Spectrum and Its Influence on 3G and Wi-Fi Architectures

A Technology Convergence (Triple-Play) Perspective

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Summary

This paper focuses on spectrum availability as the primary driver in wireless architectural design and explores the influence of spectrum policy and spectrum access techniques on the convergence role of mobile communications technology and systems. Two wireless implementations will be reviewed: Wi-Fi (IEEE 802.11) and 3G. Both are essential to convergence and triple-play strategies in the United States as well as globally, since Wi-Fi/Wi-MAX capabilities will need to coexist with 3G and its successor technologies in many parts of the world. After a brief description of the specifications and characteristics of Wi-Fi and 3G, the two will be compared across the following dimensions in more specific terms: spectrum standards evolution, mobility versus bandwidth, cellular versus island versus lily pond architecture, DSSS versus OFDM, spectrum policy, spectrum efficiency, and interference.

Conclusions and recommendations for strategic policy shifts focus on the need to reconfigure base stations, the requirement for increased use of the common model for spectrum allocation, developing global standards that drive economies of scale, maintaining cell neighborhoods that optimally balance throughput, the potential for harmonization of 3G/Wi-Fi services, and anticipation of a future where ODFM/Wi-Fi compatibility will lead to more efficient and cost-beneficial deployment of 4G systems. Two appendices describing various technical aspects of Wi-Fi and CDMA plus OFDM/CDMA comparisons are included.

Introduction

The evolution of radio technology can be viewed as a constant effort to increase efficient spectrum utilization. The first step in the evolution, spectrum allocation, was developed in the 1930s to control interference from different analog transmissions. Frequency allocations were designated for a specific purpose. Techniques such as AM/FM were designed to fit within allocations based on low cost transmitter and receiver technology rather than spectrum efficiency. As spectrum became more congested and digital technology emerged, the next step was the development of spectrum conservation methods. Examples of spectrum conservation methods include multilevel data transmission or cellular radio zones that enable spectral reuse. The success of spectrum conservation methods has permitted the global access to telecommunication services that we enjoy today.

In the future, communication systems will need to become more pervasive with even higher data rates. The cost and scarcity of spectrum could be a major barrier to the development of the mobile multimedia market. Insufficient spectrum to meet the needs of the marketplace will result in the access network becoming a service bottleneck. Under these circumstances, prices for market access would rise and service development would

	Voice	Data	Video
Delay	<100ms	Application dependent	<100ms
Packet Loss	<1%	~0.	<1%
Bit Error Rate	10-3	<10-6	<10-6
Data Rate	8-32 Kbps	1-100Mbps	5-25Mbps
Traffic	Continuous	Bursty, variability in when the traffic arrives, the rate at which it arrives, and the number of bits in the messages	Continuous

Table 1: *Multimedia Requirments*

be suppressed. Wireless networks were originally optimized for voice traffic. The patterns associated with voice communications are well known, having been observed since the invention and widespread use of the telephone. Voice traffic statistics are predictable, allowing traffic engineers to use a standard methodology to estimate the amount of capacity needed in a communications system. In contrast, there is a much wider range of requirements and characteristics for wireless multimedia communications than there is for voice. General multimedia requirements are listed in *Table 1* and indicate greater breadth of performance characteristics. This variability prohibits data from being efficiently carried over the hierarchical networks designed for voice traffic, whether wireline or wireless. The key wireless difference, of course, is that high data rate services are constrained by spectrum access.

Mobile wireless communications have traditionally posed difficult performance challenges for converged networks. These challenges include the vagaries of the wireless environment, the limited applicability of wired protocols to manage congestion in high bit error rate wireless links, the wide range of requirements and characteristics for voice, video, and data communications, and the need for efficient spectrum utilization. Designing for the optimum use of spectrum has become of increased importance as spectrum planning and allocation have become protracted, expensive, and uncertain. This is especially true of wireless systems that require approval from multiple countries, have legacy interoperability requirements, and cannot easily be reconfigured once installed.

Our focus is primarily on spectrum availability as the primary driver in wireless architectural design and the influence of spectrum policy and spectrum access techniques on the evolution of mobile converged networks. Tens of millions of new wireless users are expected to enter the market in the next several years. Spectrum access is considered key to improving the quality of video and data services and to increase productivity through applications such as wireless credit processing and inventory management. Two specific wireless implementations—Wi-Fi and 3G—are particularly interesting in elaborating the spectrum access issue. We will emphasize the potential for coexistence between 802.11 and emerging 3G and successor (4G) deployments.

3G and Wi-Fi Background

This section provides a general background on 3G and Wi-Fi to permit a framework for additional comparison. Note that other efforts to compare 3G and Wi-Fi frequently focus on the business case[1] or do not consider a direct comparison due to the inherent application differences.[2] While there are many other emerging communications technologies such as ultrawideband, Wi-MAX, etc., 3G and Wi-Fi can be considered the two most significant technologies to have gained market acceptance and will define the near-term mobile communications landscape.

3G refers to an umbrella of standards developed as part of an International Mobile Telecommunications 2000 (IMT-2000) project designed to provide higher bandwidth for digital communications. From a user's perspective, the key feature of 3G mobile service is that it offers (nearly) ubiquitous and continuous coverage. To support this service, mobile operators maintain a network of interconnected and overlapping mobile base stations that hand off customers as they move among adjacent cells. Each mobile base station may support users up to several kilometers away. A backhaul network provides interconnection to the public switched telephone network (PSTN) and other services and connects the cell towers to each other. The mobile system operator owns the end-to-end network from the base stations to the backhaul network to the point of interconnection to the PSTN (and perhaps owns parts of the PSTN as well). Service providers are anticipated to upgrade the existing network to support 3G standard data rates of 384 kbps up to 2 Mbps. Most commercial applications are anticipated to offer data rates closer to 100kbps in practice.[3] *Appendix 1* describes key 3G specifications.

Short for wireless fidelity, Wi-Fi is used generically when referring to any type of 802.11 network, whether 802.11b, 802.11a, dual-band, etc. The term is promulgated by the Wi-Fi Alliance.[4] Since the 1980s, the IEEE has approved a series of Ethernet standards to support higher capacity LANs over a diverse array of media. The 802.11x family of Ethernet standards is for wireless LANs.[5] WLANs are typically deployed in a distributed way to offer approximately 100-meter connectivity to a wireline backbone network. It is possible to provide contiguous coverage over a wider area by using multiple base stations. Still, the WLAN technology was not designed to support hand-offs associated with users moving between base station coverage areas (i.e., the problem addressed by 3G mobile communication systems). In contrast to mobile, WLANs were principally focused on supporting data communications.

Comparisons between 3G and Wi-Fi Architectures

This section examines key differences between 3G and Wi-Fi wireless architectures, especially spectrum performance, interference, standards, and operating performance. This is not intended to be an exhaustive technical analysis but an illustration of how technology and policy interact to influence the design of wireless systems. *Appendix 2* summarizes the major differences between 3G and Wi-Fi that are discussed in subsequent sections.

Mobility versus Bandwidth

3G and Wi-Fi provide a different range of mobile services. Local mobility, the ability to move devices with cables, is one of the key advantages of WLANs over traditional LANs. WLANs trade the range of coverage for higher bandwidth, making them more suitable for local hotspot service. 3G, on the other hand, provides ubiquitous mobility. 3G offers much narrower bandwidth but does so over a wider calling area and with more support for rapid movement between base stations. Although it is possible to cover a wide area with Wi-Fi, it is most commonly deployed in a local area with one or a few base stations being managed as a separate WLAN. In contrast, a 3G network would include large number of base stations operating over a wide area as an integrated wireless network to enable load-sharing and uninterrupted hand-offs when subscribers move between base stations at high speeds. *Figure 1* shows the performance space for mobility versus bandwidth between 3G and Wi-Fi. Wi-Fi is not designed for the high mobility/car traffic scenario. The small "cell" sizes of Wi-Fi systems would require unacceptably high hand-off rates. System efficiency would be degraded by dedicated hand-off control functions rather than communication.

Comparing Cellular, Lilypond, and Island Architectures

Three architectures—cellular, lilypond, and island—can be considered for 3G and/or Wi-Fi deployment. *Figure 2* displays a rough picture outline of the three models. The cellular architecture represents the classic mobile communication concept which employs spatial frequency re-use techniques on an interference-limited basis. This

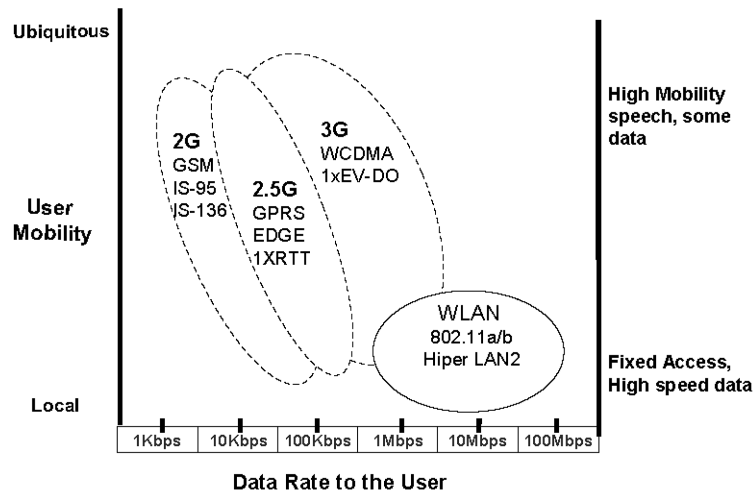

Figure 1: *Mobile Wireless System Landscape*

is achieved by dividing the service areas into smaller cells, ideally with no gaps or overlaps, each cell being served by its own base station and a set of frequency channels. The power transmitted by each station is controlled in such a way that the local mobile stations in the cell are served while co-channel interference in the cells using the same set of radio channel frequencies is kept acceptably minimal. An added characteristic feature of a cellular system is its ability to adjust to the increasing traffic demands through cell splitting. The basic business model is the telecommunications services model in which service providers own and manage the infrastructure (including the spectrum) and sell service on the infrastructure. In this architecture, Wi-Fi systems are viewed as independent extensions of wired data networks providing un-tethered data access for indoor office/home applications.

Nicholas Negroponte of MIT has suggested that nationwide telecommunication networks that were created in a top-down manner are about to be replaced by a “lily pond” patchwork of Wi-Fi stations created by generous individuals, entrepreneurs, and public/private institutions from the bottom-up. He referred to this as “a broadband system built by the people for the people.”[6]

The wide-scale implementation of telecommunication lilypond was not considered feasible until low cost Wi-Fi components created the option of an individual establishing his own version of a cell tower. Lilypond networks use the existing Internet infrastructure to aggregate independent WLANs. Individuals are motivated to participate in the ad hoc network structure by a series of cost incentives: WLAN hardware technology embedded (at low cost) in personnel computers/handheld devices, Internet service providers (ISPs) providing low cost data access rates, etc.

Interference mitigation in lilypond networks is conducted at each access point via a set of dynamic technical options that include low power emission, selection of different frequency bands, and an inherent assumption that owners will tolerate reduced data rates in times of congestion. This scenario is considered most viable for urban settings that integrate indoor hotspots such as hotels and airports. Note that the lilypond scenario has not been implemented yet and represents an ideal—the direct opposite of the centralized cellular model.

The island, or hotspot, model attempts a symbiotic relationship between Wi-Fi access technology and 3G by coupling the WLAN (when needed) with 3G services. Integrating 3G and Wi-Fi networks provides the opportunity to offer good voice/data telephony support while providing high data rate island connectivity in high demand areas, like airports. This is a hybrid of the cellular and lilypond

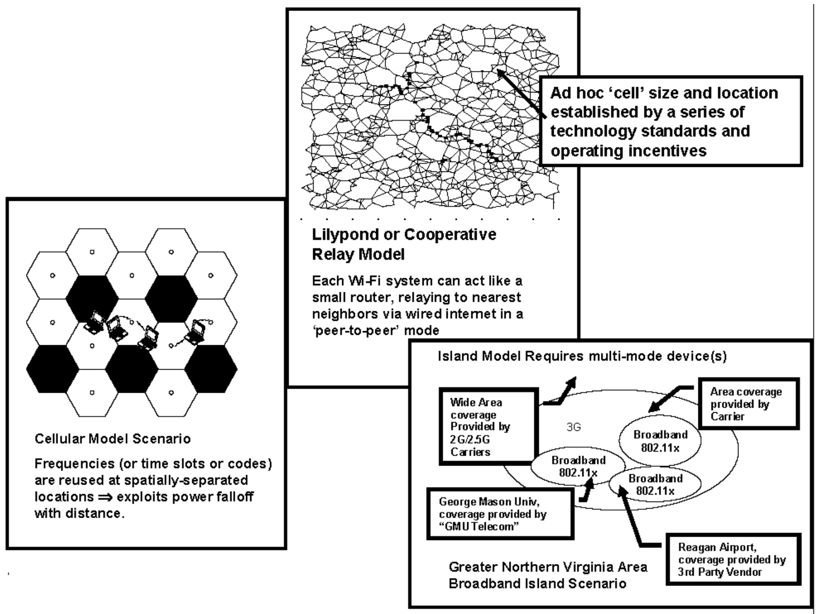

Figure 2: *Different Mobile Communication Architectures*[31, 32, 33]

model and is frequency described as the "convergence approach" by industry representatives.[7]

DSSS versus OFDM

One of the key differences between Wi-Fi and 3G is the radio access method. Wi-Fi/802.11a uses OFDM (orthogonal frequency division multiplexing) as opposed to the usual DSSS (direct sequence spread spectrum) method used by 3G and 802.11b. These access methods have inherent differences since DSSS (used in CDMA, wideband CDMA, and cdma2000) forces a multiplication of the signal in the time domain that spreads it in the frequency domain while OFDM uses a forced multiplication in the frequency domain to spread the symbol in the time domain. There is a major debate in the industry as to whether OFDM has inherent advantages over CDMA in cellular networks. IEEE 802.16 (as supported by the Wi-MAX Forum) has chosen OFDM as the basis of its radio technology. OFDM is also used in IEEE 802.11a, IEEE 802.11g, and IEEE 802.11n.

OFDM is a modulation technique where information symbols are transmitted in parallel by applying them to a large number of orthogonal subcarriers. The attractive advantage of using OFDM is that the modulation can be expressed in a discrete frequency domain after going through a transformation. It is considered a power-efficient modulation in which less spillover energy is outside the bandwidth.[8] OFDM offers multiple signal processing benefits that have not been available in 3G modulation methods, and it possesses a number of unique features[9, 10] that make it an attractive choice for high-speed broadband wireless communications:

- OFDM is considered robust against multipath fading and intersymbol interference because the symbol duration increases for the lower-rate parallel subcarriers.
- OFDM allows for an efficient use of the available radio frequency (RF) spectrum through the use of adaptive modulation and power allocation across the subcarriers that are matched to slowly varying channel condition.
- Unlike other competing broadband access technologies, OFDM does not require contiguous bandwidth for operation.
- OFDM makes single-frequency networks possible, which is particularly attractive for broadcasting applications.

OFDM's advantages may not be significant when compared to 5MHz 3G since data rates may not be limited by intersymbol interference. But with next generation systems that will deliver throughput rates in the 10 Mbps to 100 Mbps range, the advantages could become significant. Third Generation Partnership Project (3GPP) has a work group studying how current cellular technologies might best evolve, including looking at OFDM. OFDM, however, is not the only option. Another viable possibility is multicarrier CDMA where multiple CDMA channels are combined for higher throughputs.

Spectrum

The simple observation can be made that performance is anticipated to favor lower 3G spectrum since free-space propagation path loss increases with frequency. Note however that this may be partially offset by practical antenna gain which also is frequency-dependent. The different spectrum policies that govern 3G and Wi-Fi establish the foundation for many of the technical differences between 3G and Wi-Fi.[11] Consider, for example, the regulations governing 1.9 GHz PCS and 2.4 GHz industrial, scientific, and medical (ISM) bands. The ISM band power limit in the United States is 4 watts compared with the PCS base station limit of 1600 Watts. Consequently, the licensed band system has a huge advantage in the downlink power budget. The downlink power advantage is precisely what enables the licensed CPE (customer premises equipment) device to work indoors without the need for an outdoor, elevated, near-line-of-sight, high-gain receive antenna.[12]

The main difference between cellular and Wi-Fi is that the cellular system uses the licensed spectrum and Wi-Fi is implemented in unlicensed bands. The economic basis for its implementation is therefore completely different. The success of Wi-Fi has made many people look to the unlicensed spectrum as the future of wireless access, rather than spectrum licensed and controlled by large corporations. The fact that Wi-Fi and 3G use different spectrum allocation models[13] creates distinct technical design objectives for cost of service and congestion management. The following sections review two specific areas where spectrum has had an impact on wireless systems design objective. The first examines how spectrum standards have evolved to create Wi-Fi economies of scale; the second discusses spectrum efficiency comparisons between Wi-Fi and 3G systems.

The Evolution of Spectrum Standards

Different methods of standard evolution characterize 3G and Wi-Fi development. Global Wi-Fi standards are coordinated via an IEEE process and have developed a single standard. This is in contrast to the multiple 3G standards develop by industry consortia. *Appendix 1* describes the technical characteristics of the three 3G standards and compares it with Wi-Fi.

3G "standards" have so many mutually exclusive options that all the 3G systems launched so far can claim compliance with it, yet none actually interoperate with each other. An example is the failure of the 3G spectral harmonization effort which was initiated in 1992 with the goal of a global standard. After years of debate a compromise was accepted that permitted operation in both 1.885–2.025 GHz and 2.110–2.2 GHz.[14] By that time, the vision of a global standard was discarded as competing technology—wideband code division multiple access (CDMA) in Japan and CDMA 2000 in the United States—require different spectrum allocations.[15] Efforts to extend 3G spectrum continue as the United States prepares to allocate an additional 90 MHz. The Commission intends to commence an auction for advanced wireless services licenses in the 1710–1755 MHz and 2110–2155 MHz bands as early as June 2006. These bands represent a portion of the spectrum identified at the World Radiocommunication Conference (WRC-2000) for 3G wireless use.

In contrast to 3G, Wi-Fi has been able to develop a global spectrum standard. During the late 1990s, wireless local-area networks, notably the IEEE 802.11 family of standards, known as Wi-Fi, and the European HIPERLAN system, became popular as broadband wireless systems. They were based on projected needs for additional spectrum beyond the previously defined bands in the 2.4-GHz band proponents requested and received an additional 355 MHz of spectrum in the 5-GHz region.[16] The Part 15 rules were amended in 1998 to provide for operation of unlicensed national information infrastructure (U-NII) devices in the 5-GHz band (5.15–5.35

GHz and 5.725–5.825 GHz). The FCC recognized that developments in a number of different digital technologies had greatly increased the need to transfer large amounts of data from one network or system to another. In making this spectrum available, the FCC concluded that providing additional spectrum for unlicensed wideband operation would benefit a vast number of users, including medical, educational, and business/industrial users.[17]

To support growing interest in real-time services such as voice and video over IP networks, multiple new 802.11 standards are under development by the IEEE.[18] These new standards will provide a range of new applications, spectrum management, and interoperability with cellular systems:

- IEEE 802.11j: Japanese regulatory extensions
- IEEE 802.11k: Radio resource measurements
- IEEE 802.11n: Higher throughput improvements via MIMO techniques
- IEEE 802.11p: WAVE, wireless access for the vehicular environment
- IEEE 802.11r: Fast roaming
- IEEE 802.11s: Wireless mesh networking
- IEEE 802.11u: Interworking with non-802 networks (e.g., cellular)
- IEEE 802.11v: Wireless network management

Spectrum Efficiency

The ideal spectrum metric would provide a comprehensive measure of how efficient the system is, regardless of the modulation and multiple access techniques employed. Such a measure should also be independent of the technology implemented with an allowance for new techniques that may improve the spectral efficiency and/or system quality. Objective spectral efficiency measures are useful for establishing performance benchmarks, estimating ultimate performance capacity, and establishing minimum spectral efficiency standards for regulation.

Despite the intended value of spectrum efficiency standards, the current communication environment often makes establishing objective standards a fruitless task. The FCC Spectrum Task Force[19] recently concluded that it is not appropriate to select a single, objective metric that could be used to compare efficiencies across different radio services. Inherent in the assumptions of any metric would be advantages to certain services and technologies and disadvantages to others. Rough estimates of spectrum efficiency are considered useful in certain situations since they allow for some comparisons between technologies.

General observations concerning Wi-Fi- versus 3G-efficiency favor Wi-Fi due to fundamental range (small diameter cell) scenario assumptions:

- Lee[20] concluded that C/I (carrier-to-interference) of a wireless system under a non-fading (considered fixed-to-fixed) condition is always less then the required C/I ratio of a cellular system under a mobile multipath fading condition.

- Hammada[21] describes how the efficiency (channels/Mhz/km2) of a given modulation technique is inversely proportional to the “cell” or coverage area. Wi-Fi, with its small coverage areas, is thus anticipated to always outperform 3G systems. This general rule does not take into account, however, factors which may reduce efficiency, such as additional control channels to account for a high hand-off rate due to small cell size.

Another approach to compare OFDM and CDMA is to establish a level playing field where each technology is compared against the same operating constraints. This was done by Lawrey[22] for a cell phone model (see *Appendix 2*). OFDM was found to perform very well compared with CDMA, and it outperformed CDMA in many areas for a single and multicell environment. OFDM was found to allow up to 2–10 times more users than CDMA in a single cell environment and from 0.7–4 times more users in a multicellular environment. The difference in user capacity between OFDM and CDMA was dependent on whether cell sectorization and voice activity detection is used. OFDM would require a frequency reuse pattern to be used in a multicellular environment to reduce the level of intercellular interference. The general conclusion is that OFDM has comparable spectral efficiency performance to CDMA and that small cell sizes are critical to providing reduced multipath and high teledensity environments.

Interference

Unlike 3G systems, Wi-Fi systems must adapt to a variety of interactions within a particular electromagnetic environment. 802.11b systems are more susceptible to radio frequency interference than 802.11a because of many sources of interference in the 2.4 GHz band. Microwave ovens, Bluetooth devices, 2.4-GHz cordless phones, and other nearby 802.11 wireless LANs can cause significant and damaging (radio frequency) interference with 802.11b systems. Most brands of cordless phones can bring a wireless LAN to a standstill while the phones are in use within 75 feet of 802.11 devices. Radio frequency interference with 802.11a in the 5 GHz band is less common even though there a variety of radar and satellite communications that share the band on a co-primary basis.

802.11a and 802.11b use a carrier-sensing protocol that enables the sharing of a common radio channel. An end user's radio network interface card (NIC) senses the air medium and only transmits if no radio frequency waves above a certain threshold are detected. The presence of a radio frequency signal causes the radio NIC to hold off from transmitting, and an interfering signal strong enough will make the channel appear as busy. As a result, the radio NIC will wait until the interference goes away (which could be minutes, hours, or days). Radio frequency interference competes with the transmission of 802.11 frames and can significantly reduce the throughput and availability of a wireless LAN.

The 802.11a standard supports much higher data rates on a channel. DSSS (similar to CDMA) basically uses a single carrier, and it is subject to "single point failures" where a fading trough is encountered on that carrier. OFDM further spreads data across multiple sub-carriers in the allocated band, and allows redundant coding to recover data in a noisy environment, because it is unlikely that all sub-carriers will experience an identical fading trough simultaneously. This mechanism is less likely to have a "single point failure."

The Wi-Fi industry long-term approach to interference mitigation relies on upgrades to the 802 standard to permit dynamic spectrum management. Dynamic frequency selection (DFS) allows devices to detect such transmissions and switch to an alternative channel. Additionally, a transmit power control protocol will allow users close to an access point to reduce transmission power in order to reduce interference with other users. Dynamic management techniques such as DFS may enable the management of spectrum in real time. These systems first identify what spectrum is available and then assign it to users for the best benefit. Such opportunistic use of the spectrum may ultimately provide the highest values for spectral efficiency over given time period and geography.[23]

Synthesis and Conclusions

This paper focused on spectrum availability as the primary driver in wireless architectural design and explored the influence of spectrum policy and spectrum access techniques on the evolution of mobile converged networks. The ability to guarantee spectrum availability is becoming a critical driver in wireless system design and has broad implications for global market development, localized network performance, and requirements for new communication technologies.

Perhaps the most significant observation is that spectrum engineering must be conducted at the global level. Technical differences often are driven by spectrum policy and the politics involved in creating global standards. The harmonization of the 5 GHz spectrum, which came about as a result of the World Radiocommunications Conference and ratification of IEEE 802.11h—a standard to reduce interference in the 5 GHz band—stands as a compelling example. Together, these two achievements will allow products that utilize the 5 GHz band to achieve the same economies of scale that aided the success of earlier products in the 2.4 GHz band. Previously, manufacturers had to create an unwieldy array of products to match a patchwork environment. Now they will be able to concentrate more efficiently on one standards-based solution.

3G "standards" have so many mutually exclusive options that all the 3G systems launched so far can claim compliance with it, yet none actually interoperate with each other. Wi-Fi standards, on the other hand, are established through an IEEE process which has a more evolutionary approach and, when it is accepted, will achieve the objective of a true worldwide standard.

Another important observation is that high data rate triple-play services are inherently a local phenomena. As data rates increase, physics dictates that small coverage areas provide the greatest efficiency. 3G base stations will need to be packed tighter to be competitive with data rates. Small area networks can be tailored to support increased link predictability and higher teledensities due to the reduced multipath, improved propagation predictability, and higher link margins. Current 3G metropolitan networks and Wi-Fi local area networks may represent the first steps toward an intermediate neighborhood area network (NAN)[24] architecture. NANs represent a new architectural system for broadband wireless local distribution that provides services tailored to local user applications, interfaces with wired facilities, and permits automatic radio resource spectrum management.

Successful wireless systems must simultaneously satisfy global standards that drive economies of scale while maintaining small cell characteristics that optimally balance throughput to mimic wired performance. We refer to this as the global neighborhood requirement for wireless design. Global standards optimized for local neighborhood performance establishes the foundation for new technologies and wireless services.

New communications technologies are providing opportunities to obtain more services and capacity from spectrum. Despite the universal 3G acceptance of CDMA, OFDM may become the lead technology for 4G[25] networks. While there are many technical issues with adapting OFDM for a large scale cell phone network,[26] Wi-Fi OFDM has changed the landscape by creating an OFDM industry base, an OFDM Wi-Fi interoperability requirement, and an alternate approach to achieving spectrum efficiency. *Figure 3* depicts the influence of Wi-Fi on 3G standards; the arrows are designed to show the influence of spectrum on the design on future wireless systems.

Wi-Fi's greatest long-term implication is that it may establish the benefit of alternate communication options—not only specific technologies such as OFDM but substantiation of the commons models as prudent government spectrum allocation policy. The model of licensed "exclusive" spectrum providing optimum quality of service and government revenue is under challenge by the unlicensed common spectrum allocation model. Since Wi-Fi essentially has "free spectrum" while 3G must pay a spectrum "tax," Wi-Fi has an incredible advantage. Wi-Fi systems have the benefit of large bandwidth if they can control interference. A no-cost market entrance provides great incentive to mitigate the

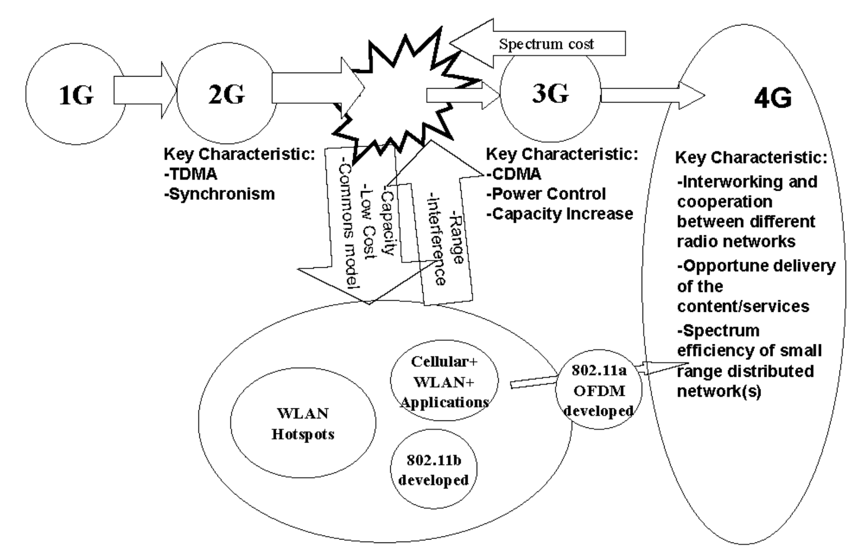

Figure 3: *Mobile System 'Possible' Evolution – Wi-Fi Impact*

inherent problems involved in spectrum sharing. On the other hand, by paying for spectrum, 3G systems buy a level of interference that permit the optimization (spectrum efficiency) of resources across a broad geographic region.

At just a 300-foot radius, Wi-Fi is clearly a local-area network. Outside of densely populated urban areas, true mobile service is impractical. A wider, albeit slower network, such as 3G, will be necessary to fill the "white space" of Wi-Fi networks. However, Wi-Fi will provide cost-effective data services for slow moving mobile subscribers that are comfortable with roaming for Wi-Fi access points. This market segmentation has the potential to usurp some of the expected revenues from 3G networks.

Perhaps the most likely outcome is that we will live in a world where 3G and Wi-Fi work together, with recognition that they are complementary, not competing, technologies.[27] Wi-Fi has a potential for low-cost networks that grow organically to serve communities of users. A number of obstacles (such as poor mobility management/roaming capability, patchy interoperability, and interference problems) must be overcome so that Wi-Fi can be competitive with 3G and Wi-Fi service can be guaranteed. Handsets and computers are being developed which will allow roaming between the two networks. This will allow 3G to take advantage of Wi-Fi's increased bandwidth in city hotspots, with 3G providing coverage elsewhere.

Appendix 1: Wireless Wi-Fi versus 3G Data[28]

See *Table 2*.

Appendix 2: Comparison of CDMA versus OFDM with Multiple Cells

A capacity comparison of CDMA versus OFDM with multiple cells is provided for cellphone networks to illustrate the efficiency advantage of OFDM. Data, formulas, and assumptions developed to model OFDM (from Lawrey[29]) have been extended to CDMA (from Rappaport).[30]

OFDM Calculations and Assumption
The OFDM example used a bandwidth of 1.25 MHz. The OFDM system could handle 64 users each at 39 kbps, or 128 users at 19.5 kbps depending on the spectrum allocation. The figure of merit derived was 2-4/bits/sec/hz depending on BER.

Rappaport derives the capacity of a single cell CDMA system to be

$$N = \frac{G}{d}\left[\frac{N_o}{E_b}\frac{W}{R} - \frac{n}{S}\right] + 1$$

where
G is the antenna sectorization, 2,55;
d is the voice duty cycle, .4;
E_b/N_0 is the energy per bit to noise ratio, 8dB;
W is the total transmission bandwidth,1.25 MHz;
R is the base band bit rate,19.5KHz;
n/S is the ratio of received thermal noise to user signal power(assuming no thermal noise).

$$N = \frac{2.55}{0.4}\left[\frac{1.25\times10^6/19530}{6.31}\right] + 1 = 65.7$$

The spectral efficiency is thus

$$= \frac{65.7\times19.53\times10^3}{1.25\times10^6} = 1.026 bit/Hz$$

This is roughly half the capacity of the OFDM system: 2.1bits/sec/Hz.

OFDM was found to perform very well compared with CDMA, with it out-performing CDMA in many areas for a single and multicell environment. OFDM was found to allow up to two to 10 times more users than CDMA in a single cell environment and from 0.7 to four times more users in a multicellular environment. The difference in user capacity between OFDM and CDMA was dependent on whether cell sectorization and voice activity detection is used. OFDM would require a frequency reuse pattern to be used in a multicellular environment to reduce the level of intercellular interference.

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	3G	**Wi-Fi**
Generic Performance	Low data rate, wide coverage	High data rate, point coverage
Standards	Internationally sanctioned by service providers and standards organizations: 3GPP and 3GPP2	Evolution with Internet industry standards organization: IEEE 802 LAN/MAN Standards Committee
Spectrum (GHz)	Generic coverage includes 1.885–2.025 GHz and 2.110–2.2 GHz Europe's Universal Mobile Telecommunications System: 900–2025 MHz and 2110–2200 MHz 1710–1755 and 2110–2170 to be made available in the United States in 2006	*802.11a* 5.15–5.25 (USA UNII lower band) 5.25–5.35 (USA UNII middle band) 5.470–5.725* (USA/Europe) 5.725–5.825 (USA UNII upper band) *802.11b* 2.401–2.473 1000 mW/MHz (North America) 2.401–2.473 100 mW/MHz (Europe) 2.483 10 mW/MHz (Japan)
Access	DSSS/CDMA multiple channel configurations available	802.11b DSSS 4 channels @ 80 Mhz in the United States 802.11g OFDM 802.11a OFDM 12 channels @ 300 Mhz in the United States
Spectrum Model	Exclusive spectrum rights model gives the licensee the rights to the spectrum within a defined geographic area and then that licensee manages that spectrum for its optimal use, transferring the right to use it if that is appropriate	Common spectrum model allows unlimited numbers of unlicensed users to share the spectrum where usage is governed by technical standards or protocols; wireless applications demonstrate this concept: wireless LANs, Bluetooth devices, etc.
	Licensed 120 MHz (US), cost: millions of US dollars	Unlicensed 383.5 MHz (US), cost: free
	Centralized allocation and control of resources permits allocation of scarce resources to mange congestion and maintain quality	Sharing spectrum may challenge quality and prevent delay sensitive services, limited mobility management/roaming capability
Interference	Protected from interference	There is no right to protection from interference; cordless phones and microwave ovens all share the same frequencies.
Applications	Technologies geared toward consumer voice and data	Technologies geared toward data in the enterprise

* Subject to use of dynamic frequency selection (DFS) and transmit power control (TPC). Not yet approved for use in the United States.

Table 2

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