additional delay on existing users, it may cause problems with real-time communication. In the case of automated vehicles in AHS, V2V communication must also be fair, i.e., provide access to all the users.

We introduce *space division multiple access (SDMA)*, an innovative scheme for medium access control with bounded delay for all users. It also provides address resolution. The proposed architecture is scalable and is independent of the number of users and network topology. SDMA makes efficient use of the bandwidth by minimizing the MAC and address resolution protocols. Finally, SDMA is a self-organizing architecture.

The paper is organized as follows. Section II explains the specific characteristics of V2V communication networks. Section III briefly overviews the major existing wireless ad hoc technologies and explains why they are not appropriate for V2V communication. Sections IV and V discuss SDMA in detail and present an example of its application for automated vehicle networks, respectively. Section VI discusses how SDMA can be further enhanced for more efficient use of the bandwidth. Section VII concludes the paper.

II. BACKGROUND

Two main challenges for wireless mobile ad hoc networks at the data link layer are medium access control and communication address resolution. The physical layer in wireless communication can take advantage of advanced RF technology. The other layers [5] are not very different from the conventional networks.

A. Medium Access Control

Medium access control (MAC) refers to controlling user access to the communication channel, i.e., sharing the bandwidth amongst the users. Ideally, the bandwidth

Soheila Bana is with 3Com Corporation. E-mails: Soheila.Bana@3com.com .

Pravin Varaiya is a professor at the Department of Electrical Engineering and Computer Sciences at the University of California at Berkeley. Email: Varaiya@eecs.berkeley.edu .

would be shared fairly with some quality of service considerations. When communication is used for real-time information, there needs to be a bound on the delay that a user experiences before it can successfully access the channel. If users need to exchange MAC protocols to obtain access, then it is desired that MAC protocols use a minimal portion of the bandwidth.

B. Communication Address Resolution

Communication address resolution in conventional networks such as the Internet and telephony is the unique binding between a user's personal ID and the location of its communication device. An email address, soheila@eecs.berkeley.edu, is an example of a binding of a personal ID, soheila, and the Internet address, eecs.berkeley.edu which specifies a host in the Berkeley campus. Similarly, the phone directory keeps a binding between a user's personal phone number and the location of her telephone. In the case of a cellular phone, the phone company has a harder time to keep track of the location, i.e., mobility management [6]. However, the nature of the binding is the same.

In the context of V2V communication, address resolution is defined differently [7]. Consider three vehicles on the road as depicted in Figure 1. If the front vehicle wants

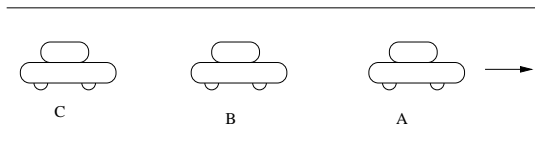


Fig. 1. Vehicle *A* wants to communicate with its behind vehicle, *B*.

to warn the vehicle immediately behind it about its decreasing velocity, it needs to address it by its relative position *BEHIND*. Here, the personal ID of the vehicle behind or its driver is not relevant. But address resolution is defined as a binding between the *relative position* of the addressee, i.e., *BEHIND*, and its receiver communication address. In Figure 1, call the vehicles from front to back *A*, *B*, and *C*, respectively. The binding that *A* needs is $\langle \textit{BEHIND}, B\text{-Receiver-ID} \rangle$. Then *A* can send a message to the vehicle behind it by addressing it to *B-Receiver-ID*. Note that if *A* sends a message that is addressed to *BEHIND*, then *B* cannot figure out that it is the addressee.

What makes MAC and address resolution in V2V communication more complicated is the fact that any practical solution to these problems must be *scalable* to accommodate the increasingly large number of users.

III. EXISTING AD HOC NETWORKS

We review two popular wireless ad hoc network technologies used for personal data communication. We briefly describe their major characteristics with respect to the MAC layer and then explain why they are not appropriate solutions for V2V communication.

A. Bluetooth

Bluetooth is a wireless technology optimized for short range communication with low power. It is specially appropriate for cable replacement and for use with portable devices in pervasive computing applications [8], [10].

A Bluetooth ad hoc network, called a *piconet*, accommodates up to seven users. Piconets that have common users can form a *scatternet*. However, the common user can be active in one piconet at a time. In a piconet, an arbitrary user plays the role of the “master” and the other users act as “slaves”. Initially, different users have different clock times but in a piconet the slave clocks are synchronized with the master clock. A slave can be in the active communication or standby mode. The master controls the medium access. It polls the slaves for communication and schedules the transmission of the active users based on traffic demands to and from the different slaves. In addition, it supports regular transmissions to keep slaves synchronized to the channel.

B. Wireless Local Area Network (WLAN)

WLAN is based on the IEEE 802.11 standard. It provides two services, synchronous and asynchronous, that can be implemented with or without infrastructure, respectively. We focus on the asynchronous or ad hoc mode. The MAC protocol for the ad hoc mode is carrier sense multiple access with collision avoidance (CSMA/CA). A user senses the medium before attempting a transmission. If it senses the medium is idle for an interframe space, then it transmits its data. If it senses the medium is busy, then it back-offs for a random interval between zero and a maximum contention window. The backoff interval is decremented when the channel is idle until it reaches zero and the user attempts to access the medium. The receiver sends an ACK to the sender when the transmitted data is received. If the sender does not receive an ACK, it attempts another transmission [9], [11].

Currently, WLAN is mostly used with an access point in the synchronous mode where the access point polls the users, similar to the master-slave scheme in Bluetooth.

C. Bluetooth and WLAN Shortcomings for V2V Communication

Both Bluetooth and WLAN technologies support wireless ad hoc networks. However, *mobility* needs to be considered with more care in wireless technology. Mobility should be distinguished from *portability*. Portability means the group of users can form a network at any point as long as they are within communication range of one another. Mobility refers to forming an ad hoc network *during the move* when the network users are within the communication range of one another. The wireless ad hoc network technologies that are discussed above provide portability, but not mobility. Mobility introduces issues such as users joining and departing the network at high rate and speed. Moreover, V2V communication is likely to be multicast. ACK is used in the current unicast personal wireless com-

munication to confirm lack of data collision. In the multi-cast mode of V2V communication, a problem is how to verify lack of data collisions. Finally, a characteristic of V2V communication is the large number of users that is impossible to accommodate by current wireless ad hoc network technologies.

IV. SPACE DIVISION MULTIPLE ACCESS (SDMA)

Space division multiple access (SDMA) is an ad hoc network architecture that provides a fair and delay-bounded medium access to all the users, and the rate at which the users join or depart the network does not impair the network organization. SDMA provides medium access to the users based on their position in space. Thus, every user must have real-time position information.

The geographical area where the users are located is divided into smaller space divisions where there is a one-to-one map between the space divisions and the bandwidth divisions. The bandwidth could be divided according to any multiple access scheme such as TDMA, CDMA, FDMA, etc. Let us consider the geographical space \mathcal{S} and partition it into n space divisions $\{S_1, S_2, \dots, S_n\}$ where every space division holds at most one user. Moreover, assume that the bandwidth \mathcal{B} is also partitioned into n divisions $\{B_1, B_2, \dots, B_n\}$ where the divisions could refer to time slots, frequency divisions, etc. Now consider a one-to-one map such as

$$\mathcal{F} : \mathcal{S} \longrightarrow \mathcal{B}$$

that assigns a unique bandwidth division to every space division. Thus, SDMA assigns medium access to the users based on their position.

Every user needs to know its real-time position in the geographical space, and the unique map of its position to the set of bandwidth divisions, \mathcal{F} . Therefore, the user requirement is the knowledge of (i) position in real-time and (ii) the one-to-one map from space divisions to bandwidth divisions.

A. Medium Access Control (MAC)

Let us take time slots as bandwidth divisions assigned by SDMA. That is, SDMA provides time division multiple access (TDMA) based on the space position of the users. Consider the map $\mathcal{F} : \mathcal{S} \longrightarrow \mathcal{T}$ where \mathcal{T} is a time period. Consider a user x that has its position information with respect to the space divisions in real-time denoted by $S_x(t)$. x uses the map \mathcal{F} to find its time slot, say, T_i . Therefore, x can access the communication channel without contention. The users do not exchange MAC protocols and still can access the communication channel without data collision. Thus, the bandwidth is used efficiently for data communication. If the time slots are equal intervals, SDMA provides equal bandwidth to all users.

When users are mobile, their space positions may change in real-time. That is, the position of the user x at time t' may be not the same as its position at time t , $S_x(t') \neq S_x(t)$ when $t \neq t'$. The new position of x maps to a new time slot, say, T_j where $T_j \neq T_i$. In other words, the access

time of x varies within a period as it moves. However, the delay is bounded in the sense that every user can access the channel at every period.

B. Address Resolution

In V2V communication every vehicle communicates with its neighboring vehicles where the exact definition of “neighboring” vehicles is specified by the level of vehicle automation and communication objectives. We assume that the communication range covers the “neighboring” vehicles. Address resolution for a vehicle i is a set of bindings with regards to its neighboring vehicles where each binding is defined between the communication receiver ID of a neighboring vehicle j and its relative position with respect to i . In a mobile V2V communication network, the network topology is dynamic and this binding is dynamically changing and needs to be updated periodically. The binding information needs to be current in real-time and a delay bound is necessary.

Here we explain how address resolution is possible by SDMA. Using SDMA, every user can access the communication channel periodically and broadcast its communication receiver ID along with its position when it accesses the medium. Suppose that user i broadcasts its communication receiver ID and position. Every neighboring vehicle j receives the information and compares the position of i with its own, and hence, deduces the relative position of i . Thus, every neighbor of i builds an accurate binding between the communication receiver ID of i and its relative position.

C. Robust Network Organization and Maintenance

SDMA provides robust network organization. The initial organization phase of an ad hoc network is bypassed by providing prior information in terms of dividing the bandwidth amongst the users. That is, the network is formed instantly without the need for users to page and detect one another. This instant communication not only saves time and power but also provides address resolution to all users. Moreover, the network organization does not depend on the presence of specific users, or the number of users. When a user or a number of users leave the network, the communication of other users is not impaired. Finally, fair access to the medium is provided to all users regardless of the time they join the network.

D. Bandwidth Efficiency

SDMA advantages come at the price of positioning information and bandwidth efficiency. The bandwidth efficiency of SDMA depends on the number of WAN users on the space divisions and when users are not present at some space divisions, the assigned bandwidth would be wasted. The result is that the bandwidth efficiency of SDMA scheme is variable and proportional to the number of occupied space divisions. In Section VI, we discuss how SDMA can be enhanced to provide more efficient use of bandwidth.

E. Positioning Accuracy and Error Margins

SDMA assumes that every user is aware of its position with respect to the space divisions in real-time. Moreover, it assumes that there can be at most one user per space division. These assumptions require an accurate vehicle positioning system. The positioning error may cause a user to try to access a bandwidth division that is assigned to a different user. Consider users i and j at space divisions S_i and S_j , respectively. Suppose the positioning error of i may cause it to assume that it is located at S_j . Then i transmits at the bandwidth share of j , causing a data collision.

Today, global positioning system (GPS) is the most widely used positioning system with relatively high accuracy. However, its accuracy depends on the surrounding environment and weather conditions. GPS receivers in metropolitan areas suffer from the multipath problem [12]. Therefore, the highest level of accuracy of GPS is not reliable.

Another positioning system for vehicles is the magnetic positioning system [13]. Theoretically, this positioning system is similar to GPS in terms of range measurement through pseudo-noise sequence codes. However, the signal in the magnetic positioning system is carried through the magnetic markers that are installed on the road. Magnetic signals are provisioned to be used in automated roads at the center of every lane. The accuracy of this system is subject to design.

We need to consider the reliable range of the vehicle positioning system that is used and partition the geographical space into divisions according to the positioning accuracy. Moreover, we can add error margins to space divisions in order to avoid possible data collisions. Consider two adjacent space divisions S_1 and S_2 which contain users that transmit at time divisions T_1 and T_2 , respectively. Furthermore, assume that the maximum positioning error by a user is e_s . The time margins that we consider for space margins are such that T_1 correspond to the user in the space division $S_1 - e_s$. Similarly, T_2 correspond to the space division $S_2 - e_s$. Figures 2 and 3 illustrate that space divisions overlap by the amount of positioning accuracy, e_s , while the time divisions do not overlap.

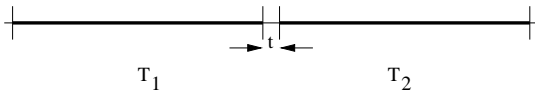


Fig. 2. Time divisions T_1 and T_2 for two users within one TDMA period where the time margins for the synchronization error is indicated by t .

Finally, we need to examine if our assumption of one user per space division is realistic with respect to the positioning accuracy achieved by the current positioning systems. A vehicle size could be as small as 3-4 meters and when vehicles move slowly, they could be as close as a sub-meter distance from each other. That is, a positioning accuracy of $\pm 2m$ is required. This is achievable by the magnetic positioning system [13]. However, the magnetic position-

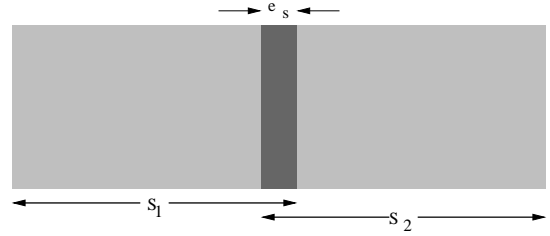


Fig. 3. The space divisions S_1 and S_2 with space margins that correspond to the positioning error e_s .

ing system requires an infrastructure of magnetic markers on the road. With GPS we need to consider larger space divisions in order to guarantee that we have a reliable positioning accuracy. A larger space division can accommodate more than one user.

In the next section, we present an example of using magnetic positioning system with SDMA and then we discuss the case of multiple users per space division.

V. EXAMPLE: SDMA FOR AUTOMATED VEHICLES

We present an example of employing SDMA for address resolution and medium access control for automated vehicles in a three-lane automated highway system [1], [14], [15], [16], [17]. We use TDMA for the bandwidth divisions. The positioning system for automated vehicles is assumed to be the magnetic positioning system [13] which provides the desired positioning accuracy reliably. We make the following technical assumptions about the clock synchronization and positioning accuracy based on GPS and magnetic positioning system technologies, respectively.

- The relative clock accuracy of vehicles is within 100 nanoseconds.
- Positioning accuracy is ± 2 meters.

Moreover, we consider the following technical specifications about the communication structure.

- Every vehicle broadcasts every 20 milliseconds approximately 100 bytes of data.
- The longitudinal safety margin between two vehicles is 10 meters which is maintained during normal AHS operation.
- The communication range of vehicles is 150 meters in each direction.
- A time division within a time period can be used simultaneously by two vehicles if they are at least 500 meters apart.

We consider the maximum number of vehicles that occupy 500 meters of the road. First, we divide the road into space divisions such that no two vehicles can be on the same space division at one time. Then, we divide a time period of 20 milliseconds among these space divisions. This assignment of time divisions to the space divisions can be repeated every 500 meters on the road.

These assumptions lead to the following calculations for the length of space and time divisions. In each lane of the 500 meter segment of the road there are ($500 \text{ meters} \div 10 \text{ meters} =$) 50 vehicles. In the three lanes, there are ($3 \times 50 =$) 150 vehicles. These vehicles need unique time

divisions within a 20 millisecond period. In order to guarantee that positioning errors will not cause a problem, we consider every space division to be 5 meter long. That is, we double the number of space divisions ($2 \times 150 = 300$). The fact that vehicles are 10 meters apart at all times guarantees that positioning errors will not cause data collisions. Every vehicle has a time division of ($20\text{millisecond} \div 300 =$) 65 microseconds which is sufficient for transmitting 100 bytes of data by the currently available 2.4 GHz wireless technology. Figure 4 depicts the related time allocations

1	4	7	10		298	1
2	5	8	11		299	2
3	6	9	12		300	3

Fig. 4. The space divisions on the road that correspond to the time divisions.

for the space divisions on the road.

VI. ENHANCED SDMA FOR BANDWIDTH EFFICIENCY

We can enhance SDMA to increase bandwidth efficiency, and moreover, allow different medium access intervals to different users for different data types and quality of service considerations. The enhanced SDMA does not provide control over the entire bandwidth, but provides the opportunity for all the users to access the bandwidth for a limited time interval and share their address information and communication needs. Consequently, they can access the rest of the bandwidth according to their traffic demands and communication needs. This allows for a range in the quality of service for personal data communication.

Enhanced SDMA uses a portion of the bandwidth to control the rest of the bandwidth. In one portion of the bandwidth the users transmit their communication ID and position information. Moreover, every user transmits the amount and type of data (synchronous, asynchronous, high priority, etc.) that it has to transmit. This allows every user to (i) learn the communication addresses of its neighboring users, and (ii) learn the number of users around it and their communication needs. Assuming that all users have *a priori* agreement on sharing the bandwidth according to the priorities, they can share the rest of the bandwidth without contention and collision.

Without loss of generality, let us assume bandwidth divisions in terms of time slots. Consider Figure 5. At the beginning of every time period, there is an SDMA window, T_{Access} , which allows every user to transmit their communication ID and position information as well as the amount and type of data that it has to transmit. This access window T_{Access} allows the maximum possible number of users, say n , to access the medium and transmit their information and communication needs. Thus, it is divided to n smaller windows, $T_{Access}^1, \dots, T_{Access}^n$. The rest of the bandwidth T_{Data} is accessed by the users with high priority data. The

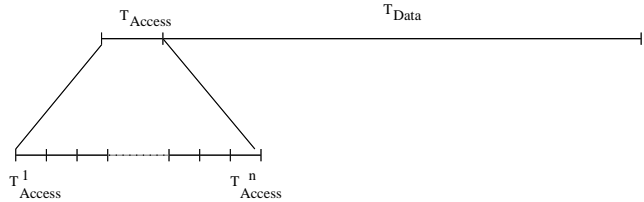


Fig. 5. The bandwidth is divided between the access time T_{Access} , that allows all users to share their information and communication needs, and data transmission time, T_{Data} , for the users with high priority data.

ratio of T_{Access} to T_{Data} can be determined with respect to the desired frequency for information update and the mean number of users. This ratio is a determining factor in the efficiency of the bandwidth.

A. Positioning Accuracy

SDMA demands a positioning accuracy that is achievable (and affordable) by all users. If the geographical area is divided into very small divisions, the required accuracy may not be achievable. Moreover, when the the geographical area is divided into many small divisions but the number of users is small, then the bandwidth dedicated to the unoccupied space divisions is wasted. On the other hand, if the space divisions are too large, then there may be more than one user per division at a time, causing data collisions.

We suggest the following scheme which does not need the assumption of one user per space division and allows for a scalable ad hoc network of vehicles. Again, we divide the geographical space into a number of space divisions with respect to the available positioning system accuracy and the mean number of users in the area. Let m and n denote the number of space divisions and the mean number of users, respectively, where we assume $m < n$. Assume that the maximum number of users per space division at any given time is equal to or smaller than p . Divide the SDMA window T_{Access} into m smaller windows $T_{Access}^1, \dots, T_{Access}^k, \dots, T_{Access}^m$. At each window T_{Access}

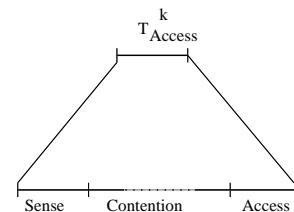


Fig. 6. Each access time T_{Access}^k is dedicated to the multiple users that are located at the corresponding space division.

the users at the corresponding space division contend for the medium access. The specific design for the contention at every T_{Access}^k window, depicted in Figure 6, can be determined according to the specific physical layer that is being used and the objectives of the communication network.

The MAC rule at each window could be similar to the IEEE 802.11 standard at asynchronous mode. This scheme

localizes the contention among a small number of users and therefore it drastically reduces the number of users that contend for the medium access, and decreases the amount of collisions. Thus, the bandwidth is utilized more efficiently.

B. Bandwidth Efficiency

By reducing the SDMA window T_{Access} that is necessary for network organization and address resolution, we effectively increase the amount of the bandwidth that is utilized for data transmission. This is because we reduce the amount of the bandwidth that is not utilized due to the lack of users in some space divisions. The main portion of the bandwidth is dedicated to the users who have data. Moreover, the SDMA window T_{Access} allows users to announce their data priority and thus, use the rest of the bandwidth with respect to the data priorities.

VII. CONCLUSIONS

SDMA is an innovative scheme for medium access control in vehicle ad hoc networks. SDMA relies on real-time position information by the users and provides a mapping of the user position to a share of the bandwidth. The advantages of SDMA are: (i) robust and instant network initialization, (ii) real-time and accurate address resolution, (iii) network maintenance, and (iv) scalability. Moreover, these advantages come without using extra MAC or address resolution protocols. The disadvantage of SDMA is that bandwidth efficiency depends on the number of users and decreases with decreasing number of users. We proposed enhanced SDMA to improve bandwidth efficiency. In addition, we argued that a high accuracy positioning system is not necessary for SDMA. When positioning accuracy is not sufficient to assume one user per space division, we allow multiple users at a space division to use a contention scheme such as IEEE 802.11 standard to access the medium. Localized contention increases the bandwidth efficiency and allows for robust ad hoc organization at a larger scale.

REFERENCES

- [1] Pravin Varaiya, *Smart Cars on Smart Roads: Problems of Control*, IEEE Transactions on Automatic Control, Vol. 38, Feb 1993.
- [2] A. Hsu and F. Eskafi and S. Sachs and P. Varaiya, *Protocol Design for an Automated Highway System*, Kluwer Academic Publishers, Boston, 1993.
- [3] Sonia Mahal, *Effects of Communication Delays on String Stability in an AHS Environment*, University of California at Berkeley, M.S. Thesis, May 2000.
- [4] S.V. Bana, *Coordinating Automated Vehicles via Communication*, University of California at Berkeley, Ph.D. Thesis, 2000.
- [5] Jean Walrand, *Communication Networks: A First Course*, McGraw-Hill Higher Education, Second Edition, 1998.
- [6] T. Imielinski and H. F. Korth, *Mobile Computing*, Kluwer Academic Publishers, 1996.
- [7] S. Bana and P. Varaiya, *Address Resolution in a One Lane Automated Highway*, California PATH Research Report, UCB-ITS-PRR-00-21, 1999.
- [8] B. A. Miller and C. Bisdikian and A. Edlund, *Bluetooth Revealed*, Prentice Hall, 2000.
- [9] Gil Held, *Data Over Wireless Networks Bluetooth, WAP, & Wireless LANs*, McGraw-Hill, 2001.
- [10] <http://www.bluetooth.com> ,
- [11] <http://www.IEEE802.org> ,

- [12] M. K. Simon and J. K. Omura, *Spread Spectrum Communications Handbook, Revised Edition*, McGraw Hill, 1994.
- [13] S. Bana and P. Varaiya, *Automated Vehicle Navigation via Magnetic Signals*, Proceedings of International Association of Institutes of Navigation Congress/Institute of Navigation Annual Meeting, San Diego, June 26-28, 2000.
- [14] P. Varaiya and S. Shladover, *Sketch of an IVHS systems architecture*, Proceedings of the Vehicle Navigation and Information Systems Conference, Dearborn, MI, 1991.
- [15] D. N. Godbole, *Hierarchical Hybrid Control of Automated Highway Systems*, California PATH Research Report, UCB-ITS-PRR-95-8, 1995.
- [16] J. Frankel and L. Alvarez and R. Horowitz and P. Li, *Safety-Oriented Maneuvers for IVHS*, Vehicles Systems Dynamics, Vol. 26, No. 4, 1996.
- [17] J. Lygeros and D. Godbole and S. Sastry, *Verified Hybrid Controllers for Automated Vehicles*, IEEE Transactions on Automatic Control, Vol. 43, No. 4, April 1998.

Soheila V. Bana received her B.S., M.S., and Ph.D. degrees in Electrical Engineering and Computer Sciences at the University of California at Berkeley in 1990, 1994, and 2000, respectively. She is currently a senior technology architect at 3Com Corporation. Her research interests include wireless mobile networking and use of positioning systems in ad-hoc wireless networks.

Pravin Varaiya is Nortel Networks Distinguished Professor in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley. His areas of research are control of transportation systems, hybrid systems, and communication networks. He is a Fellow of IEEE, and a Member of the National Academy of Engineers. He is on the editorial board of several journals. The second edition of his book, "High-Performance Communication Networks," with Jean Walrand, was published in 2000 by Morgan-Kaufmann.