In Proc. of IEEE Vehicular Technology Conference (VTC 2005 Spring)

A Radio over Fiber Network Architecture for Road Vehicle Communication Systems

Hong Bong Kim, Marc Emmelmann, Berthold Rathke, and Adam Wolisz
Telecommunication Networks Group
Faculty of Electrical Engineering and Computer Science
Technical University of Berlin Sekr FT5 Einsteinufer 25 10587 Berlin Germany
Email: {hbkim, emmelmann, rathke, wolisz}@tkn.tu-berlin.de
Tel:+49-30-314-24576, Fax:+49-30-314-23818

***Abstract*— The road vehicle communication system is an infrastructure network to be deployed along the roads for future intelligent transportation systems. Recently, in order to provide high bandwidth data traffic a radio over fiber based network at millimeter-wave bands has been proposed. In this network a control station is connected to functionally simple base stations via optical fibers. Due to millimeter-wave properties the cell size is very small; therefore, the system is characterized by small cell and high mobility. As a result, it is obvious that mobility management becomes very significant. In this paper we propose a medium access control scheme featuring fast handover and dynamic bandwidth allocation using the ability of centralized control of radio over fiber networks.**

I. Introduction

The demand for intelligent transportation systems (ITSs) using the latest mobile communication technologies continues to increase to exchange traffic information and achieve safe, smooth, and comfortable driving. These systems can be categorized into road vehicle communication (RVC) systems and inter-vehicle communication (IVC) systems. The RVC system is an infrastructure network for ITS which will be deployed along the road. The design requirements discussed in [1] for future RVC systems indicate that data rate of about 2–10 Mbps per mobile host (MH) will be required. In particular, the system supports not only voice, data but also multimedia services such as realtime video under high mobility conditions. Since current and upcoming mobile cellular systems (e.g., GSM, UMTS) at microwave bands cannot supply a high-speed user with such high data rate traffic [2] [3] millimeter-wave (mm-wave) bands have been considered such as 36 or 60 GHz bands [1] [4] [5]. Although these bands have higher bandwidth, it leads to very small cell size (up to tens of meters) due to its higher free space propagation loss as compared to conventional microwave bands. Thus, this system is characterized by very small cell that means numerous base stations (BSs) are required to cover long roads and high user mobility. We see two challenging issues here: (1) the system should be cost-effective and (2) it must support a fast and simple handover procedure.

One promising alternative to the first issue is a radio over fiber (ROF) based network since in this network functionally simple and cost-effective BSs (in contrast to conventional wireless systems) are utilized [6] [7]. In particular, a large number of BSs, which will be deployed along the road and serve as remote antenna units for MHs, are interconnected with a control station (CS) that performs all processing such as modulation/demodulation, routing, medium access control (MAC) and so on. This configuration leads to a centralized network architecture that could efficiently be used for resource management [6]. During the last decade great efforts has been made to develop simple and cost-effective BSs and mm-wave generation/transport techniques over optical fiber. Data rates more than 100 Mbps per cell over tens of kilometers of optical fiber link has been reported in several laboratory demonstrations [8] [9] [10].

However, the second issue, i.e., fast handover procedure, still remains challenging. In order to consider the requirements the system imposes on handover management, imagine a highway where a vehicle with an ongoing communication session is running at a speed of 100 km/h and the cell size is 100 m, then it will request handover every 3.6 sec. In addition, if the overlapping area between two adjacent cells is 10 m, handover must be done within 0.36 sec. This example suggests that a fast and simple handover procedure is indispensable in contrast to conventional mobile cellular networks where cell size as well as overlapping region is so large that there is enough time to treat handover. In this paper we propose an MAC protocol for ROF RVC systems featuring fast handover and dynamic bandwidth allocation. It utilizes centralized control ability of ROF networks for efficient mobility management.

This paper is organized as follows. In section II we mention related works and in the following section the proposed ROF network architecture is described. An MAC protocol is presented in section IV which is followed by a description of mobility support and resource allocation in section V and VI, respectively. Finally, we conclude the paper in section VII.

II. Related Works

In [4], an ROF network at mm-wave bands for future RVC system based on CDMA has been proposed and implemented. To facilitate handover management all the BSs connected to a CS simulcast the same signal to communicate with MHs.

*This work has been partly supported by the EC under the e-Photon/ONe project.

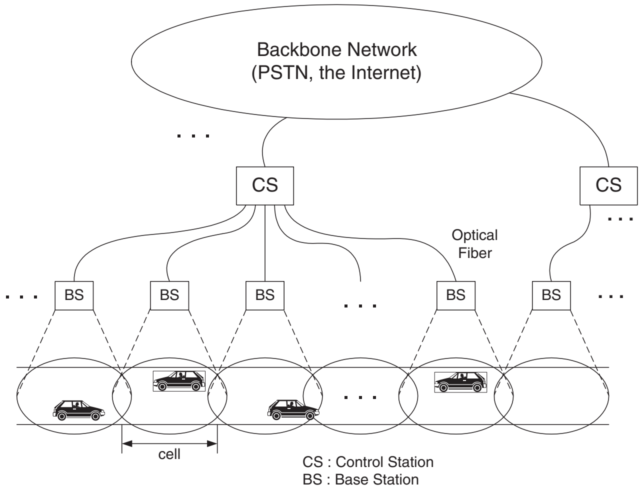

Fig. 1. Road vehicle communication system based on radio over fiber technology.

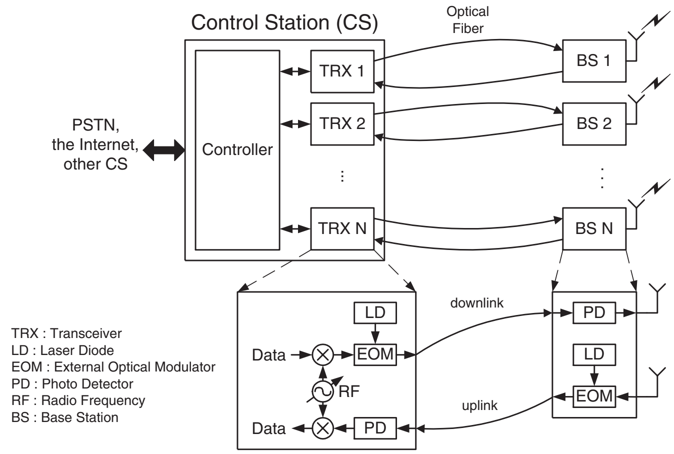

Fig. 2. An access network architecture for road vehicle communication system based on radio over fiber technology.

A drawback of the system is that data cannot be properly received in the overlapping region between cells because of co-channel interference. An MAC protocol for ROF RVC system has been proposed in [5] that is based on reservation slotted ALOHA and dynamic slot assignment. This architecture also assumed simulcasting from all the BSs connected to a CS, having co-channel interference problem in overlapping areas. In contrast, the proposed architecture in this paper avoids co-channel interference between cells, leading to seamless handover.

IEEE 802.11p is currently working on a draft standard for wireless access in vehicular environments (WAVE) using dedicated short-range communications (DSRC) operating at 5.9 GHz frequency bands [12]. However, it does not consider micro-cellular architecture deployed along the roads [13]. Combined with IEEE 802.11r for fast roaming the system has a potential for fast handover although its handover latency would be much longer compared to our scheme and high bandwidth service considered in this paper would not be supported.

III. System Description

A. Network Architecture

An RVC system based on ROF technology is shown in Fig. 1, where a CS is interconnected with a larger number of BSs via optical fibers, and BSs are deployed along the road to support communication link to vehicles. In this paper, we consider only one-dimensional road, and assume that the direction of MH's movement is known to the CS as it is easily determined while the MH moves. A CS is in turn connected to backbone networks such as public switched telephone network (PSTN) or the Internet. Each BS covers an area called "*cell*" and we assume that there is small overlapping area between two adjacent cells. In this study we focus on mm-wave band, e.g., 36 GHz or 60 GHz; therefore, the cell size could be very small up to a few tens of meters. As a result, a large number of BSs are required to cover a long road.

Several ROF technologies have been proposed to develop simple BS and transport mm-wave signals over optical fiber (for more information refer to [11]). In this paper an ROF architecture is assumed where TDMA/TDD operation is possible. Though there exist several possible options to implement such a system using different technologies, we present for explanation purpose an example ROF architecture based on external modulation as shown in Fig. 2.

For downlink transmission (from CS to MH) user data first modulates radio frequency (RF) source which, in turn, modulates optical light source using an external optical modulator (EOM). This signal is carried over the downlink optical fiber to a BS, where the optical signal is converted into wireless signal and emitted from the BS. For uplink transmission (from MH to CS), the wireless signal received at the BS is changed into optical signal by modulating light source. It is then transported over uplink optical fiber to the CS, where a photo detector (PD) first demodulates optical signal to obtain electrical signal which is again demodulated using oscillator to acquire user data. In this architecture the CS has as many transceivers (TRXs) as BSs, and each TRX constitutes a light source such as laser diode (LD) for downlink transmission, a PD for uplink reception, and a modem to transmit and receive user data in the RF domain. The BS is basically composed of a PD, an LD, an EOM and amplifiers, and it has no processing functions. For flexibility in system resource management, we assume each TRX is equipped with a tunable RF oscillator.

B. Basic Operations

Suppose a CS is connected to N BSs based on the ROF architecture shown in Fig. 2, and the BSs are deployed along one-dimensional road. The N BSs are subdivided into S groups, $1 \leq S \leq N$, where a set of BSs in the same group must be contiguously deployed, and the area covered by a group is called *"virtual cellular zone (VCZ)"*. TDMA is utilized in the system for which a fixed-size super-frame

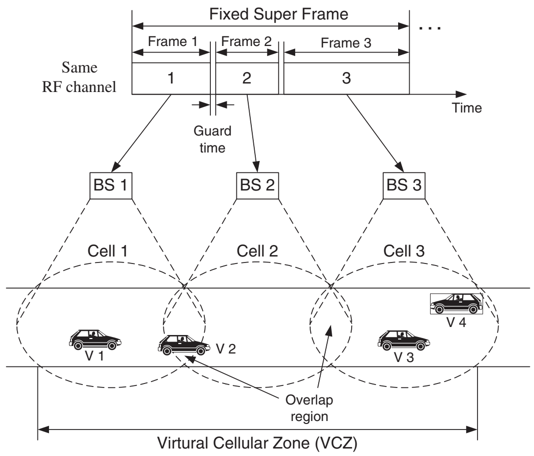

Fig. 3. Frame allocation example.

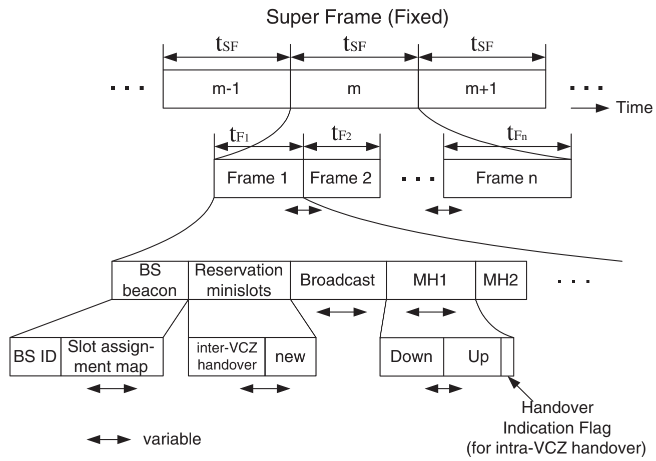

Fig. 4. Frame structure. For simplicity, guard time is not represented.

consisting of M slots is defined for each VCZ with each slot fitted into the minimum size data packet. The RF channel in a VCZ is the same, and adjacent VCZs must not use the same RF channel to avoid co-channel interference. Therefore, while a vehicle is running within a VCZ it does not have to change RF channels. It must change RF channels only when it enters a new VCZ. A super-frame for a VCZ is subdivided into frames for the cells in the VCZ, and a frame is composed of downlink and uplink portion (detailed description of frame structure is given in section IV). The size of a frame for a cell can be made proportional to the traffic demand of the cell.

Fig. 3 depicts a single VCZ constituting three cells and how three frames are allocated to each cell in the time domain while using the same RF channel. It should be emphasized here that during a time period for frame i only the corresponding BS i is activated by the CS; that is, BSs in a VCZ are supported by the CS in disjoint time periods (i.e., frames). Therefore, although one RF channel is employed there is no co-channel interference between cells within a VCZ. If a vehicle is in non-overlapping area it will receive only one frame that corresponds to the cell where the vehicle is located, while if it is in overlapping area it will listen to two frames within a super-frame time. For instance, in the figure vehicle 1 (V1) receives only frame 1, while vehicle 2 receives frame 1 and 2 since it is in the overlapping area between cell 1 and 2. Moreover, the figure also indicates the fact that a frame can support multiple vehicles as described in cell 3. Note that if a CS has multiple VCZs, as many super-frames as VCZs are served simultaneously.

IV. Medium Access Control

In this section we propose an MAC protocol for the system. Design goals of the MAC include a support of fast handover and capability of adaptive resource allocation for high throughput based on dynamic TDMA.

A. Frame Structure

The proposed architecture assumes a centralized MAC entity located at the CS offering a reservation-based, collision-free medium access. For each VCZ, the MAC regulates the medium access employing a super-frame-based slotted access (Fig. 4). The super-frame structure determines the "air-time" given to each BS within the VCZ, i.e., the time period each BS uniquely uses to communicate with MHs located in its coverage area. Even though the length of the super-frame is fixed to t_{SF} seconds, the duration of the frame assigned to each BS (t_{F_j} with respect to $BS\ j$) may be variable as long as

$$\sum_{i=1}^{n} t_{F_j} \leq t_{SF}$$

where n denotes the number of BSs accommodated in the current VCZ.

Each frame belonging to a certain BS begins with *"beacon"* field generated at the CS that consists of BS identification (ID) number and slot assignment map specifying the start slot position and length for each MH. The following field is *"reservation minislots"* which is accessed by MHs that have not yet reserved any slots but have data to transmit. This field has a fixed size minislots and is accessed in contention-based way. In addition, it subdivides into minislots for inter-VCZ/inter-CS handover request (which will be described in section V), and those for new connection request. The CS can change the portion of the minislots so that handover latency could be smaller than new connection requests. For contention resolution conventional method such as p-persistence can be utilized. The results of reservation trial in the previous super-frame is broadcast in the *"broadcast"* field, which is followed by downlink and uplink slots assigned to each MHs as specified in the slot assignment map. In the uplink slot there is a one-bit field called *"handover indication flag"* for fast inter-VCZ handover as explained later.

B. Initialization

When an MH wants to initiate communication with the system, it must first scan RF channels. After having identified the RF channel used in the cell, it must send a request for bandwidth to the CS using reservation mini-slots. If the request is successful and the system has enough bandwidth to accommodate the requested bandwidth, the vehicle will be assigned the bandwidth in the next super-frame. Here, we assume that the super-frame time is longer than round trip time between the CS and BS and processing time for reservation at the CS.

V. Mobility Support

A. Types of handovers

Within the proposed system architecture, we have three kinds of handovers:

- handover between two BSs belonging to the same VCZ (intra-VCZ handover),
- handover between two BSs belonging to different VCZs (inter-VCZ handover),
- handover between two BSs which are controlled by two different CSs (inter-CS handover).

In the following the handover procedure for each of the three types is described. For all cases, an overlapping area between two adjacent BSs is assumed to be large enough to complete the handover procedure. For example, if an MH is running at 100 km/h the time it takes to run 1 m is 36 ms. Thus, when the super-frame time is small (say, 1–5 ms) a few meters of overlapping area would be enough for most practical cases.

B. Intra-VCZ Handover

As all BSs of a VCZ utilize the same RF channel an MH entering the overlapping region BSs begins receiving two beacons each containing a different BS-ID during a super-frame time (t_{SF}). The MH sends in turn the CS a handover request by setting the "*handover indication flag*" then the CS reserves bandwidth for it in the next cell and releases bandwidth used by the MH in the old cell. It should be noted that resources to handover a connection from one BS to its successor BS are always available as the centralized MAC may adjust (i.e., shorten) the frame length of the BS the MH is leaving and can hence increase the frame duration of the successor BS in order to provide the MH with the required resources. As a result, in intra-VCZ handover zero handover latency and zero handover dropping are possible; moveover, bandwidth is allocated along the MH's movement. This is a main feature of the proposed architecture.

C. Inter-VCZ Handover

In this case, the MH cannot listen to a beacon from the new VCZ because adjacent VCZs must not use identical RF channel to avoid co-channel interference. Similar to conventional procedure, the MH may scan RF channels in the next VCZ, corresponding to so-called hard handover. However, since the CS knows the direction of the MH, it can inform the MHs running in the last cell of the VCZ about the RF channel in the next VCZ. In this approach as soon as the MH is informed about the new RF channel, it begins to scan the new RF channel in a period during which it is not assigned bandwidth. If it receives the new RF channel, it sends a handover request using one of the reservation minislots for inter-VCZ handover. If the request to the new VCZ is successful and there is enough bandwidth in the new VCZ, the MH can continue its communication session; otherwise, the request is dropped. Thus, unlike intra-VCZ handover successful inter-VCZ handover involves not only changing RF channels but also bandwidth management. The CS may give the MH requesting handover higher priority than new connection requests. The issue is closely related to the so-called bandwidth reservation and connection admission control problem in mobile cellular networks which will be discussed in section VI.

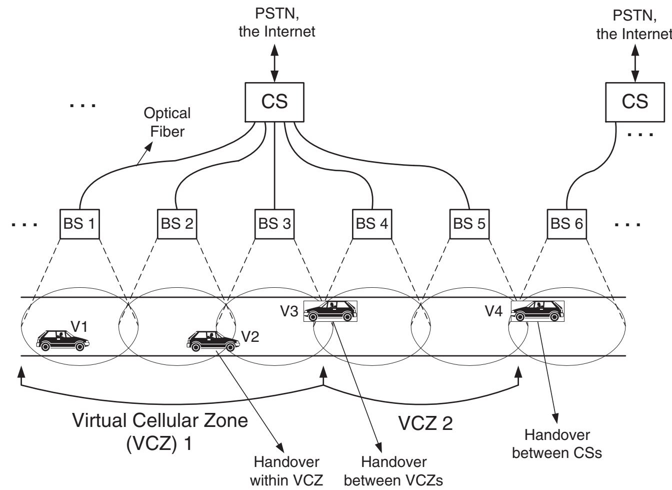

Fig. 5. An example of the proposed architecture where cell 1,2,3 and 4,5 constitute VCZs, respectively.

D. Inter-CS Handover

The handover between two CSs, i.e., between two VCZs controlled by two mutually different centralized MAC entities, is the most critical in terms of guaranteeing quality of service (QoS) parameters to any ongoing connection. The handover procedure is similar to inter-VCZ handover except that the two VCZs associated with it are controlled by two different CSs. Therefore, the same handover procedure for inter-VCZ handover can be applied. But, it requires the CSs to exchange control traffic for handover and if the traffic is based on internet protocol (IP), the problem becomes significant as handover involves change of routing path. This issue will not discussed any more in this paper.

E. Operation Example

Fig. 5 shows a simple example where a CS connected with five BSs. It consists of two VCZs, each of which has three and two BSs, respectively. The figure depicts that vehicle 2,3, and 4 request intra-VCZ handover, inter-VCZ handover, and inter-CS handover, respectively. The corresponding two super-frames and their frame allocations before and after handover are indicated in Fig. 6.

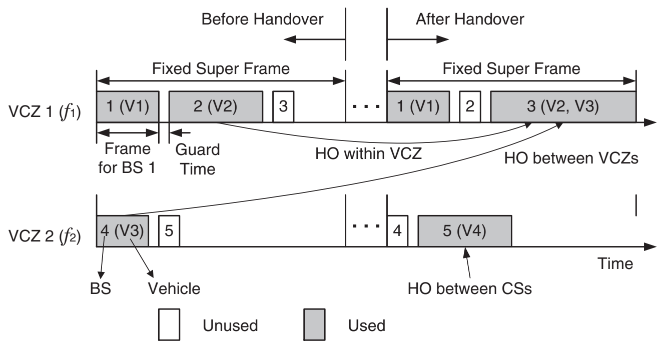

Fig. 6. Frame allocation example for Fig. 5.

VI. Resource Allocation Issues

For successful handover between VCZs (and CSs) bandwidth management is essential. From the user's point of view, having a connection in progress abruptly terminated is more annoying than being blocked occasionally on a new connection attempt. To improve the QoS as perceived by the users, various methods have been devised to prioritize handover requests over connection initiation requests when allocating bandwidth. In conventional mobile cellular networks, a representative method for giving priority to handovers is called the *guard channel concept*, whereby a fraction of the total available bandwidth in a cell is reserved exclusively for handover request from ongoing connections which may be handed over into the cell [14]. This method can be applied to inter-VCZ (and -CS) handover with some modification; that is, in this case each VCZ (not each cell) reserves some bandwidth for handover connection. A lot of research efforts has been made for this issue, and our future works include applying some of them to our system and evaluating the performance.

The proposed system poses also another challenging issue. To see it more clearly, consider a CS that is interconnected to N BSs. If the total traffic load can be supported by one super-frame, N BSs form a single VCZ. From handover point of view such case would produce best performance as inter-VCZ handover is not involved while a vehicle crosses the area covered by the CS. On the other hand, if traffic load of each cell is high and the CS's capacity is enough that it can support N VCZs, then each cell may become a VCZ. In such case whenever an MH crosses a cell boundary it requires inter-VCZ handover, resulting in possibly poor handover performance. So, we can see there is a trade-off between the number of VCZs and handover performance. An interesting issue can be described as follows. Given traffic load what is the minimal number of VCZs and the optimal number of cells in each VCZ? Moreover, these two quantities can be changed dynamically according to traffic load, however, in this case overhead is involved since when a cell belonging to a VCZ changes to other VCZ the MHs in the cell must change RF channels accordingly. Future works also contain a study on this issue.

VII. Conclusions and Future Work

Future road vehicle communication systems will operate at mm-wave bands to support high data rate traffic (2–10 Mbps per user). The system is characterized by small cell size due to high propagation loss of mm-wave band signal and high user mobility. Thus, handover management becomes a very significant and challenging issue. In this paper we have proposed an MAC protocol for future RVC systems featuring a support of fast handover and dynamic bandwidth allocation according the movement of MHs using a centralized MAC entity of ROF networks. In summary, the system has the following characteristics: (1) fast and simple handover since an MH (vehicle) needs not change RF channels while running within a VCZ, (2) zero handover dropping within a VCZ, (3) no co-channel interference between cells, and (4) dynamic bandwidth allocation according to the movement of the MH. Moreover, handover types/procedures associated with the proposed system and resource allocation issues have been discussed. Performance evaluation of resource management schemes is now under way, and preliminary results show the proposed architecture is efficient in handover management for future RVC systems.

References

[1] K. Abe, T. Tobana, T. Sasamori, and H. Kolzumi, "A Study on a Road-Vehicle-Communication System," *Proc. Parallel and Distributed Sys. International Conf. on*, pp. 343–348, July 2000.

[2] A. Furuskär, S. Mazur, F. Müller, and H. Olofsson, "EDGE: Enhanced Data Rates for GSM and TDMA/136 Evolution," *IEEE Pers. Commun.,* pp. 56–66, June 1999.

[3] E. Dahlman, G. Gudmundson, M. Nilsson, and J. Sköld, "UMTS/IMT-2000 Based on Wideband CDMA," *IEEE Commun. Mag.,* pp. 70–80, Sep. 1998.

[4] H. Harada, K. Sato and M. Fujise, "A Radio-on-Fiber Based Millimeter-Wave Road-Vehicle Communication System by a Code Division Multiplexing Radio Transmission Scheme," *IEEE Trans. Intelligent Transport. Sys.*, vol. 2, no. 4, pp. 165–179, Dec. 2001.

[5] M. Okita, H. Harada, and M. Fujise, "A New Access Protocol in Radio-on-Fiber Based Millimeter-Wave Road-Vehicle Communication Systems," in *Proc. IEEE VTC 2001 Fall.*, vol. 4, pp. 2178–2182, Oct. 2001.

[6] H. Al-Raweshidy and S. Komaki, editors, *Radio over Fiber Technologies for Mobile Communications Networks*, Norwood: Artech House, 2002.

[7] E. I. Ackerman and C. H. Cox, "RF Fiber-Optic Link Performance," *IEEE Microwave,* pp. 50–58, Dec. 2001.

[8] G. H. Smith, D. Novak, and C. Lim, "A millimeter-wave full-duplex fiber-radio star-tree architecture incorporating WDM and SCM," *IEEE Photon. Technol. Lett.,* vol. 10, pp. 1650–1652, Nov. 1998.

[9] T. Kuri, K. Kitayama, and Y. Ogawa, "Fiber-Optic Millimeter-Wave Uplink System Incorporating Remotely Fed 60-GHz-Band Optical Pilot Tone," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 7, pp. 1332–1337, Jul. 1999.

[10] K. Kitayama, A. Stöhr, T. Kuri, R. Heinzelmann, D. Jäger and Y. Takahashi, "An Approach to Single Optical Component Antenna Base Stations for Broad-Band Millimeter-Wave Fiber-Radio Access Systems," *IEEE Trans. Microwave Theory Tech.*, vol. 48, no. 12, pp. 2588–2594, Dec. 2000.

[11] K. Kitayama, "Architectural considerations of radio-on-fiber millimeter-wave wireless access systems," *Signals, Systems, and Electron., 1998 URSI International Symposium*, pp. 378–383, 1998.

[12] J. Zhu, and S. Roy, "MAC for Dedicated Short Range Communications in Intelligent Communication System," *IEEE Commun. Mag.,* pp. 60–67, Dec. 2003.

[13] IEEE 802.11p Draft – Wireless Access in Vehicular Environments (WAVE), 2004.

[14] T. S. Rappaport, *Wireless Communications.* Upper Saddle River, NJ: Prentice-Hall, 1996, pp. 34.