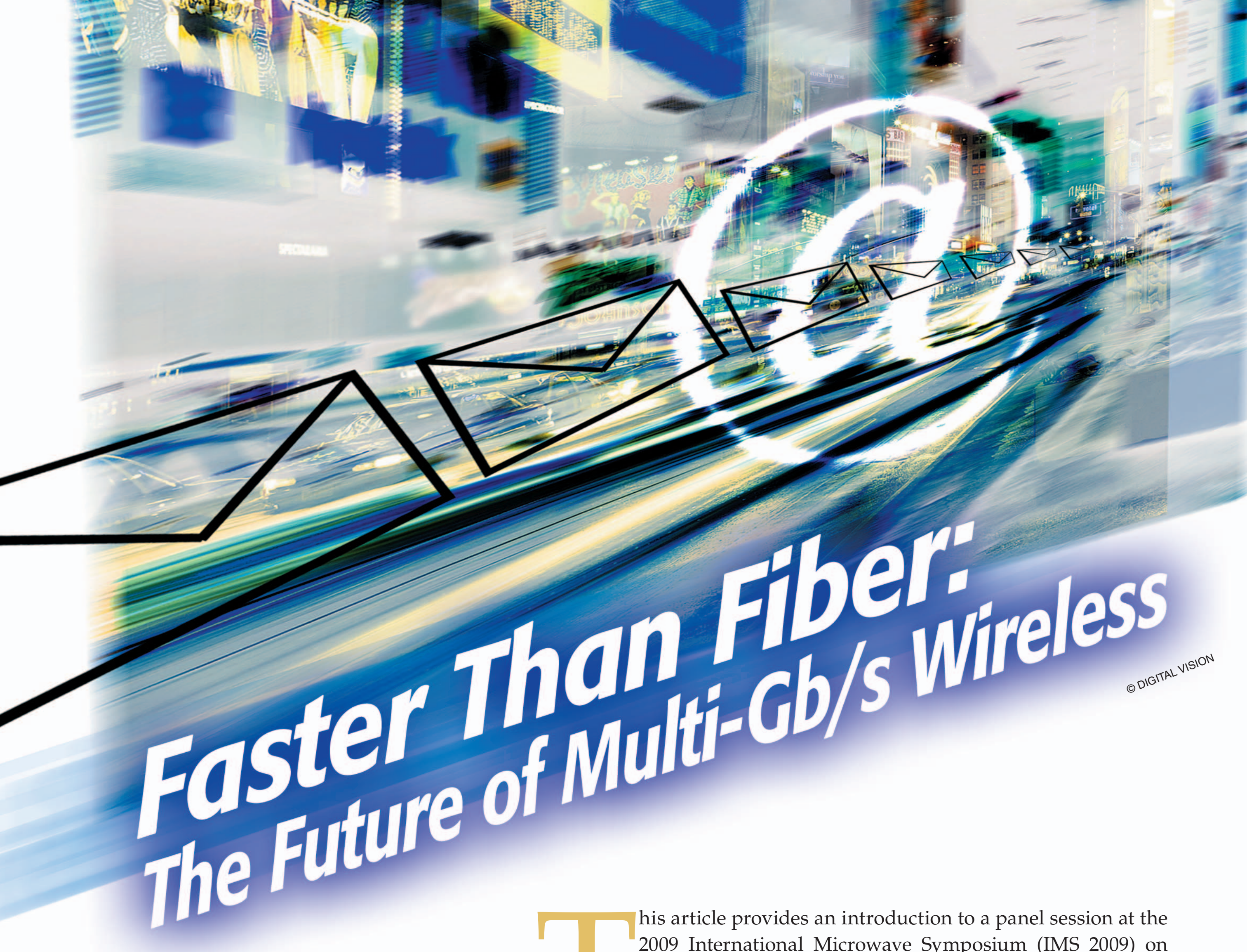

Faster Than Fiber: The Future of Multi-Gb/s Wireless

Jonathan Wells

This article provides an introduction to a panel session at the 2009 International Microwave Symposium (IMS 2009) on enabling multi-gigabit per second (Gb/s) wireless communication links. Blasting beams of high-speed data through free space is not new. Terahertz spectrum near visible light has been used for ultrahigh-speed optical links for many years. Newly released millimeter-wave (mm-wave) bands provide a similar potential but with different operating characteristics. Advances in manufacturing are yielding high-reliability, high-frequency mm-wave devices, faster digital field programmable gate arrays (FPGA) processors, and super-fast analog-to-digital (A/D) and digital-to-analog (D/A) converters that enable higher frequency transceivers, faster modems, and more cost-effective radio architectures that need to be reliably realized. This panel session will explore the technologies being developed within the industry to enable this new field of communications. The strengths and weakness of each technology will be debated, and the viability of each to provide a compelling alternative to fiber will be determined. The panel will bring together leading device engineers with system providers to provide a complete overview of the state-of-the-art Gb/s communications and a road map for the future.

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Wired Versus Wireless Technology

In the wired world, gigabit Ethernet (GbE) has become the de facto protocol for data transmission. Most PCs now ship with a GbE networking port as a standard. However, faster versions are available, and more than 1 million 10-Gb/s Ethernet (10-GbE) ports were shipped in 2007. This protocol is becoming widely used in the fiber-optic core of telecom networks and is even available as backplanes for ultrafast commercial equipment enclosures. Even faster 40- and 100-GbE Ethernet standards are under consideration by the IEEE 802.3 Higher Speed Study Group (HSSG) under the IEEE 802.3ba designation.

Wireless transmission speeds have in the past lagged a long way behind their wired counterparts but have recently began catching, and in some cases, exceeding wireline progressions. For the last few years, wireless equipment capable of 1 Gb/s and faster speeds has been commercially available using a variety of different technologies. Some wireless systems can be found that operate at 10 Gb/s and even as high as 40 Gb/s over short distances. Such speeds have been enabled by global rule-making, encouraging high data rate usage of the higher mm-wave regions of the spectrum, and the availability of faster and higher frequency components and devices.

Strictly speaking, the term mm wave refers to wavelengths less than 1 cm or frequencies of 30 GHz and above. However, in the wireless communications world, it is more convenient to refer to mm waves as operating at higher frequencies. This is because the widely used, globally available bands of 6–40 GHz, commonly called the microwave bands, are relatively consistent in characteristics and are managed similarly by regulators around the world. However, the bands at 55 GHz and above have different atmospheric propagation characteristics and are treated differently by regulators, and it is therefore more convenient to define them differently. The convention here is to refer to mm-wave bands as those of 55 GHz and higher.

With the opening and use of the mm-wave bands at around 60 GHz and higher, right up to the optic frequencies, channels can be made wide enough to support the bandwidths required for multi-gigabit transmission speeds. The success of these Gb/s solutions are due to the high cost of leasing high-speed fiber services (typical lease costs of 1-GbE services are US$10,000 per month in the United States and United Kingdom), meaning that dedicated wireless systems have fast paybacks. Also, wireless is an excellent alternative where fiber is too expensive to lay (trenching costs can reach US$250,000/mi in metro areas) or in areas where fiber simply cannot be laid without significant disruption or environmental impact. There exists a demand for GbE and even 10-GbE wireless speeds for ultrafast local area network (LAN) and enterprise connectivity, similar to the wired standards.

For this reason, there is interest in the mm wave and higher frequency bands for ultrahigh data rate wireless transmission. To support data rates of 10 Gb/s and higher wirelessly, channel bandwidths of many tens of gigahertz will be required. Only at the higher mm wave and optic wavelengths can such bandwidths be achieved.

The High Data Rate Communication Landscape

Figure 1 highlights the major higher capacity wireless technologies and shows how they fit together to make up the current high data rate landscape.

WiFi: 802.11a/b/g/n

Wireless Fidelity (WiFi) is a short distance multiaccess technology, popular for local area residential or hotspot connectivity. The newest variation of the standard, draft 802.11n, offers theoretical data rates up to 600 Mb/s by employing multiple antennas, complex beam-forming and wide channel transmissions. Speeds in excess of 200 Mb/s have been demonstrated in laboratory environments [1], [2]. However, like most technologies, WiFi has a number of limitations that significantly reduce practical speeds below theoretical peaks and laboratory demonstrations. In real life, data rates are dependent on the environment, the distance from the access point, the number of users sharing the capacity, and the usually constrained access point's broadband connection. For this reason, users typically realize about 1–2 Mb/s connectivity in commercial hotspot environments, much less than the theoretical maximums. In addition, by necessity WiFi is an unlicensed broadcast technology, resulting in interference, data contention, and security concerns for installers and system architects.

4G: WiMAX, LTE

Fourth-generation (4G) wireless systems, the generic name for worldwide interoperability for microwave access (WiMAX) and long-term evolution (LTE) technologies, promise a substantial increase in throughput over existing second- and third-generation (3G) cellular systems. Many proprietary pre-WiMAX networks and a few fixed (802.16-2004) and mobile (802.16e-2005) WiMAX installations are already successful in operation around the world. WiMAX addresses many of the quality-of-service (QoS) and security issues inherent with WiFi and is usually implemented using secure licensed frequency bands. Theoretical data rates of many tens of megabit per second are possible, although real implementations provide data rates of closer to 2–4 Mb/s. Future extensions to the WiMAX family (for example, 802.16m) will further extend user data speeds and experiences. WiMAX does offer the benefit of mobility, making the analogy to advanced cellular systems more accurate than to WiFi networks. LTE by contrast has been designed as the next generation of the existing

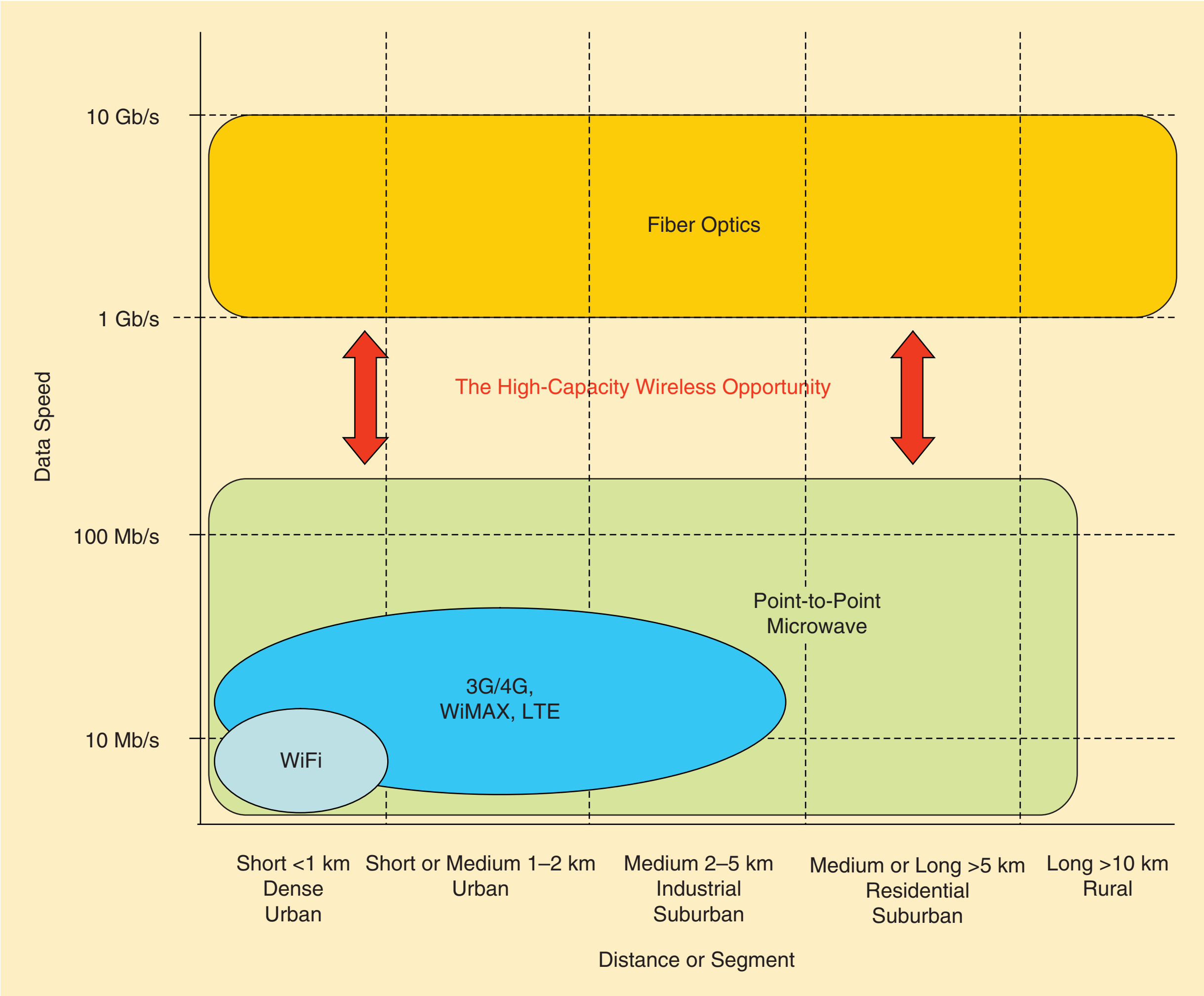

Figure 1. *Typical operating characteristics of the major high-speed wireless technologies, showing the opportunity for ultrahigh-capacity wireless.*

3G cellular technologies. Theoretically, data rates to 100 Mb/s and beyond are possible. Complete standards are likely to be realized in the next few years, and early experimental systems demonstrating improved data throughput are already being seen today [3].

Point-to-Point Microwave

Fixed wireless radios operating in the microwave frequency bands from 6 to 38 GHz are widely used for connecting together cell sites, buildings, campuses, and providing other high-speed point-to-point (PTP) data connectivity. PTP microwave is able to support some high-speed standards [for example, 100-Mb/s fast Ethernet and 155-Mb/s STM1 synchronous digital hierarchy (SDH) and OC-3 synchronous optical networking (SONET)] but is limited in providing higher speeds by the relatively narrow channel sizes implemented by regulators (typically, up to 28 MHz or occasionally 56 MHz in Europe and up to 50 MHz in the United States). Systems are available that employ sophisticated signal processing circuitry and high-order 128- or 256-quadrature amplitude modulation (QAM) to squeeze data into the narrow available channels, resulting in data rates up to around 311 Mb/s (2xSTM1) and occasionally higher. Furthermore, parallel links can be used with techniques as cross polarization interference cancelers (XPIC) to reuse frequencies for dual data streams, doubling the effective data throughput. In 2008, over 1 million PTP microwave radios were sold worldwide.

It is worth noting that all the PTP wireless systems considered here [microwave, mm wave, and free space optics (FSOs)] operate at frequency division duplex (FDD), meaning that both transmitting and receiving transmission paths are operated simultaneously. Simplistically, a 100-Mb/s microwave radio will be transmitting 100 Mb/s whilst simultaneously receiving a 100 Mb/s data transmission. Thus, the instantaneous data rate over the air is actually 200 Mb/s. Nevertheless, convention requires that this be described as a 100-Mb/s wireless connection. In the wired and the lower frequency multiaccess wireless worlds, systems usually operate at time division duplex (TDD), meaning that a unit is either transmitting or receiving but never both. Thus, a 100-Mb/s TDD connection might be operating at 100 Mb/s in one direction and nothing in the other, or an average of 50 Mb/s, in both directions.

High-Capacity Wireless Opportunity

Fiber optic cable remains the panacea of high data rate technologies. Fiber optic technology offers wide bandwidth and low loss transmission, meaning that very high data rates can be transmitted over very long distances. Substantial global investments have been made in fiber rollouts, meaning that optical transmissions can be made almost anywhere in the world.

Despite these advantages, fiber has many limitations. Fiber is not everywhere. A vast majority of commercial buildings do not have fiber connections, and those that do can be charged up to US$10,000 per month for a Gb/s connection. Trenching fiber can also be very expensive, with costs per mile approaching US$250,000 in large urban cities. Some cities have implemented moratoriums on fiber trenching because of the significant disruption and environmental impact that trenching brings.

Because of these limitations, there has recently been significant investment in alternative high-capacity technologies to address the large void between fiber and the more common wireless technologies. Standard bodies have helped develop new standards, and regulatory rules have been introduced that promote new high-speed wireless technologies at the mm-wave and higher frequency bands.

Spectrum for Gb/s Wireless Transmission

The key to transmitting ultrahigh data rate traffic wirelessly is spectrum. As data rates increase, proportionally larger frequency bandwidths are required to support the increased data rate. At low transmission frequencies such as the microwave bands up to 40 GHz, regulators deliberately slice the available spectrum into many narrow channels to encourage competition and permit users to use the services without interference. Only at the higher mm wavelengths are channels large enough to support the highest data rates. Figure 2 shows this trend. In the sub-10 GHz region, popular wireless LAN and WAN standards exist (e.g., cellular, WiFi, WiMAX, etc.) that can support data rates of up to several tens of megabit per second. In the microwave bands of 6–40 GHz, popular for long distance transmission, cellular backhaul and enterprise connectivity, data rates of up to a few hundred Mb/s are available. To transmit data at speeds of 1 Gb/s and above, the mm-wave frequency bands of 60, 70, and 80 GHz can be utilized [4], [5]. For 10 Gb/s and higher transmissions, bands of around 100 GHz and higher are required [6], [7].

The physics of atmospheric propagation reveals several frequencies where radio-wave attenuation is minimized, allowing superior wireless transmission [8], [9]. These so-called atmospheric windows naturally occur at 35, 90, 140, 220 GHz, and upwards (Figure 3). The frequencies around 35 GHz have already been widely used for commercial satellite and terrestrial communications. The frequencies around 90 GHz have similarly long been exploited for military communications. The molecular absorption peaks of 60, 119, 183, and 325 GHz are to be generally avoided as they will limit transmission distances, but the windows in between, centered at approximately 80, 140, and 220 GHz, show a great potential for extremely

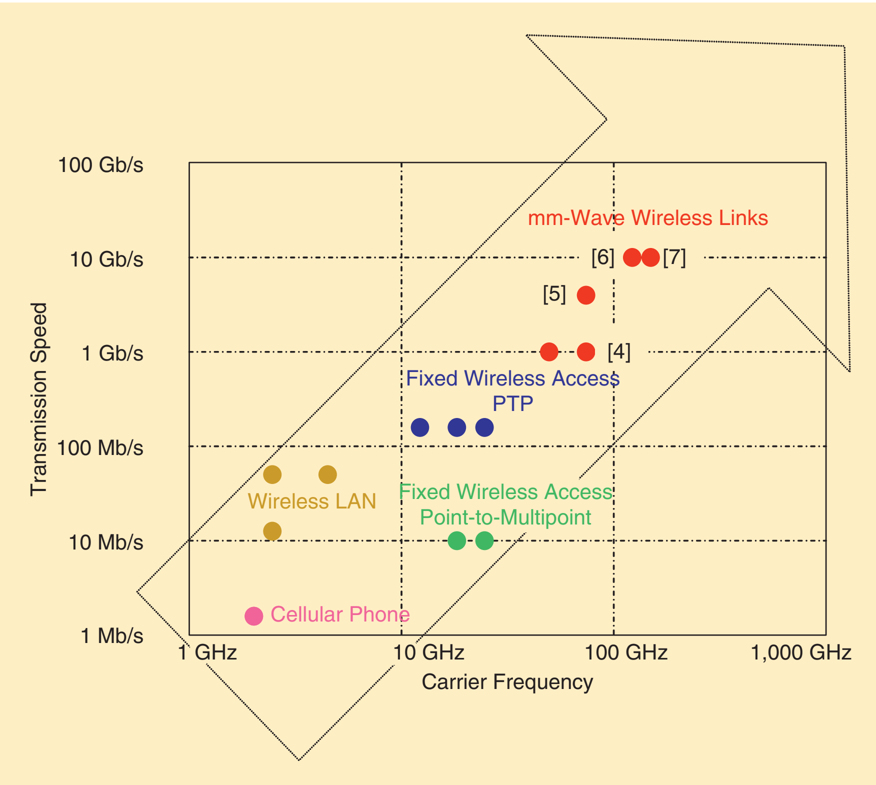

Figure 2. *To transmit higher data rate traffic, a proportionally higher frequency carrier is required.*

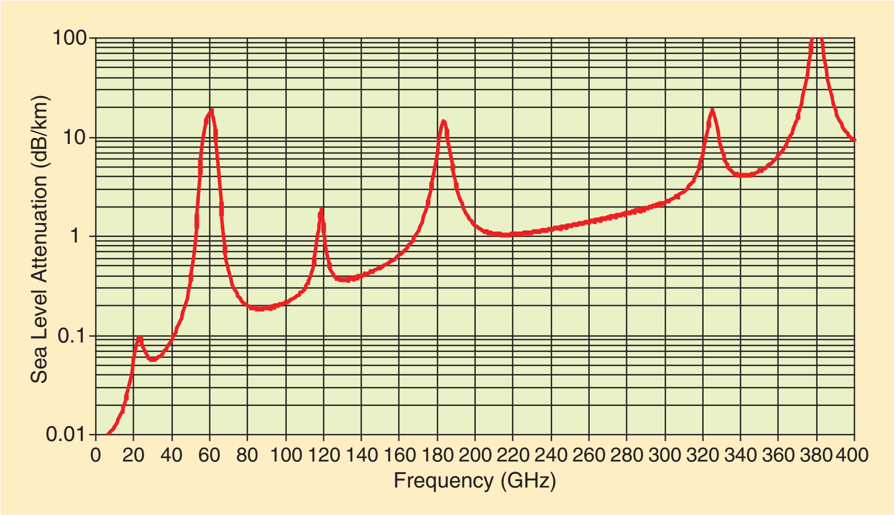

Figure 3. *Average millimeter-wave atmospheric absorption.*

high data rate communications because of the large potential bandwidths available.

Unfortunately, however, not all these bands are available for commercial services. Figure 4 shows the major frequency bands commercially available in the United States. The lower frequency microwave bands up to 40 GHz can be seen with the relatively narrow channels allocated at those frequencies. The bands at 60 GHz (57–66 GHz, often referred to as *v-band*) and 70/80 GHz (71–76 GHz paired with 81–86 GHz, often referred to as *e-band*) clearly show the large channel sizes available, demonstrating sufficient bandwidths to support Gb/s operation. The 90-GHz allocation (92–94 GHz and 94.1–95 GHz) also has significant bandwidth, but its uneven allocation and proximity to military bands at 94–94.1 GHz make it practically difficult to use.

Thus, the 60-GHz and 70/80-GHz bands are of most use for high data rate applications. However, noting Figure 2, 60 GHz occurs at an atmospheric peak, meaning that transmission distance is limited. Thus, 60 GHz is useful for short-range transmissions; however, 70/80 GHz occurs in an atmospheric window permitting multiple kilometer transmissions. Both technologies require line of sight (LOS), meaning that links require an obstruction-free path between antennas. Antenna gain and directivity increases with increasing frequency, hence high-gain antennas for mm-wave communication links can be realized with footprints much smaller than the lower frequency microwave bands.

The 60-GHz and 70/80-GHz bands are managed very differently in different parts of the world. In Europe, for example, the 60-GHz band is currently split into two relatively small allocations, making it of much less use for high data rate transmissions than the 7-GHz wide allocation available in the United States. (Fortunately, European regulators are currently reviewing the band to address this discrepancy.) Similarly, many other regions of the world allocate the 60-GHz band differently, with different equipment specification and homologation requirements. The 70/80-GHz bands are used almost identically in the United States, Europe, and the growing number of countries adopting the bands, making the bands very attractive commercially. The 90-GHz allocation is available only in the United States. Figure 5 shows the availability and allocations of all three bands in various major markets across the world.

Another region of the spectrum that has generated much interest in the past is the spectrum higher than 275 GHz, which is not currently allocated by the International Telecommunication Union (ITU); in particular, the significantly higher optical frequency bands. The FSO technologies operate in the very highest regions of the frequency spectrum, i.e., near visible light. The FSO technologies employ a laser transmitter to generate a focused optical light wave that carries data through the atmosphere to an optical receiver located at a fixed distance from the transmitter. Very wide bandwidths are available in the optical part of

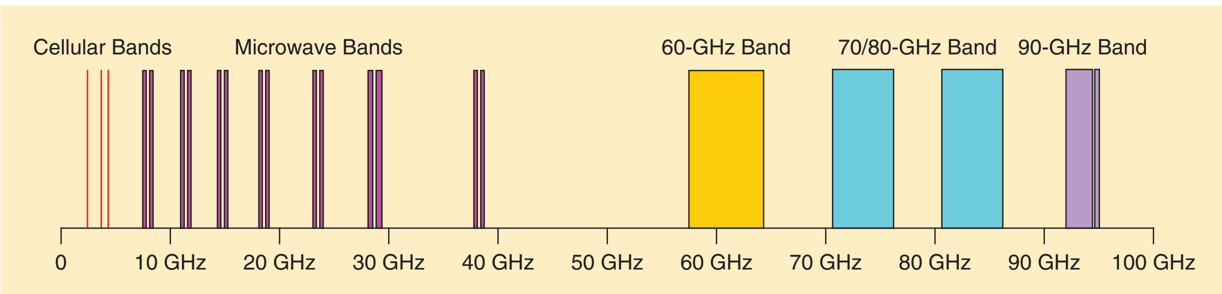

Figure 4. *Major U.S. frequency band allocations.*

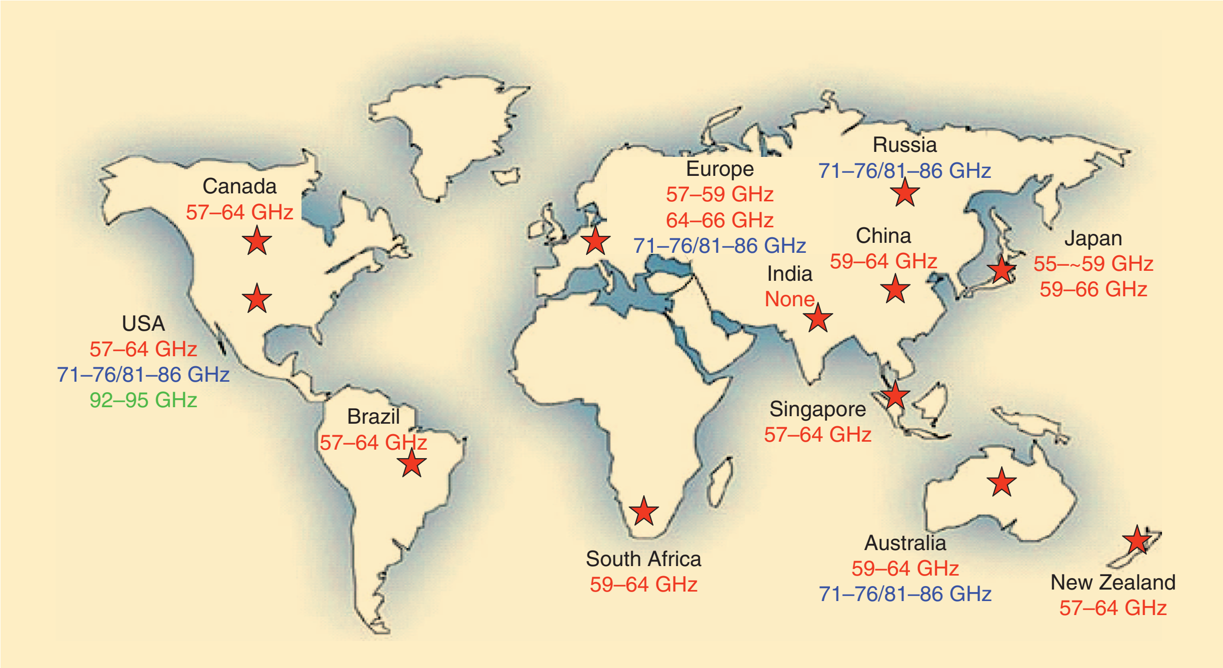

Figure 5. *Millimeter-wave band availability and allocations in major global markets (as of November 2008). (© AJIS LLC, reproduced with permission.)*

the spectrum that enables very high data rates to be achieved. Commercially available equipment can be found, offering 1, 10, and even 40 Gb/s transmission rates [10]. Since these optical bands have little atmospheric attenuation under clear conditions, practical links for high data rate transmission can be realized.

Practical Gb/s Wireless Operational Characteristics

All the high-capacity technologies covered so far yield very different operational characteristics, resulting from the unique properties of the various frequency bands.

60-GHz Wireless Systems

Sixty-gigahertz wireless systems operate at an oxygen absorption peak, reaching a maximum of 15 dB/km absorption at sea level. This high level of attenuation severely limits link distances, making 60 GHz useful for only short-distance transmission. Some equipment vendors offer outdoor communication links that deliver 1 Gb/s data reliably over distances of 400–800 m using 30–60 cm antennas. The high atmospheric attenuation adds advantages such as high-frequency reuse and secure communications because of the difficulty in eavesdropping. Also for out-of-atmosphere communications, for example, between satellites, 60 GHz excels as the oxygen absorption limitations disappear and essentially free space communication conditions exist.

Despite the availability of outdoor communications equipment, the real growth potential for 60-GHz high-capacity wireless is for short distance, unlicensed wireless personal area network (WPAN) use, particularly for delivering uncompressed high definition television (HDTV) wirelessly in a home environment. The WirelessHD consortium recently released version 1.0 of a specification that permits up to 4 Gb/s to be transmitted in the 60-GHz bands over distances of 10 m distances (a nice-sized living room) [11]. Many heavyweight consumer electronic brands are supporting this standard, and demonstrations of the technology were given by both Toshiba and Panasonic at the consumer electronic show (CES) 2008. A similar competing standard, published by Ecma International and supported by Phillips, has also recently been released [12]. Furthermore, the IEEE is also supporting high data rate 60-GHz transmission under the 802.15.3c standard family, which purports to offer similar data rates and distances.

One key benefit of 60-GHz wireless versus other mm-wave technologies is that, being of lower frequency, links can generally be realized at lower cost prices. Many researchers are working on 60-GHz complementary metal oxide silicon (CMOS) devices, and general radio building blocks such as transceivers, power amplifiers, low noise amplifiers, mixers, etc. are more readily available at 60 GHz than the higher mm-wave frequencies.

70/80-GHz Wireless System

Although only recently made available, the 70/80-GHz (and 90 GHz in the United States) e-band wireless characteristics have been well documented [4]. Both bands operate in an atmospheric window

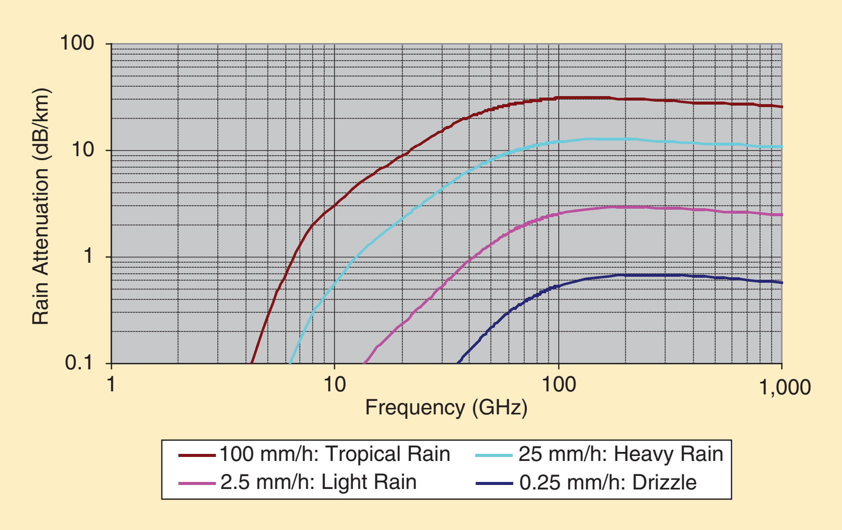

Figure 6. *Rain attenuation at microwave- and millimeter-wave frequencies.*

One strong benefit of 70/80-GHz wireless is that, with the exception of rain, it is unaffected by most other transmission deteriorations. Because the transmission wavelength is about 1 mm, and relatively large compared to most small particle airborne effects, 70/80-GHz wireless is unaffected by water particles (fog and mist), sand, dust, or other small-particle transmission path impairments. Thick fog, for example, at a density of 0.1 g/m^3 (about 50 m visibility) has just 0.4 dB/km attenuation at 70/80 GHz [16], yielding negligible effect on typical link distances.

where clear air absorption is less than 0.5 dB/km, meaning that links can transmit across many miles. However, practical links are much shorter due to rain attenuation. Similar to all high-frequency radio propagation, rain attenuation has to be considered when planning a link. Figure 6 shows that propagation at 70/80 GHz can experience large attenuations in the presence of heavy rain [9], [13]. Fortunately, the most intense rain tends to fall in limited parts of the world; mainly, the equatorial countries. In most of the Unites States and Europe, maximum rainfalls experienced tend to be no more than 100 mm/h, yielding up to 30 dB/km attenuation, and generally occur only at that intensity in short bursts. Such severe weather tends to form in small, dense clusters within a larger, lower intensity rain cloud, and is usually associated with a severe weather event that moves quickly across the link. Therefore, rain outages tend to be short and are only problematic on longer distance transmissions.

The ITU and other bodies have collected decades of rain data from around the world, and so rainfall characteristics are well understood [14], [15]. With such information, radio links can be engineered to overcome even the worst weather or be designed so that predictable levels of weather outage can be achieved. Currently available 70/80-GHz equipment can achieve 1 Gb/s connectivity with 99.999% weather availability (equivalent to only 5 min of weather outage per year; often referred to as carrier class performance) over distances of 2–3 km throughout most of the United States and Europe. For a lower 99.9% availability (8 h of weather outage per year), distances of 5 km can be routinely achieved. When configured in a ring, effective distances increase for the same availability because of the dense, clustering nature of heavy rain and the diversity that ring configurations provide.

Free Space Optics

The characteristics of FSO links are rather like 70/80 GHz in that there is little clear air attenuation. Thus, long-distance links can be achieved in good weather environments. Also like 70/80-GHz wireless, FSO experiences rain fades similar to the mm-wave bands. However, one weakness of FSO is that optical frequency device ranges are drastically shortened by fog. The 0.1 g/m^3 thick fog (about 50 m visibility) that yields just 0.4 dB/km attenuation at 70/80 GHz gives 225 dB/km attenuation at FSO frequencies [17]. Since fog occurrences are difficult to predict, and when experienced can last for many hours, FSO link outages can be significant. For this reason, FSO is not a practical technology for carrier class systems beyond a few hundred yards in fog-prone coastal and metropolitan areas.

Several other physical effects need to be accounted for when designing or selecting FSO equipment or planning FSO links. These include the following.

- *Pointing effects*: Birds flying through a narrow optical beam can block the path, causing momentary outages that affect timing-sensitive data traffic. Similar effects occur with small airborne particles such as snow, sand, dust, flying debris, or agricultural burning residue.
- *Precise alignment*: Tower sway or movements of solid buildings as they naturally heat up and cool down during the day can misalign narrow beam systems.
- *Scintillation*: Longer east or west facing optical links can be affected by diurnal sunlight effects.

Properly designed FSO equipment compensate for these effects through multiple beam architectures, beam-tracking technologies, and optical filtering, adding to the complexity of the system.

There are two areas to be discussed. First, since they operate at frequencies much higher than are regulated in almost all regions of the world, there are no

TABLE 1. Comparison of key system parameters for leading high data rate technologies.

	Mb/s Wireless Technologies			Gb/s Wireless Technologies			
Parameter	**WiFi**	**4G**	**Microwave**	**60 GHz**	**70/80 GHz**	**FSO**	**Fiber Optics**
Typical data rates	Variable, 1–2 Mb/s	Variable, 5–10 Mb/s	To 400 Mb/s	1 Gb/s	1 Gb/s (to 10 Gb/s in the future)	1 Gb/s (to 10 and 40 Gb/s in the future)	1 Gb/s (to 10 and 40 Gb/s in the future)
Typical distances for carrier class performance	20 m	3 km	5 km	400 m	3 km	200 m	Unlimited
Spectrum availability and licensing	Freely available for unlicensed use	Spectrum very scarce. Owned and fiercely protected by select incumbents	Usually available for the area licensing from country regulators	Wide variations country by country. Available for unlicensed use in the United States	Available worldwide, usually as a low-cost, rapidly available light license	Spectrum freely available as technology not regulated	n/a
Guaranteed interference and regulatory protection	No	Usually	Yes	No	Yes	No	Yes
Relative cost of ownership	Very low	High	Medium	Low or medium	Medium	Low or medium	High
License, install, and commission time	Hours	Years	Weeks or months	Hours or days	Hours or days	Hours or days	Years
Relative high data rate system complexity	Medium	High	High	Low	Low	Medium	Low

licensing restrictions, and links can be installed and commissioned with minimum hurdles. Second, given the enormous bandwidths that are available at optical frequencies versus the regulated limits of the mm-wave bands, theoretical maximum achievable data rates are essentially unbounded.

High Data Rate Wireless and Fiber Comparisons

All the high-capacity wireless systems discussed so far have strengths and weaknesses, meaning each has a role to play in different circumstances. Under many conditions, each offers a compelling alternative to buried fiber. A summary of how the most important system parameters and network characteristics compare are detailed in Table 1.

Conclusions

Although fiber remains the transmission technology of choice for high data rate networking and data transmission, it has severe limitations. It is expensive and time consuming to install, commission, or lease, and it is not widely available to commercial buildings. However, there are available technologies that provide cost-effective wireless Gb/s transmission capabilities, providing compelling alternatives to buried fiber. The three technologies—60-GHz wireless, 70/80-GHz wireless, and FSOs—are all able to support multi-Gb/s data rates. The 60-GHz wireless standards are available to yield up to 4 Gb/s speeds. Commercial 70/80-GHz equipment has been available that offer 1.25 Gb/s for several years. Standards recently released by the European Telecommunications Standards Institute (ETSI) in Europe for these bands permit high-order modulation operation and radio interface capacities (RICs) up to 19 Gb/s [18]. FSO links are commercially available that offer 40 Gb/s transmission. Mapping these recently available and near-term technologies to the traditional high data rate landscape discussed earlier shows that there are many opportunities to challenge fiber for ultrahigh-speed data (Figure 7). Each of these technologies has relative strengths and weaknesses, indicating that each has a commercial role to play depending on the end users' different installation needs, link performance requirements, and budget.

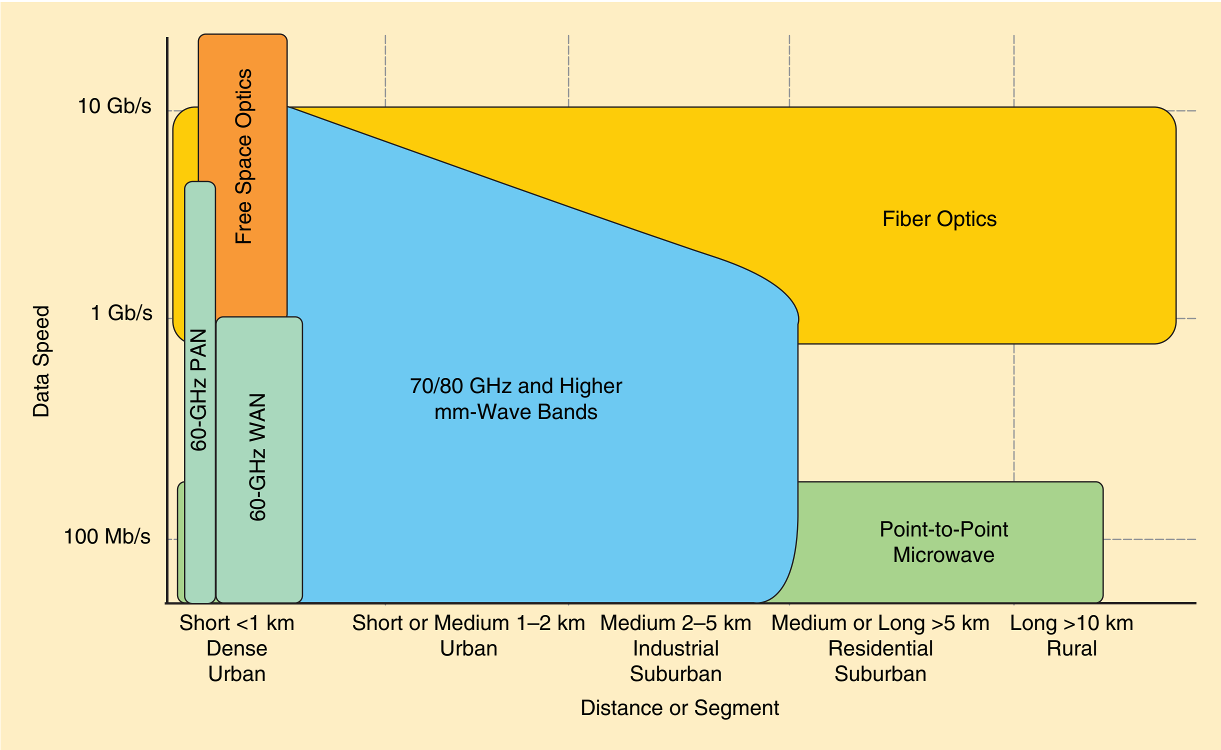

Figure 7. *The recently available and near-term ultrahigh-speed wireless and wired technology landscape.*

There is also consideration underway to open up further mm-wave bands to enable even higher data rate transmissions. There are many unused spectrum blocks allocated for fixed-service spectrum in the atmospheric windows around 140 and 240 GHz. By aggregating some of these bands and opening up wide channels of perhaps 50 or 60 GHz, regulators would enable 40 Gb/s radios with the simplest modulations and 100 Gb/s radios with slightly more sophisticated modulation. With the enormous bandwidths that are available at optical frequencies, FSO links can be envisioned with similar data rates or perhaps even faster. With these innovations, such high-speed wireless links can truly be described as comparable to or perhaps faster than fiber.

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