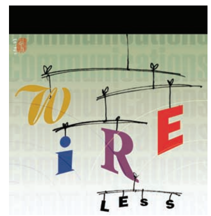
A Long-Term View of Short-Range Wireless



Economic forces and physical laws are driving the growth of a new wireless infrastructure that will become as ubiquitous as lighting and power infrastructures are today.

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Take a moment to look around, whether you're reading this article in an office, airport, hotel, convention center, restaurant, shopping mall, library, dorm, or even your own home. A casual glance will reveal walls and ceilings festooned with lighting fixtures, phone jacks, power outlets, ventilation ports, fire sprinklers, motion detectors, temperature sensors, and other infrastructure artifacts now so common we usually overlook them. You may also see a LAN access jack, which signals the presence of a *wired* connection to the Internet, arguably the fastest-growing global infrastructure in history. All these infrastructures will soon be joined by another that provides high-speed, low-cost, low-power, wireless access to the Internet over very short range.

Next-generation cellular systems have been designed to bring fast, wireless data connections to users. However, currently planned systems limit data speeds to 2 megabits per second or less because, at the distances they must cover to remain economical, these technologies encounter constraints imposed by physical laws that govern channel bandwidth, power, and available spectrum.

Short-range wireless is a complementary class of emerging technologies meant primarily for indoor use over very short distances. SRW links will offer peak speeds of tens or even hundreds of megabits per second—at very low cost and with very low power—to many closely spaced users. In its base set of applications, SRW technologies will provide cableless connections among the portable devices people wear and carry daily, including cell phones, headsets, PDAs, laptop computers, digital cameras, audio and video players, and health monitoring devices. SRW will also give these users wireless access to a host of new services provided by in-building LANs and their wired Internet connections, as well as services offered via more traditional voice and data connections.

FIVE CORE ATTRIBUTES

Were wireless an ideal medium, we could use it to send a lot of data, very far, very fast, for many separate uses, all at once. Unfortunately, physical laws make it impossible to implement all five of these attributes simultaneously—we must compromise on one or more if we wish to do well on the others.

In the early days of wireless, users found the ability to send data "very far" the most important attribute. Marconi willingly compromised on the other four attributes when he sent the world's first transatlantic radio transmissions in December 1901. The past 100 years of wireless, however, show a clear trend toward improving the other four attributes at the expense of distance. The obvious example, cellular telephony, typically covers distances from 30 kilometers to as little as 300 meters. Distances this short are useful only when supported by an underlying wired infrastructure—namely, the existing telephone network.

ENTER SHORT-RANGE WIRELESS

As Figure 1 shows, in the past few years shorter-range systems—from 10 to 100 meters—have emerged, driven primarily by data applications. In these cases, the Internet rather than the telephone network usually forms the underlying wired infrastructure.

Four trends are driving SRW's growth:

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1. growing demand for wireless data capability in portable devices at higher bandwidth and at lower cost and power consumption than that envisioned for third-generation cellular;
2. crowding in radio spectra that regulatory authorities segment and license in traditional ways;
3. growth of high-speed wired access to the Internet in enterprises, homes, and public spaces; and
4. shrinking semiconductor cost and power consumption for signal processing.

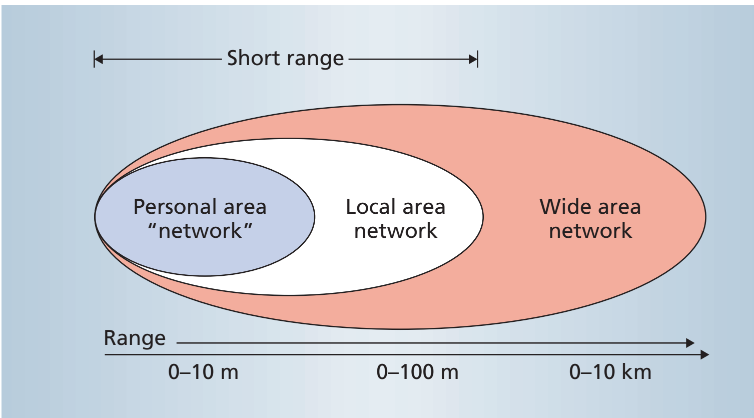

Figure 1. Short-range wireless systems have a range of 100 meters or less. They often combine with systems wired to the Internet to provide communication over long distances.

Trends 1 and 2 favor systems that offer not just high peak bit rates, but also high *spatial capacity*, defined as bits per second per square meter, or bps/m^2. Many researchers have used this term, including Jan Rabaey at the University of California, Berkeley.[1] An equivalent and more descriptive term might be *spatial efficiency*. The late Marc Weiser, Xerox PARC's chief technologist, lectured on the importance of spatial capacity in 1996,[2] although at the time he focused on infrared as the medium and bits per second per cubic meter as the metric. I consider the square meter a more appropriate metric for SRW because the relevant coverage area usually involves a two-dimensional rather than a three-dimensional space.

Just as the wired telephone network underlies cellular telephony, Trend 3 makes possible high-bandwidth, in-building service provision to low-power portable devices that use SRW standards like Bluetooth and IEEE 802.11b—described in the

Wireless PANs and LANs

As in the early days of telephones, electric power, and personal computers, there are today multiple short-range-wireless technologies and visions.[1-4] In general, these technologies fall into two broad but overlapping categories: personal area networks (PANs) and local area networks (LANs).

PAN Technologies

Wireless PAN technologies emphasize low cost and low power consumption, usually at the expense of range and peak speed. In a typical wireless PAN application, a short wireless link—typically under 10 meters—replaces a computer serial cable or USB cable.

Today's best-known PAN technology, Bluetooth, offers a peak over-the-air speed of about 1 Mbps and a range of about 10 meters. The maximum speed available to the Bluetooth user is about 700 Kbps. Bluetooth power consumption is low enough for use in personal, portable electronics such as PDAs and cell phones. An optional high-power mode in the current specification allows for ranges up to 100 meters.

LAN Technologies

Wireless LAN technologies emphasize higher peak speed and longer range at the expense of cost and power consumption. Typically, wireless LANs provide wireless links from portable laptops to a wired LAN via *access points*.

To date, IEEE 802.11b has gained acceptance rapidly as a wireless LAN standard. It has a nominal open-space range of 100 meters and a peak over-the-air speed of 11 Mbps. Users can expect maximum available speeds of about 5.5 Mbps.

Complements and Conflicts

Although each technology is optimized for its target applications, no hard boundary separates how devices can use wireless PAN and LAN technologies. In particular, as Figure A shows, both could serve as a data or voice access medium to the Internet, with wireless LAN technologies like IEEE 802.11b generally best suited for laptops, and wireless PAN technologies like Bluetooth best suited for cell phones and other small portable electronics.

Unfortunately, today, these short-range wireless technologies present a problematic environment. Both the Bluetooth PAN and IEEE 802.11b LAN technologies use the same unlicensed band: 2.400 to 2.483 GHz. When operated simultaneously in the same physical space, these two technologies degrade each other's performance. The amount of degradation depends on many factors, but studies have shown that if users can keep the receiver and the interfering transmitter separated by more than about 2 meters, the throughput reduction will be acceptable for many purposes.[5] When Bluetooth and IEEE 802.11b must be operated simultaneously in the same laptop, special measures must be taken to avoid excessive interference.

Over the long run, researchers anticipate that wireless LANs will migrate to the 5-GHz unlicensed band, which may eliminate

"Wireless PANs and LANs" sidebar—and an emerging technology called ultrawideband.

Finally, Trend 4 makes possible the use of portable-device signal-processing techniques that would have been impractical only a few years ago.

SPONTANEOUS, DISPOSABLE CONNECTIONS

A fundamental concept behind SRW systems, especially personal area network (PAN) systems, asserts that any time two SRW-equipped devices get within 10 meters of one another they can form—either automatically or under user control—a spontaneous, just-in-time, disposable connection for whatever purpose is at hand. From an end-user perspective, these purposes fall into three broad categories.

Leveraging device synergies

The first and simplest category makes personal electronics easier to use by eliminating cables and allowing devices to offer their capabilities to one another even when they weren't originally designed to do so. For example, a handheld GPS device or digital camera has no room for a QWERTY keyboard. But with a wireless system like Bluetooth, a nearby PDA, laptop, or desktop machine can serve as a human interface, offering HTML-like pages for entering or retrieving data and images. These spontaneous, synergistic connections will help solve the human-interface problems that arise from stuffing more and more complexity into smaller and smaller packages.

Making queues obsolete

The second category saves people time. In 1989, researchers estimated that in the United States alone people spent more than 100 million person-hours per day waiting in line.[3] Typically, these queues form because only the person at the head of the queue can access the system needed to execute functions such as hotel check-in, airline seat assignments, or cash transactions. In most of these cases, customers could serve themselves without waiting if they could obtain secure access to the same system via a handheld device like a PDA or cell phone equipped with SRW-based access.

Grouping Internet users efficiently

The third category grants efficient Internet access in public places or private enterprises like large corporations. Most of us already spend the majority of our

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most coexistence issues. In particular, the companion standard IEEE 802.11a, designed for the 5-GHz band, will operate at peak over-the-air speeds up to 54 Mbps over distances up to 50 meters. Maximum data speeds available to users are projected to be between 24 and 35 Mbps.

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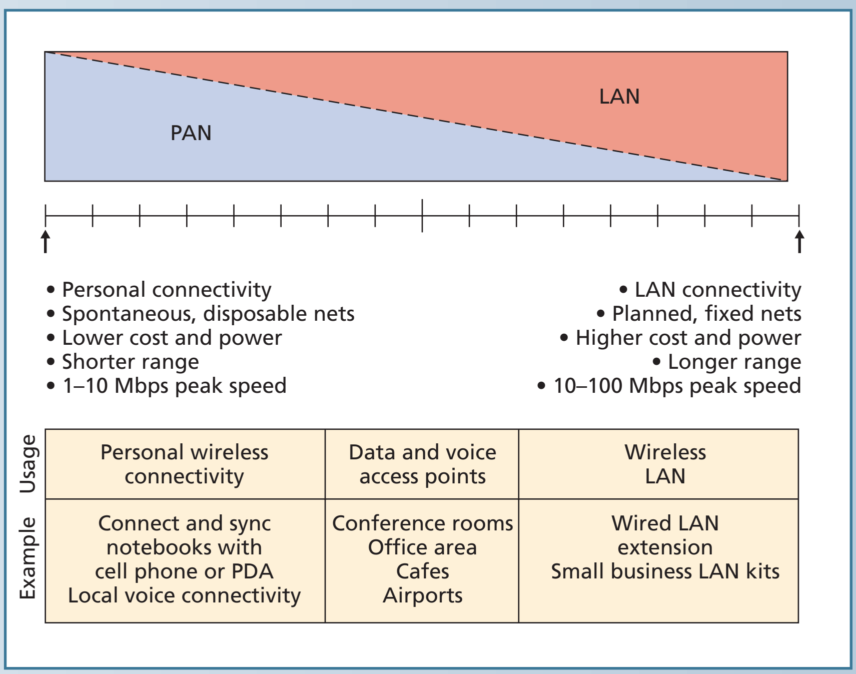

Figure A. Wireless PAN and LAN technologies complement each other, with LANs generally best suited for laptops, and PANs best suited for small portable devices like cell phones.

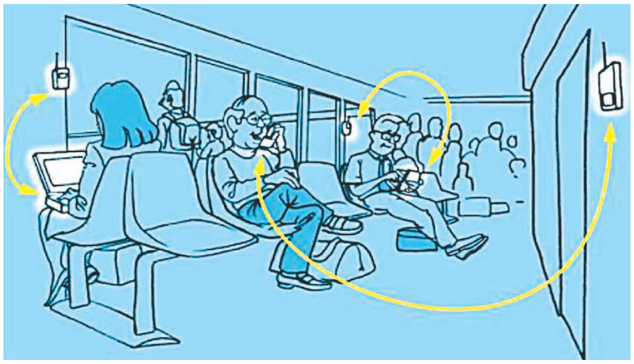

Figure 2. Short-range wireless networks could offer ready Internet access to densely packed users who occupy a small space—such as travelers waiting in an airport terminal.

day within 10 meters of some kind of Internet port. The number of places and hours per day that we spend in that state will only increase. An airport terminal offers a good example, as Figure 2 shows. Other examples include hotels, convention centers, lecture halls, shopping malls, sports stadiums, and theme parks. Wherever densely packed users gather in small spaces, some yet-to-be-determined business entity could use SRW to offer data connections at much higher speeds, for many more users, with far longer battery life than that possible with cellular-based—even 3G—systems.

THE BIRTH OF IN-BUILDING SERVICE PROVISION

The business models for providing voice and data services over SRW and the Internet may differ radically from those for providing traditional, carrier-based, wireless service. Widely available at reasonable cost, SRW technology uses unlicensed spectra, and its rights-of-way require no zoning approvals. These attributes mean that small entrepreneurial companies could develop *in-building service provision* (IBSP) businesses with no direct regulation from utilities commissions or other government authorities.

We do not yet know what business models will support IBSP in public places or private enterprises, but several new, small companies are already experimenting with it. If successful, these companies could offer, at least in the short term, a competitive and possibly disruptive alternative to 3G or other advanced cellular systems. Longer term, it appears likely that IBSP will complement cellular technology. In doing so, it will preserve precious licensed cellular spectrum and system capacity for service where SRW is unavailable or simply will not work, such as providing connectivity to cars speeding down a highway.

SRW TECHNOLOGIES AND SPATIAL CAPACITY

In general, developers have not explicitly designed SRW systems to maximize spatial capacity. Indeed, a key figure of merit for a wireless system has traditionally been its range, because longer range has generally meant lower cost, especially during early deployment. In the early days of radio telephony, a single tower with a high-powered transmitter had the range to cover an entire city. Unfortunately, this approach also meant that, because of the limited capacity of available frequencies, few customers could be served. As recently as 1976, radio telephony providers in New York City could handle only 545 mobile telephone customers using such systems.[4] That number seems absurdly small by today's standards.

Single-tower, long-range systems offered radio telephony a low-cost way to get started and build demand, but that approach quickly ran out of capacity. Serving today's customer demand required developing much-shorter-range, lower-power, cellular systems that allow massive frequency reuse. We can expect to see the same phenomenon repeated for SRW systems. Emerging SRW standards and technologies vary widely in their implicit spatial capacities, as follows:

- *IEEE 802.11b*. This technology has a rated operating range of 100 meters in free space. In a circle with a 100-meter radius, three IEEE 802.11b systems can operate on a noninterfering basis, each offering a peak over-the-air speed of 11 Mbps. The total aggregate speed of 33 Mbps, divided by the area of the circle, yields a spatial capacity of approximately 1 Kbps per square meter.
- *Bluetooth*. In its low-power mode, Bluetooth has a rated 10-meter range and a peak over-the-air speed of 1 Mbps. At least 10 Bluetooth piconets can operate simultaneously in the same 10-meter circle with minimal degradation,[5] yielding an aggregate speed of 10 Mbps. Dividing this speed by the area of the circle produces a spatial capacity of approximately 30 Kbps per square meter.
- *IEEE 802.11a*. With a projected operating range of 50 meters and peak speed of 54 Mbps, this technology—when applied to 12 simultaneously operating systems within a 50-meter circle—should achieve an aggregate speed of 648 Mbps. Therefore, the projected spatial capacity is approximates 83 Kbps per square meter.

In principle, any radio system can increase its spatial capacity simply by reducing its transmission power and, consequently, its range. Doing so will raise costs, however, because the range reduction will require a higher density of access points to cover a given area. Spatial capacity per dollar, bps/m^2/dollar, is an appropriate metric for comparing systems on a basis that includes cost. Power consumption is a critical factor in SRW systems meant to serve personal handheld electronics. In these cases, spatial capacity per dollar per watt, bps/m^2/dollar/watt, is an appropriate metric. We cannot, however, make such comparisons easily today—cost and power consumption specifications are changing rapidly and vary widely among current SRW component manufacturers. Nevertheless, at least qualitatively, these metrics appear to favor *ultrawideband*, an emerging technology that can provide very high data speeds, at modest cost, using very low power.

ULTRAWIDEBAND, THE SRW WILD CARD

Traditional wireless systems operate within the confines of a narrow band of frequencies assigned by government regulatory authorities. Ultrawideband is different.[6,7] UWB technologies occupy a broad swath of frequencies, typically 1.5 to 4 GHz wide, that cover many already-assigned frequency bands in the 1- to 6-GHz range. UWB purports to occupy these frequencies without causing undue interference. It does so by emitting a power so low that it meets US Federal Communication Commission constraints, FCC Part 15, set for *incidental radiation* from devices like laptops, hair dryers, and electric drills. However, UWB systems need a waiver from the FCC Part 15 rules because they function as *intentional* radiators. The FCC has published a Notice of Proposed Rule Making[8] that could lead to such a waiver.

Because of their very low radiated power, UWB systems are impractical for long-range communication use, but they appear ideal for SRW applications, particularly in the wireless PAN range of 10 meters or less. Laboratory systems have already demonstrated data bandwidths in excess of 100 Mbps over distances greater than 10 meters, with less than 200 microwatts of average radiated power—about one fifth that of a low-power Bluetooth link.

Technically, a UWB system is defined as any radio system that has a bandwidth greater than 25 percent of its center frequency, or greater than 1.5 GHz. UWB technology first appeared in the 1980s, primarily for use in radar.[9] Recent advances in low-cost, low-power switching technology and processing have made it practical to consider using UWB for consumer-grade communication devices. UWB systems emit very narrow pulses with sharp rise times, with the narrowness of these pulses giving rise to UWB's broadbanded nature.

Systems based on this emerging technology vary widely in their projected spatial capacity, but one UWB developer has measured peak speeds of more than 50 Mbps at a range of 10 meters. That developer projects that at least six such systems could operate within the same 10-meter-radius circle and experience only minimal degradation.[10] Following the same calculation process, the projected spatial capacity for such a system would be more than 1,000 Kbps per square meter.

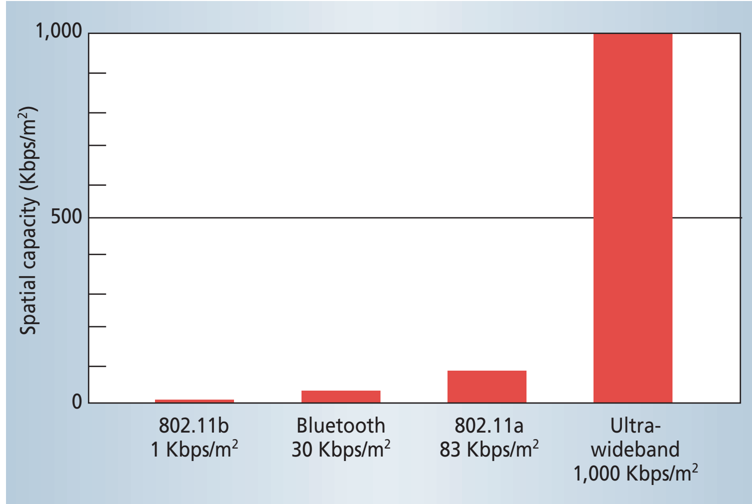

Figure 3. Comparison of spatial capacity of several short-range wireless technologies. We define spatial capacity as bits per second per square meter.

The Hartley-Shannon law

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

Where:
C = Maximum channel capacity, in bits per second
B = Channel bandwidth, in Hertz
S = Signal power, in watts
N = Noise power, in watts

Figure 4. The Hartley-Shannon law binds all telecom systems. UWB systems have greater headroom for expansion because the upper bound on a channel's capacity grows linearly with the total available bandwidth.

Figure 3 provides a side-by-side comparison of the SRW technologies described to date. As shown, UWB appears to offer a substantial advantage.

The Hartley-Shannon law offers a plausible reason for UWB's spatial-capacity advantage, as Figure 4 shows. Because the upper bound on a channel's capacity grows *linearly* with the total available bandwidth, UWB systems, which occupy 1.5 GHz or more, have inherently greater headroom for expansion than more bandwidth-constrained systems.

UWB technology for SRW communications is still in its earliest days. It is not yet standardized, has its own multiple competing variations, and has not received necessary regulatory approvals. Nonetheless, as a long-term target, UWB appears to have enormous potential, especially as a wireless PAN technology.

Short-range wireless offers the highest bandwidths at the lowest power levels, in the most crowded spaces, for the most users. With these advantages, the growth of SRW as a new wireless infrastructure seems inevitable. However, SRW will take time to converge on a set of common standards, and a period of business experimentation and consolidation will likely occur as SRW links spread to public venues and private homes.

Because SRW links will be unlicensed and owners of individual premises rather than government authorities will grant installation permissions, SRW business models may differ radically from those of traditional telecom carriers. Some carriers may see SRW as a threat and actively oppose it, while others may see it as a powerful complement to their current technologies. In the interim, a new class of in-building service providers may emerge, along with new business opportunities to supply them with in-building systems. Although this field is somewhat unpredictable, the next five to 10 years promise exciting growth. ✷

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