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The Next Challenge for Cellular Networks: Backhaul

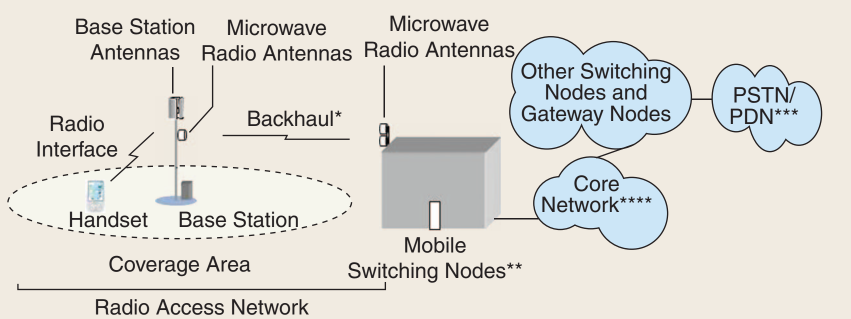
Growth in the number of mobile users, coupled with the strong uptake of wireless broadband services, is driving high transport capacity requirements among cellular networks. However, revenues are not scaling linearly with increases in traffic. Demand for optimizing the cost efficiency of backhaul is becoming as critical as investment in the radio infrastructure. As a result, new transmission technologies, topologies, and network architectures are emerging in an attempt to ease the backhaul cost and capacity crunch.

To explore this fundamental industry shift, we need to examine some of the existing and emerging network technologies and protocols that may be unfamiliar to some of the readers. We endeavor to define terms as we progress, but to enable a better comprehension, please also see "Summary of Selected Terms." We provide an overview of the technical challenges faced by wireless operators in providing cellular backhaul and examine the availability of new technology solutions that may meet these challenges.

Background

The Basics

In a cellular network, backhaul (also known as *cellular backhaul*) is the communication link between a base station and the associated mobile switching nodes, see Figure 1. The base stations serve to provide radio coverage over a geographical area, supporting radio



*Microwave radios are used in this example; the backhaul is also called the "last mile" network.

**For simplicity, we collectively called the base station controller, radio network controller, and mobile service switching center the "mobile switching nodes." These nodes may be collocated or distributed in real life deployments.

***PSTN/PDN = public switched telephone network/public data network.

****The core network is usually a nationwide optical fiber-based network connecting the main switching nodes, such as radio network controllers (RNCs) and packet data gateways (PDGs), and is usually highly structured, resilient, scalable, and employs feature rich transport network protocols, which is increasingly based on the Internet protocol/multiprotocol label switching (IP/MPLS) [2].

Figure 1. *A simplified cellular radio system for supporting voice or data service, showing the direct connection from a base station to the mobile switching nodes using a pair of microwave radios for backhaul.*

Summary of Selected Terms

Asynchronous transfer mode (ATM)	A packet-switching protocol that encodes data into small fixed-sized cells and provides data link layer services
Carrier Ethernet	An extension to Ethernet for use in wide area networks to leverage the economies of scale of traditional Ethernet
Circuit emulation services over packet service network	A protocol that allows circuit-switched services to be carried across a packet-switched network
Circuit switching	A channel has to be established between two nodes of a network before the users can communicate
E-carrier	An improvement to the American T-carrier technology and a part of the PDH
Ethernet	A local area network protocol commonly used in enterprises
Ethernet over MPLS	Ethernet protocol is transported as "pseudo-wires" using MPLS label switching paths
IEEE 1588 version 2	A precision timing protocol that is able to deliver timing and synchronization over packet-switched networks
IMT Advanced	A concept proposed by the ITU for mobile communications that have capabilities beyond the current third-generation mobile systems
Internet Protocol	A protocol used for communicating data across a packet-switched network using the Internet Protocol Suite
Generalized MPLS	An enhancement to MPLS that enables interconnection of new and legacy networks by allowing end-to-end provisioning, control, and traffic engineering
Multiprotocol Label Switching (MPLS)	A highly scalable, protocol-agnostic data-carrying mechanism; data packets are assigned labels and packet forwarding is based on the label without the need to examine the packet content
MPLS-TE	MPLS-TE allows MPLS-enabled networks to be replicated and expand upon the traffic engineering capabilities of ATM networks
Packet switching	A network communication method that facilitates the sharing of the network between one or more types of data transmissions
Plesiochronous Digital Hierarchy (PDH)	A multiplexing protocol for transferring multiple data streams over digital transport equipment, such as microwave radio and optical fibers
Provider Backbone Bridge (PBB)	An evolution of Ethernet that enables scalability and secure demarcation of customers' traffic, which form the basis of carrier Ethernet
Provider Backbone Bridge – Traffic Engineering (PBB-TE)	Provide traffic engineering capability to carrier Ethernet
Pseudo-Wire Emulation	A protocol for emulation of services such as ATM, Ethernet, TDM over a packet-switched network
Synchronous Digital Hierarchy (SDH)	A highly time-synchronized multiplexing protocol for transferring multiple high-capacity digital data streams; standardized by the ITU
Synchronous Ethernet	A transport timing protocol that reproduces in the Ethernet world the same synchronous mechanisms at the physical layer of the traditional time division multiplexing world
Synchronous Optical Networking (SONET)	A multiplexing protocol closely related to SDH and standardized by the American National Standards Institute
T-carrier	A digitally multiplexed telecommunication carrier systems originally developed by Bell Labs

communications with individual mobile handsets over the radio interface. Signals at the base station are transported to and from the mobile switching nodes for interconnecting into the public switched telephone system or the public data network.

It is relatively common for microwave radios to be used for cellular backhaul. They may be installed by the service provider or leased from a third-party network provider. The choice is usually a business decision or one constrained by regulatory requirements. The former is known as *self-build*, while the latter is leased lines. To facilitate interoperability, transmission equipment based on T-circuits or E-circuits interface standards are used depending on the region of the world. These circuits are summarized in Figure 2. When more capacity is required, scaling is achieved simply by leasing more circuits or installing more microwave radios. When the use of equipment with a higher capacity is more economical, a migration can take place to take advantage of the cost structure.

The physical medium for backhaul is not limited to microwave radios but may also include optical fiber or other transmission technologies, such as free-space optical links. A typical base site arrangement using microwave radio backhaul is shown in Figure 3.

A number of base stations are usually connected to a single set of mobile switching nodes. Each base station has at least one backhaul link to the mobile switching node. Depending on the traffic volume, higher-capacity links may have to be used to match the bandwidth demand. As the number of base stations increases, the number of backhaul links will have to grow accordingly. Figure 4 shows a more complex cellular system scenario. In this case, the traffic from individual base sites is first concentrated before being backhauled to the mobile switching nodes. The figure also illustrates the use of microwave radios and fiber for backhaul.

	T-Circuits[1] Line Rate (North America)	E-Circuits[2] Line Rate (Europe)
Level 0	64 kb/s (aka DS0[3])	64 kb/s
Level 1	T1: 1.544 Mb/s (24 Circuits) (aka DS1)	E1: 2.048 Mb/s (32 Circuits)
Level 2	Not Commonly Used	Not Commonly Used
Level 3	T3: 44.736 Mb/s (672 Circuits) (aka DS3)	E3: 34.368 Mb/s (480 Circuits)
Level 4 and above	Not Commonly Used	Not Commonly Used

Notes:
aka = also known as

1) T-circuit or T-carrier is the generic name for digitally multiplexed telecommunications carrier systems used in North America, Japan, and Korea.
2) E-circuit or E-carrier, where E stands for European, is used in most locations outside of North America, Japan, and Korea. The E-carrier standards also form part of the Plesiochronous Digital Hierarchy (PDH) where groups of E1 carriers are bundled onto higher capacity E3 circuits; E1 are commonly used between base sites and mobile switch centers or hubs and E3 are used between switch sites.
3) DS (as in DS0 or DS1) means "digital signal"with DS0 having a basic signalling rate of 64 kb/s.

Figure 2. *Common communication interface and data rate standards used for backhaul: T-circuits and E-circuits.*

From a network hierarchy perspective, the mobile network can be broadly divided into three parts: last mile, regional network, and core network, see Figure 5. The backhaul network covers the last mile and regional network and can be defined as the network connecting the base stations to the core network elements.

The transport distances for the last mile and regional and core networks vary greatly, depending on many factors. This may include base site density, terrain characteristics, and the point of presence of the transmission infrastructure. The transmission distance and terrain characteristics frequently dictate the technology to be used and affect the business case, while the cost and availability of leased line infrastructure could influence the decision to lease versus build. Long-term network capacity growth, cost optimization, and resilience are some of the fundamental factors that further influence the choice.

Some Trends

The rapid expansion of radio coverage footprint has meant that the backhaul network has had to grow accordingly. For a long time, the relatively low efficiency of the radio access technology has firmly placed the throughput bottleneck at the radio interface of the cellular network.

As the radio interface technology improved over the years and demand for higher throughput and higher-data-rate services increased, the bottleneck of the cellular network gradually has also shifted from the radio interface towards the backhaul network. Yet there have been relatively few breakthrough solutions so far to fundamentally resolve the backhaul bandwidth scaling problem. For most mobile operators, it is common practice to rely on time-division-multiplexing-based leased lines and microwave radio links. These are not necessarily scalable solutions when the bandwidth demand is in multiples of the current level but the revenue increase is barely catching up. The evolution of cellular technology, the associated data rates, and typical transmission technologies are shown in Figure 6.

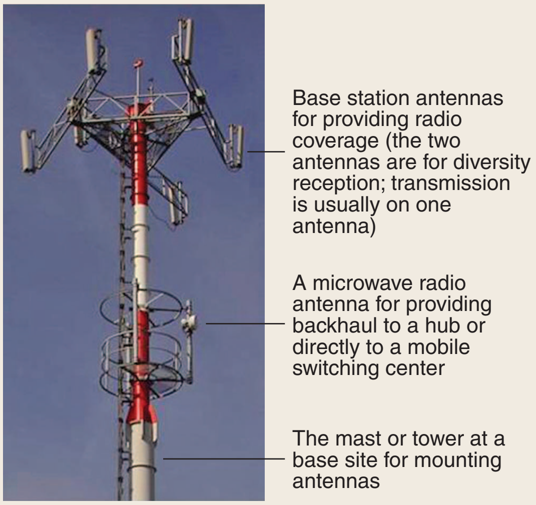


Figure 3. *A real-life example of a base station for a cellular radio system using microwave radios for "backhaul." This image is courtesy of Vodafone.*

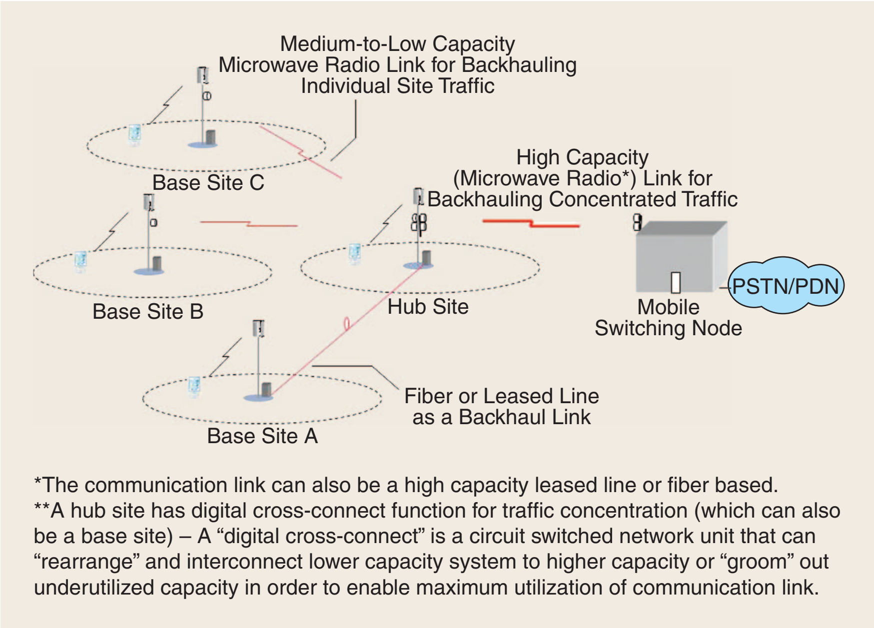


Figure 4. *A more complex cellular radio system scenario shows the relationship of base stations, a hub, and a mobile switching center for supporting voice service.*

latest third-generation mobile systems], new techniques of traffic offloading and the use of in-band relay are believed to be some of the potential solutions, at least for some dense urban deployment scenarios. These are discussed in more detail later in this article.

That said, new technologies are also emerging. These include the proliferation of carrier Ethernet-based solutions and millimeter-wave radios and the return of satellite backhaul solutions. In addition, as cellular radio access technology evolves to support data rates of 100 Mb/s and beyond under the banner of IMT-Advanced [a concept from the International Telecommunications Union (ITU) for mobile communications with capabilities that go beyond the

Business Drivers

Before diving into the technology advances, it is pertinent to take a brief look at the driving business imperatives that the whole industry is hinged upon. Backhaul is historically the largest portion of a wireless carrier's operating expenditure. Depending on the size and the traffic volume of the radio access network, this could amount to over half of a wireless carrier's recurring operating cost. More specifically, information from the cellular industry seems to suggest that transport equipment, excluding administrative costs, for example, can amount to around 40% of the construction cost of a backhaul network, whereas in the case of leasing backhaul communication capacity, transport costs could account for up to half of the total network operational costs, with backhaul contributing to three-quarters of this cost [1].

In most markets in the developed world where adequate fixed infrastructure is available, it is generally more expedient to use leased lines. This is true in both North America and Europe. However, in locations where leased lines are not available, self-build becomes the only option, with the possibility of infrastructure sharing by the collocated network operators. To maximize the utilization of the leased lines to save cost, concentration of multiple last-mile links via a hub with digital cross-connect function is frequently employed in a hierarchical network.

As mobile broadband radio access technologies improve, it is becoming more feasible to offer high-data-rate broadband services to end-users. Competition has driven operators down the path of embracing flat-rate pricing, leading to an explosive growth in mobile data traffic since around the 2006/2007 time frame, as seen in Figure 7. A key challenge to the backhaul network is to reduce the cost per bit as the volume of traffic increases exponentially. This can be achieved through adopting new transport technologies that have a lower cost structure, by employing transmission topologies where the bandwidth can be utilized more efficiently than the classical hierarchical hub-and-spoke architecture, or by sharing the

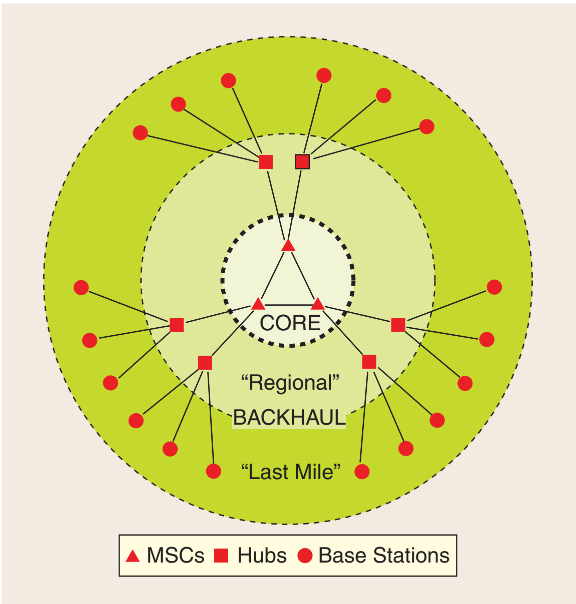


Figure 5. *A schematic hierarchical network architecture for a cellular network. The exact architecture would be dependent on the size of the network, terrain characteristics, and the point-of-presence of the backhaul infrastructure.*

transport bandwidth with other services by adopting a converged transport platform. Clearly, a mixture of solutions is frequently adopted by mobile operators as needed.

Convergence Based on Packets

Convergence to packet-based technology has been a key development in enabling better utilization of the transport network and improving cost efficiency. Internet protocol/multiprotocol label switching (IP/MPLS) is increasingly used by mobile operators in the core network. With IP/MPLS, many mobile networks can implement a unified core network for supporting a multitude of services. IP/MPLS is a consolidated and mature carrier-grade transport technology that offers quality of service, service management, scalability, and rapid recovery from failure [2]. The protocol operates between the data link layer and network layer and can be employed to carry many different kinds of traffic, including IP packets, as well as native asynchronous transfer mode (ATM), synchronous optical network (SONET), and Ethernet frames. The properties of circuit-switched networks (a network that needs to establish a channel between two nodes before the users can communicate) are emulated using the concept of MPLS paths. IP/MPLS requires the configuration and maintenance of MPLS paths and is particularly useful for the regional part of a backhaul network. There are not as many nodes to be configured for connecting to the packet data gateways or the radio network controllers. Thus, relatively fewer path configurations are needed. For the last mile part of the access network, the situation is different. The large number of base stations would mean that an IP solution based on plain Ethernet could be more advantageous in terms of configuration and maintenance overhead.

Today, many new base stations can already support IP interfaces, but the intermediate backhaul network is rarely IP routed. Backhaul infrastructure legacy nodes based on ATM and time division multiplexing (TDM) remain abundant. To enable a converged transport of multiple services on the access network—meaning that the same transport is to be used for supporting multiple services—and better utilization of bandwidth but a lower cost, the migration to Ethernet is occurring. The approach of using IP interfaces is sometimes referred to as layer 2 aggregation and it is becoming the dominant trend of the industry, see Figure 8. In practice, as there are a large number of legacy base stations already deployed, a mixed service approach will be needed to achieve smooth evolution.

TDM and ATM were originally chosen for cellular backhaul because of their ability to deliver consistent and configurable quality of service. As we migrate to packet-based backhaul, this characteristic needs to

Time Frame	Before 1999	1999	2002	2005	2009	2010
Nominal Generation	1G	2G	3G	3G	3G	3G+/4G
Standard	GSM HSCSD	EDGE	WCDMA	HSDPA	HSPA+	LTE
Peak Data Rate	10 kb/s	200 kb/s	384 kb/s	3-21 Mb/s	42 Mb/s	>60 Mb/s
Typical Backhaul	TDM	TDM	ATM	ATM	ATM / IP	IP

GSM HSCSD = GSM high-speed circuit-switched data, the data rate depends on the number of timeslots with about 10 kb/s per timeslot
EDGE = Enhanced data rate for GSM evolution, data rate depends on the number of timeslots and coding and modulation scheme
WCDMA = Wideband Code Division Multiple Access also known as 3G was standardized to support 384 kb/s in moving vehicles more than a 5-MHz channel
HSDPA = High-speed downlink packet access, support up to 21.1 Mb/s with multilevel-modulation more than a 5-MHz channel
HSPA+ = High-speed packet access, with multiple-input–multiple-output antennas and multi-level modulation over a 5-MHz channel
LTE = Long-term evolution; Peak downlink data rate is 178 Mb/s with 2×2 multiple-input–multiple-out antennas over a 20-MHz of spectrum
TDM = Time division multiplexing
ATM = Asynchronous transfer mode
IP = Internet protocol

Figure 6. *An illustration of the rapid increase in data rates over the radio interface, which translates to a steady increase in backhaul bandwidth demand, by successive generations of cellular technologies over a decade.*

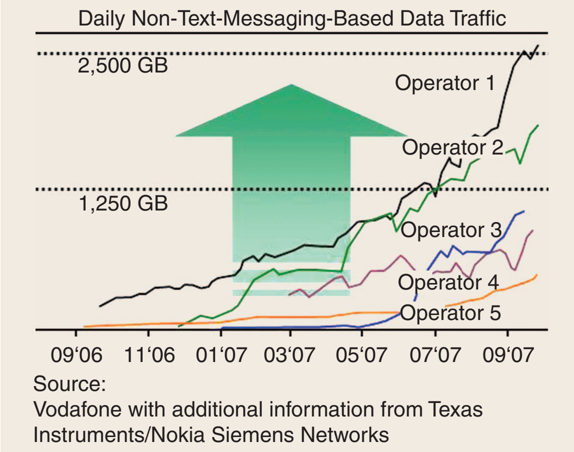


Figure 7. *The rapid increase in data traffic in 2006/2007 for selected European mobile operators. The traffic grew in multiples after the introduction of "flat-rate" pricing, but the revenue growth was only in submultiples. It is therefore not sustainable unless the cost per bit for transport is significantly reduced.*

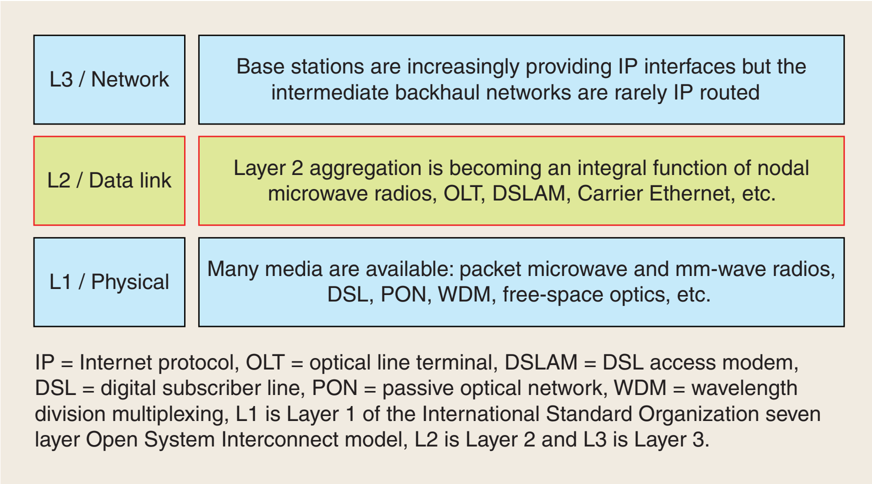


Figure 8. *The landscape of mobile backhaul from an open system interconnect layer perspective, indicating that Layer 2 (data link layer) aggregation is likely to dominate since it could enable better utilization of the transport bandwidth and the same performance as leased lines but at a lower cost.*

be preserved when TDM bits and ATM cell streams are packetized and transmitted over a packet-switched network. The migration is thus likely to be gradual, see Figure 9. A first step to convergence may be achieved using pseudo-wire emulation edge-to-edge (PWE3)—a protocol that emulates services such as ATM, TDM, etc. over a packet network—and circuit emulation service over packet service network (CESoPSN) techniques—a protocol that emulates circuit switching over a packet network—to packetize ATM cell streams and TDM bit streams and transport the aggregated packet stream over a packet-switched network.

Carrier Ethernet

In more recent times, IP-based backhaul technologies have become more popular. The increasing maturity of carrier Ethernet and a wider spread of fiber infrastructure in urban areas and beyond have enabled them to become an attractive means for backhaul. This is because IP- and packet-based transport networks allow concentration (bringing a number of tributaries into a single transport pipe) and statistical multiplexing (dynamic sharing of transmission bandwidth) to be achieved more readily. In addition, Ethernet-based microwave radio has also become more widely used. Not only is it possible to multiplex multiple data streams, such as alarms and surveillance video feeds, onto the same IP radio backhaul, it can also use adaptive modulation to selectively throttle the transmission speed depending on radio propagation conditions.

Native Ethernet, where the traffic is presented directly to the network in Ethernet frames supported by a highly scalable transport mechanism that facilitates rapid restoration of services, service quality monitoring, automated provisioning, and operation and maintenance, is a relatively new protocol for backhaul. Most traditional implementation of Ethernet services actually uses Ethernet over MPLS due to their superior carrier-grade characteristics and ability to reuse existing infrastructure. It is not until recent times that carrier-grade native Ethernet or carrier Ethernet, also known as *provider backbone bridge—traffic engineering* (PBB-TE) or provider backbone transport (PBT), has been made available by a subset of transport vendors to provide a true carrier-grade pure Ethernet transport solution. The advantages of carrier Ethernet are shown in Figure 10. With PBT, it will be possible to build networks completely based on Ethernet technology without the need for supporting protocols, such as MPLS, to ensure carrier-class quality.

A schematic diagram of carrier Ethernet is shown in Figure 11. Carrier Ethernet connections can be provisioned using a network management system rather than signaling protocols, leading to a simpler and easier-to-manage network. Packets will have a deterministic path that is similar to MPLS paths [3].

The Carrier Ethernet specification is referred to in IEEE documents as *PBB-TE*. It was originally developed in 2006. In April 2009, the draft standard, IEEE 802.1ay, has completed the IEEE sponsored ballet process and entered the final phase of ratification.

Given the development stage of PBB-TE, most operators are currently opting for the more proven MPLS-based transport technologies, such as MPLS, MPLS-TE, or G-MPLS (generalized MPLS). MPLS-based technologies allow operators to leverage the low-cost Ethernet-based transport interfaces but rely

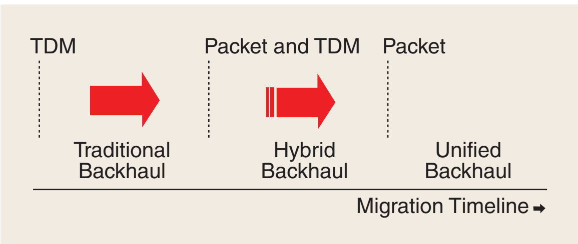


Figure 9. *A typical backhaul migration path for mobile operators. The migration timeline is dependent on whether mobile operators build their own backhaul network or rely on leased line services. It may also be dependent on whether a mobile operator has a fixed line business for pursuing convergence.*

on mature MPLS-based techniques to implement control plane functionality featuring scalability, reliability, service management, quality of service, and support for legacy TDM services. The possibility of a widespread adoption of carrier Ethernet will depend on whether it can deliver the technical and economic benefits over MPLS-based solutions.

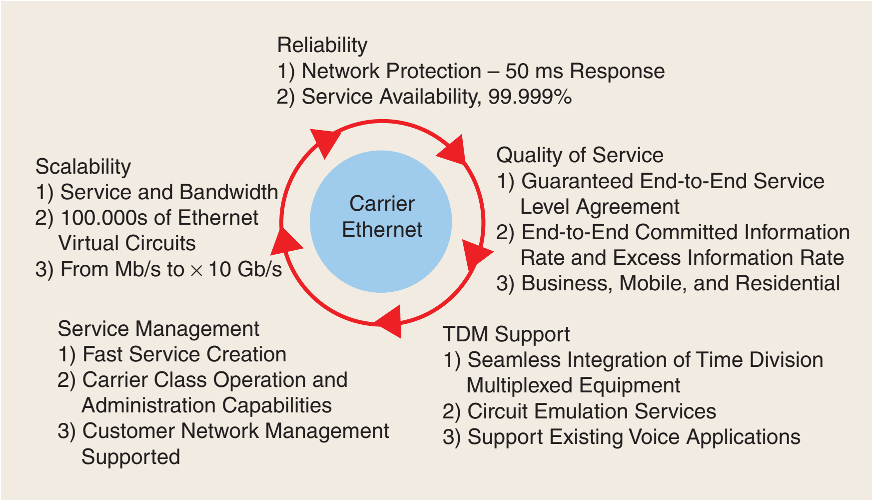


Figure 10. *The merits of carrier Ethernet are many and may include network reliability, scalability, end-to-end quality of service support, flexible service management support, and legacy time-division multiplexing equipment support.*

Synchronization

End-to-end synchronization (aligning the timing of network elements for the purpose of transmitting and receiving signals) is a challenge for Ethernet transport. Accurate network synchronization is needed to minimize interference between base stations and to ensure optimal intercell handover performance. Circuit transport networks have been built using circuit technology such as E1, T1, synchronous digital hierarchy (SDH), and synchronous optical network (SONET), which is inherently synchronous as bit rate and line utilization are always the same value (e.g., E1 has 2,048-b periods as well as 2,048 clock cycles). Two techniques are emerging in the packet world to ensure the availability of carrier-grade synchronization signals:

- Synchronous Ethernet
- IEEE 1588 version 2.

The term synchronous Ethernet (ITU-T G.8262 and G.8264) applies to the network clock, which is the clock that is controlling the bit rate leaving the Ethernet interface. Synchronous Ethernet reproduces in the Ethernet world the same synchronous mechanisms at the physical level of the traditional TDM world. Although synchronous Ethernet ensures the required frequency stability to cellular systems based on frequency division duplex (FDD), it requires every node of the transmission network to be capable of it, which may engender considerable investments. Synchronous Ethernet does not provide time information, required by time division duplex (TDD) systems.

IEEE 1588 version 2 is a packet-based synchronization mechanism where timing packets transmitted over dedicated data sessions are used to propagate the clock signal from a primary reference source (master) to destination (slave) nodes. Since they are based on IP packets, the accuracy of the clock recovered at the client side depends on the type of network transport used and loading conditions. For this reason, the deployment of IEEE 1588 version 2 requires careful planning to ensure the accuracy needed by cellular networks is delivered. Each timing packet contains a timestamp, which can be used to retrieve the time of day. For this reason, IEEE 1588v2 can deliver both frequency and timing stabilities, the latter required by TDD cellular networks. Mobile operators will typically deploy a mix of synchronous Ethernet and IEEE 1588 version 2 in their future backhaul infrastructures. The synchronization of base stations is a critical building block for cellular backhaul networks. With such provision, mobile operators will be able to utilize packet-based networks while still

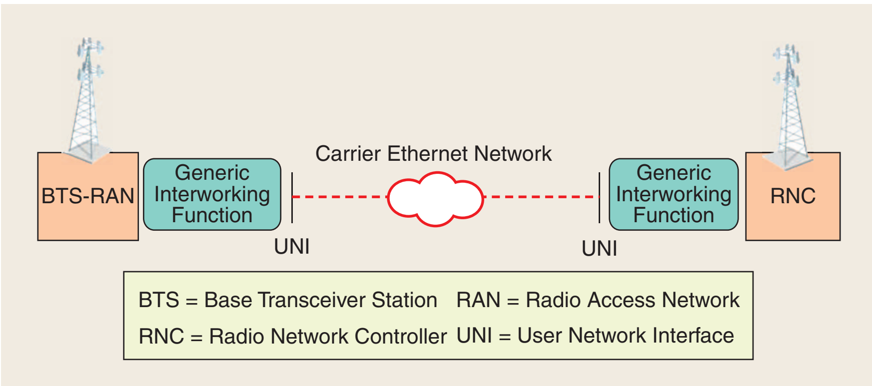


Figure 11. *Carrier Ethernet could be the ultimate convergence transport technology but its widespread adoption will depend on the real advantages offered over the more mature MPLS-based technologies.*

Growth in the number of mobile users is driving high transport capacity requirements among cellular networks.

meeting the timing requirements to deliver transport performance [4], [5].

Backhaul Transport Technologies

The types of transport technology and network topology employed are also evolving to provide the necessary data capacity at contained costs. For the access part of a backhaul network, several alternative transport technologies are available and some are currently widely used by wireless carriers.

Leased Lines

Leased lines are today extensively used for cellular network backhaul because they can save a mobile operator from having to manage its own transmission infrastructure or be concerned with the underlying technologies and evolution. Most leased lines suffer from high cost due to the legacy time-division technology they are based upon. They also suffer from a lack of granularity of the bandwidth provided, which is typically offered in increments of E1 or T1. More leased-line providers are positioning themselves to adopt Ethernet to reduce costs and provisioning time. This also reduces configuration overhead and increases the granularity of the bandwidth provided and quality of service management. Ethernet-based connectivity has started to become the de facto standard for all the current and future leased-line offerings.

Microwave Radios

Microwave radio has gained much popularity in recent years for providing last-mile connectivity, given its life-cost advantage over leased lines. However, spectrum is always a consideration, see Figure 12. Microwave radio links are generally less expensive to operate but attract high initial investment due to installation and equipment cost. In addition, microwave radio—especially when operating in higher frequency bands—is a technology dependent on line-of-sight transmission. The relatively high site survey cost and complex calibration process further render the overall up-front cost expensive. Newer generations of microwave radio products can support native Ethernet transport, enabling statistical multiplexing gain (an efficiency advantage achieved by dynamically sharing the transmission bandwidth across multiple services) and adaptive modulation, which can increase throughput efficiency. In particular, adaptive modulation implies that different modulation schemes can be used depending on channel conditions as dictated by weather conditions. Adaptive modulation must be used in conjunction with quality of service to prioritize traffic during periods of poor weather. The frequency bands allocated for microwave radio relay are market specific. Common frequency bands used are 7, 18, 23, and 35 GHz. As usual, the lower bands are preferred due to good radio wave propagation characteristics but have less bandwidth available due to incumbent usage and are more prone to long-range interference.

Going forward, the use of millimeter-wave radios is also emerging. This is believed to be an alternative solution to the last mile connectivity challenge. Millimeter-wave radio is a new generation of point-to-point wireless microwave radio operating at very high frequencies in the bands around 70 GHz. Typically, these frequency bands may include 71–76, 81–86, and 92–95 GHz. These frequency ranges are above the peak in oxygen absorption around 60 GHz. The limited range makes this solution unsuitable for use by long-distance backhaul networks, though

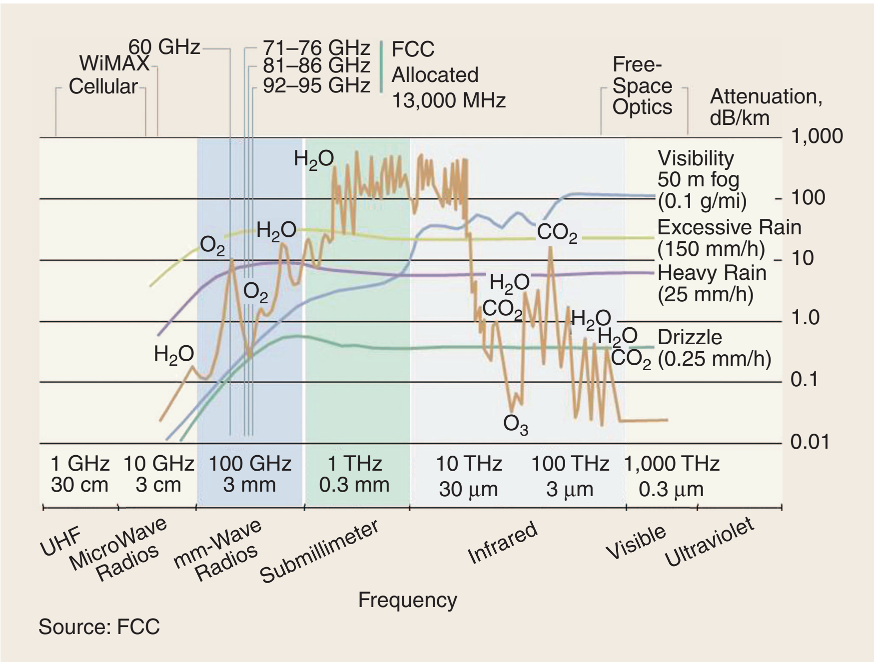


Figure 12. *Spectrum of various radio and free-space optics-based transmission technologies. Lower-band microwave technologies have the advantage of non-line-of-sight transmission, while higher-band technologies, including optical transmission, have the advantage of wide availability of spectrum.*

it can play a prime role in supporting high-data-rate wireless applications over short, last-mile range backhaul, such as in dense urban settings. The relatively compact size of the equipment and the antenna is an added advantage for positioning in urban environments. That said, typical cell site density of today's networks is not sufficiently high to fit with the low ranges supported by these products. The situation is likely to change in the future where the provision of ever-increasing capacity to end users will be met with a considerable increase in the number of sites deployed. For the time being, the most expedient backhaul approach is still a hybrid solution with a mixture of microwave radios and optical fibers.

With the availability of fixed WiMAX products mostly based on IEEE 802.16d, mobile operators are gradually replacing proprietary microwave radio links with standards-based products. In addition, the frequencies for WiMAX are typically in the lower bands of 2.5 and 3.5 GHz. Given the limited amount of spectrum available, the maximum data rates supported by these types of products are not as high as higher-frequency microwave and millimeter-wave radio products. The big advantage of these products is their non-line-of-sight capabilities. Operators may also exploit the unlicensed spectrum, such as in the 5-GHz band, using products based on IEEE 802.11a/g standards.

DSL Backhaul

Due to their modest cost structure, digital subscriber line (DSL)-based technologies have become a prominent candidate for cellular traffic backhaul that is not delay sensitive. DSL is widely used for residential broadband and its current data-only requirement makes the DSL suitable for femtocell (a small home base station) as well as for best effort (no service-level guarantee) cellular data applications [6]. Many variants of DSL technology exist with symmetric high-speed DSL (SHDSL) being the variant that is increasing in popularity because the standards include multiple copper pairs to either increase data rates or extend the reach. Being symmetrical, SHDSL is a good candidate to replace leased lines for best effort last mile access.

Free-Space Optical Backhaul

Free-space optical backhaul is another means of high bandwidth transmission technology, see Figure 13. In recent years, wireline operators are migrating to optical Ethernet in metropolitan areas to carry enterprise and residential services. Wire-line operators who also own a mobile arm may converge mobile and fixed services onto a single metro network by extending optical Ethernet to mobile backhaul. Free-space optical backhaul is a line-of-sight technology using invisible beams of light to provide optical bandwidth connections. The advantage of free-space optical technology is that it does not require fiber-optic cable or the securing of spectrum licenses for radio frequency solutions. The down side of the technology is that it requires high-stability mounting and is susceptible to obstructions and fog attenuation, among other impairments [7], [8].

New transmission technologies, topologies, and network architectures are emerging in an attempt to ease the backhaul cost and capacity crunch.

Satellite Backhaul

For very remote locations, satellite links are the only viable means of backhaul from the cost performance perspective. The absolute cost is nevertheless still relatively high, especially for high-date-rate transmission. The long round-trip transmission delay over a geostationary satellite is not helping with real-time interactive applications, but medium earth orbit satellite solutions promise to improve the performance.

Specifically, providing service to rural and remote areas is becoming increasingly important to cellular operators for capturing the next billion customers.

	Free-Space Optical Link	Millimetric Wave Radio
Typical Date Rate	1 Gb/s, STM-4	1 Gb/s, STM-4
Clear Air Atmospheric Loss	<1 dB/km	< 1dB/km
Precipitation Impairment	Thick Fog (75 m Visibility: 100 dB/km)	Heavy Rainfall (6 in/h 50 dB/km)
Path Length at 99.9% Availability	1 km	5 km
Path Length at 99.999% Availability	500 m	1.5 km
Beamwidth	1°	2°
Transmitter Technology	Laser or LED	MMIC Amplifiers
Regulatory Constraint	No	Light Licensing
Mounting Stability	High	Medium

Note: STM-4 or Synchronous Transfer Module-4, also called Optical Carrier 12 (OC-12), has a data rate of 622.08 Mb/s.

Figure 13. *A comparison of free-space optics and millimeter-wave radio. While both can provide gigabit transmission rate, the requirement of high-stability mounting for free-space optics and the potential of beam obstruction have rendered free-space optics less attractive for large-scale mobile backhaul deployment.*

The physical medium for backhaul is not limited to microwave radios but may also include other transmission technologies.

Satellite backhaul, based on very small aperture terminal (VSAT) technology, granting coverage and quick infrastructure deployment advantages, is becoming important. For many emerging markets, such as India and China, mobile traffic in urban areas has attained saturation. Operators are now actively expanding services into remote locations. Managing the infrastructure cost structure for network deployment in rural areas is very different from urban locations and it offers the opportunity for satellite backhaul to become a potential solution. Yet, the high cost of the satellite space segment has been one of the biggest market constraints in adopting satellite backhaul solutions. The evolution of satellite backhaul technologies toward IP and packet data platforms that improve efficiency in space segment usage has lowered the price of bandwidth provisioning. Bandwidth on demand and quality of service for prioritizing calls and data traffic allow several backhaul circuits to share a small pool of bandwidth and thus reduce cost. The round-trip propagation delay is always a challenge for satellite links. For a single hop of 22,500 mi in each direction, the delay is 0.27 s. This delay can be problematic for networks that require acknowledgement in the data transmission process, as the delay can be confused with network congestion [9], [10].

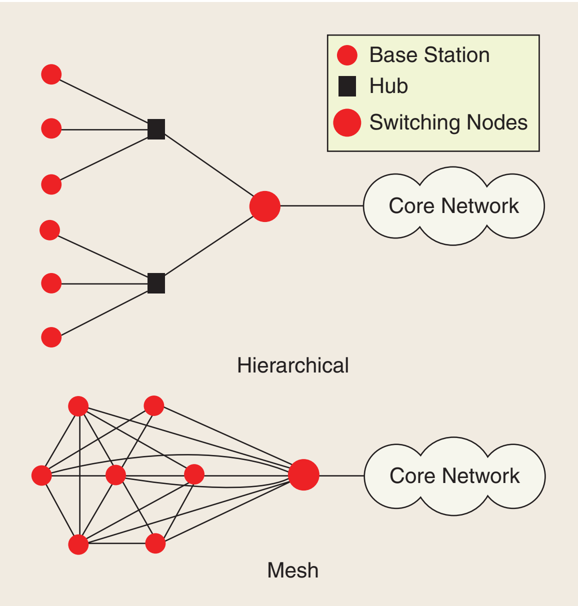


Figure 14. *A schematic diagram showing the hierarchical backhaul network architecture as compared to the mesh network architecture.*

More recently, the use of medium earth orbit satellite has been proposed to ensure lower round-trip latency of around 0.12 s. This type of technology also promises to reduce the cost per bit by a factor of eight and is due to enter service by 2010 [11], [12]. However, there are technical challenges associated with this approach, especially in regard to efficiently and cost effectively tracking multiple satellites.

Backhaul Topologies

Most cellular networks to date are based on hierarchical topologies. With the migration to a more data-centric network, the traditional network topology will evolve to one that is flatter (meaning that peer-to-peer communications between the end-nodes do not always have to go through a node higher up in the hierarchy), as shown in Figure 14.

Mesh Connectivity

As the network architecture becomes flatter, with functionality shifting to the base station, mesh connectivity would be more appropriate for ensuring flexibility in route optimization and avoiding tromboning of traffic paths. In other words, the traffic from an individual base station will not have to always backhaul to a point further up in the network hierarchy before relay to another base station but can be transferred to a nearby peer base station directly. Until now, mesh topology has been used to provide resilience in networks linking wirelessly inexpensive Wi-Fi access points and backhaul traffic towards the public Internet. These networks are also known as *metropolitan Wi-Fi access*, where IEEE 802.11a/g technology is used for the backhaul links. Depending on the expected traffic load in the network, different types of mesh network can be deployed. A single shared radio, where the same radio is used for both Wi-Fi access and backhaul, is the least expensive solution. Dual radio shared nodes have two distinct radio systems, one for access and one for backhaul. The backhaul lines all use the same frequency. The multiple radio solution is the most expensive solution, but ensures the maximum capacity as well as reduced latency in the traffic relay process. The mesh backhaul concept using unlicensed 5-GHz spectrum is less suitable for cellular networks due to the inadequacy of unlicensed spectrum in satisfying the 99.999% service availability due to fluctuations in interference level affecting the overall achievable data rate [13].

Given the expected high density of sites for systems such as LTE, it is expected that some degree of self-configuring mesh network could be used among small islands of base sites. These islands will be connected via high-capacity links to the hubs. In theory, multiple backhaul technologies can be used for different links in a mesh network. However, this tends to increase the management complexity.

Alternative Approaches

The backhaul network is usually separate from that for providing cellular radio coverage, even if both use radio technologies. There are two alternative approaches—in-band backhaul and in-band relay—that utilize the same frequency spectrum of providing radio coverage for backhaul. The pro is that no new spectrum is needed in the short term, while the con is that scalability could potentially be a problem if the traffic grows in the long term. In addition, the traffic can be offloaded through the customers' own femtocells or the public Internet.

In-Band Backhaul

In-band backhaul has been used by suppliers to create the backhaul-free base station solution by utilizing existing cellular spectrum to carry traffic. In other words, the backhaul network shares the same bandwidth allocation as the cellular network. This solution mainly targets low-traffic locations such as highways, remote suburbs, or rural areas, where bandwidth is not a concern. The advantages are low cost and quick installation, but the downside is the limitation in capacity expansion [14], [15].

In-Band Relay

In more recent times, IEEE 802.16j has defined in-band relay where the backhaul uses the same carrier or channel as the base station radio interface for subordinate station communication [16]. Full duplex relay stations can transmit and receive simultaneously in a single frequency band, giving a number of advantages including potential increases in spectral efficiency and reutilization of base station–relay station link resources as relay station–mobile station link resources. Other advantages include reduced overhead and no loss in uplink coverage. IEEE 802.16j [16] indicates that

> The use of in-band wireless backhaul may significantly reduce the cost, but sharing bandwidth with the backhaul results in reduced access rates relative to that of cell-splitting with fixed backhaul. Further cost savings may be achieved with the use of low power, low complexity relays in lieu of the additional base stations. It can be shown that a cellular architecture with base stations supplemented by simple decode-and-forward relays can provide significant capacity improvements despite the overhead associated with in-band backhaul.

With suitably low power, fair usage, and a high density of cellular infrastructure in an urban area, the penalty due to shared capacity may not be a first concern to the network. However, in the long run, the solution may not be infinitely scalable.

TDM and ATM were originally chosen for cellular backhaul because of their ability to deliver consistent and configurable quality of service.

Traffic Offloading

There also exists the proposal of using femtocells to offload backhaul traffic from end users, such that individual residences or enterprises provide backhaul for their traffic through their own broadband connectivity subscription. This only works for developed markets where DSL or fiber cable access is available. The solution is not applicable to emerging markets where there is little or no fixed infrastructure.

Operators may also choose to partially offload non-real-time traffic onto the Internet for transporting data packets back to the switching center using DSL access and only carry real-time or near real-time traffic through their dedicated backhaul networks.

The Future

In the longer term, we may still be using GSM and WCDMA for voice and HSPA for interactive data services, while there will be a new generation of mobile broadband networks based on LTE and IMT-Advanced enabling user access to the Internet ubiquitously to larger and more capable terminals [17]. Ultimately, in urban areas, the size of a cell will shrink until the small radio nodes are deployed in significant numbers, with the network relying on the availability of a passive optical network on every street.

To meet the strong demand for lower-cost-per-bit for cellular network transport, backhaul equipment suppliers are increasing the effort to develop new technologies that have low cost structures and better utilize existing bandwidth, enabling the sharing of bandwidth across multiple services. With the number of base stations multiplying rapidly to provide high data rate services, a passive optical network will be the answer for providing enough capacity in urban environments. In the near term, mobile operators will continue to migrate to IP- and Ethernet-based backhaul technology. The challenge will be to balance transport cost-per-bit reduction against the revenue decline and pricing pressure due to flat-rate pricing by seizing the opportunity created by the development and availability of new backhaul transmission technologies.

For instance, mobile operators are actively conducting trials on Ethernet microwave radio to smooth out operational issues. These new Ethernet microwave radios can quadruple current backhaul capacity by increasing peak capacity from around 32 Mb/s to around 180 Mb/s using the same radio frequency channel bandwidth. Commercial products are scheduled to be available for deployment from the end of 2009 [18]. Many mobile operators have already deployed hot spots offering theoretical peak downlink data rate of 7 Mb/s using HSPA technology. These operators are planning to migrate to a next generation of the technology called HSPA+ that can achieve downlink data rates of up to 20 Mb/s [18]. Some are even contemplating the 42 Mb/s version of the technology. The continuous growth in the cellular user base, the growing demand of data services, and the growth in competition are likely to be some of the driving forces that push mobile operators to increase backhaul capacity from a few megabits per second to perhaps an order of magnitude higher or more over the next few years with spending in double-digit percents [17], [19]. Operators will most likely employ a mixture of backhaul technologies depending on the constraints such as technology maturity, physical environment, and cost structure. That said, the recent economy downturn could reshape the market demand and the industry.

It is worth mentioning that there is a tendency of enabling quad-play in the telecommunications industry where operators provide telephony, data, entertainment based on IP Television (IPTV), and mobile services as a complete package to customers. In this scenario, the backbone network will potentially share the same transmission facility with the cellular network. To this end, suppliers are already providing carrier-Ethernet-based solutions where the operators may leverage existing capabilities to monitor both network and service quality.

On the other hand, mobile television is also emerging. For both streaming and broadcast mobile television, delay and jitter in the network will lead to impairment on the signal transmission. Typically, the TV decoder will adapt to the condition by reducing the color depth, picture granularity, or frame rate in the decoding process. At this time, there is no special provision in the backhaul network to compensate for the impairments, and the transmission is best-effort only.

As a whole, with the increasingly strong demand for backhaul capacity and efficiency due to the improvement in the cellular radio transmission technology and the convergence of fixed and mobile service offerings, engineers are already working in earnest to find cost-effective solutions and technology breakthroughs that will move the industry forward. It is a space that all communication engineers should watch, as it could be one of the areas that see fast technology advancements. Alternately, it may become the bottleneck for the industry. Ideally, the backhaul problem can be solved by ubiquitous fiber deployment. This ideal will probably not happen in many locations for a very long time, especially for locations far away from urban centers. To this end, microwave radios and even satellite links will continue to play a strong role in the interim.

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