NOTE FROM THE SERIES EDITOR/STEVEN S. GORSHE

When most people think of broadband access networks they naturally think of xDSL using the existing telephone network subscriber loops or cable modems using the existing cable television coaxial network. No broadband access series would be complete, however, if it didn't include the activities in the wireless arena. In the past, the bandwidth limits of wireless access networks severely restricted the amount of data traffic that could be carried economically. Thanks to some new technologies, that situation is changing. Indeed, wireless technology has been call the "dark horse" of the broadband access race. Wireless access brings some tremendous advantages in terms of portability and relative ease of reaching new subscribers. The three articles in this issue's Broadband Access Series provide an introduction to wireless broadband networks, along with their advantages and limitations and the modern technologies that are making them possible.

BIOGRAPHY

STEVEN S. GORSHE [SM '91] (steveg@eluminant.com) received his B.S.E.E. degree from the University of Idaho in 1979 and his M.S.E.E. degree from Oregon State University in 1982, where he is also currently a part-time Ph.D. candidate. He has been involved in applied research and development of transmission and access systems since 1982. He began his career in the GTE Lenkurt Advanced Development Group and has been at NEC since 1988, where he is currently chief architect. His work at NEC Eluminant Technologies involves systems architectures and hardware design for subscriber access and SONET transmission equipment. He is also past the chairman of the IEEE Communications Society's Transmission, Access, and Optical Systems Committee, and is Chief Editor for the ANSI-T1X1 Subcommittee responsible for SONET interface standards. He has 20 patents issued or pending.

Wireless Broadband Communications: Some Research Activities in Singapore

Kee Chaing Chua, K. V. Ravi, Brahim Bensaou, and Teck Chien Pek

Center for Wireless Communications, National University of Singapore

ABSTRACT Almost a decade ago, Singapore started crafting and implementing its IT2000 master plan to transform the city-state into an information-technology-based intelligent island. Since 1997, the main infrastructure of a high-speed ATM-based backbone network, called SingaporeONE, has been in place along with a host of commercial and governmental application service sites providing a plethora of online services. Because of its small size and extensive wired infrastructure, broadband access to homes and offices is currently provided via ADSL and cable modems. There is, however, interest in the use of wireless broadband communication technologies to access SingaporeONE, motivated primarily by its lower cost and faster deployment. In this article we describe some of our R&D activities motivated by the above interest to provide wireless broadband access to SingaporeONE. Specifically, we describe our study of LMDS, and the design and development of a wireless ATM LAN.

In recent years, the information and (tele)communications industries have been inundated and excited by research, development, and business activities in wireless communication and Internet technologies. While basic (and increasingly enhanced) wireless telephony and access to the Internet, for Web surfing, file transfers, e-mailing, and (increasingly) e-commerce, are fairly well entrenched in the developed world, research interests are now focused on enabling broadband interactive communications anywhere, anytime. The push toward broadband interactive communications is in line with current developments to equip the global Internet with the capabilities to support integrated services and evolve into the global information infrastructure. The preoccupation with anywhere, anytime communications, on the other hand, is driven by the convenience of being tetherless, and, in our view, the lure of new business opportunities based on the exploitation of location information and other data.

Wireless broadband communication technologies are being developed for three major business segments: fixed access networks, mobile cellular access, and local area networks (LANs), including home networks. In fixed access networks, the use of wireless communication technologies is attractive in that deployment costs and time are generally considered much lower and shorter, respectively, than those of putting in a wired infrastructure. The need for mobility, at vehicular and higher speeds, in the case of mobile cellular access simply demands the use of wireless communication technologies. Finally, in the case of LANs, the attractiveness of wireless communication technologies again lies in ease and lower costs of deployment. In addition, the convenience of being tetherless is an attractive feature. Each of the above major business segments of fixed access, mobile cellular access, and LANs presents specific technical challenges that need to be addressed.

Almost a decade ago, Singapore started crafting and implementing its IT2000 master plan to transform the city-state into an information-technology-based intelligent island. Since 1997, the main infrastructure of a high-speed asynchronous transfer mode (ATM)-based backbone network, called SingaporeONE [1], has been in place along with a host of commercial and governmental application service sites providing a plethora of online services. Because of its small size and extensive wired infrastructure, broadband access to homes and offices is currently provided via asymmetric digital subscriber line (ADSL) and cable

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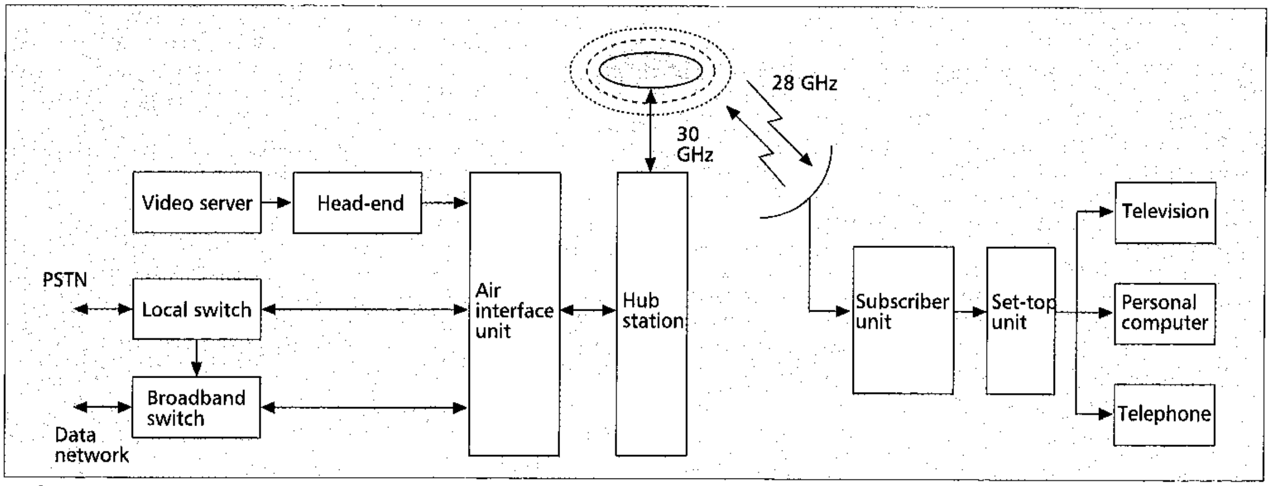


■ **Figure 1.** *LMDS system functional blocks.*

modems. There is, however, interest in the use of wireless broadband communication technologies to access SingaporeONE, motivated primarily by its lower cost and faster deployment. In particular, as the local telecommunications market is liberalized, this consideration is important for a new access network provider to reduce its initial infrastructure setup cost and to rapidly deploy its network in order to gain market share against the incumbent providers. Yet another motivation is to exploit SingaporeONE and its applications as a live platform for the development and deployment of relevant wireless broadband communication technologies and systems.

In this article we aim to describe some of our R&D activities motivated by the above interest in providing wireless broadband access to SingaporeONE. Our activities cover each of the three business segments mentioned above. In the area of fixed wireless broadband access, we describe our study of local multipoint distribution service (LMDS). For mobile cellular access, we are currently conducting, jointly with NTT DoCoMo and a local cellular network operator, SingTel Mobile, a wideband code-division multiple access (WCDMA) pilot service trial with connectivity to SingaporeONE. However, since this service trial is ongoing, we refrain from describing it further. For wireless local area networking, we describe the design and development of a wireless ATM LAN, and present our conclusions.

Local Multipoint Distribution Service

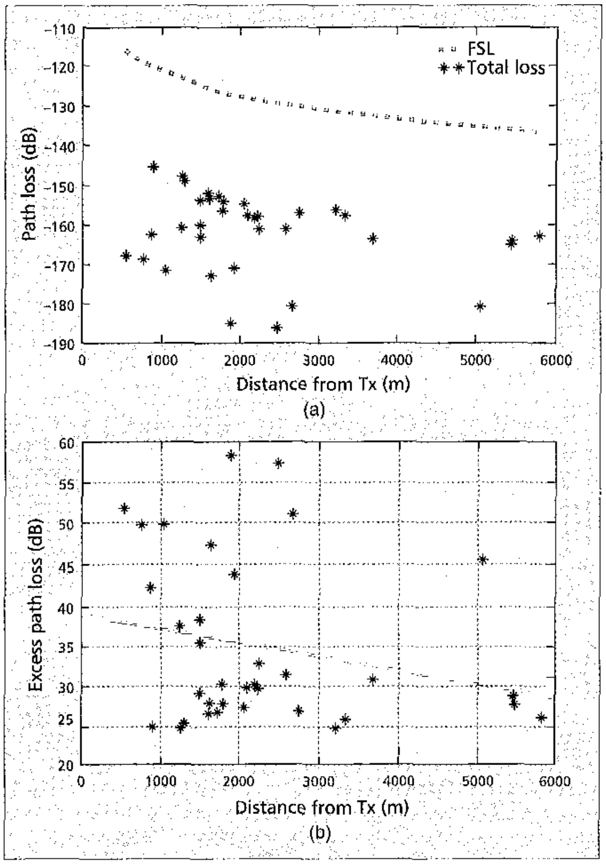
LMDS is a millimeter-wave broadband access service generally operating above 20 GHz. The technology offers several advantages such as the availability of a wide bandwidth (i.e., 1.3 GHz) and the ability to handle bursty digital traffic [2, 3]. The U.S. FCC has allocated use of the 28–31 GHz band for LMDS, while Singapore has identified frequencies in the 20–40 GHz range. LMDS is based on a cellular architecture. However, it differs in that it uses fixed links between a multidirectional hub and a number of dispersed fixed subscriber terminals. It also requires line-of-sight (LOS) communications since the millimeter waves form pencil-like beams that can easily be reflected and/or attenuated by the physical obstructions along their paths. An LMDS network typically comprises multiple overlapping cells of 2–6 km diameter each. Each cell basically consists of a hub with an omnidirectional or sectorized antenna and a number of subscriber terminals, each with a directional antenna (Fig. 1). The antenna for the hub is typically mounted on either a tall tower or the rooftop of a tall building that is centrally located to establish possible LOS links with subscribers' roof-mounted antennas.

Propagation Measurements and Modeling

Because millimeter waves attenuate rapidly and are highly sensitive to the makeup of the physical environment (i.e., buildings and foliage) and weather conditions (e.g., fading effects of rainfall[1]), the characterization of the local propagation channel model is an important prerequisite in the design of an LMDS system [4, 5]. We have made fairly extensive propagation measurements at two typical urban and suburban environments in Singapore as part of our activities in the study and design of an LMDS system. The measurements are aimed at providing various characteristics on path loss, delay spread, and other impulse response parameters that give valuable insight into the coverage limitations and radio planning of an operational LMDS system. The wideband behavior of the propagation channel is studied in terms of the average delay, rms delay spread, delay window, and correlation bandwidth. A mathematical tapped delay line channel model is developed that captures the time-varying dispersive channel behavior more realistically [6]. This is then used in a system-level simulation to investigate suitable modulation and coding schemes to enhance LMDS performance [7].

Field Measurements — We carried out measurements using a radio channel sounder that used the Swept Time Delay Cross-Correlation (STDCC) technique to measure the impulse response of a wideband channel at 27.4 GHz [6]. The transmitter employed a 511-bit m-sequence at a chip rate of 50 Mchips/s, providing a delay spread resolution of 20 ns. Measurements were made at two hub sites at the National University of Singapore (NUS) and Clementi Town, representing typical suburban and urban areas in Singapore, respectively. At each site, the transmitter was located centrally on the rooftop of a tall building, and rooftops of surrounding residential blocks of 13–25 floors within a radius of 0.5–6 km were used as receiver sites. At these sites, the factors that affected the service quality of an LMDS system included attenuation by natural vegetation, blockage by adjacent buildings, and the density of surrounding buildings. More than 35 receiver locations for each hub site were selected to facilitate the study of LOS loss, and blockage effects such as partial blockage by a

[1] *We were unable to do realistic measurements to study these effects because the equipment we used could not be operated outdoors in heavy rain.*



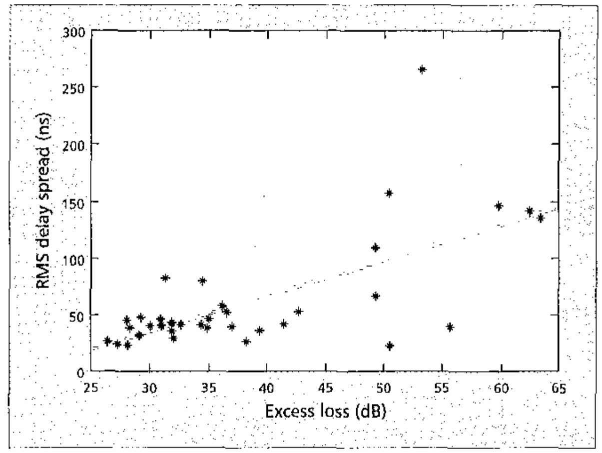
■ **Figure 2.** *Scatter plot of: a) path loss vs. transmitter distance; b) excess path loss vs. transmitter distance.*

building, complete blockage by one or two tall buildings, and so on. Circles of different radii were drawn around the transmitter in such a way that the receiver sites falling on each circle had different blockage conditions that facilitated study of the effects of blockage. The receiver sites falling on different circles but in the same azimuth direction were used to study the effects of distance on channel behavior.

For each measurement, 100–1000 complex channel impulse responses were recorded over a period of one pseudo-noise (PN) code length (511 * 20 ns = 10.22 μs) in each direction. The averaged impulse response was then used to derive the tapped delay line channel model, while the series of complex impulse responses were used to study the time-varying nature of the channel. After recording the received signal in the LOS direction, the receiver antenna was rotated in the azimuth direction in steps of 5° and the received signal strengths recorded over a 360° range. This provided enough information on the multipath signals resulting in a significant peak in the non-LOS directions.

The Measurement Results and Analysis

Path Loss Characteristics — The total path loss can be viewed as the summation of the free space loss (FSL) and attenuation along the path. Figure 2a[2] shows the measured total path loss for one of the sites considered as a function of distance. It can be observed that the measured data follows the FSL curve with an additional loss due principally to the attenuation caused by the surrounding environment, which includes local multipath and shadowing effects. This additional path loss, commonly known as *excess path loss*, is plotted in Fig. 2b as a function of distance. The excess path loss ranges from 24–60 dB, is more dominant at shorter distances and is almost constant at longer distance. Based on the blockage nature, receiver locations can be broadly classified into four categories, namely clear LOS, near LOS, partially blocked by a single building and/or foliage, and completely blocked by multiple buildings. Accordingly, the excess path loss lies in the range of 25–35 dB for clear LOS and 35–45 dB for partial blockages. When blocked by a single and/or multiple foliage trees, the excess path loss increases above 45 dB. Blockage by multiple buildings causes an excessively high loss of 55 dB. In addition, when measurements were made in the presence of slight rainfall, high excess loss was noted. The effects of heavy rainfall, however, require further investigation since the rain fading effects often dominate the multipath fading at these frequencies.



■ **Figure 3.** *Scatter plot of rms delay spread vs. excess path loss.*

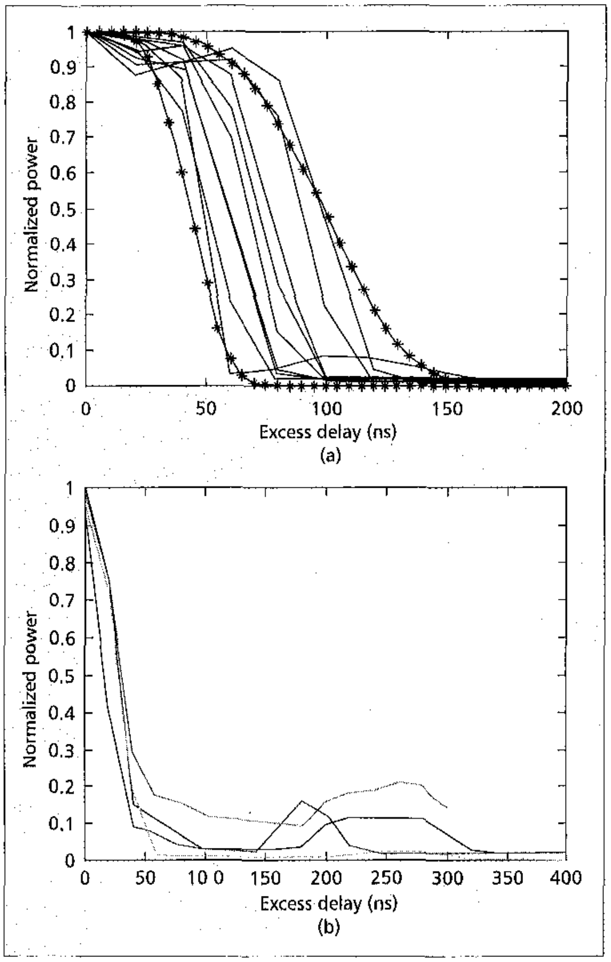
Delay Characteristics — The power delay profile shows the variations of relative power density of the signal received as a function of average delay. The time dispersive nature of the propagation channel can be characterized using parameters such as the root mean square (rms) delay spread and mean excess delay. The average delay is the power-weighted average of the excess delays given by the first moment of the impulse response. The rms delay spread is the power-weighted standard deviation of the excess delays given by the second moment of the impulse response, and provides a measure of the variability of the mean delay.

These parameters were evaluated for each receiver loca-

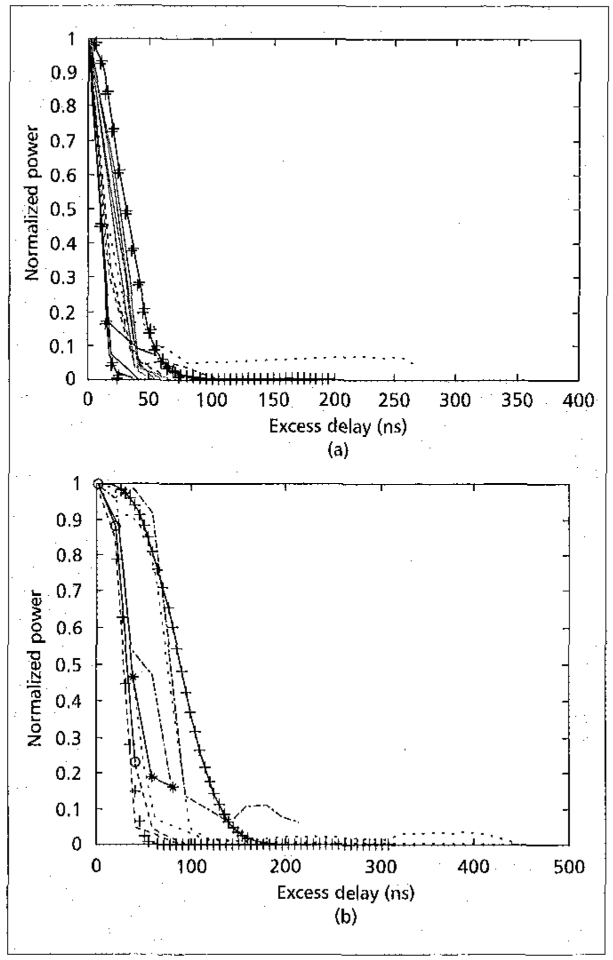
Channel parameter	NUS hub	Clementi hub
Received power	–105 to – 65dBm	–105 to –70dBm
Excess path loss	25–60 dB	40–65 dB
Mean delay	20–300 ns	20–110 ns
RMS delay spread	20–250 ns	12–200 ns
Delay window	Up to 1600 ns	Up to 500 ns
Correlation bandwidth	2–16 MHz	4–16 Hz
Doppler frequency	500–100 Hz	50–100 Hz
Rician *K* factor	2–12 dB	–4–12 dB

■ **Table 1.** *A summary of channel characteristics.*

[2] *The negative sign for path loss in Fig. 2a is used only to indicate loss; the actual path loss is given by its absolute value.*



■ **Figure 4.** *Typical pwer delay profile of the NUS hub site: a) case 1; b) case 2.*



■ **Figure 5.** *Typical power delay profile of the Clementi hub site: a) case 1; b) case 2.*

tion (see the summary of channel characteristics in Table 1). It can be observed that receiver locations around the Clementi transmitter hub have comparatively worse path loss characteristics and better delay characteristics than the NUS hub. This is because the suburban NUS site has fewer obstructions in the vicinity of its transmitter that enables the transmitted energy to be spread in all directions, leading to the reception of more multipath components. In contrast, the urban environment of the Clementi site has adjacent buildings of comparable height surrounding its transmitter, causing fast signal attenuation and relatively less multipath. This observation suggests the importance of site selection for hub location.

The Tapped Delay Line Channel Model — The impulse response of the radio channel is important in the design, development, and planning of radio systems because it completely describes the radio propagation channel. Once the impulse response of the channel is known, the actual received signal can be obtained by convoluting it with any specified transmitted signal in the presence of additive white Gaussian noise (AWGN).

The measurements reveal that the received signal varies from –5 to +5 dB about the signal local mean for most of the locations. The signal distributions are observed to follow a Nakagami-Rician distribution with *K*-factors ranging from –4 to 12 dB. In the tapped delay line channel model [6], the delay profile is the main feature that describes the channel behavior for various environments. Figure 3 presents the rms delay spread versus excess path loss, which shows that the receiver sites with high excess path loss also suffer from large rms delay spread. Figures 4a and 4b show the typical measured power delay profiles for two channel conditions. In these figures solid lines without markers correspond to power delay profiles from measurements, while solid lines with markers correspond to the mathematical equations derived that fit the data with a mean square error of 2–5 percent [6].

The power delay profile for various receiver locations around the Clementi hub are shown in Figs. 5a and 5b for two typical cases. Because of the partially covered transmitter location, delay profiles are found to have less spread, and there is no second cluster with significantly delayed multipath components.

In summary, the measurement results show that the excess path loss is the most serious propagation impairment that affects the performance of an LMDS system. The LOS condition between transmitter and receiver is necessary to ensure good signal quality. The excess path loss for various blockage conditions has to be compensated for by providing suitable link margins. The mean excess delay and rms delay spread indicate that more than 90 percent of the locations observed are below 150 ns and 200 ns, respectively. The maximum mean excess delay observed is 300 ns, and that of the rms delay spread is 250 ns. The short-term fluctuations of the received signal reveal the fact that the channel shows strong Rician behavior with K-factors in the range of -4–12 dB. The channel is modeled as a wideband time-varying channel with approximate exponential power delay profiles defined for various environmental conditions. This model is used in a system-level simulation to investigate the optimum modulation and coding techniques.

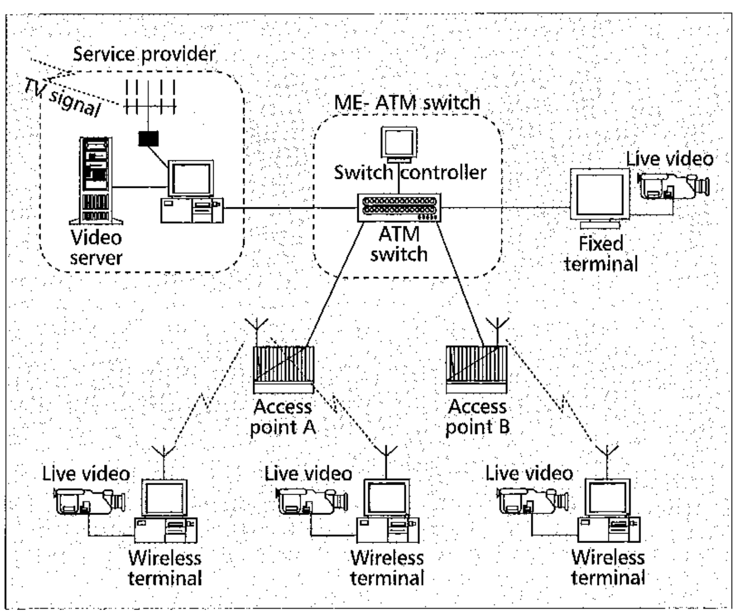
Optimum Modulation and Channel Coding

Using the channel model derived through measurements, we have investigated by simulation, the performance of orthogonal frequency-division multiplexing (OFDM) with concatenated RS convolutional codes, convolutional interleaving, and multilevel quaternary phase shift keying/quadrature amplitude modulated (QPSK/QAM) signaling, and derived suitable OFDM parameters such as the fast Fourier transform (FFT) length and cyclic prefix [7]. We insert one pilot OFDM symbol in every other 10 symbols and employ a one-tap zero-forcing equalizer. Our simulations suggest the use of FFT of length 64 and a cyclic prefix of eight symbols. We have also compared the performance of OFDM with a least mean square (LMS) equalizer-based QAM modulation. Our simulations show that coded OFDM with QPSK signaling can achieve error-free transmission at an affordable SNR, while 16/64-QAM may be used when a higher BER is tolerable. On the other hand, traditional equalizer-based QAM gives poor performance in the measured channel.

Wireless Asynchronous Transfer Mode

Unlike legacy LANs, ATM LANs provide guarantees on quality of service (QoS) to end terminals. WATM is complicated by the fact that users may move from the coverage area of one access point (base station) to that of another, thereby necessitating support for handover, and the fact that transmissions on a wireless channel are more susceptible to corruption by noise and interference. These characteristics complicate significantly the design of a WATM LAN.

We began a project jointly with the Kent Ridge Digital Laboratories (KRDL) in Singapore and Ericsson Radio Systems AB to develop a 25 Mb/s WATM LAN operating in the 5.15–5.3 GHz frequency band in 1997. In the following, we describe briefly, the parts of the project that we have undertaken. Essentially, the target system was meant to extend the reach of an enterprise ATM LAN to the wireless domain. Similar systems have been developed at NEC [8] and ORL [9] at Cambridge, for example.



■ **Figure 6.** *The prototype WATM testbed context.*

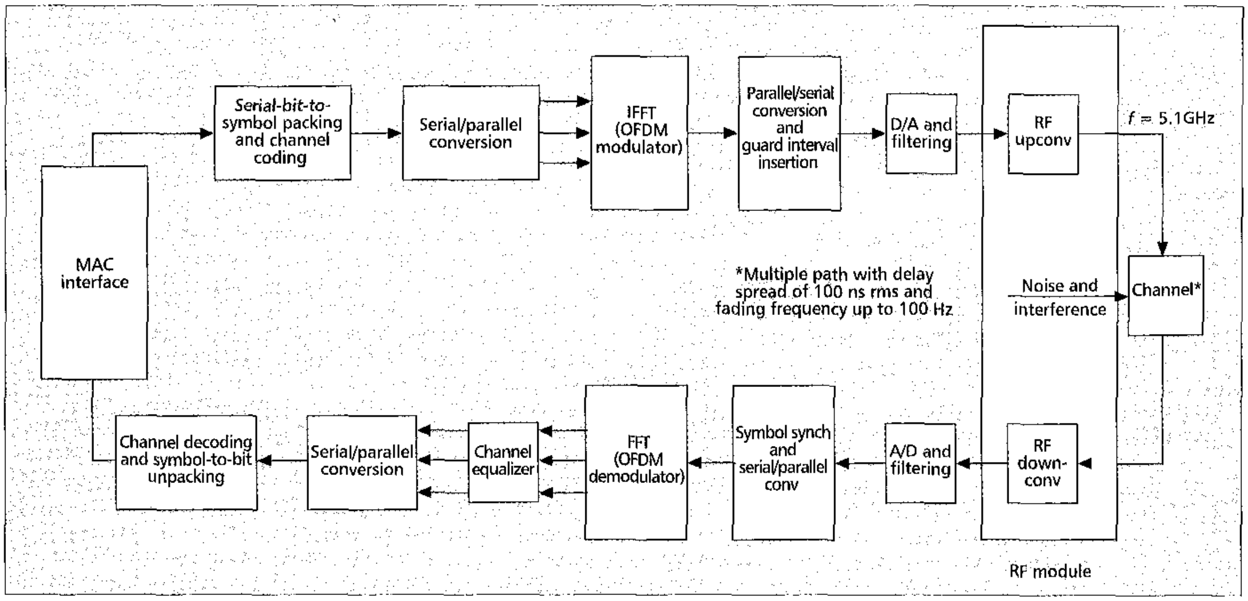
The Prototype Testbed

Figure 6 gives an overview of the testbed context in which the prototype WATM LAN is developed and tested. Complete prototypes of the access points (APs) and wireless terminals (WTs) have been developed, along with the signaling and ATM switch management functions to enable the support of QoS guarantees to mobile end users. In the following, we describe briefly the medium access control (MAC), logical link control (LLC), and physical layer designs of the prototypes that have been developed.

MAC and LLC Layers — The MAC and LLC layers comprise two major functions each. MAC framing assembles the MAC protocol data units (PDUs) and transmits them over the air interface. MAC scheduling assigns air resources (i.e., slots in the MAC frame) to the wireless terminals, whereas LLC scheduling decides the connection that should be given the assigned resources. LLC framing assembles the LLC PDUs.

The prototype employs time-division multiple access (TDMA) with time-division duplexing (TDD) in the air interface between an AP and the WTs. This enables asymmetric and dynamic allocation of bandwidth based on the traffic contract of the different connections. The MAC frame is divided into four parts, comprising the uplink and downlink channels, each of which comprises two parts. In the downlink channel these are the broadcast field, which contains the announcement and assignment lists as well as other vital control information for the current frame, and the downlink data slots, which carry the MAC PDUs from the AP to the WTs. Because of its vital importance in defining the layout of the whole frame, the broadcast field is highly protected. The assignment and announcement lists are compressed lists that indicate to the different WTs the downlink/uplink slots to receive/send their PDUs. The uplink channel is divided into two parts comprising the uplink data slots and a random access channel (RACH) where different terminals compete for access using a slotted Aloha protocol. The RACH is used either to transmit dynamic bandwidth requests when a WT does not have any uplink slots to piggyback its requests, or to support other functions such as the attachment of a new terminal to the AP. To reduce the protocol overhead, PDUs originating from the same WT are clustered together, and a single header is appended to the cluster in the uplink.

The DLC Scheduler — The scheduling architecture is hierarchical. This is done to reduce the overhead incurred due to excessive bandwidth reservation requests. There are two levels of hierarchy; the MAC scheduler allocates MAC slots to the different WTs without specific knowledge of the connections to which the slots are assigned. It need only know the service category for which the



■ **Figure 7.** *An OFDM modem overview.*

slots are reserved. The LLC scheduler divides the slots obtained from the MAC scheduler among the different connections in the targeted service category. This in fact addresses a major problem that arises from the remote property of the uplink queues. For example, between the time a reservation is transmitted and the time it is granted, the status of some of the queues might change. By allowing a WT to decide to which connection the granted slots are allocated, the most up-to-date queuing status can be used.

In the prototype we have developed, we considered only constant bit rate (CBR) and unspecified bit rate (UBR) services. The MAC scheduler allocates time slots to the different WTs based on their queuing information. The queues in the central MAC scheduler are in fact virtual queues, each representing the sum of the capacity requests transmitted per WT per service category. To allocate the MAC PDUs fairly and consistently among the different WTs, the MAC scheduler uses a weighted round-robin algorithm where the weights are proportional to the queue lengths for CBR service, and the egalitarian round-robin algorithm is adopted for UBR service. Note that although this would guarantee fairness among the UBR connections, it is not necessarily true that the weighted round-robin algorithm is appropriate for CBR. However, in the absence of very complete per-cell timing information, it is impossible for the MAC scheduler to be accurate. We believe that this approach is a good compromise between guaranteeing QoS on one hand and enhancing the MAC protocol throughput on the other. To compensate in this trade-off of QoS for throughput, the LLC schedulers distribute the obtained air resources among their respective connections based on timely per-VC queuing information which is available locally. For example, assume a WT requests five slots for a CBR connection and six slots for a UBR connection. Assume also that by the time the MAC scheduler allocates the 11 slots to the WT, the CBR connection has generated two more cells. When the LLC scheduler receives the allocation of 11 slots, it can decide to allocate seven slots to the CBR connections and four to the UBR connection.

The Physical Layer — The physical layer uses the 5.15–5.3 GHz frequency band allocated to HIPERLAN. To combat the co-channel interference, the WATM system uses error coding in conjunction with automatic repeat request (ARQ). Furthermore, antenna diversity is used to reduce the impact on frequency-selective fading and Rayleigh fading, and thereby improve the carrier-to-interference ratio. The OFDM modulation technique is used in our implementation because of its known capability in combating multipath fading.

Figure 7 shows the block diagram of the OFDM modem. The incoming bitstream from the MAC interface is first packed into 3 b/symbol. These inputs are channeled to a rate 3/4 trellis encoder. The output of the channel is a complex number determined by the 16-QAM signal constellation. These QAM data are then converted from serial into parallel N complex QAM symbols. This is termed a block of symbols, which is modulated by an inverse FFT (IFFT) process. The output of the IFFT forms an OFDM symbol, which is converted back to serial data for transmission. The guard interval is easily generated by cyclically repeating part of the OFDM symbol. The discrete output from the digital-to-analog converter (DAC) is filtered and output for RF upconversion. Before each transmission three overhead OFDM symbols are inserted. The three overhead symbols comprise two repeated symbols for both OFDM frame synchronization and carrier recovery, and a third symbol for channel estimation.

At the receiver, the received signal from the RF module is digitized and sent to the OFDM demodulator. The performance of an OFDM system depends on the correct sampling of the N points for FFT operation. The N points sampled should avoid the intersymbol interference (ISI) corrupted cyclic prefix interval. The frame synchronizer is designed to make use of the inserted repeated OFDM symbol for this purpose. At the same time as synchronization is being performed, the frequency offset inevitably introduced due to component tolerance of the reference oscillator at both the transmitter and receiver ends is derived. In our design, besides the frame synchronization and carrier recovery, we have devised a digital automatic gain control (AGC) method making use of the computed power and correlation values. This method is effective in reducing the dynamic range of the subsequent processing and hence lower implementation complexity. With the frequency offset compensated, the demodulation process is performed by an FFT operation. A one-tap equalizer is used to correct any channel distortion, and the channel coefficients are obtained from the pilot symbol transmitted immediately

Number of carriers	38 out of 48 carriers, 4 pilot carriers
Modulation scheme	16 QAM
Guard interval	0.75 μs (cyclic prefix of 12 points)
OFDM symbol	3. 75 μs
Channel coding	TCM (rate 3/4)
Effective data throughput per symbol	114 bits

■ **Table 2.** *A summary of OFDM parameters.*

after the synchronization symbols. To keep track of any residual phase error due to the variance of the frequency error estimator, additional scattered pilot symbols are inserted in the data symbols. The residual phase error is compensated before the trellis decoding of the transmitted sequence. The output of the channel decoder is channeled to the MAC interface circuit to extract the MAC frame.

The system design parameters for the OFDM modem are summarized in Table 2.

The OFDM modem is implemented using eight Altera Flex10K-100 field programmable gate arrays (FPGAs). From our measurements, the OFDM modem delivers a bit rate of around 29 Mb/s, which theoretically allows the prototype to deliver the standard 20–25.6 Mb/s data rate.

CONCLUSIONS

Singapore is well on its way to providing broadband connectivity to every household on the island. Although this will be primarily based on a wired infrastructure utilizing ADSL and cable modems, there is significant interest in exploring the use of suitable wireless broadband communication technologies to provide access to the SingaporeONE backbone. In addition, wireless broadband communication technologies are being considered in the local area network to distribute broadband services within homes and offices. In this article we describe very briefly some of our R&D activities in LMDS and WATM as potential technologies to provide wireless broadband fixed access and wireless broadband local area networking, respectively. While the WATM work is nearing completion with the development of a working prototype, the LMDS work is only beginning with a study on the characterization of the channel under local built and natural environments, and the use of the channel model in determining suitable modulation and channel coding schemes. Our future work in LMDS will be to specify, design and prototype an LMDS system with connectivity to SingaporeONE.

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BIOGRAPHIES

KEE CHAING CHUA [M] (chuakc@cwc.nus.edu.sg) is an associate professor in the Department of Electrical Engineering at the National University of Singapore, and is concurrently deputy director of the Centre for Wireless Communications (CWC), a national telecommunications R&D center. His research interests are primarily in computer communication networks, with a current focus on wireless/mobile multimedia networking. He served as Chair of the Singapore Chapter of the Society in 1993–1994. He also served on the Society's Member Affairs Council and acted as Region 10 Chapters Chair Coordinator. He has also served as Finance Chair of IEEE GLOBECOM '95 and on the Technical Program Committees of some IEEE INFOCOM and PIMRC conferences.

K. V. RAVI [SM] (cwckvr@nus.edu.sg) is a member of technical staff at the CWC of the National University of Singapore, where he conducts research in the area of coded modulation techniques including trellis and turbo coding for applications to WCDMA, LMDS, and other broadband radio access networks. As a senior R&D manager at CWC, he has recently successfully led a project team on LMDS activity. Earlier, he was an assistant professor at the Indian Institute of Technology, Kharagpur (1994–1997), and also worked as a scientist/engineer for the Indian Space Research Organization (ISRO) on various R&D programs in digital satellite communications and CDMA systems (1983–1994). He received a Ph.D. from the University of Bath, United Kingdom, as a commonwealth scholar in 1991, a post-graduate degree in electrical communication engineering from the Indian Institute of Technology, Kharagpur, in 1983, and a graduate degree in electronics and communication engineering from Sri Venkateswara University, Tirupati, India, in 1981.

BRAHIM BENSAOU [M] (brahim@cwc.nus.edu.sg) received a Diplome d'Ingenieur from the University of Science and Technology Houari Boumediene, Algiers, Algeria, in 1987, and an M.Sc. degree from University Paris XI, Orsay, France, in 1988, both in computer science. From 1990 to 1993 he worked toward a Ph.D. in computer science with the Performance of Multiservice Networks research group of France Telecom Research Laboratories, CNET. In 1993 he earned his Ph.D. from University Pierre et Marie Curie, Paris VI, France. From 1995 to 1997 he was a research associate with the Department of Electrical and Electronic Engineering of the Hong Kong University of Science and Technology. After that he joined the CWC, National University of Singapore, where he is currently a senior member of technical staff, leading the networks research group. His research interests include traffic control and scheduling in both wired and wireless multimedia networks, quality of service, and, in general, traffic engineering.

TECK CHIEN PEK (cwcpektc@nus.edu.sg) is currently an executive R&D manager in the CWC. He received his B. Eng. degree with first class honors in electrical engineering from National University of Singapore in 1992. He was with a multinational company involved in consumer electronics product development for more than a year before joining the CWC in 1993. Since then, he has been involved in a number of projects including spread spectrum packet radio development, repeater design, and military communicator and OFDM modem development.

Number of carriers	38 out of 48 carriers, 4 pilot carriers
Modulation scheme	16 QAM
Guard interval	0.75 µs (cyclic prefix of 12 points)
OFDM symbol	3. 75 µs
Channel coding	TCM (rate 3/4)
Effective data throughput per symbol	114 bits

■ **Table 2.** *A summary of OFDM parameters.*

after the synchronization symbols. To keep track of any residual phase error due to the variance of the frequency error estimator, additional scattered pilot symbols are inserted in the data symbols. The residual phase error is compensated before the trellis decoding of the transmitted sequence. The output of the channel decoder is channeled to the MAC interface circuit to extract the MAC frame.

The system design parameters for the OFDM modem are summarized in Table 2.

The OFDM modem is implemented using eight Altera Flex10K-100 field programmable gate arrays (FPGAs). From our measurements, the OFDM modem delivers a bit rate of around 29 Mb/s, which theoretically allows the prototype to deliver the standard 20–25.6 Mb/s data rate.

CONCLUSIONS

Singapore is well on its way to providing broadband connectivity to every household on the island. Although this will be primarily based on a wired infrastructure utilizing ADSL and cable modems, there is significant interest in exploring the use of suitable wireless broadband communication technologies to provide access to the SingaporeONE backbone. In addition, wireless broadband communication technologies are being considered in the local area network to distribute broadband services within homes and offices. In this article we describe very briefly some of our R&D activities in LMDS and WATM as potential technologies to provide wireless broadband fixed access and wireless broadband local area networking, respectively. While the WATM work is nearing completion with the development of a working prototype, the LMDS work is only beginning with a study on the characterization of the channel under local built and natural environments, and the use of the channel model in determining suitable modulation and channel coding schemes. Our future work in LMDS will be to specify, design and prototype an LMDS system with connectivity to SingaporeONE.

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BIOGRAPHIES

KEE CHAING CHUA [M] (chuakc@cwc.nus.edu.sg) is an associate professor in the Department of Electrical Engineering at the National University of Singapore, and is concurrently deputy director of the Centre for Wireless Communications (CWC), a national telecommunications R&D center. His research interests are primarily in computer communication networks, with a current focus on wireless/mobile multimedia networking. He served as Chair of the Singapore Chapter of the Society in 1993–1994. He also served on the Society's Member Affairs Council and acted as Region 10 Chapters Chair Coordinator. He has also served as Finance Chair of IEEE GLOBECOM '95 and on the Technical Program Committees of some IEEE INFOCOM and PIMRC conferences.

K. V. RAVI [SM] (cwckvr@nus.edu.sg) is a member of technical staff at the CWC of the National University of Singapore, where he conducts research in the area of coded modulation techniques including trellis and turbo coding for applications to WCDMA, LMDS, and other broadband radio access networks. As a senior R&D manager at CWC, he has recently successfully led a project team on LMDS activity. Earlier, he was an assistant professor at the Indian Institute of Technology, Kharagpur (1994–1997), and also worked as a scientist/engineer for the Indian Space Research Organization (ISRO) on various R&D programs in digital satellite communications and CDMA systems (1983–1994). He received a Ph.D. from the University of Bath, United Kingdom, as a commonwealth scholar in 1991, a post-graduate degree in electrical communication engineering from the Indian Institute of Technology, Kharagpur, in 1983, and a graduate degree in electronics and communication engineering from Sri Venkateswara University, Tirupati, India, in 1981.

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