

Broadband Communication on the Highways of Tomorrow

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ABSTRACT

Consumer demands for broadband communications at highway speeds will not likely be met by next-generation proposals. Although solutions exist for incremental improvements in capacity and bandwidth, the wireless industry has not yet offered an economical method for providing the broadband channels demanded by mobile consumers on the highway.

The following article examines a proposed high-capacity infrastructure with moving base stations for providing broadband communication services that are not limited by a user's speed. Moving base stations provide moving communication cells to mobile users traveling along a roadway. This broadband solution provides communication services with data rates of 20 Mb/s or more at any vehicular speed at costs comparable to wireline. In addition to presenting a general technical description of the proposed infrastructure, the following discussion includes a brief overview of wireless technology and obstacles encountered in designing a high-capacity system providing high-bandwidth channels to users traveling at highway speeds.

INTRODUCTION

Commentaries and predictions regarding wireless broadband communications and wireless Internet services are cultivating visions of unlimited services and applications that will be available to the consumer "anywhere at anytime" [1]. Consumers expect to surf the Web, check e-mail, download files, have real-time videoconference calls, and perform a variety of other tasks through a wireless communication link [1]. The consumer further expects a uniform user interface that will provide access to the wireless link whether shopping at the mall, waiting at the airport, walking around town, or driving on the highway [1, 2].

Current wireless infrastructures, however, as well as next-generation proposals cannot furnish the necessary bandwidth and capacity to provide these services to users traveling at highway speeds [3]. Unfortunately, highway travelers will likely be the most demanding of bandwidth and wireless services. A huge captive audience occupying the

world's multilane highways will eagerly devour bandwidth to take advantage of time in the car or to enjoy various entertainment services. Commuters can turn a normally frustrating commute to work into productive time with the appropriate applications and bandwidth. The leisure traveler can access a limitless library of music and travel information or entrance the children with a downloaded movie or computer game. Clearly, a broadband wireless solution is needed to provide mobile users the high-bandwidth mobile service they demand at a low cost. The proposed infrastructure discussed below is intended to be implemented as part of a global wireless communication system providing high-bandwidth communication services with a uniform user interface independent of the location or speed of the user.

THE WIRELESS GOAL

It is becoming increasingly apparent that future mobile wireless communication systems must provide high-bandwidth low-cost reliable mobile services comparable to wireline. The mobile user will expect a consistent interface as well as uniform functionality and performance independent of the user's location or speed [1].

For wireline, "broadband communication" refers to communication of digital information where the information transfer rate ranges from a minimum of 1.544 Mb/s (2.048 Mb/s in Europe) to a maximum of 155 Mb/s (synchronous optical network, SONET; OC-3). Broadband communication will support multimedia broadband applications for the home and office such as wideband Internet access and information retrieval, videoconferencing, imaging and graphics, high-definition TV, video on demand, stored voice, and other services.

Although wireline technologies can provide the necessary bandwidth and data throughput to meet the consumer demands at the home or office, current wireless infrastructures are insufficient to provide high-data-rate services in a mobile environment. Furthermore, the proposed next-generation mobile wireless infrastructure will also be severely bandwidth-limited. Third-generation proposals, which have not yet been implemented, limit the overall data rate to 2 Mb/s and will not provide more than 144 kb/s at highway speeds [3].

THE BROADBAND SOLUTION

The most economical and practical infrastructure for providing wireless broadband channels to a high concentration of users likely includes a large number of small cells communicating at extremely high frequencies. Systems operating at millimeter-wave frequencies, particularly at 60 GHz, can utilize large sections of continuous frequency bandwidth while exploiting the signal propagation characteristics observed at these frequencies for frequency reuse [3].

SMALL CELLS

It is clear that for a given service area and a fixed available frequency bandwidth, a wireless infrastructure utilizing small cells can provide more capacity than a system using larger cells [2]. Furthermore, the small cell system can provide larger-bandwidth channels to the same number of users in the given service area than the large cell system [2]. Assuming that the capacity of a cell remains constant as its size is reduced, the number of channels that can be provided within the service area increases as the cell size is reduced. The increase in available traffic channels is proportional to the inverse of the square of the decrease in size of the cells of the system. If the diameter of a cell is decreased by a factor of N , the number of cells that cover the same service area increases by a factor of N^2 , and the number of available channels within the given service area increases by a factor of N^2 . Although small-cell systems require a greater number of base stations to cover a given service area than large-cell systems, the infrastructure cost per channel for small-cell systems is significantly less than for large-cell systems [2].

MILLIMETER WAVES

It is becoming increasingly apparent that in order to provide wireless communications with bit rates in tens or hundreds of megabits, a large amount of bandwidth in the millimeter-wave spectrum range (30–300 GHz) must be utilized [2, 3]. In order to efficiently provide high-data-rate communications to a large number of users, a wide, continuous frequency bandwidth must be used. Antenna and radio transceiver technologies currently limit the total maximum allocated bandwidth to roughly 10 percent of the carrier frequency. Therefore, high carrier frequencies can provide a wide continuous bandwidth. Many frequency spectrum regulatory agencies around the world, including the FCC, have allocated several large sections of spectrum in the millimeter-wave frequency band. In addition to the high carrier frequencies and continuous spectrum, these blocks of frequency spectrum are particularly attractive for use in a broadband communication system due to propagation characteristics observed in some bands.

Millimeter-wave characteristics dictate short-range line-of-sight propagation with minimal refraction and reduced interference while providing a bandwidth capacity approaching coax or optic fiber. These millimeter-wave characteristics require a cellular network topology to be based on a large number of small cells. As discussed above, the small cells facilitate frequency reuse, resulting

in a large number of traffic channels per service area and thus high network traffic capacity.

60 GHz

The 60 GHz frequency spectrum is especially suited for a network topology with extremely small cells due to the resonant absorption of electromagnetic energy by oxygen molecules at that frequency [3]. The attenuation of electromagnetic waves at 60 GHz is approximately 15 dB/km [3]. This particularly high electromagnetic wave attenuation present in the 51.4–66 GHz frequency band (labeled *absorption band A1*) facilitates a high rate of frequency reuse in small cells. The high attenuation minimizes co-channel interference in a small-cell system, allowing a particular frequency to be used more often than would be possible at other frequency bands [3].

Under FCC Part 15, the 59–64 GHz band is available for general use by unlicensed devices based on severe propagation losses protected from interference [4]. The FCC stated that the goal was to foster novel broadband communications, and that 59–64 GHz offers the greatest potential to allow for the development of short-range wireless radio systems with communications capabilities approaching those now achievable only with coaxial and optic fiber cable [4]. In Europe, 62–63 GHz and 65–66 GHz are allocated for licensed operation, specifically for the Mobile Broadband System (MBS). In Japan, the 59–64 GHz band is regulated for use by the MBS. It appears, therefore, that the 60 GHz band is geographically widely available.

THE HIGH-SPEED HANDOFF PROBLEM

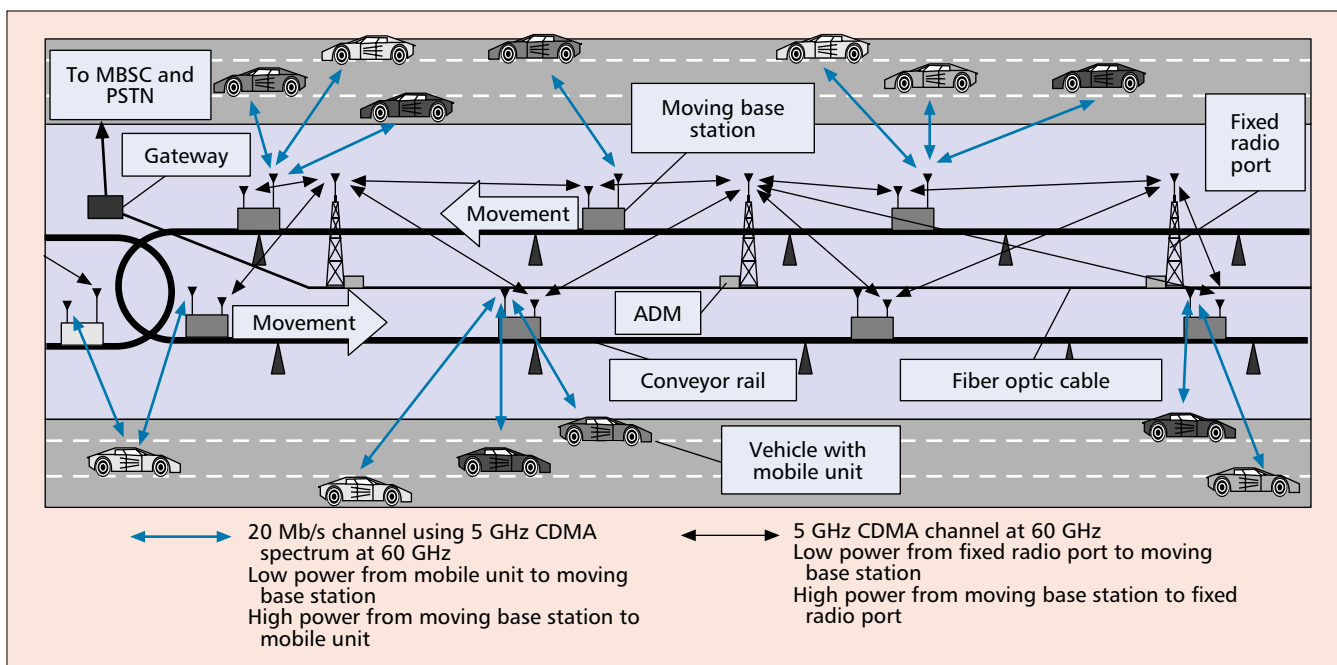
Apparently, an infrastructure utilizing small cells in the 60 GHz frequency range can provide large-bandwidth channels to an almost unlimited capacity of wireless users. Frequency reuse coupled with large-bandwidth frequency spectrum can be exploited to provide large bandwidth channels. Systems such as this, however, have been suggested in the past and have not gained widespread acceptance due to the fallacy that high-speed mobility cannot be supported in a small-cell environment. Although few will argue that a small-cell infrastructure can provide large bandwidth channels on the order of 100 Mb/s to mobile users traveling at pedestrian speeds, it seems impossible to most that mobile users traveling at speeds in excess of 60 mph can be accommodated in a small-cell system. These fallacies are based on the observation that as the size of the cells is reduced, the mobile unit tends to cross cell boundaries more often, requiring a large number of handoffs to the point that the calls will be dropped if mobile units are moving at high vehicular speeds.

A PROPOSED BROADBAND MOBILE CELLULAR SYSTEM DESCRIPTION

OVERVIEW

The proposed infrastructure examined in this article provides a solution to the high-speed mobility limitations discussed above. Furthermore, the proposed system can be integrated with

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■ **Figure 1.** A mobile broadband communication system with moving base stations.

other infrastructure to enable high-bandwidth wireless service at a cost competitive to wireline communication. The small-cell architecture of the proposed system enables the use of extremely lightweight low-power mobile units that can be used almost anywhere. The proposed infrastructure is especially suitable for high-speed multilane divided highways in urban high-traffic environments. Advantages of cordless and cellular systems are integrated by deploying very small picocells along high-traffic roadways. Although each of the picocells has a radius on the order of 100 ft, the system can easily facilitate high-bandwidth communications to mobile units traveling at speeds up to and in excess of 100 mph.

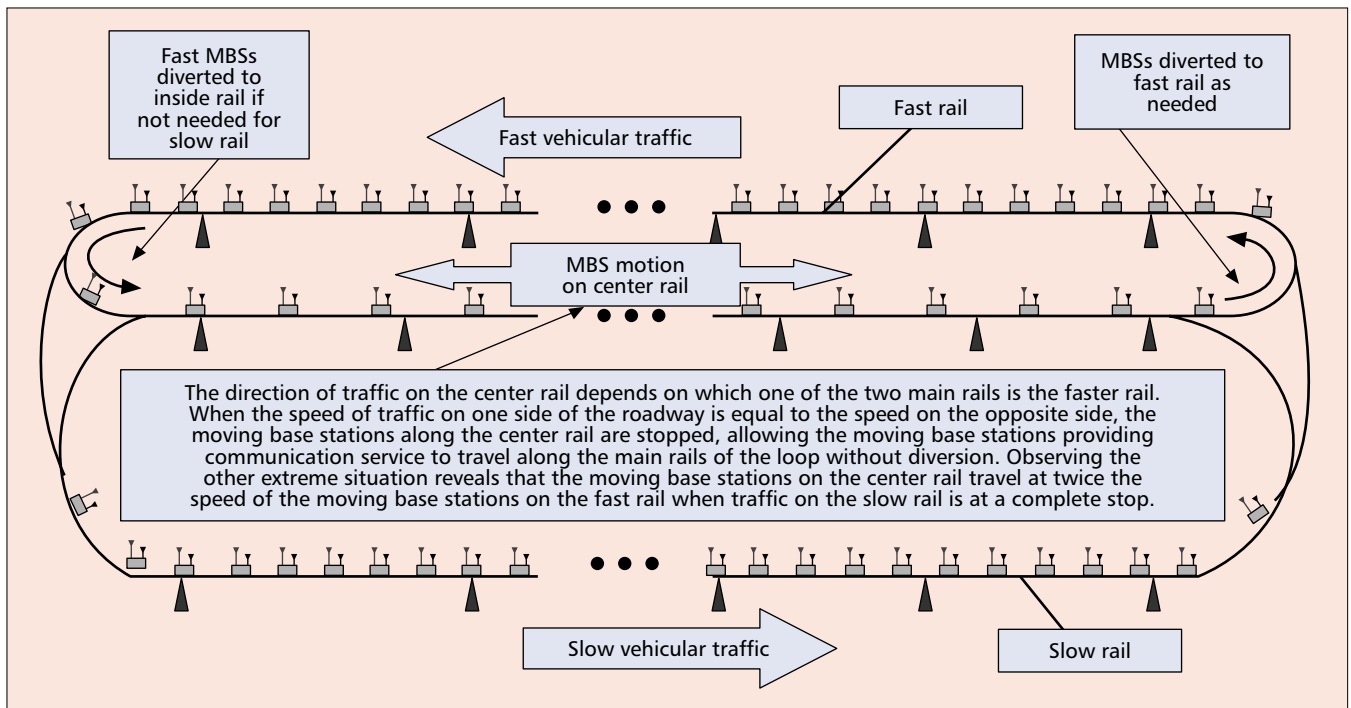
This is accomplished by interposing moving base stations between mobile units traveling down the roadway and fixed radio ports uniformly distributed along the median of the roadway. The moving base stations allow communication links to be established between the mobile units traveling on the roadway and a fixed communication network through the fixed radio ports. As can be seen, the number of mobile unit handoffs in this proposed system is significantly reduced from those of conventional small-cell systems since the moving cells provided by the moving base stations track the mobile units. The moving base stations complete the communication link to a fixed network such as a public switched telephone network (PSTN) through a radio link to the fixed radio ports. The fixed radio ports are interconnected with a fiber optic ring, or a similar signal-transmitting device, to a gateway telephone office and mobile broadband switching center (MBSC) connected to the PSTN. Mobile units stopped on the highway or traveling at significantly slower speeds than the majority of traffic are coupled to the wired communication network through fixed base stations.

The proposed highway system is intended to

be part of a complete high-bandwidth wireless solution where the same mobile units can be used at the home, in the office, and while traveling by foot or in a high-speed vehicle. The requirement to provide high-bandwidth channels to a high density of mobile users traveling at speeds on the order of 60 mph arises in predictable areas such as highway and train systems. Although users in rural areas may demand high-bandwidth channels while traveling at high speeds, the service to these users can easily be provided with larger cells since system capacity is not threatened. Small-cell systems with fixed base stations can be used to provide high-bandwidth services to pedestrians or fixed wireless users where the density of users may be high but the highest user speed is well below any handoff limitations. The moving base station infrastructure, therefore, is intended to be implemented in areas with a large number of users traveling at high speeds, while other types of infrastructure are used to provide services in other areas.

PHYSICAL CONFIGURATION

As shown in Fig. 1, the moving base stations are arranged along a conveying device, such as a rail, and move in the same direction and at approximately the same speed as the traffic flow along a highway. The conveyor device is implemented in a narrow elliptical loop such that a series of fixed radio ports are positioned along the median of the highway and between the two long ends of the loop. Several loops are arranged along the highway and overlap slightly. The moving base stations are spaced apart by a selected distance equivalent to the diameter of the cell served by the moving base station, which is approximately 200 ft. Each of the moving base stations provides a moving cell that travels along the highway in accordance with the mobile users it services. The fixed radio ports distributed along the median of the highway between both



■ **Figure 2.** Moving base station speed management.

rails use directional antennas to communicate with each of the two groups of moving base stations servicing the two corresponding traffic flows of mobile users.

Since the moving base stations track the motion of the mobile units, the relative speeds between the moving base stations and mobile units are less than speeds found in cordless systems. It appears that cordless systems can easily facilitate call handoffs between base stations at pedestrian speeds up to 30 mph. Since all traffic does not travel at the same speed and the moving base stations will travel faster than some of the mobile units and slower than others, the moving base stations can typically handle mobile units traveling up to 30 mph slower or faster than the speed of the mobile base stations. For example, if the moving base stations are traveling at a speed of 60 mph, the moving base stations can provide communications to mobile units traveling at speeds from 30 to 90 mph. Although highway traffic situations rarely involve speed differentials of more than 60 mph, additional features may be implemented to cover those situations. Those features are discussed in detail in [5] and are beyond the scope of this article.

To avoid interruption in communication, the ends of the loops are sufficiently close or overlapping to provide an overlapping area of coverage for mobile units traveling in the area of loop ends. A handoff procedure is performed to transfer mobile units serving a moving base station nearing the end of a loop to a moving base station on an adjacent loop.

Any one of several techniques may be used to accommodate the different speeds of traffic on the two sides of the roadway. Some of these techniques are discussed in [5] and include using multiple loops or multiple rails and performing mobile unit handoffs to maintain uniform spacing between

moving base stations. A particularly efficient method for providing a speed buffer between the two sides of the roadway involves implementing a single additional rail between the two main rails. As shown in Fig. 2, mobile base stations are directed to and from a center rail as needed. The speed and direction of the mobile base stations traveling on the center rail depend on the speed differential between the two main rails.

A fiber optic cable couples the fixed radio ports to a gateway. Add/drop multiplexers (ADMs) facilitate the transfer of signals between the fixed radio ports and the fiber optic cable. The fiber optic cable forms a continuous ring in accordance with SONET or synchronous digital hierarchy (SDH) transmission protocols. The gateway provides an interface to an MBSC. The MBSC, which could be implemented as part of the gateway, performs switching functions analogous to a mobile switching center in other types of mobile systems. The MBSC is coupled to a wired communication network such as a PSTN. Preferably, all the fixed radio ports associated with a particular loop are connected to a single gateway. The need for moving base stations to register to a gateway is avoided since the moving base stations only communicate through one gateway and do not need to be handed off to another gateway, as would be necessary in a conventional cellular system.

COMMUNICATION LINKS

All wireless communications within the proposed system use direct sequence code-division multiple access (CDMA) spread spectrum techniques within a 5 GHz frequency band part of absorption band A1 at 60 GHz. Using time-division duplex (TDD) methods, the entire 5 GHz band is used for upstream and downstream communication. In the upstream half of the TDD cycle,

After extracting the downstream data from the time slot corresponding to the particular mobile unit channel, the moving base station appends appropriate signaling information to the data and retransmits the downstream data to the intended mobile unit.

data is sent from the mobile units to the fixed radio ports by transmitting upstream signals from the mobile unit to the moving base station and transmitting corresponding upstream signals from the moving base station to the fixed radio ports. In the downstream half-cycle, data received from the wired communication network is sent from the fixed radio ports to the mobile units by transmitting downstream signals from the fixed radio ports to the moving base station and corresponding downstream signals from the moving base station to the mobile units.

Upstream signals are received from the mobile units at the moving base station and retransmitted to several fixed radio ports using time-division multiplexing (TDM) techniques where the communication channel for each mobile unit corresponds to a time slot within the retransmitted upstream signal. Multiple channels between the moving base station and the fixed radio ports are time-division multiplexed as time slots in a data stream. The data stream is spread with a pseudo-random code over the allocated spectrum. A pilot sequence inserted into the transmitted signal facilitates synchronization using known techniques.

The corresponding upstream signals are received at the several fixed radio ports and forwarded to a gateway through the fiber optic ring. Each fixed radio port receiving the signal from the moving base station determines a quality indicator for each signal based on signal strength and signal-to-noise ratio. The ADMs connecting the fixed radio ports to the fiber optic ring forward the upstream signals and the corresponding quality indicator measurements to the gateway. The gateway processes the signals using the quality indicator measurements to produce a high-quality upstream signal that is provided to the wired communication network.

Downstream signals are received from the wired communication network through the gateway and are directed to the appropriate fixed radio ports based on the location of the moving base station serving the mobile unit intended to receive the downstream data. The downstream signals are transmitted through the fiber optic ring and received at several fixed radio ports through the ADMs. Each signal is transmitted from multiple fixed radio ports in the vicinity of the moving base station serving the mobile unit. The signals are directed to the appropriate moving base station using a unique moving base station address derived from an identification code and a Walsh code. The mobile base station processes and combines the several signals received from the fixed radio ports to produce a high-quality downstream signal. After extracting the downstream data from the time slot corresponding to the particular mobile unit channel, the moving base station appends appropriate signaling information to the data and retransmits the downstream data to the intended mobile unit.

As discussed above, the moving base stations have one set of directional antennas aligned to service moving traffic and a second set aligned to communicate with the fixed radio ports. The downstream signals transmitted from the fixed radio ports to the moving base stations are at a relatively low power level, while the downstream

signals transmitted from the movable base stations to the mobile units are at a relatively high power level. Due to the characteristics of direct sequence spread spectrum CDMA communications, the higher-power-level signals overpower the lower-level signals such that the mobile units do not receive communications from the fixed radio ports and only receive those signals transmitted from the movable base stations.

Upstream signals are transmitted at a relatively low power level from the mobile units to the moving base stations compared to the upstream signals transmitted from the base stations to the fixed radio ports. Any direct communication between the mobile units and the fixed radio ports, therefore, is minimized. Accordingly, the 5 GHz spectrum is efficiently used by the radio interface between the moving base stations and the fixed radio ports and the radio interface between the moving base stations and the mobile units. Each radio interface is not affected by the communications within the other interface.

THE MOVING BASE STATION-FIXED RADIO PORT INTERFACE

The radio interface between each moving base station and the fixed radio ports includes 15 channels, each having a 20 Mb/s data rate. The channels are TDM in 15 time slot frames, resulting in a total bit rate of 300 Mb/s. To achieve a processing gain of 9 dB, the frame rate is multiplied by a factor of 8, yielding a 2400 Mb/s data rate. Due to the TDD communication link, the 5 GHz band has an effective bandwidth of 2500 MHz. If a modulation rate of 1 b/Hz is used, the 2400 Mb/s data is transmitted in the 2500 MHz effective bandwidth of the appropriate duplex half-cycle. In addition to the 12 channels for bearing communication traffic, the 15 channels include 3 channels for signaling, control, base station identification, and error coding.

The spacing of the fixed radio ports, together with the strength of the signal transmitted between moving base stations and the fixed radio ports, determines the number of fixed radio ports with which a moving base station can communicate at any point in time. The spacing and signal strength is preferably such that each fixed port receives signals from three moving base stations. The fixed radio port receives the upstream signal which includes the upstream data in addition to the address of the moving base station that received the data. A processor in the fixed radio port computes a signal quality indicator for the received upstream signal where the quality indicator is a figure of merit based on signal strength and signal-to-noise ratio. The quality indicator is transmitted to the gateway in addition to the upstream signal through the ADM.

WALSH CODES

The moving base stations are distinguished and identified using predefined code sequences derived using Walsh functions and the identification code for the moving base station. The combination of a Walsh code and the identification code yields the unique address for each of the moving base stations. An eighth order Walsh function provides eight orthogonal codes. The 0

Walsh sequence is used as the pilot carrier with the other seven sequences available for providing communication for the moving base station. Each of the moving base stations, therefore, has one of seven assigned codes in addition to its identification code. The Walsh codes are assigned to the moving base stations so that two moving base stations with the same Walsh code will be physically separated by a sufficient distance to prevent interference in communications between fixed radio ports and moving base stations with the same identity code. For example, the codes may be assigned in sequence such that the codes are repeated in the pattern "12345671234567 ..." to the sequence of adjacent moving base stations arranged along the loop. The Walsh codes are further multiplied by pseudo-noise codes to improve communication performance.

In order to preserve the order of Walsh codes when moving base stations are diverted to the center rail, the moving base stations are only redirected in blocks equal to the number of Walsh codes. For example, if a surplus of moving base stations results at the faster rail and Walsh codes 1–7 are in use, moving base stations are directed to the center rail from the faster rail in groups of seven such that the "1234567" sequence of Walsh codes is maintained for the moving base stations along the loop.

SYNCHRONIZATION

Pilot signals are transmitted from the moving base station to the fixed radio port and from the fixed radio port to the moving base station. The moving base station is synchronized in phase and time to the fixed radio port by phase-locking to the pilot signal. For system synchronization purposes, the moving base station receives a Global Positioning Satellite (GPS) Universal Time Coordinated (UTC) timing signal once each second.

UPSTREAM GATEWAY FUNCTIONS

The gateway receives the same data from several fixed radio ports and stores each version of the data in an internal memory in association with the corresponding moving base station address and the address of the fixed radio port receiving the particular version of the data. Accordingly, multiple copies of the same data transmitted by a single moving base station are stored in the memory of the processor in the gateway. The signal quality indicators computed by the processor in each of several fixed radio ports are compared to a predefined signal quality indicator threshold. Versions of the data corresponding to a signal quality indication below the threshold value are discarded. A cyclic redundancy code transmitted with the data is used to detect any TDM frame errors. The data associated with the upstream signal having the best quality indicator is transferred from the gateway to the wired communication network using the appropriate protocols.

DOWNSTREAM GATEWAY FUNCTIONS

The data received from the wired communication network at the gateway and intended for a registered mobile unit is stored in the memory of the processor in a register particularly associated with the moving base station currently serving the mobile unit. This data is sent through the

optical ring to all fixed radio ports that are identified in the memory of the processor as fixed radio ports with an acceptable quality indicator as determined by the previously received upstream signals. The received data is transmitted from each of the fixed radio ports which received the data together with the address of the moving base station to which the data is directed. The transmission of data from different fixed radio ports is intentionally staggered by introducing different transmission delays so that the signals can be received and separated at the moving base stations. The transmission delays can be precisely controlled by means of synchronous distribution via the optical ring in SONET or SDH format. The processor in the receiving moving base station compares, aligns, and combines the multiple copies of the received data signals for the best reception.

THE MOBILE UNIT–MOVING BASE STATION INTERFACE

The communication interface between a moving base station and the mobile units is direct sequence spread spectrum CDMA. Each moving base station communicates with a maximum of 12 mobile units through 12 20-Mb/s channels. Preferably, at least one channel is reserved to accommodate mobile unit handoffs. Although the overall bit rate is 25 Mb/s, 25 percent of the channel is used for error correction, resulting in the 20 Mb/s effective data rate. Due to the application of the spreading function, each 25 Mb/s channel is spread to the 2500 MHz bandwidth to achieve a processing gain of approximately 18–20 dB. This is sufficient for the short-range line-of-sight radio signal propagation.

TRANSMISSION LAYERS

As shown in the system interconnection model in Fig. 3, the moving base station mobility is concealed within the lower transmission layers and transparent to the upper layers. Accordingly, functions such as registration, authentication, and paging as well as control, signaling, and traffic channels are implemented at a transmission layer transparent to the fixed radio ports and the gateway. The mobility of the moving base stations is supported by the functions and subsystems illustrated within the colored block in Fig. 3. The mobility of the moving base stations is transparent to the functions and subsystems outside the colored block.

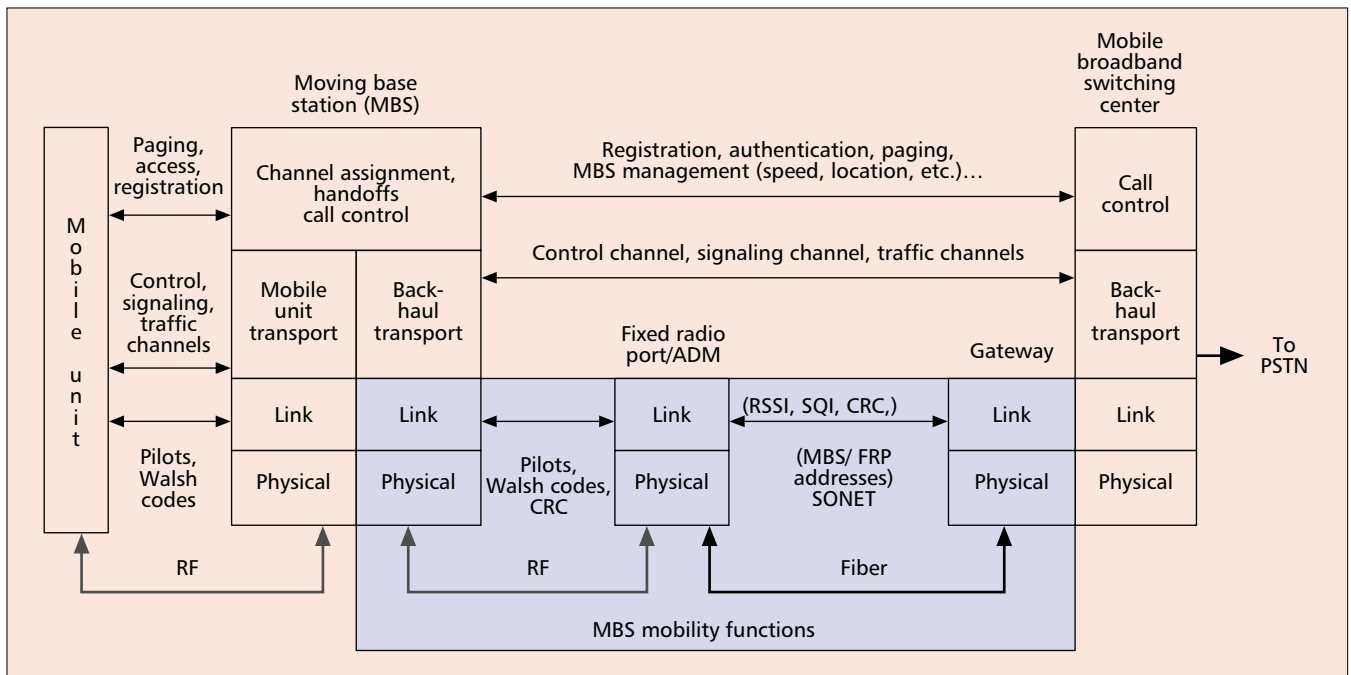
SYSTEM CAPABILITIES

The proposed high user capacity infrastructure provides 20 Mb/s data channels to mobile units traveling at speeds anywhere from zero to over 100 mph. Users traveling on highways can productively utilize time spent in a vehicle, or enjoy the various entertainment or convenience applications only achievable using high-data-rate channels. As described below, the cost per channel of the proposed system is comparable to the cost per channel of wireline networks.

COMPARISON TO OTHER SYSTEMS

At first glance, some existing communication systems appear to provide similar communication services as the proposed system. After care-

[T]he moving base station mobility is concealed within the lower transmission layers and transparent to the upper layers. Accordingly, functions such as registration, authentication, and paging as well as control, signaling, and traffic channels are implemented at a transmission layer transparent to the fixed radio ports and the gateway.



■ **Figure 3.** A system interconnection model for a moving base station communication system.

ful examination, however, it is apparent that these other systems are limited in user capacity, bandwidth, and/or user speed. Figure 4 illustrates a comparison between mobility and data rates for the moving base station system and other proposed and existing communication systems.

As explained above, systems using only large cells are limited in capacity and bandwidth. Due to finite available frequency spectrum, the size of a cell and the data rate of a channel dictate the capacity of the system. By reducing the size of the cell, capacity and channel bandwidth is increased at the cost of user speed.

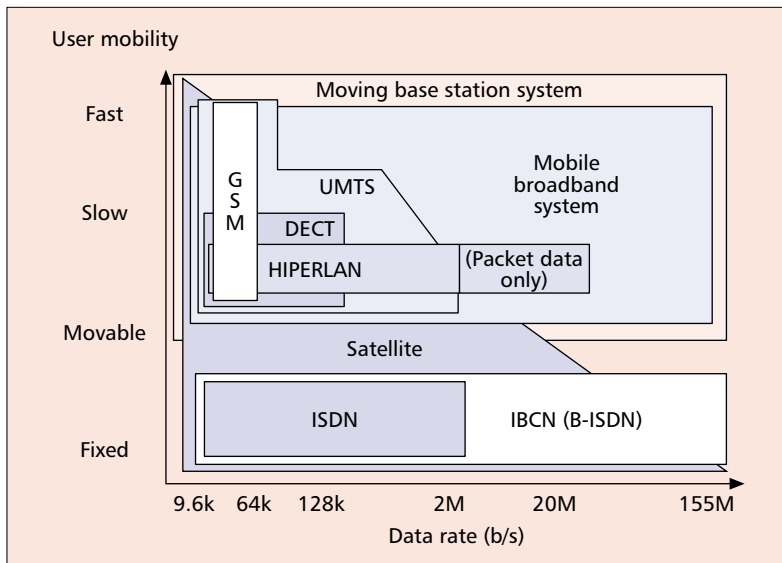
One approach taking advantage of both small-cell and large-cell systems includes using two cell sizes where a large cell and several small cells

overlap [6]. The use of a large cell, however, still limits the bandwidth and number of users traveling at high speeds. Such a two-tier system is severely limited in areas where a high concentration of mobile users are traveling at high speed. For example, the third-generation (3G) proposal which takes advantage of the two-tier approach still limits high-speed users to only 144 kb/s channels, while the proposed moving base station system can provide channels on the order of 20 Mb/s.

Although satellite systems appear to provide huge data channels, after careful examination it is clear that proposed satellite systems are not well suited for providing broadband channels to high concentrations of mobile users traveling at highway speeds due to the fact that extremely large cells are used [2].

SYSTEM COST AND REVENUE OVERVIEW

The wireless infrastructure portion of the proposed highway broadband system is expected to cost less than \$1.9 million/mi of roadway. This wireless infrastructure cost estimate is based on costs of existing infrastructures and pricing quotations from several sources, and includes costs for the two main rails, the center rail, 52 active moving base stations, 13 spare moving base stations, and 26 fixed radio ports without ADMs. As in all wireless infrastructures, additional costs will apply for the backhaul, which will include elements such as fiber optic cable, ADMs, and gateways. The total infrastructure cost for the proposed system, including the radio portion and backhaul to the MBSC, is less than \$4.3 million/mi. The division of costs associated with the radio portion and backhaul is provided to emphasize that most of the system cost is associated with the backhaul and that any system providing such a large number of 20 Mb/s channels in a highly concentrated area will most likely require a similar sophisticated backhaul infrastructure.



■ **Figure 4.** A comparison of moving base station systems to other proposed and existing infrastructures.

SYSTEM COST AND REVENUE ANALYSIS

Although additional investigation is required to obtain estimates with a high level of confidence, the following cost analysis is provided as a starting point for future discussions and research. At the request of an information source, some of the estimates used for the analysis are not referenced in order to preserve the confidentiality of proprietary discussions between the source and third parties. Cost and revenue estimates are presented in Tables 1 and 2, respectively.

A monorail transportation design expert estimated that a suitable conveyor system would likely cost about \$480,000 for the two main rails along both sides of a mile-long stretch of highway. Based on the information provided by the expert, it is estimated that each additional rail implemented adjacent to one of the main rails will cost about \$85,000. The cost of the conveyor infrastructure, therefore, including the center rail is \$565,000.

The carriage portion for each moving base station was estimated at \$2500 by the monorail expert. The carriage includes the chassis in addition to all motors, control systems, power systems, and mechanical components.

The analog and digital circuitry performing the communication functions of the moving base stations, including power circuitry and antennas, is expected to cost approximately \$10,000. This estimate is based on high-volume costs for existing small-cell systems such as the Personal Handphone System (PHS). Development costs associated with the base stations will most likely be associated with the 60 GHz aspect of the design since the remainder of the required circuitry is similar to current cellular and personal communications services (PCS) designs.

Although initial development costs may require additional expenditure to cover issues likely to be encountered with 60 GHz designs,

Equipment	Cost/unit	Qty/mile	Cost/mile
Conveyor System Rails (2 main plus 1 center)	–	–	\$565,000
Moving base station carriage (main rails)	\$2500	52	\$130,000
Moving base station carriage (For Center Rail and Spares)	\$2500	13	\$32,500
Moving base station circuitry (main rails)	\$10,000	52	\$520,000
Moving base station circuitry (for center rail and spares)	\$10,000	13	\$130,000
Radio port — ADM	\$85,000	26	\$2,210,000
Radio port — radio circuits	\$10,000	26	\$260,000
Radio port — other	\$10,000	26	\$260,000
Fiber optic cable	–	–	\$100,000
Gateway (including ADM)	\$500,000	0.08 (2 per 25 mi)	\$40,000
Total			\$4,247,500

■ **Table 1.** Infrastructure costs per mile.

these costs are likely to be recouped in the high-volume manufacturing advantages, and size and integration benefits of high-frequency circuitry. Technology currently being developed for other 60 GHz applications may provide shortcuts for much of the required development. For example, base stations for fixed applications are currently commercially available and may be modified to accomplish the desired RF functions of the proposed system. It is clear, however, that further research and development is required to

Parameter	Assumption	Assumption	Calculation	Result
Average number of vehicles per 200 foot lane	35 ft spacing between vehicles *	* See [8]	$200 \div 35$	6
Average number of vehicles per moving base station	3 lanes/highway	200 ft spacing between moving base stations	6 (3)	18
Erlangs of communication traffic	50% usage/vehicle	–	18 (50/100)	9
Channel occupancy	50% usage/vehicle	12 total traffic channels per moving base station	$(9 \div 12)(100)$	75%
Number of base stations per mile	200 ft spacing between moving base stations	Two-way highway	$(5280 \div 200) (2)$	52
Average number of channels in use per moving base station	50% usage/vehicle	–	18 (50/100)	9
Average number of channels in use per mile	52 moving base stations/mi	9 channels/moving base station	52 (9)	468
Revenue/minute per mile	\$ 0.50/min/channel	–	0.50 (468)	\$234
Number of revenue minutes per year	8 hours rush hour/day	250 rush hour days per year	8 (60)(250)	120,000
Revenue/year per mile	–	–	120,000(234)	\$28,080,000

■ **Table 2.** Revenue per year per mile.

Utilizing many proven technologies in conjunction with a moving cell infrastructure results in a relatively inexpensive approach to providing high-bandwidth communication channels to a large number of users traveling at highway speeds.

produce the 60 GHz circuitry included in the moving base station.

The majority of the cost of a fixed radio port is due to the high-speed ADMs needed to couple the signals to the fiber optic cable. Based on an estimate obtained from a manufacturer, an ADM should cost approximately \$85,000 in high volume. Due to the similarities in requirements, the RF circuitry portion of the radio port is estimated to cost the same as the moving base station RF circuitry. An additional \$10,000 is included to cover miscellaneous costs such as those associated with building an adequate structure for supporting the radio portion of the fixed radio port. A fixed radio port, including an ADM, radio circuitry, and tower, is estimated to cost no more than \$105,000 in high volume.

The cost of implementing fiber optic cable appears to be continually falling. At least one source estimates the cost for implementing fiber along a highway to be \$100,000/mi [7].

In the proposed system, a single gateway for each 25 mi of roadway should be sufficient for performing the required functions. In order to increase the robustness of the system and minimize potential service interruption, a redundant gateway is included for each 25 mi of highway.

Therefore, the total cost of the moving base station infrastructure, including backhaul, is approximately \$4.24 million/mi. As mentioned above, the various cost estimates were either obtained from manufacturers, based on similar existing systems, or derived using a combination of information resources. Additional research is required to obtain manufacturing cost estimates with a higher level of precision.

REVENUE

Revenue generation is, of course, highly dependent on the demand for wireless services, and further market research is needed to obtain predictions of consumer needs for the future. Accordingly, the following assumptions may be interpreted as being either too aggressive or too conservative due to the variance of predictions related to consumer demands for wireless service. The overriding assumption is that consumers will use 20 Mb/s channels while on the highway if the cost per minute is comparable to other landline and wireless services.

The estimates are based on a typical three-lane urban highway that experiences rush hour traffic for 4 hr in the morning and 4 hr in the afternoon. In order to simplify the revenue estimates, only rush hour traffic is included in the estimates. This simplification appears reasonable since these hours will experience the highest amount of traffic, and include the highest numbers of wireless and Internet users with a desire to minimize down time while driving to work. Additional revenue will likely be generated during the weekends and non-rush hour times, but is omitted from the revenue estimate. Vehicular traffic models are discussed in [8].

HEALTH CONCERNS

Due to the high frequencies utilized by the proposed system, concerns regarding human exposure to RF signals are likely to be raised. It is clear that all electromagnetic radiation should be continually examined and that the effects of RF signals on the human body should continually be researched.

The small-cell infrastructure allows the transmission of signals at power levels on the order of 1–10 mW, resulting in an overall lower level of RF radiation exposure than with other systems. Furthermore, higher-frequency signals have lower penetration into the human body [3].

CONCLUSION

The proposed wireless system discussed above may provide a unique solution for the highway portion of the high-bandwidth global communication system of the future. Utilizing many proven technologies in conjunction with a moving cell infrastructure results in a relatively inexpensive approach to providing high-bandwidth communication channels to a large number of users traveling at highway speeds. The scene of base stations gliding along the centers of the highways of tomorrow may soon be a sight as common as telephone poles lining the highways of today.

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