On the Scalability of Fixed Broadband Wireless Access Network Deployment

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Abstract

Fixed broadband wireless access systems, such as the local multipoint distribution service, use an open system architecture that supports a scalable solution for Internet services over IEEE 802.16 wireless networks. This article presents an overview of various features of BWA systems toward realizing a high level of scalability to support a potentially fast expanding network. This is achieved by optimizing various network resources, which include utilizing the available bandwidth efficiently, making a minor enhancement to an existing system that minimizes the disruption to network services during the network expansion process, and combining the benefits of different features to increase network capacity.

Introduction

The global demand for multimedia data services has grown at a remarkable rate in recent years. The increase in demand is likely to grow at an even faster pace in the future due to advances in multimedia distribution services. Network scalability thus becomes an important consideration for both equipment manufacturers and service providers. The overall system capacity has to be made expandable in terms of the number of subscribers supported, data rate, and geographical coverage. There are many factors that influence the scalability of a network. Furthermore, the persistent demand for enhancement in multimedia data services is becoming an important driving force for network expansion and deployment so that the network is capable of supporting new services when they become available. At the same time, network capacity must keep up with demand. A scalable network provides an economical means of expanding an existing network to expeditiously meet future demands with minimal interruption in service availability caused by the expansion process. Each hub in the network has its effective coverage, which is determined by important parameters such as the selection of modulation scheme, the amount of cell overlap, and, more persuasively, climatic and environmental factors, such as rainfall statistics.

Fixed broadband wireless access (BWA) systems, such as the local multipoint distribution service (LMDS) [1], provide multimedia services to a number of discrete customer sites with IP and offer numerous advantages over wired IP networks. This is accomplished by using base stations to provide network access services to customer sites based on the IEEE 802.16 WirelessMAN™ standard [2, 3]. First published in April 2002, the IEEE 802.16 standard has recently been updated to IEEE 802.16-2004 (approved in June 2004). The standard focuses on the "first-mile/last-mile" connection in wireless MANs. Its purpose is to facilitate the optimal use of bandwidth from 10 to 66 GHz, as well as interoperability among devices from different vendors. Typical channel bandwidth allocations are 20 or 25 MHz (United States) or 28 MHz (Europe), with Nyquist square-root raised-cosine pulse shaping with a rolloff factor of 0.25 [3]. IEEE 802.16 has over the years developed into a family of standards as summarized in Table 1 (for more details on the standard, please refer to http://www.ieee802.org/16/). The progress of the standard has been fostered by the keen interest of the wireless broadband industry to capture the emerging WiMax (worldwide interoperability for microwave access) market, the next-wave wireless market that aims to provide wireless broadband Internet services. The WiMax Forum, formed in 2003, is promoting the commercialization of IEEE 802.16 and the European Telecommunications Standard Institute's (ETSI's) high-performance radio metropolitan area network (HiperMAN).

Among the several advantages offered by such BWA systems, it is generally less expensive and faster to install them, especially in situations where a large number of locations have to be covered. In addition, its deployment is based on demand, which makes the system expandable with its scalable architecture by using open industry standards. This way, network service providers can easily expand their existing networks without being bounded by the restriction of certain manufacturers. Other advantages include flexible hub configurations and the deployment of frequency reuse schemes within its allocated frequency band of operation. The scalability of deploying LMDS in response to the ongoing network expansion demands stems from the fact that LMDS uses a wireless last mile access medium. This eliminates the need for costly and time-consuming cabling and/or wire upgrading. Its wireless nature also makes LMDS an attractive choice for cost-effective expansion of MANs. As pointed out in [4], the Ethernet-supported IP-over-wavelength-division multiplexing (WDM) ring paradigm provides a flexible solution for the next-generation metropolitan optical network. An LMDS system equipped with Ethernet-aware optical multiplex/demultiplex components can easily be configured into a low-cost scalable access aggregator to the MAN optical ring; thus, in essence, becoming an optical add-drop multiplexer (ADM) with wireless capability.

Projection of BWA network scalability primarily depends on attributes associated with customer sites. These include issues of geographic density of customer sites, node density on each floor of the building, expected growth in demand, and quality of service (QoS) requirements such as peak/off-peak data rates and concentration ratios. These attributes can be translated into a specific demand in terms of data bandwidth

Designation	Classification	Remarks	Status
802.16	Air Interface	WirelessMAN™ standard (air interface for fixed broadband wireless access systems) for wireless metropolitan area networks	Published April 2002
802.16a	Air Interface	Amendment to 802.16; purpose is to expand the scope to licensed and license-exempt bands from 2 to 11 GHz	Published April 2003
802.16c	Air Interface	Amendment to 802.16; purpose is to develop 10–66 GHz system profiles to aid interoperability specifications	Published January 2003
802.16REVd	Air Interface	Converted from 802.16d, now published as the most recent update to the standard	Approved as 802.16-2004 in June 2004
802.16.2	Coexistence	Recommended practice on coexistence of broadband wireless access systems for 10–66 GHz	Published September 2001; now replaced by 802.16.2-2004
802.16.2a	Coexistence	Amendment to 802.16.2; purpose is to expand scope to include licensed bands from 2 to 11 GHz and to enhance the recommendations regarding point-to-point systems	Subsequently converted and published as 802.16.2-2004 in March 2004
802.16/Conf01	Conformance	Conformance01 PICS for 10–66 GHz	Published August 2003
802.16/Conf02	Conformance	Test suite structure and test purposes for 10–66 GHz	Published February 2004
802.16/Conf03	Conformance	10–66 GHz radio conformance tests	Approved May 2004
802.16/Conf04	Conformance	PICS for < 11 GHz	Pending

Table 1. *The family of IEEE 802.16 standards.*

required by a unit area of coverage. LMDS/BWA is also a tempting opportunity for incumbent operators to enhance their flexibility and competitive advantage.

In this article we present an analysis of provisioning a scalable fixed BWA network by LMDS based on various implementation scenarios. The network can evidently be made scalable in order to support future growth in demand with features such as versatile cell division, combined use of various modulation schemes and multiple access methodologies, optimization of frequency diversity, and application of alternate polarization. We describe how each of these features contributes to providing a scalable solution to support high-speed multimedia network services. By giving an overview of how scalability is supported by an open network architecture and briefly describing ways of optimizing system deployment by carefully making in-bound interference, modulation, and channelization schemes as flexible as possible, readers may be convinced that maximum network scalability can be achieved in terms of both data capacity and subscriber capacity.

An Overview of the Network Architecture

In a fixed broadband wireless network such as an LMDS network, a switching component connects the system to the IP network backbone. Figure 1 illustrates the connection between the radio hub and the service provider via a 155 Mb/s OC-3 link. However, because of the wide operating bandwidth of LMDS (usually above 1 GHz), the data rate at the base station radio unit can reach over 100 Mb/s. Therefore, in the system depicted in Fig. 1, the bottleneck would be at the OC-3 link. Scalability should be guaranteed either by a proper design of the radio hub architecture or by a proper functional distribution. For example, a local switching functionality may be implemented at the base station (intelligent base station) so that communication among customers connecting through the same base station can be switched/routed by the base station rather than by the switches at the service provider. This arrangement reduces the traffic on the bottleneck link. Both approaches improve scalability at the cost of increased radio hub complexity. In addition, it is also possible to increase the number of sectors by using antennas with a smaller beamwidth at each hub and to add antennas with alternate polarity in order to further increase the number of subchannels. Furthermore, the network can be optimized by balancing a trade-off between fixed and adaptive bandwidth allocation based on demand according to the density of subscribers and projected growth in demand for different types of services. Finally, although not at the architectural level but rather at the protocol level, fixed broadband wireless systems present a great challenge and rooms for improvement of data transporting protocols for optimum utilization of the network resources.

Naturally LMDS as wireless technology is subject to higher bit error rates (BERs) and signal strength fading than the wired medium. Weather conditions, such as lightning, and flying objects, such as low altitude helicopters, can all cause temporary blackouts. Forward error correction (FEC) coding is a classical way to combat the relatively high BER to a certain extent, but traditionally at the cost of higher hardware complexity of both the base station and the custom premises equipment. With recent technological advances, however, FEC implementations such as a Reed-Solomon coder/decoder are becoming less complex and are often incorporated into chipsets.

For more than two decades, TCP has been the dominant transport layer protocol for Internet applications, particularly for bulk data transfer applications. Since these applications are most susceptible to the errors caused by high BER and blackouts, improvement of TCP to better deal with communication errors in the wireless data link has been a very active area of research. Among the various proposed solutions, software protocols based on end-to-end TCP modifications such as TCP-Jersey [5] are the most flexible and scalable solutions to achieving optimum utilization of the wireless link capacity. In fact, any TCP modifications are reasonably easy to add to closed systems, but in general deployment can be a problem due to a lack of support by end users' operating systems. Scalability of these protocol solutions, specially designed for wireless links, also stems from their compatibility with the wired network versions and the ability of partial and gradual deployment.

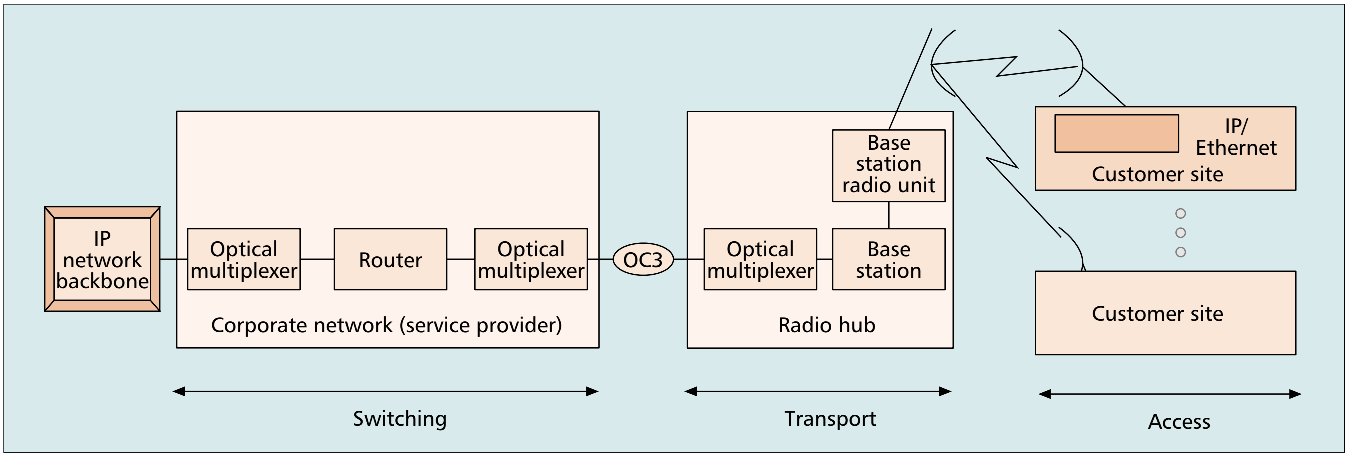


Figure 1. *The system layout of an LMDS system that offers a high degree of scalability. The system consists of three major components: switching: provides a connection point for the system to be linked to the internet; transport: the radio hub connects the base station to a wired IP network backbone with an OC-3 connection and converts the data into a form that is suitable for modulation; access: at the customer end, each remote site has an outdoor antenna with a subscriber radio unit for signal reception. The received signal is then processed by a subscriber access system where demodulation takes place followed by forwarding data to the destination node. Each of the black "zigzag" lines between the radio hub and each customer site's antennas in the figure represensts both a single link serving a customer's premises as well as the return channel.*

Scalability Analysis

The deployment of BWA networks has scalability implications on a number of factors. Many BWA systems operate in the very congested portion of the spectrum, where bandwidth limitation is a major constraint to network scalability. Therefore, parameters other than channel frequency bandwidth must be controlled to maintain a high degree of network scalability. Factors such as cell planning and utilization of subchannels within the licensed range of available frequencies have to be addressed in the early stage of network planning. Subsequent modification to an operational system may be difficult once the hub locations are fixed, especially when the narrow beamwidth antennas at subscriber sites need to be adjusted to facilitate new hubs. Other factors, such as routing and multiple access methods, can be changed according to demand without causing much interruption to the network operation. With an ever-increasing demand in data density that requires an increase in both data throughput and coverage to support future multimedia services, a scalable network architecture is an essential parameter for BWA network implementation. This is particularly so given the limitation in spectrum allocation, which is usually determined by local authorities, and the fact that the network must operate only within its allocated band.

In summary, we can ensure a high level of scalability by:

- Cell planning for addition of sectors and cell splitting into microcells with hub spacing, coverage, and number of sectors per hub optimization.
- An appropriate modulation scheme that offers optimal performance in both spectral efficiency and geographical coverage. It should be noted, however, that sometimes the choice of modulation scheme may be limited in a standardization process due to interoperability and regulation requirements. Some adaptation is still possible as part of the standard, as is evident in the evolution of IEEE 802.11. The IEEE 802.16 standard provides even greater latitude in this regard.
- Access options that provide efficient downstream and upstream links to maximize utilization of channels to support both constant and variable bit rate services.
- Optimal application of frequency reuse and alternate polarization where a combination of frequency diversity and cross-polarization between sectors can be deployed to increase data capacity.

The following sections will discuss these factors in more detail.

Cell Planning

More closely packed cells with smaller coverage per cell can increase geographical coverage and lead to a decrease in hub spacing [6]. The location of each adjacent hub can be offset by as much as 1/3 to maintain comprehensive coverage without leaving any out-of-coverage areas between cells. A two-layer IP-LMDS network architecture [7] provides additional coverage by further splitting each cell into microcells. This results in an extended coverage without the requirement of the line of sight (LOS) at carrier frequencies below 25 GHz (typically in the range of 5–17 GHz). At higher frequencies, the LOS requirement obviously affects the scalability of the system in terms of its geographical coverage (e.g., a new building rises up in front of an existing subscriber building blocking the LOS path). On the other hand, using an ultra high operating frequency allows very high gain directional antennas to be fabricated in small physical form factors, which will reject multipath signals arriving from directions other than LOS.

In addition, high gain antennas, especially those mounted at a high elevation, and high signal transmission power using a high gain amplifier facilitate cell enlargement. This leads to a trade-off between cell coverage and the cost of providing such coverage. In general, scalability can be controlled by transmitter and antenna gain adjustments to improve geographical coverage. Optimizing the antenna aperture efficiency to minimize signal loss due to free space attenuation can maximize the range as well.

The number of sectors per hub can be increased to achieve higher data capacity. Normally, a system is set up with four 90˚ sectorized antennas, each covering one sector. The data rate can be (very nearly) doubled by increasing the number of sectors from four to eight while maintaining omnidirectional coverage. The network can be further expanded by another sectorization as shown in Fig. 2a, where an initial deployment of a 7 MHz channel with four sectors gives each hub a maximum data rate of 32 Mb/s. Each sectorization yields a doubling in data capacity, giving 64 Mb/s with eight sectors. However, each doubling of sectorization reduces link coverage by approximately 33 percent. Network capacity increase can therefore be achieved by splitting a cell into more sectors in order to effectively generate more subchannels that can sup-

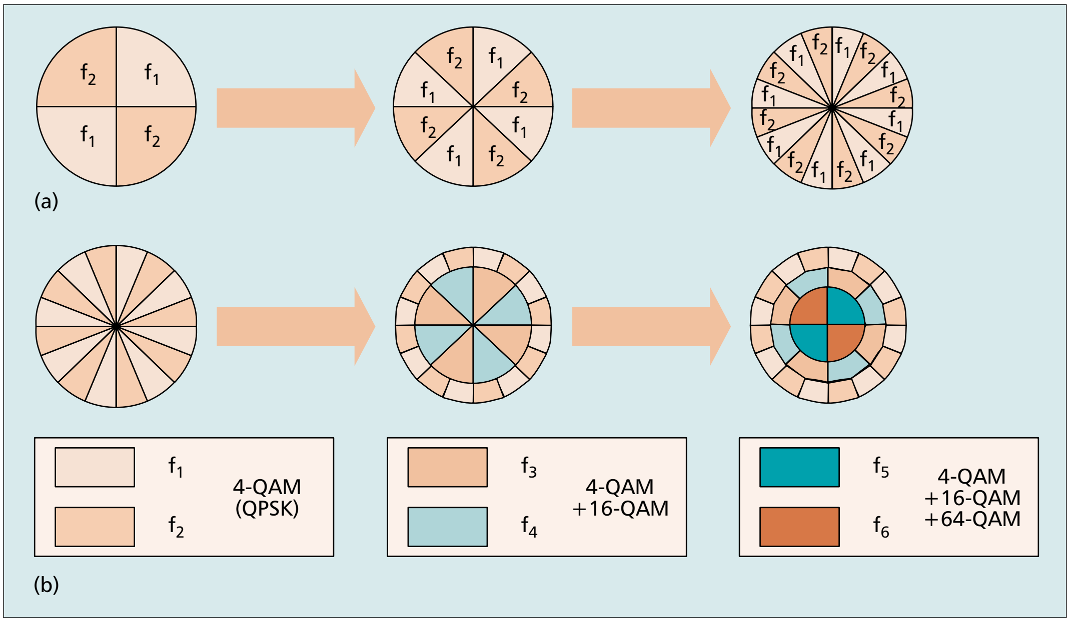


Figure 2. *a) Increasing system capacity by sectorization; b) scalability is achieved by sectorization with multiple modulation schemes. Initial deployment uses 16 QPSK hubs; another eight sectors are increased by adding eight 16-QAM hubs. Further utilitzation of a full duplex channel can be achieved by adding four more 64-QAM hubs.*

port a higher data rate. With an increased number of hubs to cover the same geographical area, less bandwidth will be required for each hub; hence, equipment costs can be reduced. Further improvement can be achieved by increasing the data capacity with the support of a higher-order modulation scheme. This will be discussed in the next section.

Another way of improving scalability without necessarily incurring extra cost or setup is to optimize the usage of existing resources by means of channel borrowing to meet extra demand on a needed basis. Although each cell or sector is assigned to the fixed bandwidth, this bandwidth can be fluctuated in practice by employing the method of channel borrowing. This enables a busy cell or sector to access the unused channels of neighboring cells or sectors. The net effect is an optimal utilization of resources.

Modulation

The choice of modulation scheme has a significant impact on network scalability as it can easily be altered to support a higher rate. There are many factors that affect system performance of spectral efficient schemes. Multicarrier modulation such as orthogonal frequency-division multiplexing (OFDM) offers a number of advantages [8] and has been successfully used in high-bit-rate long-range applications such as digital broadcasting (e.g., digital video broadcasting, DVB, systems). However, single-carrier modulation schemes are more suitable for wireless broadband IP networks for the following reasons. First, with single-carrier modulation schemes, circuit complexity of transmission is much lower than that for reception (this attribute is particularly suitable for asymmetric operation). Other advantages include a higher level of noise immunity and better power efficiency. Also, OFDM is less tolerant to phase noise that can be as much as 12 dB worse than the requirements for a comparable single-carrier modulation scheme. Another consideration is the drawback of power amplifier backoff due to output power limitation that requires an extra 1–3 dB sensitivity with OFDM.

Although we believe single-carrier modulation is more suitable in this context, we also briefly mention OFDM, which is also included in the IEEE802.16 standard. For example, 802.16a includes three different choices, two of which are OFDM-based (the other is also single-carrier based). These are a) wireless MAN-OFDM: OFDM (256), which is mandatory for license exempt frequency bands, and uses time-division multiple access (TDMA; time-/frequency/division duplex, TDD/FDD); and b) wireless MAN-OFDMA: orthogonal frequency-division multiple access (OFDMA) (2048), OFDMA (TDD/FDD). 802.16a offers this choice because it operates in lower frequencies, and OFDM may therefore be more suitable than single-carrier modulation.

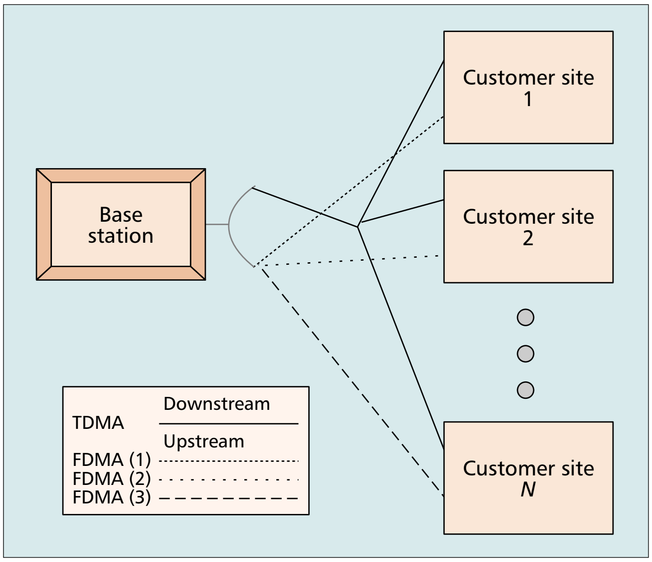
Except for some legacy systems, variants of *M*-ary QAM are used in the vast majority of LMDS systems currently deployed throughout the world. Quaternary phase shift keying (QPSK) is currently the most popular choice primarily due to cell overlap control considerations and good tolerance to distortion [9]. However, it has low bandwidth efficiency when compared to higher-order QAM schemes. The network capacity can be augmented by increasing the order of modulation due to higher spectral efficiencies; for example, a change from 4 (QPSK) to 64-QAM can increase the spectral efficiency from 1.5 b/s/Hz to 4.5 b/s/Hz, as summarized in Table 2. However, such increase is achieved at the expense of higher equipment cost because of escalated receiver structure complexity and more severe cell-to-cell interference. This may significantly decrease the area of coverage, and co-channel interference can increase by some 16 dB. Moreover, a reduction in coverage range also results with each increase, from QPSK to 16 and from 16 to 64-QAM, roughly halving cell size. Generally, selecting higher-order QAM when expansion in capacity is required with reduction in range and noise performance can maximize bandwidth utilization. Such effects can be compensated by careful cell planning using a combination of modulation schemes, as shown in Fig. 2b, to achieve a data density of over 50 Mb/s/km^2, which is good in the wireless domain.

A combination of different modulation schemes can be used to expand network capacity, as shown in Fig. 2b. In this illustration, adding two extra sectors with a 16-QAM increases the data capacity. Adding eight sectors and using two subchannels with 16-QAM can double data capacity. The range for these sectors is shorter with 16-QAM, while the original

Scheme	Spectral efficiency (b/s/Hz)	No. of sectors per hub	Relative coverage (%)	Relative link margin (dB)
QPSK	1.5	16 8 4	100 79 62	0 –3 –6
16-QAM	3	16 8 4	49 37 28	–9 –12 –15
64-QAM	4.5	16 8 4	23 16 12	–17 –20 –23

Spectral utilization efficiency (SUE) can be increased three times from QPSK to 64-QAM. Coverage and link margin are compared with reference to QPSK with 16 sectors (initial deployment, Fig. 2b).

■ **Table 2.** *A comparison of different modulation schemes.*



■ **Figure 3.** *The downstream link is multiplexed by TDMA, and FDMA is used for the upstream link.*

16 QPSK subchannels are utilized only to provide coverage in the outer part of the cell. The inner part of the cell is covered by the eight 16-QAM subchannels. The consequential reduction in coverage can be minimized by utilizing the original QPSK sectors for each customer site at the edge of each cell. In this deployment the range of QPSK is supplemented by the data capacity of 16-QAM with a composite hub configuration. The network is expandable by a further sectorization with 64-QAM as shown. This addition is primarily aimed at providing high-bandwidth links to customer sites that are close to a base station due to the increased signal power necessary for 64-QAM. Higher-order QAM schemes are subjected to higher cell-to-cell interference, but offer higher data capacity. The effects of rain attenuation cause a necessary adjustment to the fade margin; the required fade margin of 16-QAM and 64-QAM is about –9 and –17 dB relative to QPSK, respectively.

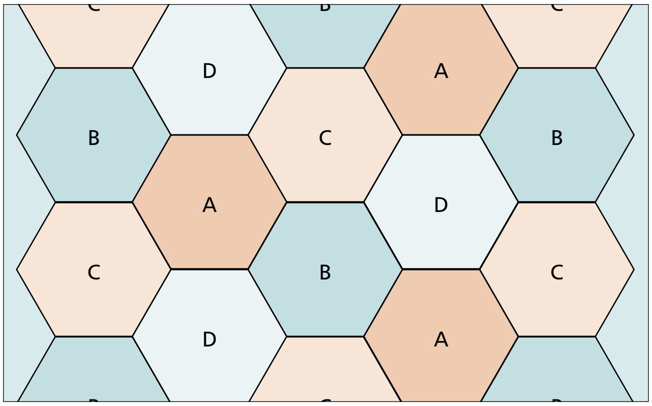
An interesting development, especially with the type of modulation discussed, is to apply it to a two-layer LMDS structure mentioned under cell planning. As demonstrated by the European Cellular Access to Broadband Services and Interactive Television (CABSINET) project (http://www.cordis.lu/infowin/acts/rus/trials/b9cabsinet.htm), a two-layer approach can offer many advantages over traditional LMDS such as flexibility and ease of implementation of end-user devices. Flexibility is achieved by giving service providers more freedom in the design of microcells. In CABSINET, base stations and individual microcells communicate at 40 GHz with LOS, while each microcell communicates at 5.8 GHz with end users. The latter means LOS is not a requirement for end-user devices, which can be made smaller and cheaper.

Multiple Access

The access methodology affects how end-user sites share the wireless network connection. Most existing systems apply either TDMA or FDMA methods for both the upstream and downstream links. In either method, the link efficiency is primarily determined by the way bandwidth is allocated. The use of TDD is generally preferred to utilize the available bandwidth in noncontiguous blocks over FDD. This is because the transmitter-to-receiver frequency spacing has to be carefully controlled in order to avoid unnecessarily complex filter and demultiplexer designs that also lead to a higher demand for additional guard-band. One of the major disadvantages of TDD is insertion losses at frequencies used in fixed BWA systems that result in an extra 3 dB sensitivity requirement because the noise power is approximately doubled.

In TDMA bandwidth allocation for each customer link is based on data bursts from the customer site. In contrast, in FDMA bandwidth is allocated approximately constant in time to a customer. Typically, TDMA is used in downstream links and FDMA in upstream links due to TDMA's bursty response and FDMA's support of a constant pipe. Dynamic allocation of bandwidth maximizes the channel efficiency, and adaptive power control provides 6 dB/s to partially compensate for the effects of rain attenuation. The links are illustrated in Fig. 3 where N geographically separated customer sites are served by the downlink stream using TDMA, and each of the N customer sites is allocated an uplink subchannel using FDMA. Further link efficiency can be achieved by wavelength allocation on a link-to-link basis using WDM with wavelength conversion to relieve data traffic congestion around the network's bottleneck. The system can therefore be expanded by increasing link efficiency, taking into account the burstiness of the data stream and selecting the most appropriate multiplexing method accordingly. Factors that determine the optimal use of a multiple access method also include the efficiency of the adopted FEC and medium access control (MAC). In most cases, the asymmetrical operation implies that the downstream and upstream links can be considered independently based on traffic volume and burstiness.

TDMA and FDMA can both be classified as centralized contention-based MAC. A distributed contention-based MAC gaining popularity in wireless LAN applications is carrier sense multiple access (CSMA). In CSMA each node that has data to send must first sense the channel. The purpose is to minimize the chance of collision, thereby maximizing throughput. A variation of CSMA is CSMA with collision detection (CSMA/CD). In CSMA/CD, each node senses the channel after sending a few bits. If there is discrepancy between what is sent and what is sensed on the channel, it knows a collision has occurred and will abort the transmission. The IEEE 802.3 Ethernet standard prescribes the use of CSMA/CD, but this is not particularly suitable for wireless applications. Another variation of CSMA is CSMA with collision avoidance (CSMA/CA), which is more suitable for wireless applications than CSMA/CD because it is more energy-efficient for end-



■ **Figure 4.** *Cells with four different sets of frequencies.*

user devices. In the IEEE 802.11 standard, CSMA/CA is used with an exponential backoff approach for collision avoidance together with the possibility of sending acknowledgments [10].

Frequency Reuse

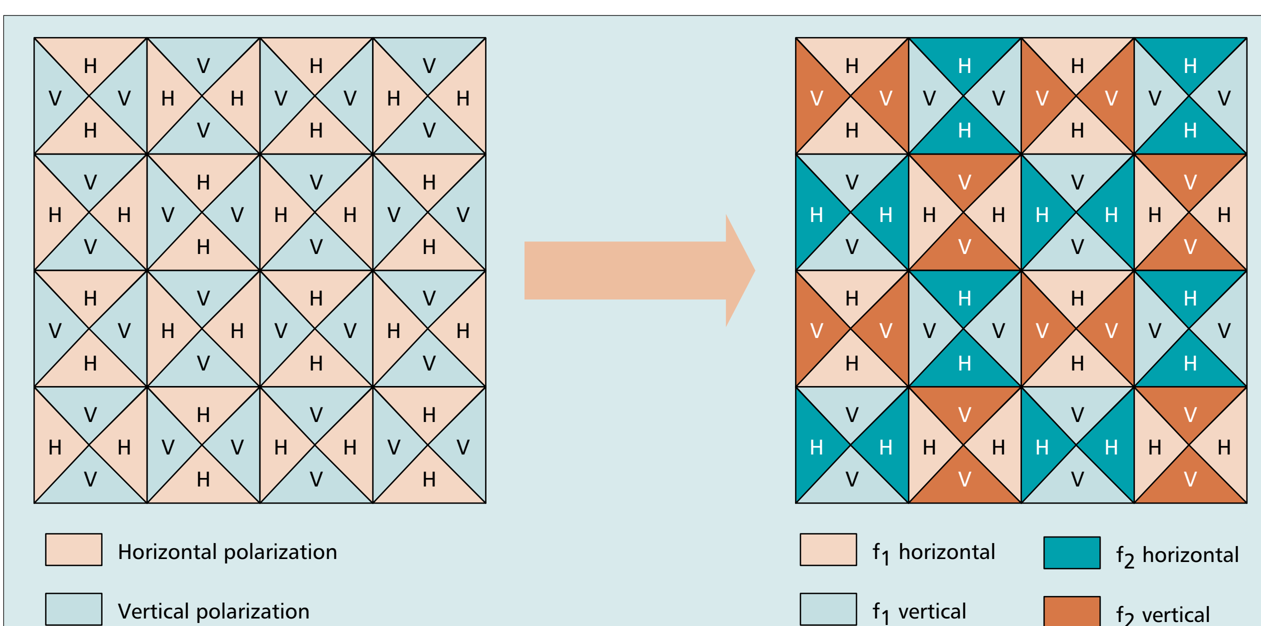
Frequency reuse can increase data capacity without compromising range. In the simplest case, the available channel is subdivided into groups, and the channel frequencies in each group are assigned to a cell with adjacent cells operating at different frequency subchannels. It is shown in Fig. 4 that a cell using frequency group A has no bordering cell that also uses A. In this illustration, the same frequencies are used in different cells of close proximity. Careful consideration is required to ensure that these frequencies do not interfere with each other. It is therefore desirable to use more frequencies to further separate cells of the same frequencies.

Frequency reuse can also be optimized by both sectorization and polarization [11]. Referring back to Fig. 2a in our earlier discussion with a split into eight sectors, it reuses the same two frequency subchannels as the initial scenario with four sectors, and the capacity is thus doubled. It is also possible to add more subchannels, which can maintain frequency diversity and minimize interference between channels. In the scenario shown in Fig. 2b, a threefold increase in signal-to-interference ratio (SIR) is required from QPSK to 64-QAM to ensure adequate separation from co-channel interference while maximizing utilization of the available channel bandwidth.

A high degree of frequency reuse can be optimized by alternating polarization for each channel. Horizontal and vertical polarization in an alternate pattern is deployed to maximize isolation between bordering sectors while increasing channel utilization twice. The deployment of alternate polarization reuse is shown in Fig. 5. In this example four subchannels are made available with two frequencies and alternate polarization. While this approach provides an additional subchannel with little alteration to the existing network, a significant fade margin increase may be necessary under heavy rainfall, particularly with higher modulation schemes [12]. It is also noted that interference between sectors and the effect of depolarization caused by rain can be partially compensated by frequency diversity and cross-polarization discrimination (XPD) [13] to a maximum of about 20 dB for effective control of interference. This results in a significant reduction of total coverage areas affected by cell-to-cell interference to less than 3 percent. The actual application of frequency reuse in a given system is restricted by rainfall statistics for the location where the system is deployed. For example, in a heavy rainfall region such as that classified in ITU-P, the effect of rain depolarization may limit frequency reuse to a very short range [12]. Although the use of orthogonally polarized signals can effectively double the number of available channels, a significant difference in range is caused by heavy rainfall, especially when a carrier frequency of over 20 GHz is used. A difference of over 5 dB/km in signal loss is induced when a 40 GHz carrier is used under persistent rain of 140 mm/h [14]. An adequate fade margin must be maintained to compensate for the effects of rain. Reference [12] has shown that horizontally polarized signals require an additional 2 dB fade margin to signals of vertical polarization in a 1 km path. Fade margin requirements impose further constraints to systems particularly equipped with a combination of different modulation schemes for combating the effects of uncontrollable rainfall.

Conclusions

Fixed BWA networks provide a scalable solution to facilitate network capacity expansion in terms of both data capacity and the number of customer nodes supported. The versatile network architecture of LMDS contributes to the scalability of a



■ **Figure 5.** *Alternate polarization between horizontal and vertical, and frequency reuse.*

system at a later stage to accommodate future growth in service enhancement. The inherent attributes of LMDS that make this system so appealing for network access services include the following:

- Ease of channel addition
- Cell splitting of high data density cells
- Sectorization with each cell having its own channels and frequencies taken from bordering cells

This article has illustrated various factors that determine the scalability of BWA networks with LMDS systems. Parameters such as cell planning and frequency allocation have to be considered at an early stage of system deployment. Other parameters that affect network scalability such as modulation and multiple access methodologies, frequency reuse, and polarization can easily be modified to meet future demands.

In the wider context, we believe LMDS/BWA systems promise to deliver much more than was achievable in this domain in the 1990s. When we combine the scalability functionalities discussed in this article with standards such as IEEE 802.16 and a hierarchical (e.g., two-layer) LMDS structure, LMDS/BWA systems are likely to become a mainstream technology, potentially with tremendous commercial value. It is for this reason there is now intense research in this domain.

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