Exhibit 2

Jeffrey H. Reed & Nishith D. Tripathi,
The Application of Network Neutrality Regulations to Wireless Systems: A Mission Infeasible

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Jeffrey H. Reed and Nishith D. Tripathi

Abstract

The FCC has proposed new regulations to apply the concept of "net neutrality" to broadband Internet access services and has sought feedback on the potential application of the proposed rules to wireless broadband networks. The proposed rules and the goals they are intended to further are briefly summarized first. Various aspects of cellular wireless networks such as evolution path, network architecture, device-network interactions, and Quality of Service (QoS) are briefly illustrated to provide a foundation for the cellular topics relevant to net neutrality. Differences between wireline and wireless networks are highlighted to develop an understanding of the implications of applying net neutrality principles to wireless networks. Technical challenges associated with wireless implementation of the FCC's proposed rules are explained using example scenarios and current and emerging practices. The paper concludes that (a) implementation of the proposed net neutrality regulations (and, in particular, sweeping "nondiscrimination" requirements and after-the-fact, *ad hoc* regulatory determinations of the "reasonableness" of particular network management practices) poses insurmountable technical challenges; (b) these rules are likely to become hurdles in achieving some of the very goals they aim to accomplish; and, indeed, (c) the application of these rules to rapidly evolving cellular networks is likely to cause irreparable harm to innovation, investment and efficient evolution of wireless services and thus harm consumer interests.

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1. Executive Summary

We have been asked by AT&T to review the FCC's recent proposals for new "net neutrality" regulations and, in particular, to assess the technical implications of applying those regulations to mobile wireless broadband Internet access services.

The FCC's recent NPRM proposes six new rules for broadband Internet access service providers. The first "access to content" rule states that "a provider of broadband Internet access service may not prevent any of its users from sending or receiving the lawful content of the user's choice over the Internet." The second "applications and services" rule states that "a provider of broadband Internet access service may not prevent any of its users from running the lawful applications or using the lawful services of the user's choice." The third "any device" rule prohibits a broadband Internet service provider from "preventing any of its users from connecting to and using on its network the user's choice of lawful devices that do not harm the network." The fourth "competition among providers" rule prohibits a broadband Internet service provider from "depriving any of its users of the user's entitlement to competition among network providers, application providers, service providers, and content providers." The fifth "nondiscrimination" rule requires a provider of broadband Internet access service to "treat lawful content, applications, and services in a nondiscriminatory manner," which the FCC interprets to mean that the broadband provider also may not impose any charges on content or application providers, whether discriminatory or not, for prioritization or enhancements for traffic traversing certain portions of their networks. The sixth "transparency" rule requires the network access provider to disclose "such information concerning network management and other practices as is reasonably required for users and content, application, and service providers to enjoy the protections specified in this part."

Each of these six proposed rules would be "subject to reasonable network management," a term which the FCC defines in somewhat circular fashion as "reasonable practices" employed to "reduce or mitigate the effects of congestion on its network or to address quality-of-service concerns," "address traffic that is unwanted by users or harmful," "prevent the transfer of unlawful content," "prevent the unlawful transfer of content," and "other reasonable network management practices." The proposed rules also include special considerations for law enforcement, public safety, and homeland and national security. The FCC proposes to apply these rules immediately and in their entirety to wireline (*e.g.*, cable and DSL) broadband services, and it seeks comment on how to apply the rules to wireless broadband services.

The FCC's NPRM recognizes that the application of the proposed regulations "to mobile Internet access raises challenging questions, particularly with respect to the attachment of devices to the network and discrimination with regard to access to content, applications, and services, subject to reasonable network management."

The FCC also notes, among other things, that

a) "mobile wireless networks are not as far along in the process of transitioning to IP-based traffic as wireline networks;"

b) the mobile wireless space is "highly dynamic;"

c) "wireless networks must deal with particularly dynamic changes in the communications link due to radio interference and propagation effects such as signal loss with increasing distance of the wireless phone from the base stations, fading, multipath, and shadowing;"

d) there "are technological, structural, consumer usage, and historical differences between wireless and wireline/cable networks;"

e) "each provider has a finite amount of spectrum available to it;"

f) "bandwidth intensive Internet services already create challenges for wireless networks, and these challenges are likely to increase;" and

g) "capacity management is a constant concern of wireless engineers."

We agree, and we respectfully submit that any careful analysis of these and other technical differences and challenges that we address below should lead the FCC to conclude that it would be a mistake to apply the proposed net neutrality regulations to wireless – particularly now as wireless networks, services and uses continue to evolve rapidly and transitions to entirely new technologies are just beginning.

We express our opinion in three parts below. We first summarize our main conclusions about the application of network neutrality regulations to wireless networks. We then explain why the proposed exceptions for "reasonable" network management not only would not address, but could well exacerbate, the challenges and objections we identify. Finally, we suggest some alternative measures that the FCC could take that would promote innovation, consumer welfare and the efficient evolution of the Internet.

Main Conclusions

We respectfully submit that any informed consideration of the technical realities and stark differences between wireless and wireline networks compels the conclusion that it would be a major mistake to apply the proposed net neutrality regulations to wireless in the foreseeable future. The major technical challenges that we address here include (i) the rapidly-changing landscape of wireless standards and networks and the co-existence of dissimilar wireless technologies, (ii) the scarcity of network resources even with the emergence of superior fourth generation (4G) technologies, (iii) explosive and unpredictable growth in the volume of wireless data traffic, (iv) the availability and ongoing development of countless applications with significant uncertainties about their QoS (Quality of Service) requirements and their impact on network resources and the performance of other applications, (v) the lack of absolute QoS guarantees and varying QoS implementation strategies within a technology and across technologies, (vi) the dynamic and unpredictable nature of the radio environment, (vii) user mobility within a technology and across different technologies, (viii) the extremely complex architectures of wireless networks requiring equally complex and variable network management, and (ix) the ubiquity and necessity of dynamic and non-standardized network management mechanisms such as radio resource management algorithms. In our view, attempting to impose a network neutrality regulatory framework in this environment would result in a reduction of innovation, competition, and network efficiency, and would undoubtedly degrade the consumer wireless experience. *To summarize our conclusions, we find that*:

(1) *There are very critical technical differences between wireline and wireless broadband networks.* These networks differ in terms of the technologies that are employed, how they operate, resource or capacity limitations, their pace of evolution, their susceptibility to performance problems, and the types and variability of practices required to address performance issues. Wireless systems have at their core, highly refined and constantly changing network management mechanisms (*e.g.*, those responsible for prioritization of different types of data and for allocation of radio resources). This is the key reason that wireless systems have made and continue to make strides in more efficient utilization of scarce wireless resources such as the available spectrum bandwidth. This approach is not merely prudent, but necessary, due to the unreliable and unpredictable wireless channel. The additional challenges posed by the wireless channel also necessitate close integration among network equipment, devices, and applications. Without the coordination facilitated by the centralized network management, the overall efficiency of the systems is diminished, and a small number of applications/users could greatly diminish the performance of the vast majority of users while driving up costs for all users. Here, it is important to understand that wireless performance issues extend well beyond "congestion" management issues, the key concern expressed in the NPRM. Uniquely wireless issues including mobility, security, and seamless integration with a variety of wireless and wireline networks complicate wireless network management even more.

(2) *Wireless networks are currently being transitioned to entirely new 4G technologies (e.g., WiMAX and LTE) that are even less understood and developed than 3G technologies, which themselves are the subjects of continuing experimentation.* While we have great expectations for these technologies in terms of performance, wireless network resources will remain scarce and precious in the foreseeable future. The transition to 4G will not obviate any of the wireless-specific issues that counsel against wireless net neutrality regulation. To the contrary, the continuing evolution is itself a powerful reason for the FCC to hold off on new regulation. Much

research and real world, "on-the-fly" experimentation will be required to learn how to structure, operate and manage networks to meet quality of service needs in these new systems.

(3) *New services and applications with unknown QoS requirements and unknown impacts on wireless resources are rapidly emerging.* The astonishing growth in consumer and business wireless broadband applications further complicates wireless network management and increases the need for experimentation. Wireless data traffic is growing at rates that have exceeded all expectations. Regulatory limits on the design space would severely limit flexibility and increase the regulatory risks (and costs) of much-needed experimentation. We note in particular the increased co-mingling of applications in an all-IP wireless network. For instance, commercial voice was the dominant application in early wireless networks, but voice is being displaced by a wide variety of applications with disparate resource demands. Example applications include time sensitive public safety; low-latency real-time video; and low data rate, large user base, and latency insensitive smart grid applications.

(4) *Wireless networks are highly complex systems, and wireless network management is an extraordinarily complex and necessarily dynamic undertaking that is not susceptible to definition through regulatory metrics.* The dynamic nature of the radio environment, the number and mobility of users and the diversity in the types of applications they use, proprietary radio resource management algorithms, and ever-changing wireless standards and wireless networks make wireless network management not only complex but also dynamic. The practices that constitute optimal or "reasonable" network management are constantly in flux between and within networks, from one location to the next, and from one millisecond to the next. In sum, the critical and rapidly widening differences between wireline and wireless mean that it would be folly to attempt to define in advance through regulations what wireless network operators can and cannot do to address security, congestion, mobility, network integration, interference and other performance issues. And, as we explain below, any regulatory regime that enforced net neutrality through after-the-fact, *ad hoc* adjudications of the "reasonableness" of engineering and business decisions would be equally damaging to wireless evolution and innovation.

(5) *Several aspects of the FCC's specific network neutrality proposals could wreak havoc in a wireless environment.* As we explain below, commanding that a wireless network allow the connections of "any" devices and "any" applications, such as computer tethering, peer-to-peer file transfers or broadcast TV redirection, without regard to the current capabilities and limitations of that network or the potential impacts on other users is a recipe for disaster in the wireless environment. The proposed "nondiscrimination" rule is simply infeasible in wireless networks; differentiation from the perspectives of services, users, resource consumption, and user devices, is inherent in any good and efficient strategy of wireless network management (and more specifically any rational QoS implementation strategy). The QoS actually perceived by a wireless user for a given service varies as a function of numerous factors such as the radio environment and the operator's network configuration and technology. The necessity of

differentiation is only growing as new wireless applications continue to emerge at a rapid rate. As we demonstrate, this differentiation takes many forms from scheduling and resource allocation algorithms to device-specific differentiation to differentiation based upon user's resource consumption pattern, the status of the radio environment or dozens of other constantly varying factors. And the FCC's proposal categorically to ban network owners from designing, deploying and offering paid QoS services to content providers that want them would almost certainly discourage beneficial innovations and arrangements that may prove essential as the diversity of applications and performance requirements – including specialized machine-to-machine and other commercial applications – continues to increase. Without incentives that stem from the ability to commercialize the extraordinary performance improvement *potential* of the 4G, IMS and PCC evolution we discuss below, much of that potential may not be realized. The proposed transparency rules raise additional concerns which we address below.

"Reasonable" Network Management

The FCC proposes to regulate on an *ad hoc* basis through after-the-fact adjudication of whether particular practices are "reasonable" network management practices. The FCC's NPRM suggests that conduct that might otherwise be prohibited by its proposed rules would be allowed if it was later deemed "reasonable network management." For several reasons, this is an unworkable approach in the wireless environment that would almost certainly reduce beneficial innovation and experimentation and ensure lower quality service. First, the term "reasonable" is much too vague. As we explain below, there are simply no objective metrics of "standard" wireless engineering practices that the FCC could employ to distinguish "reasonable" from "unreasonable" conduct. The technologies, network architectures, traffic loads and science are evolving much too rapidly, and there is far too much variation both between and within networks to allow for meaningful comparisons of "best" or "acceptable" practices. Second, the probability that the FCC would make the wrong choices – ruling beneficial wireless practices unreasonable – would be high.

The vagueness of the "reasonableness" exception would result in relentless strife among access providers, service providers, application providers, and consumers, especially in light of the complexity of radio resource management in a wireless system. And, as the applications become more diverse, the resources and practices necessary to support these applications and provide them to consumers with acceptable performance also become more diverse. Proper management of an application's data is in the eye of the beholder, and everyone is likely to consider their application the most important. The absence of any specific metric for defining proper management would thus invite a plethora of legal and regulatory disputes given that differentiation and limits on devices and applications are and will remain essential for any wireless network. For service providers to keep their customers, they must strike a balance among all customers to provide maximum aggregate throughput, coverage, and reliability, and should not be subject to intimidation from special interest groups seeking to promote one application over another.

Moreover, the probability that the FCC would make the wrong choices in its after the fact determinations would be high. And even if the FCC decision was the right one with regard to a particular network at a particular time, this decision would provide little guidance to other networks employing different technologies and facing different performance issues. Furthermore, rapidly changing technologies and applications may make the decision quickly obsolete – and wrong – even as to the current network. Standards bodies and private network owners have financial incentives and the ability to act quickly to correct errors. We fear that FCC errors would prove much more durable and could cause irreversible damage to the evolution of wireless broadband networks and services and optimal performance delivery to consumers and businesses.

Alternative FCC Approaches

A far better approach from a technical viewpoint would be actively to monitor the continuing evolution of mobile broadband Internet services and networks and ensure that network owners are transparent about their practices so that customers can make informed choices. Second, the FCC can help facilitate quality/performance improvements and provide for future growth to meet rapidly growing traffic by allocating more spectrum to mobile wireless services and continuing to streamline rules for deployment of infrastructure. Third, the FCC can encourage negotiations between network service providers to develop standards and measures that will allow uniform, improved quality of service when communications cross networks, implement smooth connectivity between dissimilar networks, and share/exchange resources such as spectrum to help during peak demand periods.

Regardless of the regulatory framework the FCC ultimately adopts in this area, we strongly caution against imposing any net neutrality regulations impacting wireless networks in the foreseeable future. In particular, during the current transition to new 4G technologies, maximum operational flexibility and experimentation are needed to address largely unforeseeable performance issues. Furthermore, such rules would be particularly damaging given the extraordinary uncertainty that is likely to persist for quite some time. It is our opinion that net neutrality rules for wireless systems would benefit absolutely no one and we repeat “no one.” “Wait and see” is the appropriate strategy. Wireless services have thus far been fair to application providers, and wireless providers compete fiercely to satisfy customers. Attempting to create rules for managing fairness in future hypothetical situations and for a technology base that is still evolving or in some cases yet to be deployed is simply unrealistic. The last thing the highly-complex wireless networks need is regulations that would stifle innovation and degrade the consumer wireless experience.

The rest of our paper is organized as follows. Section 2 summarizes the essentials of current and emerging wireless networks so that issues relevant to net neutrality in wireless can be discussed accurately and in sufficient detail. Section 3 contrasts wireline and wireless networks to emphasize how far apart these two environments are. Section 4 contains an in-depth discussion of the technical obstacles to applying the proposed rules to wireless. Section 5 offers our views on steps the FCC can take to further the goals of Internet openness and to ensure the best possible consumer experience without adversely affecting wireless innovations and consumer experience of wireless services. Finally, Section 6 summarizes our conclusions.

2. A Glimpse of the Cellular World

This section provides an overview of cellular networks[1] and creates a foundation for our later in-depth discussions of wireline/wireless network differences and of why net neutrality principles should not be extended to wireless networks. Section 2.1 sketches the evolutionary path of cellular networks. A simplified architecture of a cellular network is illustrated in Section 2.2. Section 2.3 summarizes the roles played by network management during typical interactions between the user device and the cellular network. Finally, IMS (IP Multimedia Subsystem) and PCC (Policy and Charging Control) and their emerging services and QoS architectures are described in Section 2.4.

2.1 The Evolution of Cellular Standards

First-generation (or 1G) commercial cellular networks emerged in the early 1980s, and examples of such systems include Advanced Mobile Phone System (AMPS) in the U.S. and European Total Access Communication System. The 1G cellular networks were analog and provided voice services only. The success of 1G cellular networks quickly led to the discovery of their limitations, including *capacity*, which is the number of users that can be supported simultaneously.

The second generation (2G) cellular networks were engineered to exceed the capacity of 1G networks by a factor of three to ten. Examples of 2G networks are GSM (Global System for Mobile Communications) and IS-95 (Interim Standard-95). In addition to voice services, the 2G systems could provide data services, such as Short Message Service. Typical data rates in 2G networks were in the low tens of kbps, and data services were supported inefficiently. Precious network resources had to be reserved for long periods even though they would be used for the data link only a fraction of that time. For example, network resources that were actually used only when web pages were downloaded to the user's handset remained reserved (and unavailable for other uses or users) between the loading of two different web pages (*i.e.*, while the user was reading the first webpage).

3G networks were designed to support data services more efficiently. Additionally, they enable much higher data rates (*e.g.*, 100s and now 1000s of kbps) and increase voice capacity (by a factor of two to three compared to 2G). Examples of 3G networks are UMTS (Universal Mobile Telecommunication System) and 1xEV-DO (1x Evolution- Data Optimized). Service providers have extensively used 2.5G systems, such as GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for GSM Evolution), as a cost-effective interim solution for data services during the transition from 2G GSM to 3G UMTS.

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[1] Although wireless networks, in general, include both cellular networks (e.g., GSM and UMTS) and non-cellular networks (e.g., WiFi), we use the terms "cellular" and "wireless" interchangeably in this paper to refer to "cellular" wireless networks.

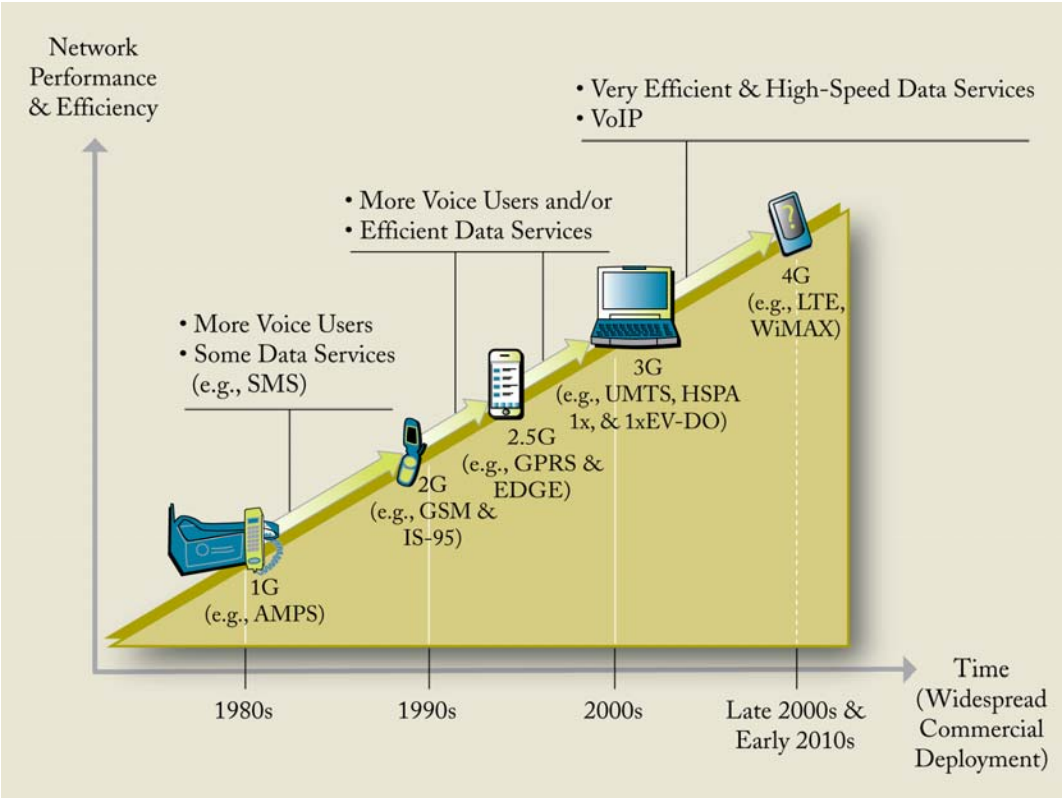

Figure 2.1. Ever-Changing Wireless Networks: 1G to 4G

Fourth generation (4G) cellular networks, such as WiMAX (Worldwide Interoperability for Microwave Access) and LTE (Long Tem Evolution), are emerging to provide higher data rates (*e.g.*, several megabits per second) and higher efficiency. The 4G networks provide voice services using a Voice over Internet Protocol (VoIP) approach, in which user speech is encapsulated inside an IP packet. Initial WiMAX networks use the standard 802.16e-2005, but WiMAX Release 2 will use the standard 802.16m to reach theoretical peak 1 gigabits per second (Gbps) data rates. Similarly, an enhanced version of basic LTE, called LTE-Advanced, will also reach theoretical peak 1 Gbps data rates.

Though Figure 2.1 depicts basic generations of cellular networks, *multiple major revisions or enhancements exist within a generation*. For example, the first release of 3G UMTS was Release 99, but many subsequent major releases have occurred, including Release 4, Release 5, Release 6, and Release 7. These releases basically enhance the overall UMTS network performance compared to Release 99. Release 4 makes the operator's internal network more efficient for carrying voice traffic. Release 5 includes a feature called HSDPA (High Speed Downlink Packet Access) that increases the peak downlink[2] data rate to about 14 Mbps from (theoretically) 2 Mbps in Release 99. Release 6 includes a feature called HSUPA (High Speed Downlink Packet

[2] Downlink is the communications link from the base station to the user device.

Access) that increases the peak uplink[3] data rate to about 5.6 Mbps from (theoretically) 2 Mbps in Release 99. HSDPA and HSUPA together are referred to as HSPA (High Speed Packet Access). Release 7 defines a feature called HSPA+ that increases the peak downlink and uplink data rates to 28 Mbps and 11 Mbps, respectively.[4] HSPA+ allows the downlink data rate of 42 Mbps in Release 8. LTE (Long Term Evolution), shown in Figure 2.1 as 4G, is a Release 8 feature of UMTS.

Active participation is required from thousands of experienced engineers around the globe to develop a given release of a standard. Once the standardization is completed or reasonably stable for a given version of the standard, wireless products such as network equipment and user devices are designed. Since wireless networks and devices are highly complex and interdependent systems, product designs need extensive experimentation via computer-based simulations, lab trials, and field trials.

Simulation involves mathematical modeling. A lab trial involves prototype testing in a lab environment. A field trial means that prototypes are tested in a real-world environment; test engineers use a real wireless network deployed in a limited area. Next, the service operator carries out network planning to determine locations of the base stations and then configures the base stations and other nodes of the network. Once the network is opened up to real subscribers, network optimization can begin to optimize network performance and user experience. *All of these activities of standardization, product design, experimentation, network planning, and network optimization can take years and must be repeated and constantly refined.* Additionally, the co-existence of various generations and revisions of standards means that the service operator must also facilitate interworking among these technologies.

As shown in Figure 2.1, cellular networks strive to become better from one generation to the next. We have already mentioned capacity, which is the maximum number of users that can be supported simultaneously and is a good performance metric for voice-centric systems, such as 1G and 2G networks. A very important performance metric for a data-centric wireless network, such as a 3G or 4G network, is *throughput,* which is measured as bits per second. For example, assume that a user downloads 100 megabits in 10 seconds. The peak user throughput then is 100 mega bits ÷ 10 seconds) = 10 megabits per second (Mbps). Different technologies have different peak throughputs.

Another data-centric performance metric is *spectral efficiency*, which measures how efficiently the available spectrum bandwidth is being used. As an example, when a Release 5 UMTS network supports a peak throughput of 14 Mbps in a 5 mega Hertz (MHz) bandwidth, peak

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[3] Uplink is the communications link from the user device the base station.

[4] The *peak throughput* is the maximum data rate a user can theoretically ever experience. The *average throughput* a user actually experiences is smaller (e.g., 2 to 3 Mbps instead of 14 Mbps). Both peak and average throughput vary significantly due to the radio environment, the capabilities of the network, and the capabilities of the user device.

spectral efficiency would be 14 Mbps ÷ 5 MHz = 2.8 bits/sec/Hz. From one generation to the next and from one release to the next, significant R&D investments and real-world optimization efforts are required to maximize capacity, throughput, and spectral efficiency. Enhanced network performance is reflected in better user experience for various services. In addition, legacy technologies are still in use when new-generation technology arrives, so operators must still accommodate users who are using phones that understand only the old-generation technology. Recall that 1G AMPS survived until 2008.

In summary, wireless standards and their commercial deployments evolve at a very rapid pace. Furthermore, multiple technologies co-exist for a given service operator.

2.2 Generic Architecture of a Cellular Network

Let's take a quick look at *simplified* architectures of 3G and emerging 4G networks as illustrated in Figure 2.2; the actual network, of course, has many more nodes or elements.

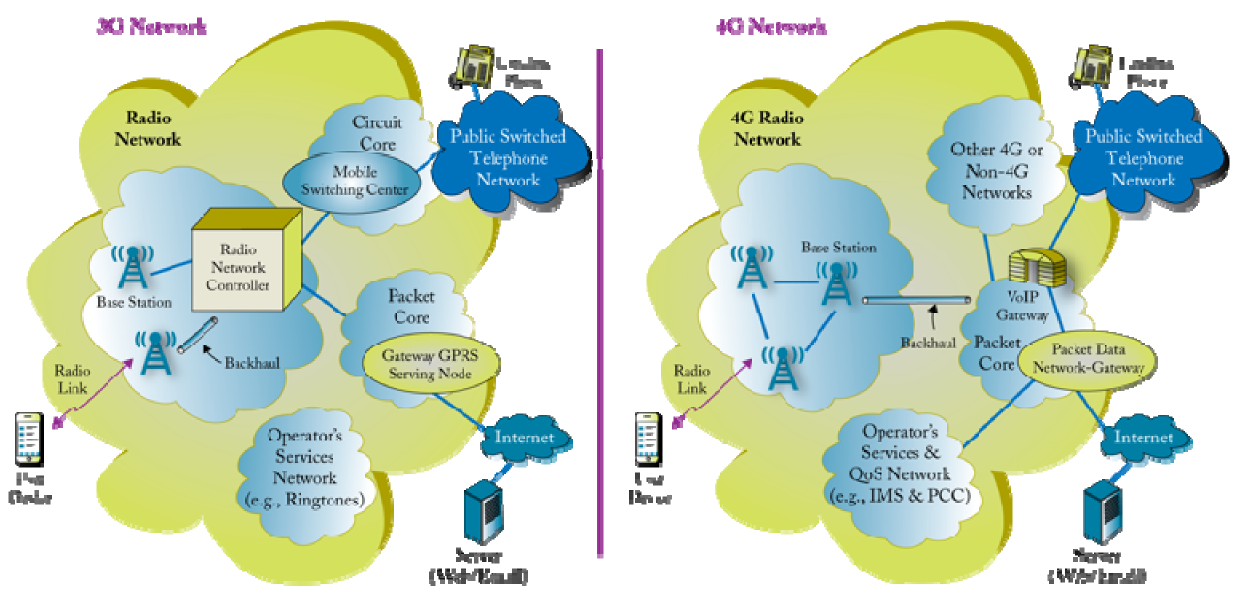

Figure 2.2. Simplified Architectures of 3G and 4G Cellular Networks

A service operator's typical 3G network includes a *radio network*, a *core network*, and a *services network*. The *radio network* includes base stations (BSs) and a radio network controller (RNC). One RNC controls hundreds of BSs. The BS is also referred to as the Node B, and, the RNC is also called the Base Station Controller. The user device communicates with the BS using a radio link that is technology-specific. For example, this radio link uses TDMA (Time Division Multiple Access) technology in 3G GSM and CDMA (Code Division Multiple Access) technology in 3G UMTS. In a CDMA system, the network allocates two different codes to two different users so that the system can differentiate between these two users even though the users occupy the same 5 MHz spectrum bandwidth. The link between the BS and the RNC is often known as <u>backhaul.</u> The core network in 3G consists of a circuit core and a packet core. The circuit core includes several elements, such as the Mobile Switching Center, and interfaces with the Public Switched Telephone Network so that the wireless user can communicate with a landline phone. The packet core includes nodes, such as the GGSN (Gateway GPRS Serving Node)[5] and provides the wireless user access to the Internet.

A *services network* in 3G is typically operator-specific and -proprietary and allows wireless users to obtain services, such ringtone and music video downloads. In other words, the interface between the GGSN and the services network is beyond the scope of the standard bodies, and its specifications are entirely within the operator's control.

Like a 3G network, a 4G network also includes a *radio network*, a *core network*, and a *services network*. The *radio network* includes nothing but the BSs. Elimination of the RNC from the radio network reduces latency or delay; the radio network controller no longer processes the packets, and the packets do not incur the transport delay on the BS-RNC interface. The radio link in 4G has higher spectral efficiency than a 3G radio link, but the exact gain from 3G to 4G is again variable and depends on the radio environment, network capabilities, and device capabilities. The *core network* in 4G consists of only a packet core. The packet core uses elements such as a VoIP (Voice over Internet Protocol) gateway to interface with the PSTN for a landline phone. The packet core also includes components such as the P-GW (Packet data network- GateWay) for wireless Internet access.

The *services network* in 4G now includes *standardized* architectures, such as IMS (IP Multimedia Subsystem) and PCC (Policy and Charging Control). Basically, these architectures serve as a catalyst for the development of innovative applications and for the implementation of "end-to-end" QoS (Quality of Service). From the user's perspective, true "end-to-end" QoS would be inter-network QoS that provides uniform quality across all networks traversed between the user and the web or email server. Realistically, however, the operator has influence only between the user device and the edge of the operator's network (*i.e.*, the Gateway GPRS Serving Node for 3G and the packet data network-gateway for 4G) since the operator owns the radio and

[5] GPRS stands for General Packet Radio Service.

core networks. The QoS between the GGSN/P-GW and networks controlled by others that are between the user and a web or email server is outside of the operator's domain of influence.

In summary, wireless networks are quite complex. Before a wireless network is ready for commercial use, extensive integration testing is required to ensure smooth interactions among the user device, the radio network, and the core network. Transitioning from one release of the standard to the next requires flurries of activities, such as upgrading the existing network nodes and testing integration. Scarcity of network resources, especially on the radio link between the user device and the base stations, renders infeasible any absolute QoS guarantees in wireless networks.

2.3 Device-Network Communications

To gain a high-level understanding of the roles wireless network management algorithms play, let's briefly consider typical interactions between the user device and the wireless network.

Figure 2.3 conveys a general idea of typical operations; exact procedures are technology-specific.

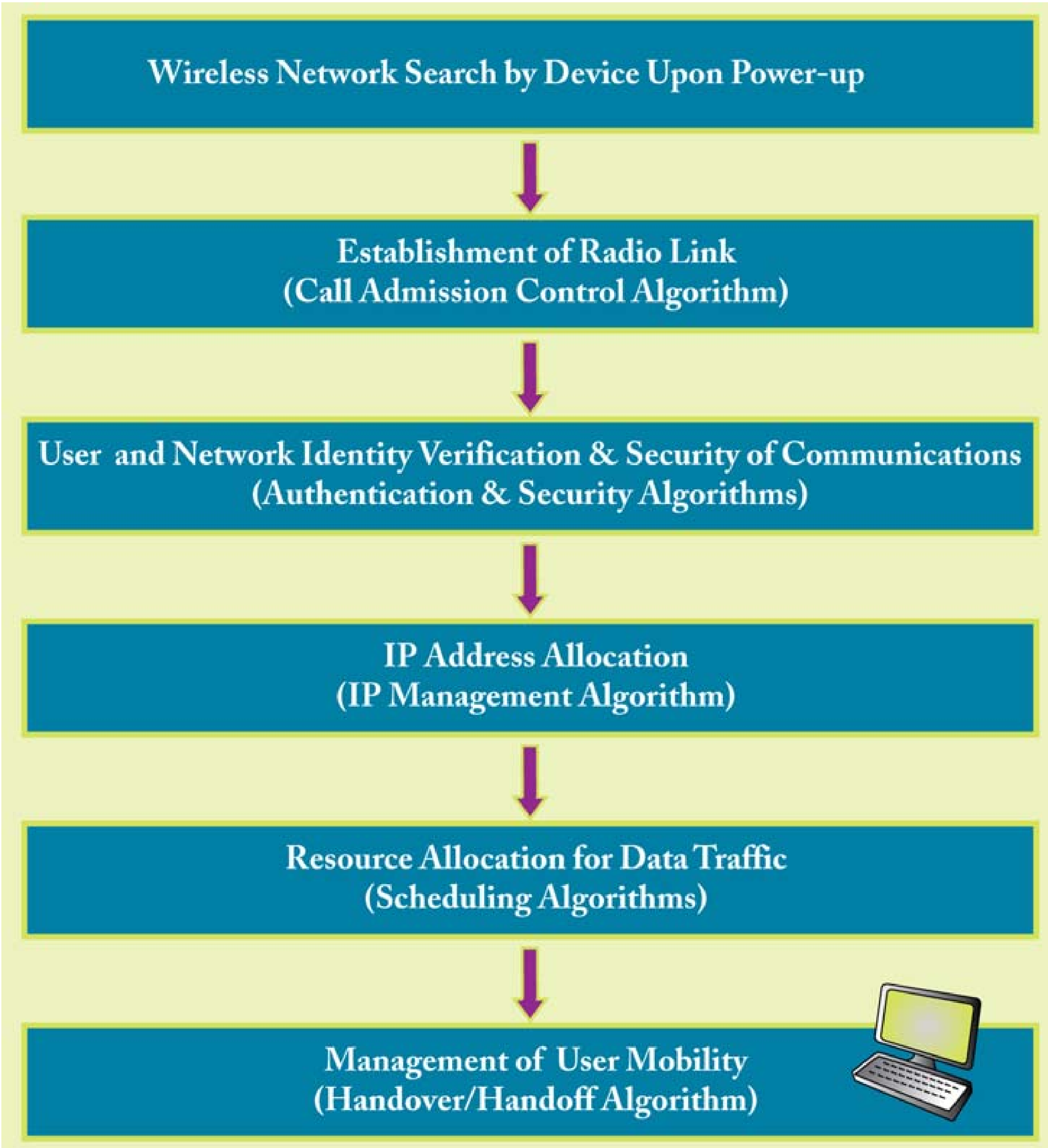

Figure 2.3. A Simplified View of Basic Device-Network Interactions

We focus here on data-capable devices. Assume that the device is powered off, and the user turns on the power and brings the device to "life." The device looks for a signal from the cellular network. If the device finds a base station that can provide a good quality signal (represented by "bars" on the handset with more bars signifying a higher likelihood of a good quality signal), it continues to observe information that base station sends. Examples of the types of information include the identity of the operator to which the detected base station belongs as well as a list of neighboring base stations. This "neighbor" list helps the device look for the best possible base station as it moves around in a geographical area.

After the device collects adequate information about the network, it registers with the network and informs the network that the device is available for communications. As part of the registration process, the radio network and the device need to establish a reliable bi-directional radio link (i.e., downlink and uplink). A call admission control algorithm checks the availability of resources and establishes the radio link if adequate resources are available. The user device and the radio network can now exchange messages. The radio network forwards the device's registration request to the core network. The core network and the user device verify one another's identity during the authentication process. At the end of the authentication process, security keys may be generated to secure over-the-air communications. The user device requests IP connectivity, and a network management algorithm allocates an IP address to the user device.

Once the user starts using applications, such as email or web browsing, a scheduling algorithm allocates network resources to the user to optimize the user's experience and the overall network performance. Fast and close interaction between the user device and the network is required. For example, in an HSDPA network, the device can report a change in the radio environment as fast as every 2 ms, and the network can change the resource allocations for users every 2 ms (*i.e.*, 500 times per second). To understand the seamless cooperation required between the user device and the network, consider the operation of the power control algorithm. The network and the user device send each other 1500 commands every second to increase or decrease the transmit power! Since the radio environment, the nature of interference, and users' data traffic are all dynamic, the network has to respond quickly, typically within a few milliseconds, to ensure optimal network performance and user experience for all active users. If the user moves from one base station's area to another's, a handover or handoff algorithm will help the user device connect to the new base station, thereby maintaining the communications link between the device and the network. The handover may involve base stations using the same technology (e.g., UMTS) or using different technologies (e.g., one base station using UMTS and another using GSM and EDGE). *In summary, various network management algorithms participate during different phases of the interaction with the device. Seamless cooperation between the user device and the network is required for the best possible network performance and user experience. Efficient design of these algorithms is essential to the ability of wireless networks to provide the best possible user experience.* Section 3 takes a closer look at several network management algorithms and their implications for applying net neutrality regulation to wireless.

2.4 Services and QoS Architectures for Wireless Networks

The wireless industry is moving toward common services and QoS architectures—IMS and PCC. Figure 2.4 highlights the main characteristics of IMS and PCC.

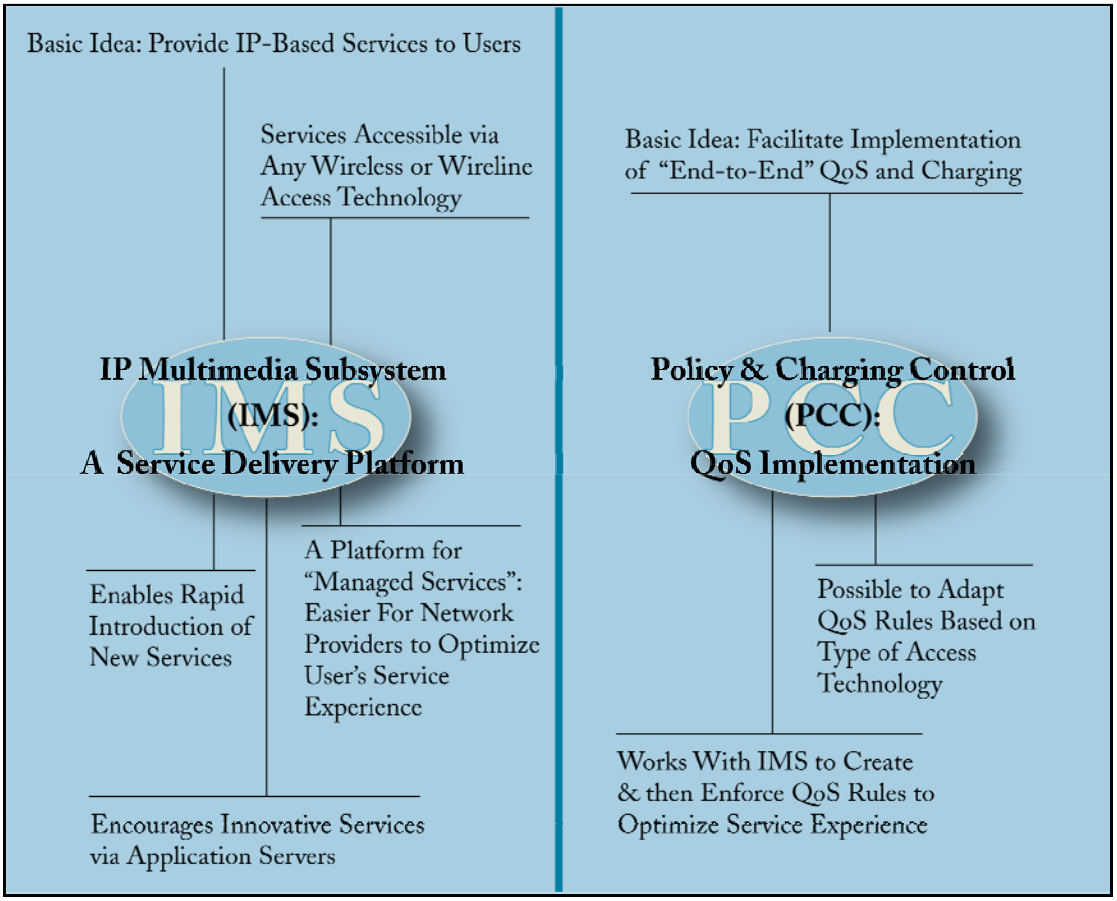

Figure 2.4. Overview of IMS and PCC

3GPP (the 3G Partnership Project, a standards body) is specifying an IMS architecture that is intended for not only wireless networks but also wireline networks. The basic idea behind IMS is to facilitate the offering of IP-based services, such as a VoIP call and a multimedia session including VoIP, video, and text, by ensuring that those services receive the network resources they need to function properly, regardless of the underlying technology platform. Application Servers customized for one or more applications can be placed in the IMS network to rapidly deploy services. IMS thus serves as a catalyst for innovative applications and enables faster third-party application development. IMS offers the wireless consumer countless application choices. Whether the user is in the home network (*e.g.*, an AT&T subscriber using AT&T's radio & core networks) or roaming (*e.g.*, an AT&T subscriber using a different provider's radio and core networks), the user can still access the same services because IMS resides in the home network (e.g., AT&T's IMS network). The user device communicates with the home network via the roaming network. IMS can connect to the core network of any access technology (e.g., HSPA, LTE, or even DSL). As part of the application setup (e.g., a VoIP call setup), the service provider's IMS network determines which application is being used and works with the PCC to attempt to provide suitable QoS (e.g., certain data rate and latency targets). For example, when a wireless user makes a VoIP call, the user's device sends a Session Initiation Protocol (SIP) INVITE message to the IMS network. The IMS network processes the INVITE request for the VoIP call and facilitates the establishment of a link between the wireless user and the destination party.

Now, let's turn our attention to the PCC. The main function of the PCC is to facilitate QoS implementation and charging. PCC allows charging in a variety of ways, such as charging based on the amount of data and the type of application. The PCC network works with the IMS network to provide QoS. The PCC includes two components, the PCRF (Policy & Charging Rules Function) and PCEF (Policy & Charging Enforcement Function). The PCEF usually resides in the service operator's core network. For example, in Figure 2.2, GGSN in a 3G network and P-GW in a 4G network act as the PCEF. The PCRF works with the IMS network to *define* rules and policies for the user's application and specifies these rules to the Policy & Charging Enforcement Function, which *enforces* these QoS rules and works with other network entities to negotiate the network resources required to meet QoS. Since the user packets always travel through the GGSN/P-GW, the GGSN/P-GW is a logical choice to enforce QoS policies. Consider a VoIP call setup. The IMS network provides the information on the required QoS to the PCRF. The IMS network may indicate that a 12.2 kbps data rate is required to support a VoIP call and that the user has indeed subscribed to the VoIP service. The PCRF constructs a QoS policy rule that informs the PCEF that it should let the VoIP packets for this user pass through. The PCEF now works with other core network entities to provide QoS. Once the availability of resources is confirmed, the call setup is completed and the actual VoIP traffic can flow between the user's device and the destination party through the radio network and the core network. As discussed in Section 4, the PCC architecture standardizes the QoS requirements for different services to ensure a good user experience regardless of the technology (e.g., EDGE vs. HSPA) the user's device employs. Such standard-defined characteristics help prioritize resource allocations for different services. Of course, the actual QoS that the user experiences does depend on the technology because different technologies have different performance capabilities.

In summary, wireless networks have evolved through several generations, with multiple revisions within each generation, in only about twenty years. Wireless engineers continually strive to improve the networks to achieve better performance and to meet the emerging data traffic demands. History has shown that experimentation and deployment experience leads to remarkable performance improvement in wireless networks. Although 4G has entered the scene and the industry is moving to common services and a common QoS framework in the form of IMS and PCC, the networks are expected to be in a state of flux in the foreseeable future.

Maximal flexibility and significant experimentation is warranted to maintain and then accelerate growth in wireless services and to advance the wireless user experience to unprecedented levels.

3. Differences between Wireline Networks and Wireless Networks

Any proposals to extend to wireless operations network neutrality principles conceived in a wireline context must contend with the vastly different technical challenges of these two types of communication networks. Section 3.1 contrasts wireline and wireless networks. Section 3.2 discusses the network management issues that are specific to wireless networks. Section 3.3 provides examples of network management mechanisms implemented in wireless networks. Two scenarios regarding the challenges wireless network management faces are illustrated in Section 3.4.

3.1 Wireline Networks vs. Wireless Networks

The NPRM correctly points out that congestion issues for wireless differ from those for wireline operation, but fails to adequately recognize the extent of the differences or that congestion and other performance issues are much more difficult to resolve for a wireless network. In this regard, many additional technical differences between wireline and wireless networks are as important as or more important than congestion management (commonly referred to by wireless engineers as the "capacity problem"). These include performance-affecting differences that are due to the propagation channel as well as dynamic network management that is required to ensure adequate reliability and coverage in the face of constantly changing propagation and mobility issues. *This section provides an overview of the differences in technical challenges between wireline and wireless systems as they relate to network neutrality regulation.* ***Key differences between wireline and wireless networks are summarized in Table 3.1.***

Wireless *channels* are quite different from wireline channels. First, the *bandwidth* for a wireless service provider might be on the order of 10s of MHz (~10^7 Hz), but that for a fiber optic system could be 10s of GHz (~10^{10} Hz). The number of users or data rates that can be accommodated is directly proportional to the bandwidth (and, in wireless systems, is also affected by the relative dispersion of the users within particular cells). Although 3G and 4G technologies can enable multi-mega bit per second wireless transfer rates (assuming adequate spectrum resources), wireless systems will never have the bandwidth of wireline systems. A wireline network can exploit advances in optical fiber technologies to achieve extremely high bandwidth exceeding thousands of Gbps (gigabits per second). In contrast, the limited amount of radio spectrum in wireless networks puts a severe constraint on the achievable data rates on a wireless link. Moreover, a "build more infrastructure" approach is much less of a solution to *capacity* issues in wireless systems than in wireline systems for a number of reasons. First, spectrum constraints place outside limits that simply do not exist in wireline. Second, *mobility and propagation* issues combine to create much greater variability in wireless traffic—the spread between peak and average traffic levels is typically much wider for wireless than wireline—which makes it infeasible to design networks to meet anything approaching peak demands. Third, issues unique to wireless are associated with deploying more capacity. Resolving these issues may require re-designing the network to create more or smaller cells, which in turn raises real estate, zoning, and other issues and involves handoff, interference, and other complexities. In general, wireless traffic *must* be categorized and prioritized to deliver content with reliability and coverage. Even with such prioritization, allocating a disproportionate amount of network capacity to certain types of traffic under various operating conditions may be necessary to maintain some connections. Wireless carriers continue to spend billions of dollars annually on infrastructure upgrades, but they will continue to face severe capacity constraints, particularly with demand growing far faster than anticipated.

In wireline systems, in contrast, capacity improvements without the large expense of laying new fiber have been made possible though better technology at the fiber ends. Such options simply are unavailable for wireless systems, and dynamic prioritization and other management techniques are and will remain essential. See Section 3.4 for a scenario that highlights the effects of the radio environment on a wireless network.

Not only is the *bandwidth of the wireless channel* severely constrained compared to wireline channels, the *reliability of the wireless channel* is well below that of a wireline channel. The reliability issue is due to a number of factors, such as *blockage* of the radio signal (called *shadowing*), echoes or multipath[6] of the signal, thermal noise, and, more importantly, interference. These *impairments to the channel* create substantial additional complexity and variability. Planning and operating a cellular deployment to ensure Quality of Service (QoS) and coverage is extraordinarily difficult because these impairments are random and unpredictable.

Interference is often the most important of these impairments, and, by its very nature, is constantly changing between and within cells. Interference occurs when multiple signals share the same spectrum. These signals are typically associated with the same service provider but often are due to another service provider using the same or adjacent spectrum bands. (Interference can also be caused by unlicensed devices.) Interference limits capacity in a wireless system on a dynamic basis, varying by location and from one millisecond to the next, and this problem has no counterpart in wireline systems. Moreover, though all wireless systems suffer from these impairments, different standards (*e.g.*, GSM and IS-95) are impacted differently.

And in addition to the radio environment issues, wireless operators must be more concerned with *privacy and security* issues. Wireless devices allow a person to be tracked, which raises obvious privacy concerns. Compared to wireline networks, security can be more difficult because

[6] In environments such as downtown areas, when the transmitter sends out a signal, multiple copies of the signal reach the receiver because the signal energy gets reflected from buildings. These multiple copies are known as multipath and cause interference.

wireless signals are broadcast and can potentially be intercepted by anyone in the coverage area, and interception is unlikely to be detected.

Network complexity tends to be greater in a *wireless* network. As discussed in Section 2.2, the architecture of a wireless network is quite complex and requires extensive initial and ongoing resource investments to achieve good user experience and good network performance. Wireline networks use more stable platforms and are better understood than wireless standards and wireless networks, which continue to evolve more rapidly (depicted by Figure 2.1 in Section 2.1).

Deployment and maintenance of wireline systems are less dynamic than wireless systems. Although wireline electronics and services continue to evolve to a certain extent, the advent of fiber has brought stability and efficiency to the wireline network architecture. In contrast, *only <u>change is constant</u> in wireless standards and networks!* As a result, network management practices must constantly evolve to address new architectures, new technologies, new standards, and new wireless applications with new performance needs.

Implementation of QoS to meet the performance needs of diverse applications is extremely difficult in a wireless network. Indeed, scarcity of network resources (especially radio network resources) makes it infeasible to provide absolute *QoS* guarantees in a wireless network. Though the evolution of cellular technologies from 1G to 3G/4G has significantly improved maximum achievable performance, the radio resources are still quite precious and can be expected to remain so for the foreseeable future. Rapid growth in data, in particular, has put even more strain on the existing cellular networks.

It is beyond serious debate that the different types of traffic that share wireless channels and spectrum require different levels of QoS. The network attempts to use various resource management algorithms to maximize user service experience. However, the actual QoS that a user experiences depends on countless factors, such as the number of users competing for resources, the types of traffic those users generate, the user's handset, and the prevailing radio environment. QoS implementation strategies, primarily in the form of resource management algorithms, vary both within an individual operator's network due to variations in technology (*e.g.*, GPRS/EDGE vs. HSPA) and between different operators' networks (e.g., due to limitations on and variations in the radio network and backhaul capacity).

New architectures, such as IMS and PCC, are emerging to facilitate improved implementation of wireless QoS and to provide a standardized framework for QoS. (See Section 2 for a brief overview of IMS and PCC.) These architectures are quite flexible, and numerous possible implementations both complicate deployment in practice and open the door to industry collaboration as exemplified by the OneVoice Profile to support IMS-based voice services

[OneVoiceProfile]. Standard-setting and collaboration are still in their early stages, and fully integrating IMS into wireless networks will take several years.

Within IMS and PCC architectures, different QoS grades are defined to support different types of traffic. Examples of QoS parameters that can be standardized include target delay, error rate, and type of service (guaranteed bit rate vs. non-guaranteed bit rate) [PCC 23.203]. As part of PCC, an access provider still has the flexibility of choosing certain QoS-related parameters such as the maximum data rate for a given service. In other words, even with "standardized" QoS characteristics, user-perceived experience would still vary. For example, a user sending e-mail may be able to do so quickly or slowly; the speed depends upon the actual data rate allocated to the user and is based on the availability of network resources. Like the radio environment and the radio resource allocation algorithms, widely varying and rapidly changing wireless QoS needs and mechanisms (i) make it nearly impossible to adhere to any verifiable and repeatable performance targets; (ii) inherently assume traffic differentiation and user differentiation for maximal network performance and optimal user experience; and (iii) preclude any objective or predictable metrics for "reasonable" or "unreasonable" management.

As discussed in Section 3.2, these issues unique to wireless communications require specialized management responses; wireless network management would be distinctively and negatively affected by the application of network neutrality regulation.

Table 3.1. Summary of Differences between Wireless and Wireline Networks

Characteristic	Wireline	Wireless
Communications Channel	Relatively clean with signal regeneration	Impaired with noise, interference, multipath, and blockage
Bandwidth	No spectrum limitations	Spectrum limitations
Mobility	None	Constant, complex, often unpredictable, and often consuming extensive resources
Security	A lesser concern due to the physical path between the provider and the user (buried or on aerial infrastructure).	A greater concern due to the possibility of tracking a user; More opportunities and vulnerabilities due to variety of interface issues [GSM_Encryption]
Response to Increased Traffic Demand (i.e., the Capacity Problem)	Capacity increases may be feasible, although soaring demand and increasing congestion issues may call for additional pricing, bandwidth limitations, and prioritization mechanisms	Primarily managed dynamically through prioritization, scheduling, and power allocation
Network Complexity	Relatively simple	Extremely complex
Network Stability, Deployment, and Maintenance	Comparatively stable platform and systems, although high growth in demand and new applications are issues	Extremely dynamic platforms and systems; Deployment and maintenance require constantly dealing with real estate acquisition and zoning issues; Planning and maintenance are imprecise, and continuous maintenance and frequent resetting of network parameters is required; Infrastructure changes to address localized capacity issues can have ripple effects through adjacent cells
Quality of Service	Easier to implement due to availability of higher capacity and predictability of resource requirements	Quite difficult to implement due to variable capacity, unpredictability of resource requirements, existence of proprietary mechanisms; Industry moving toward IMS and PCC

3.2 **Wireless-Specific Network Management Issues**

Let's discuss the network management issues faced only by wireless networks; these issues are absent in wireline networks.

Active and dynamic network management is essential to help *overcome many of the impairments* associated with the wireless channel. Of course, it is also necessary to manage mobility of the terminals. *Mobility management* often comes at a price of increased traffic, within the core network and in the wireless network. See Section 3.3 for an example of resource consumption during handoff. Redundant transmissions are often used as a mechanism to improve the reliability of the handoff process. *Traffic patterns* change throughout the day as human activity changes.

Wireless engineers must respond to constantly changing impairments and traffic patterns with constantly changing allocation of radio resources through packet formation and error correction features[7], frequency channel allocation[8], signal power[9], and time and duration of transmission[10]. Such management requires network engineers to frequently make adjustments and experiments to respond to new and ever-changing circumstances.

Wireless technologies and applications are evolving at a much quicker rate than for wireline, further complicating the network management. As discussed in Section 2.3, cellular networks have evolved – and continue to evolve – rapidly from 1G to 4G and beyond. Since technologies operate differently, they necessitate different network management techniques. Furthermore, even when newer technologies are deployed, design and experimentation on older technologies continues nonetheless to enhance these technologies and gain their maximum benefits.

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[7] Under hostile channel conditions, adding redundancy bits will make it easy to recover the packet arriving on a wireless link. This addition of extra bits to the original bits to form a packet is considered an error correction method. See footnote 11 in Section 3.4 for a simple example of "redundancy."

[8] Due to the dynamic nature of the radio environment, different radio channels experience signal degradation at different times. Hence, if a radio frequency channel, *f*1, is allocated to a user and experiences degradation, we can change the channel to *f*2 for this user. Such reallocation of frequency channels ensures that the user does not experience poor channel conditions for long on a given frequency channel.

[9] Some technologies (*e.g.*, Code Division Multiple Access based technologies such as UMTS) adjust the signals' power levels to achieve high capacity and to improve battery life.

[10] Choosing good timing for packet transmission is often possible. For example, when channel conditions are good for a given user's device, scheduling the packet transmission would result in better throughput for the user. Furthermore, spreading information over a longer time period could also provide some benefit. Even if the channel conditions are bad initially, they may improve in the short-term, resulting in better performance compared to an ultra-short transmission duration. An example technique that can yield such benefit is called interleaving.

As for applications, services, and devices, consider the case of ATT's iPhone. The iPhone was introduced less than three years ago, yet more than 100,000 new applications have been introduced. Consumers have embraced the new applications and capabilities of such "smartphones" in ways that have caused tremendous increases in broadband Internet usage. Similarly, T-Mobile reports that users of its Google G1 phone use *50 times* more data than the average user [T-Mobile_G1]. Overall data traffic has grown thousands of percent over the past few years and is expected to more than double each year for the foreseeable future [DataTrafficGrowthPrediction]. Hundreds of new, specialized wireless devices and applications from smart grid to "telehealth" to location tracking machine-to-machine communications are either coming on line or being contemplated, each with its own unique performance needs and potential interference issues. Clearly, with such a dynamic marketplace, the methodology for managing radio resources must change just as quickly. Relying on the regulatory process to quickly and dynamically guide resource management is likely infeasible.

3.3 **Wireless Network Management Mechanisms: An Overview**

Overall, best industry practices for *network management* in a wireless network are typically non-standardized and proprietary. Some parts of network management rely upon evolving, proprietary, and sophisticated resource management algorithms (e.g., a scheduling algorithm), yet other parts rely upon more standardized mechanisms (e.g., retransmissions of a web page during congestion and IP routers' QoS-based packet forwarding). Network management configures both various network infrastructure nodes and the interconnections among them. Elaborate tools are required to monitor such interconnections and to help troubleshoot problems. Configuration of these nodes (e.g., allocating identities to base stations to help the user device detect a base station) for optimal performance is an enormously complex task. Such configuration practices depend upon the specific technologies and are executed frequently during the lifetime of the technology for enhanced user experience.

Radio resource management algorithms form the core of wireless network management. Figure 3.1 illustrates the roles of the main algorithms: *call admission control*, *load balancing*, *handover*, *scheduling*, and *power control* algorithms. Let's discuss these algorithms now.

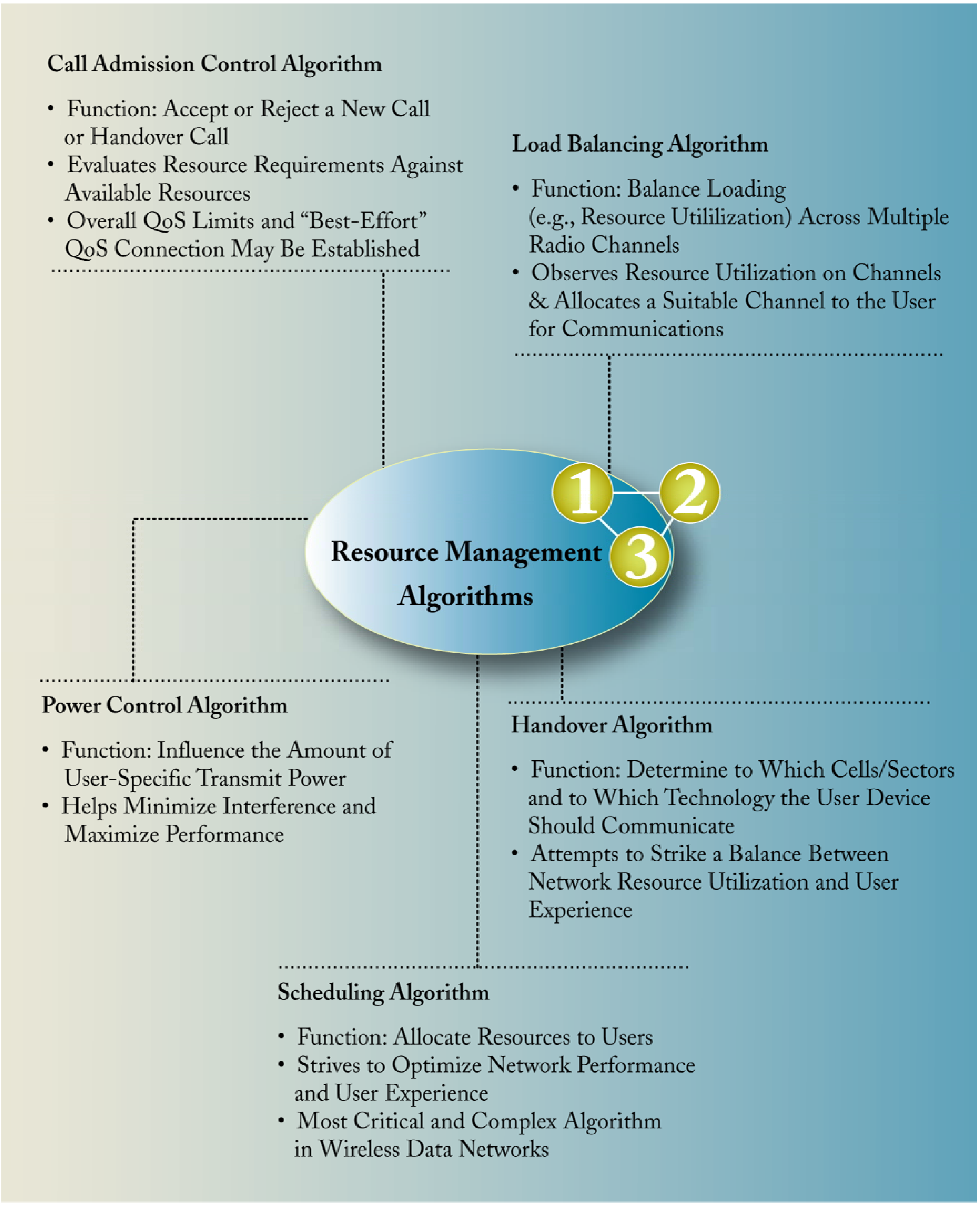

Figure 3.1. Major Radio Resource Management Algorithms

A *call admission control algorithm* is in charge of admitting or rejecting a call. For example, when a user dials a phone number or starts using a web browser to surf the Internet, the user device communicates with the network to convey the need for resources. The call admission control algorithm evaluates the resource needs for such a call and accepts or rejects the call request. Basically, if adequate network resources are available, the call is accepted. Otherwise, the call is rejected. For example, a best-effort radio connection may be established upon data call acceptance, and some QoS limits (e.g., *maximum data rate* of 1 Mbps) are specified. The *actual data rate* can vary from time to time, and another algorithm, the scheduling algorithm, would influence the actual data rate. When a radio channel supports both voice and data users, the call admission control algorithm's job becomes even more challenging due to widely different resource requirements of voice and data services.

A *load balancing algorithm* tries to balance loading across multiple radio channels to improve network accessibility and overall network performance [LoadBalacing]. Initial deployments of a new technology typically use one radio channel (i.e., carrier frequency), and the network is gradually upgraded to support multiple radio channels in the same cell/sector. When a new call comes in, this algorithm decides to which of the radio channels the user should be directed. If radio channel X's resources are lightly loaded (e.g., 40% utilization) compared to heavily-loaded radio channel Y's resources (e.g., 90% utilization), this algorithm assigns radio channel X to the user. Such load balancing attempts to even-out resource utilization across multiple radio channels, resulting in lower call blocking and higher network capacity (e.g., a 10% to 15% increase in the number of simultaneously supported users).

A *handover or handoff algorithm* decides which sectors should communicate with the user's device. As the user moves from one sector to another, this algorithm determines suitable sectors for communication with the user's device. Two main types of handover are hard handover and soft handover. Hard handover allows communication between the device and a single sector, and soft handover involves communication between the device and multiple sectors (often limited to three or six in typical commercial deployments). Different technologies support different flavors of basic hard and soft handover. In a typical scenario, the network configures the user's device with handover measurements, the user's device reports measurements to the network, and the handover algorithm decides with which sector(s) the user's device should communicate. Too little handoff (i.e., fewer sectors talking to the device) or too slow handoff (i.e., a long delay in handover decision) may result in a call drop. Too high or too fast handover results in excessive utilization of network resources and adversely affects achievable network capacity.

A *scheduling algorithm* is the most critical and most complex resource management algorithm, especially in 3G and 4G wireless networks. The scheduling algorithm is an important product differentiator for network equipment manufacturers. Its main function is to allocate uplink and downlink resources/throughput to users in a cell to optimize network performance and user experience. It is executed very quickly and very frequently (*e.g.*, every 2 ms in HSPA and every 1 ms in LTE). Within such a short time, it can consider (i) the QoS assigned to users or applications, (ii) the available amount of data bandwidth, (iii) feedback from the user's devices, (iv) device capabilities, (v) network capabilities, (vi) history of data transmission for the user (*e.g.*, the average data rate allocated to the user in the past several seconds), and (vii) resource requirements for active users. Based on these factors, the scheduler decides (a) how many users (*e.g.*, one user or ten users) and which users (*e.g.*, John and Tom or John and Sue) should be allocated resources, (b) how much data rate should be allocated to the selected users (*e.g.*, 12 kbps for John's VoIP call and 1 Mbps for Tom's email download), (c) whether a previously sent packet should be retransmitted to improve reliability or whether a new packet should be sent to improve user-perceived data rate, and (d) how a packet should be created for the selected user. In other words, should the packet include a lot of redundancy to enable easier detection of the packet or should it include minimal redundancy to squeeze in a lot of bits to increase user-perceived data rate?

A *power control algorithm* influences the transmit power so that interference is minimized in the user's cell and in neighboring cells and network and device performance are maximized. For example, the network may instruct the user device that is close to the base station to use less power (e.g., 10 mW) and the distant user device to use more power (e.g., 100 mW). Both users are now transmitting adequate power to enable the base station to detect their signals. At the same time, the network has minimized overall interference in the network. If both devices were to transmit their full power (e.g., 125 mW or 200 mW depending upon the technology and the device capability), overall interference in the network would increase (and the devices' battery life would be shortened considerably). Using "bare minimum" power thus minimizes interference and maximizes battery life. The "bare minimum" power level can vary significantly for different users and is a function of the radio environment!

Basically, the numerous implementation-specific resource management algorithms (i) make it nearly impossible to adhere to any verifiable and repeatable performance targets, (ii) assume traffic differentiation and user differentiation for maximal network performance and optimal user experience, and (iii) make it extraordinarily difficult to judge whether a network management mechanism's action was "reasonable" (or to predict how a decision-maker might view the reasonableness of any such mechanism afterward).

3.4 Example Scenarios on Wireless-Specific Issues

Let's look at two example scenarios, Scenario I and Scenario II, to highlight the complexity of issues a wireless network must accommodate. A wireline network does not experience these issues. Scenario I illustrates the impact of the radio environment and user mobility on network performance and user experience. Scenario II shows the challenges of determining the "reasonableness" of network management in a wireless network.

Figure 3.2 illustrates Scenario I, *where different amounts of wireless network resources are required to support a given QoS level depending upon user mobility*. Consider User 1, who is close to a base station in Case I but moving away from the base station (Case II).

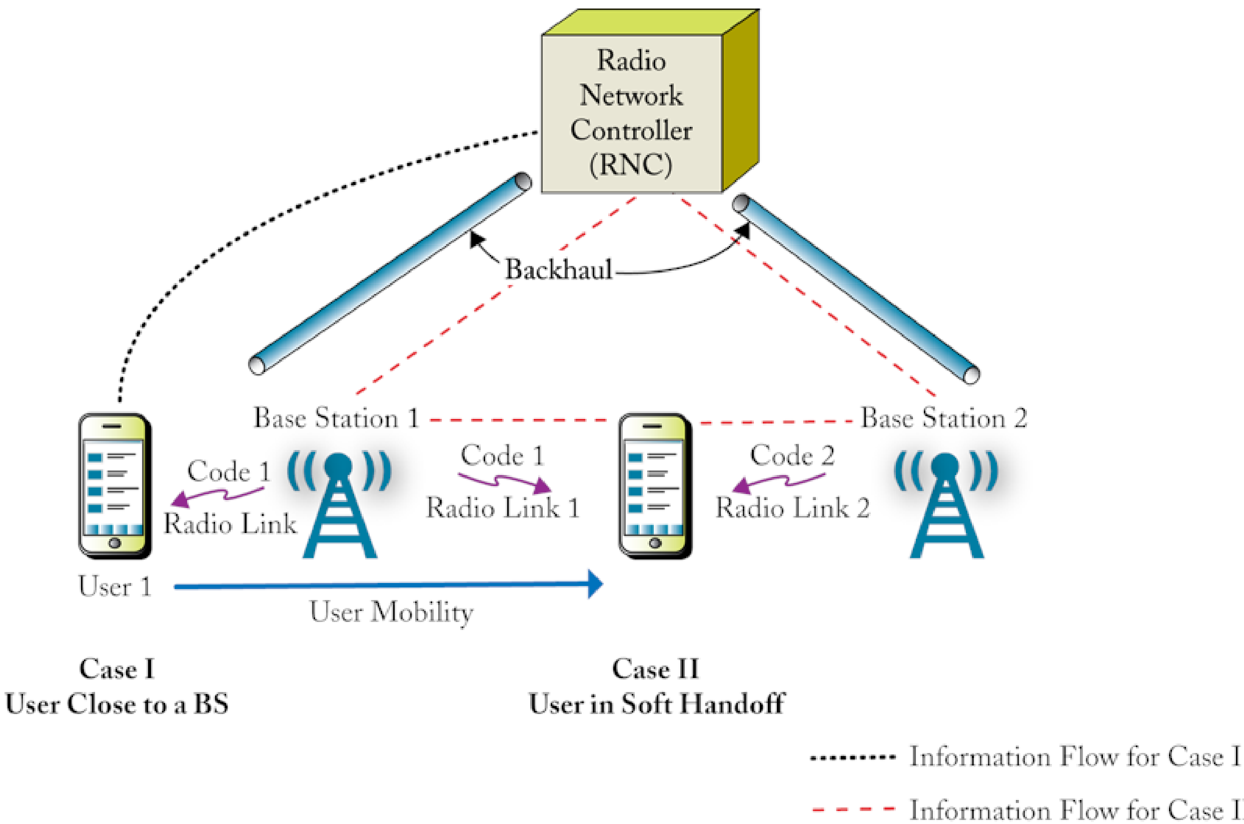

Figure 3.2. Dynamic Nature of Radio Environment: Impact of User Mobility

User 1 is served by just one base station (Base Station 1). The network resources consumed by such a user include a code, some of the power of the base station power amplifier (e.g., 100 mW), and some bandwidth on the "backhaul" interface between the base station and the radio network controller (RNC) (e.g., 15 kbps). Assume that this user moves to the region between two base stations as indicated by Case II. The user will simultaneously communicate with Base Station 1 and Base Station 2 via two radio links. Such simultaneous communication between the user and multiple base stations using multiple radio links is called soft handoff/handover. The user consumes more network resources in soft handoff. More specifically, the user will need two codes for two base stations, a total of 30 kbps backhaul bandwidth with 15 kbps on each of the base station- RNC interfaces, and some power (e.g., 150 mW) in each base station. Observe in Figure 3.2 that the user is in the border region between two base stations and is consuming one radio link with each base station. A user may be in a region where three base stations can provide adequate signal quality. Furthermore, the user can consume two radio links instead of just one radio link per base station. The scenario where the user communicates with a given base station using more than one radio link is called “softer handoff.” In this scenario, the user would be consuming resources on a total of six radio links (i.e., three base stations and two links per base station)! If the network were to limit the number of base stations to one or two, the base stations that are not communicating with the user device would cause significant interference. As is evident from Figure 3.2, the network resources consumed by a given subscriber in a wireless network vary quite significantly for a given level of service depending upon the user’s mobility. As one more example, when the user’s device communicates with three base stations in a three-way handover, it may consume about three times the resources consumed by a user’s device communicating with a single base station. Note that there is no such equivalent situation for the wireline case.

Now, let’s discuss Scenario II, in which “reasonable” in “reasonable network management” faces a real test. Consider the case of a video transmission in three-way handoff. This situation is similar to Case II in Figure 3.2; the difference is that the device is now communicating with three base stations instead of two. Assume that a 384 kbps data rate is assigned to the video “call.” A total of three channels are consumed by this call. Significant amounts of power and redundancy[11] would be required to maintain such a high data rate call at a low error rate. In this case, the wireless network may use about nine times the total bandwidth a wireline network would use to provide an equivalent video quality. This factor of nine assumes redundancy by a factor of three and the three-way handoff. Such a high demand may result in the bandwidth-limited system handling fewer voice calls. As a comparison, approximately 32 voice calls can be supported when each call uses the data rate of 12.2 kbps, where the number 32 is obtained as 384 kbps/12.2 kbps. What is “reasonable” in this situation? Is it "reasonable management" to maintain the video link since it was established before the voice call requests? Is it "reasonable management" to deny service to 32 (or more) users for the sake of one user? Does it matter that

[11] Redundancy is the process of sending repetitive information to compensate for bit errors that may occur because of the channel. If we want to get 100 bits reliably across the wireless channel, we would have to add redundancy. For example, from a simplistic perspective, we may send the same set of 100 bits three times so that the original set of 100 bits can be recovered even if the hostile radio environment introduces errors on some of the bits. Coding is one of the mechanisms used to introduce redundancy.

this one video call would be cheaper to maintain than 32 (or more) separate voice calls with the same aggregate bit rate, but higher overhead to maintain? The point is that radio resource management and traffic prioritization is a complex issue, one that must be driven by unreliable propagation and limited bandwidth. The best design does the best job possible to satisfy aggregate customer satisfaction in the particular circumstances, which will differ from network to network, at different locations within networks, and with time. All of these engineering decisions must be made in milliseconds but we understand that the FCC can take months and years to decide cases. The real world environment and the proposed regulatory overlay are simply incompatible.

Accomplishing the optimal design and most "reasonable" management is a matter of significant experimentation via R&D design efforts and lab and field verification. Furthermore, such design undergoes significant changes with new wireless standards (e.g., from basic UMTS to HSPA) and new applications that create new demands on the network. Unless and until wireless resources become available in abundance to absorb significant variations in resource requirements (especially with the emergence of 4G technology), regulation of traffic prioritization and management is simply infeasible and would discourage beneficial experimentation and innovation.

The bottom line is that net neutrality regulation is undesirable in the wireless context; it cannot be achieved without substantial negative impacts on performance and consumer welfare. Attempting to develop metrics to quantify "reasonable management" will be a moving target and will be impossible to determine until the new applications are introduced and network deployment and management has stabilized, which is unlikely to happen anytime soon, if ever.

4. The FCC's Proposed Net Neutrality Regulations for Wireless: Technical Challenges and Objections

In this section, we discuss the major technical obstacles to implementing the FCC's specific proposed net neutrality regulations for wireless communications. Rapidly evolving wireless networks, dynamic nature of the radio environment, explosive growth in wireless data traffic, and scarcity of wireless network resources pose non-trivial challenges to the implementation of net neutrality principles in wireless networks. Section 4.1 addresses technical objections to implementing the "reasonable" network management exception to the proposed regulations. Issues associated with the first three rules (*i.e.*, "any content," "any device," and "any application") are highlighted in Section 4.2. Section 4.3 discusses the very substantial obstacles and objections to the fifth rule, "nondiscrimination," and Section 4.4 discusses challenges of implementing the sixth rule, "transparency."

4.1 "Reasonable" Network Management

The six net neutrality rules proposed by the FCC are subject to "reasonable" network management. Figure 4.1 summarizes the main issues with quantifying and then enforcing "reasonable" network management.

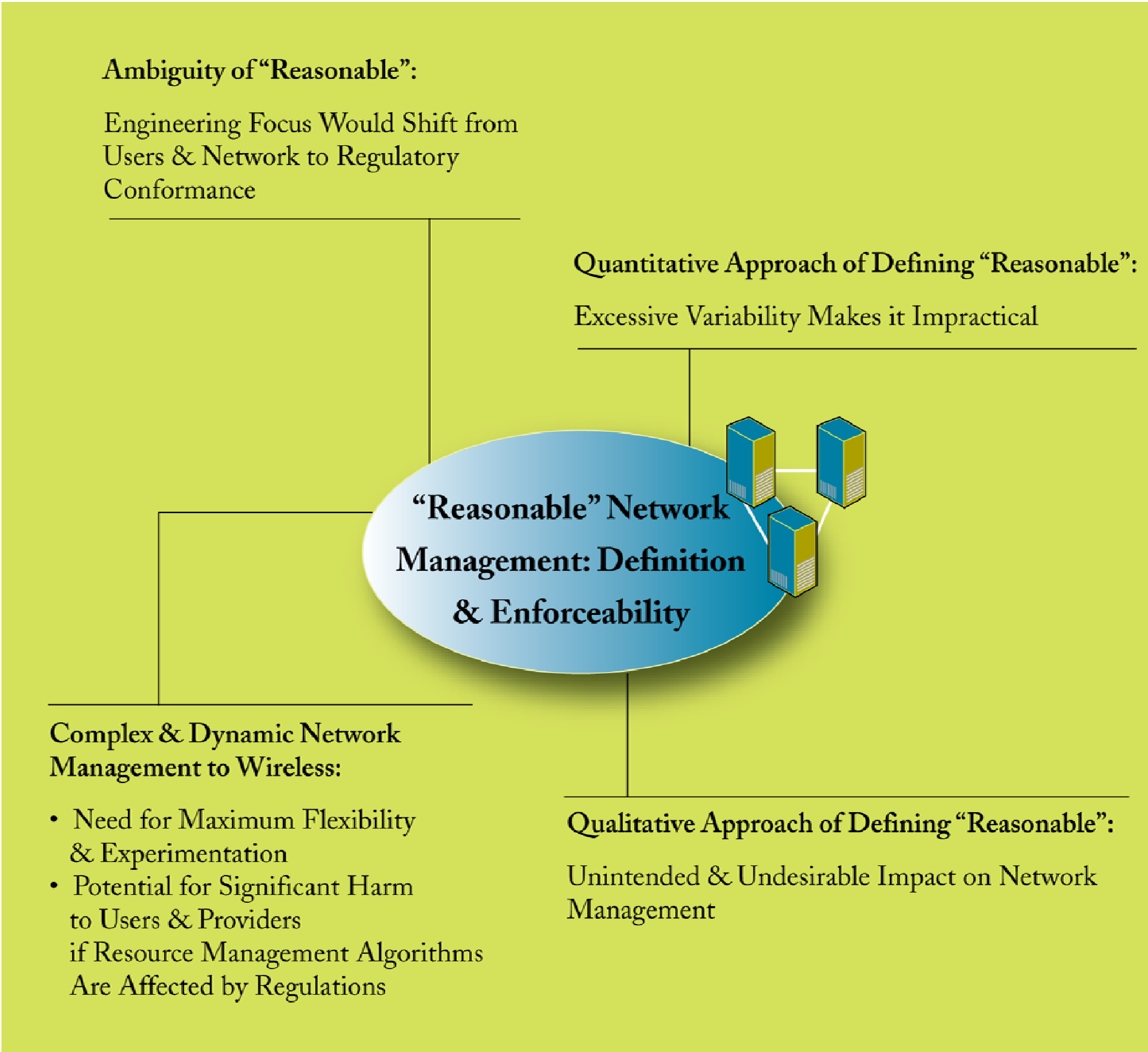

Figure 4.1. Issues with Reasonable Network Management

Network management in a wireless network is extraordinarily *complex* and has no parallels in a wireline network. The radio environment, proprietary resource management algorithms, and ever-changing wireless standards and wireless networks make network management not only complex but also *dynamic*. Recall that different resource management algorithms try to perform their assigned functions to optimize network performance and user experience. These proprietary (i.e., non-standardized and protected by Intellectual Property Rights), implementation-specific, highly complex, and technology-specific algorithms need extensive initial R&D design efforts, lab trials, and field trials. *The importance of this experimentation cannot be overly emphasized.* History has shown since the introduction of AMPS and GSM that we have achieved tremendous gains in capacity through experimentation. For example, the industry has achieved substantial capacity gains though better deployment practices (e.g., more efficient frequency planning) and improved network optimization via modifying antenna-related network parameters. Experimentation is even more critical for more complex emerging 4G technologies, such as LTE and WiMAX. We have just started applying advanced technologies, such as OFDMA (Orthogonal Frequency Division Multiple Access) and MIMO (Multiple Input Multiple Output), to a mobile wireless network. Any FCC rule that creates constraints that discourages experimentation or that forces changes counter to design assumptions and principles could seriously damage network performance and the user experience. Wireless networks are already complex; any FCC regulations guiding even just the high-level constraints on network management would serve only to further complicate their management. Such regulations would significantly reduce the *flexibility* currently available to engineers and would stifle innovation. Providers and consumers alike would suffer as a result of sub-optimal algorithm design if such algorithms were to adhere to some perceived or actual network management constraints or if fear of punishment due to an *ex post facto* determination of "unreasonableness" were to limit experimentation.

The NPRM calls for "reasonable" network management; "reasonable" is not a technical term but a vague political term that represents an unspecified set of compromises between service providers, numerous application providers, standardization groups, and equipment manufacturers, each with their own agenda. Political pressure to tailor system performance for specific applications is not going to result in a globally optimal solution. The ambiguity of "reasonable" will cause strife among service and application providers, especially in light of the complex radio resource management environment of any wireless system. The end result could be that radio resource management decisions would be made in court!

Even if we were to attempt to *quantify* "reasonable" using a set of performance metrics, verifying conformance would be yet another enormous hurdle. The achievable performance metrics would be constantly changing. Recall that the dynamic nature of the radio environment, the proprietary resource management algorithms, and the ever-changing wireless standards and wireless networks make the network performance vary significantly. To understand the challenges associated with quantifying "reasonable," let's consider a simple performance metric for a wireless network providing Internet connectivity—the *highest* data rate. We can define a hypothetical guideline to quantify "reasonable": "Management is reasonable as long as the access provider allocates to the user the data rate of *no more than X* kbps (or '*no less than Y* kbps')". Observe that we are simply specifying the highest data (or lowest) rate that could possibly be allocated to a user. Now, let's try to estimate the value of *X or Y*, which will depend upon a number of factors: the technology (e.g., HSPA and EDGE); the operator's network configuration (e.g., the maximum number of available time slots in EDGE and the maximum amount of available power and maximum number of available codes in HSPA); and the device capabilities (e.g., HSDPA category 10 and category 12). As the technology changes or the network is upgraded, we must change the value of *X*! Numerous detailed technical assumptions, such as the number of time slots, the number of codes, the amount of power, and the device capability would also need to be attached to a given value of *X* kbps. A user device with HSDPA category 10 can support a maximum data rate of about 14 Mbps when power and codes are not a constraint. On the other hand, a user device with HSDPA Category 11 and 12 can support the maximum instantaneous data rate of 2 Mbps. As is evident from this simple example, a quantitative metric for "reasonable" would be continuously evolving. How would we ever determine in practice reliably and without adversely affecting the network and users answers to following questions: (i) What data rate was actually experienced by any particular user at any particular time? (ii) What differences might be considered material or real? (iii) Was it "reasonable" under the circumstances to respond to the particular radio and user environment with some differentiation or limits? Expecting a regulatory authority to keep pace with ever-changing networks and standards would be impractical as well as resource-intensive and burdensome. Our very simple performance metric led to a conflict, and we did not even delve into the actual data rate experienced by the user. The dynamic nature of the radio environment, the limited amount of wireless network resources, and the technology-specific proprietary resource management algorithms would make it impossible to *guarantee* any specific average data rate.

Since the quantitative approach to defining “reasonable” is problematic, let’s try a *qualitative approach*. We could have a hypothetical guideline such as, “Management is reasonable as long as the network does not degrade the user experience after granting the user access to the network.” Recall that various resource management algorithms work in parallel to optimize network performance and user experience. If several new VoIP calls arrive and the network resources are being fully utilized, a commercial network commonly either downgrades the user-perceived QoS or even tears down the existing connections. In fact, observation of the emerging standardized QoS framework in IMS and PCC reveals that a given application has a certain allocation and retention priority, and network management algorithms would certainly offer preferential treatment to higher-priority applications. Though it may seem unfair to downgrade an already-admitted application in favor of new application requests, keep in mind that different applications have different QoS needs. Email requires integrity of data (i.e., packets being error free) but can tolerate delay in delivering packets. Typical email applications involve background downloads of email to mobile devices and hence can easily tolerate a temporary reduction in data rates. Our hypothetical guideline would seriously handicap an engineer’s ability to design for optimal overall network performance and optimal overall user experience. Basically, even a qualitative approach to defining “reasonable” has an undesirable impact on network management.

Design of various network management algorithms requires a razor-sharp focus on network performance and user experience within the constraints of scarce wireless resources. Engineers cannot operate in an environment in which their actions are judged *ex post facto* with no quantifiable and repeatable metrics. Regulations such as those the FCC is currently proposing would wreak havoc in the rapidly evolving environment of wireless networks. Various network management practices must be tailored on the fly to address particular situations, and much more experimentation is necessary for efficient evolution and performance.

In summary, defining “reasonable” for wireless network management is quite difficult and inadequately verifiable. Any constraint on wireless network management, arising as a result of the definition of “reasonable” or otherwise, would surely degrade both network performance and user experience.

4.3 The Proposed "Access to Any Content," "Access to Any Applications/Services," And "Any Device" Rules

Although the first three rules proposed by the FCC may appear relatively straightforward, they carry undesired consequences for wireless systems. In particular, the "any device," "any application" and "any content" rules, if applied literally, could create serious problems.

Tethering a computer to a wireless handset provides a good illustration of the problems associated with applying an "any device" or "any application" rule to wireless networks. Several wireless operators forbid tethering on some devices and/or allow tethering for some devices for a separate monthly fee. From the technical perspective, this strategy is quite reasonable and desirable. As we have explained, wireless network resources are quite precious. Tethering could cause a significant increase in data activity, which would significantly impact the performance for other users within the cell (and in adjacent cells). Restrictions on tethering help to maintain reasonable quality of service for all uses and users, and such limits, including special fees to reflect disproportionate impact of tethering on system resources, should remain in place until wireless systems have sufficient capacity to support those applications/devices. Such restrictions or fees should, of course, be disclosed to the user as part of subscription plans, protecting consumer choice and consumer rights.

Now, let's turn our attention to the "any application" and "any content" rules. As a general matter, wireless consumers today typically can download and run any lawful application compatible with the device and operating system they have chosen and access any content they want, subject to the provider's terms of service and the capabilities of the consumer's device. Mandating that wireless operators allow consumers to run *any* application and prohibiting wireless operators from imposing *any* application or content restrictions could cause large-scale problems. Let's look at an example. During the early days of Napster (a music-sharing application), some universities had to shut off access to Napster because it overwhelmed their networks -- networks with much greater capacity than cellular networks. These types of problems with new services are accentuated in wireless networks because their resources are scarcer. Consider a scenario in which users in a cell start using real time video streaming. If several users started using such applications, the wireless network could be quickly overwhelmed. This is a near-term possibility since a cell-phone can now be used to project a high-definition video on a big screen for better viewing experience. Wireless networks must remain agile to respond to unforeseen issues with new applications and services.

In summary, universal application of "any device," "any application," and "any content" rules can create grave issues for a wireless network.

4.4 The Fifth Principle: "Nondiscrimination"

The FCC does recognize the need to differentiate traffic in situations such as *public safety* and *public welfare*. For obvious reasons, public safety personnel should have higher priority than regular users. The standards for current technologies (e.g., UMTS and 1xEV-DO) and emerging technologies (e.g., LTE) do have features available to give priority to certain classes of users. For example, a regular user's device and a law enforcement officer's device can be configured to belong to different Access Service Classes. When these two types of users try to access the network, the law enforcement officer's device would be able to contact the network faster. Furthermore, in emergency situations (e.g., an earthquake or hurricane), certain Access Service Classes could be blocked from accessing the network at all, freeing up the network resources to emergency response agencies.

Machine-to-machine services and public welfare systems also need special consideration. For example, low-cost wireless monitoring of infrastructure, such as bridges, could ensure proper functioning and evaluate maintenance needs. Another example of wireless monitoring is smart grid. The smart grid involves monitoring electricity usage and turning on home appliances or factory processes during off-peak hours to reduce cost and improve energy efficiency [Wiki_Smartgrid]. The resources required to implement this service are very different from those needed to support video. Latency in such systems can be tolerated. But a very large number of users may need to be served, albeit with data rates that are relatively low for each device.[12] To make these welfare-enhancing machine-to-machine applications economically and technically feasible, we must have some form of differentiation. Due to the potentially enormous number of such devices and applications, the resource requirements for supporting such applications must be low for a wireless network. For example, the network may accommodate such devices and applications by giving them a lower priority and lower data rates with a commensurately lower cost, which may be exactly what the providers of those devices and applications want. Thus, in order to satisfy *all* of their potential customers, wireless network operators will need the flexibility not only to prioritize certain traffic associated with performance-sensitive applications, but also the ability to "de-prioritize" other traffic for applications that can tolerate lower levels of performance as discussed above.

Figure 4.2 summarizes why *service prioritization or traffic differentiation* for optimal user experience is necessary, not just desirable, in wireless networks.

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[12] One can also envision some smart grid applications for which timing is very critical, and those applications would demand very low latency. For example, various parts of the electric grid system need to be synchronized tightly for optimal performance.

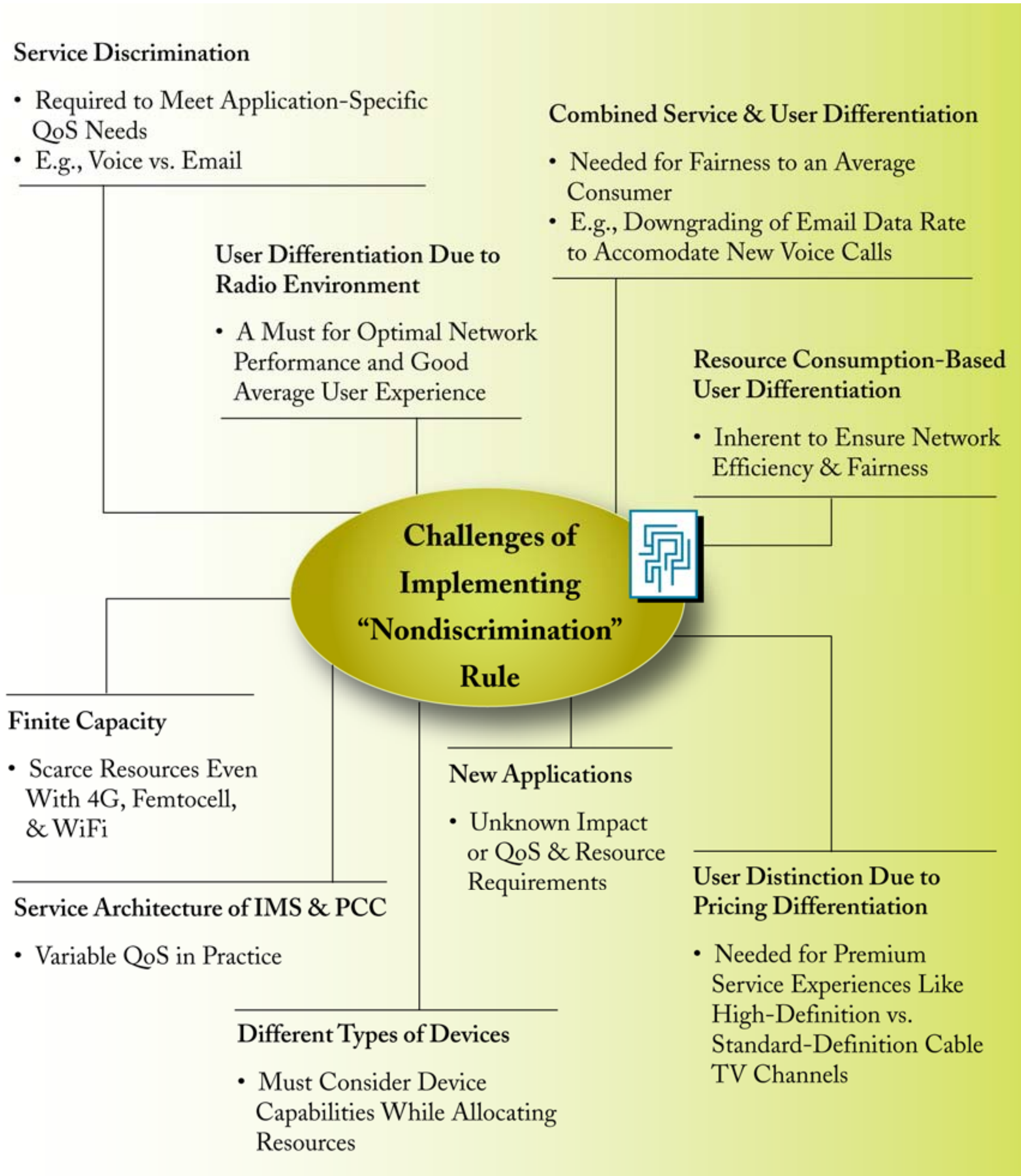

Figure 4.2. Problems of Implementing the Nondiscrimination Rule

Different applications need different qualities of service. If all types of traffic (e.g., voice, email, and video streaming) are treated equally (i.e., so called "nondiscrimination"), users would be "harmed" significantly. As a simple example, bandwidth-intensive applications, such as file downloads and video streaming, will consume a significant portion of the available network resources, ruining the user experience for delay-sensitive applications, such as voice and interactive gaming. Even the same application running on two different user devices would necessitate differentiation for overall enhanced performance as shown by Figure 4.3. In addition to the QoS for user traffic, QoS considerations are also needed for signaling (e.g., the message exchange carried out between the device and the network to set up a voice or data call). In general, signaling requires more stringent QoS than bearer traffic.

Service differentiation/discrimination is inherent in any good, efficient wireless QoS implementation strategy. In fact, the 4G LTE/PCC network architecture envisions nine QoS classes to provide differentiated performance targets for different applications and services. Table 4.1 provides examples of 3GPP-standardized QoS characteristics that numerous wireless companies have agreed upon. (The complete table is available in the standard [3GPP_23.203].) A QoS Class Indicator (QCI) specifies the QoS class. Defining different data rates for these services offers operators additional flexibility. An operator could also define proprietary QCIs. For example, QCI = 1 is suitable for applications such as VoIP. Its priority is 2, and it requires a guarantee of some minimum data rate, e.g., around 12 kbps. (Of course, keep in mind that a wireless network offers no absolute guarantees of any kind!) "Guarantee" here means that if the network agrees to grant service with QCI = 1 for a user, it will try its best to honor the granted GBR (Guaranteed Bit Rate). In the worst-case, the call may drop due to a hostile radio environment.[13]

Now, let's contrast QCI = 1 with QCI = 8. An application such as email might fall into QCI = 8. Since VoIP has more stringent delay requirements than email (e.g., 100 ms for VoIP vs. 300 ms for email), its priority is higher than email's. Also, observe that the error rate for email is lower than that for VoIP because the integrity of email bits is much more critical than the integrity of VoIP bits. So our goal is to lose no more than one of one million IP packets for email. Suitable network design, such as *convolutional coding* (which adds redundancy to the actual bits representing speech), helps achieve the target loss rate.

Table 4.1. Examples of Standardized QoS Characteristics

QoS Class Indicator (QCI)	Type of Resource	Priority	Packet Delay	Packet Loss Rate	Example Service
1	Guaranteed Bit Rate (GBR)	2	100 ms	10^{-2}	Conversation, Voice (i.e., VoIP)
8 and 9	Non-Guaranteed Bit Rate (Non-GBR)	8 & 9	300 ms	10^{-6}	TCP-Based Applications (e.g., email)

[13] The packet delay is the one-way time between the device and the edge of the operator's network, which is a gateway (such as P-GW in LTE and GGSN in UMTS/HSPA) as illustrated in Figure 2.2 in Section 2. QCI = 1 aims for a delay of less than 100 ms. (The lower the number for priority is, the higher the actual priority.) The packet loss rate of 10^{-2} = 0.01 or 1% means that an application with QCI = 1 can tolerate the loss of one of 100 packets.

3GPP has standardized QoS characteristics as a guide to network management mechanisms, but the QoS actually perceived by a given user for a given service could vary for several reasons, such as the radio environment, operator's network configuration, and technology.

User differentiation due to the dynamic nature of radio environment is fundamental to the operation of any good scheduling algorithm design. A good scheduling algorithm maximizes network performance while providing good user-perceived experience. If the scheduler treats two users with two different channel conditions (e.g., one excellent channel and one poor/noisy channel) in the same manner, the overall network performance would certainly degrade and the average user experience would also deteriorate. Consider Figure 4.3: Two users are downloading an email with a huge attachment and their channel conditions are constantly changing. Good channel conditions can support a higher data rate, and poor channel conditions support a lower rate as illustrated in Scenario 1 and Scenario 2.

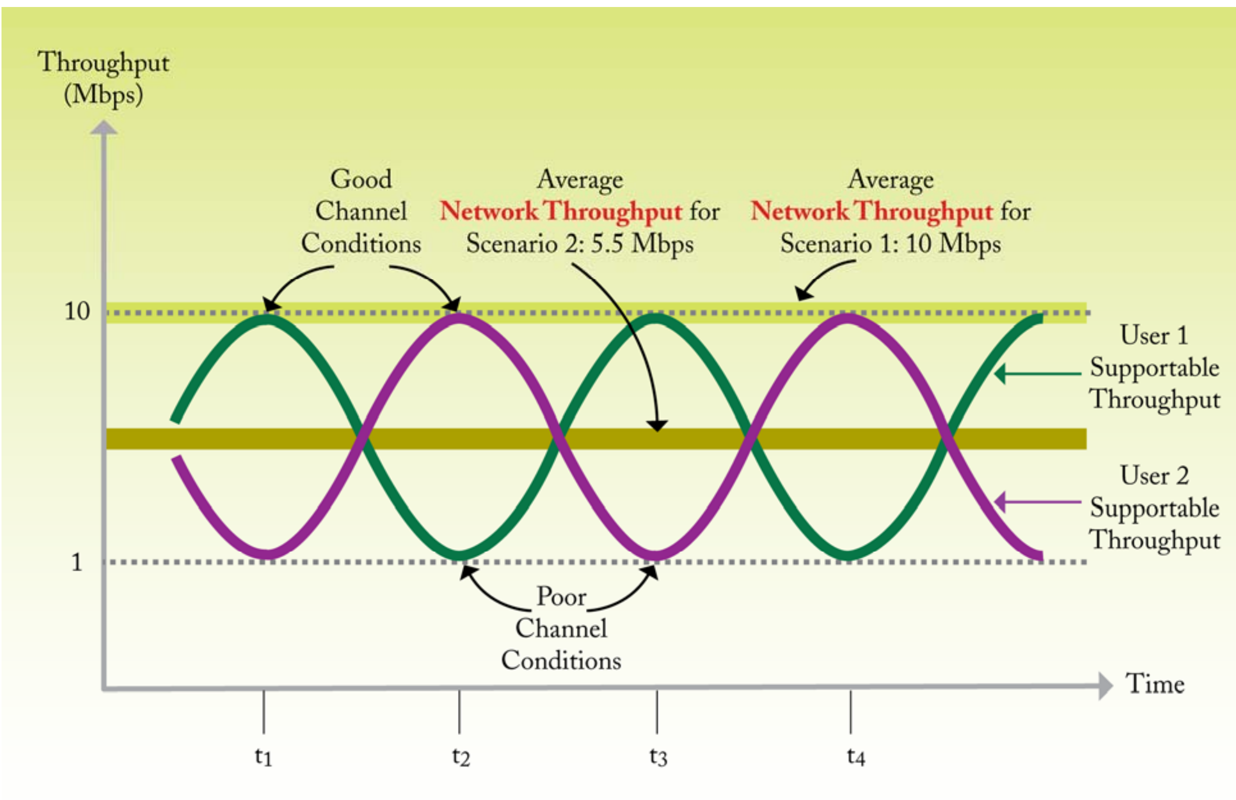

Figure 4.3. Necessity of User Discrimination due to Dynamic Radio Environment

Figure 4.3 shows the user supportable throughput when all the available resources are allocated to the user. In Scenario 1, a *high-performance scheduler* allocates all the available resources to a user with the best channel conditions and transmits packets to such user. Observe that at time t_1, User 1 has the best channel conditions and can support 10 Mbps if allocated all resources. The scheduler dedicates the entire 100% of network resources to User 1 and sends a packet to User 1 at 10 Mbps at time t_1. At time t_2, User 2 has better channel conditions, and the scheduler allocates all network resources to User 2 and sends a packet to User 2 at 10 Mbps. The average network throughput is *10 Mbps* as the network is always sending the packets at 10 Mbps. Sometimes the network sends packets to User 1, while other times, the network sends packets to User 2. The average user throughput that User 1 experiences is 50% of 10 Mbps = *5 Mbps*, and the average throughput User 2 experiences is also 50% of 10 Mbps = 5 Mbps because these users are scheduled 50% of the time.

In Scenario 2, an *equal-opportunity scheduler* equally distributes the network resources at all times. At time t_1, the network allocates 50% of resources to User 1, leading to User 1 throughput of (50% of 10 Mbps = 5 Mbps). Note that User 1 throughput is 5 Mbps and not 10 Mbps because User 1 is allocated just 50% (and not all 100%) of resources. Similarly, at time t_1, the network allocates 50% of resources to User 2, leading to User 2 throughput of (50% of 1 Mbps = 0.5 Mbps). The network throughout at t_1 is 5.5 Mbps (User 1 throughput + User 2 throughput = 5 Mbps + 0.5 Mbps= 5.5 Mbps). Now, consider time t_2, where the allocation of 50% of resources to User 1 results in User 1 throughput of (50% of 1 Mbps = 0.5 Mbps) and the allocation of remaining 50% of resources to User 2 results in User 2 throughput of (50% of 10 Mbps = 5 Mbps). Again, note that the users experience only 50% of the throughput values shown in Figure 4.3, because the throughput values correspond to a hypothetical case where all 100% of network resources are allocated to a single user. The network throughout at t_2 is (User 1 throughput + User 2 throughput = 0.5 Mbps + 5 Mbps= 5.5 Mbps). The average network throughput is then 5.5 Mbps. Let's calculate average user throughput. User 1 experiences 5 Mbps 50% of the time and 0.5 Mbps remaining 50% of the time, leading to the average user throughput of 2.75 Mbps (0.5*5 Mbps + 0.5* 0.5 Mbps = 2.75 Mbps). Similarly, the average user throughput for User 2 is also 2.75 Mbps. In other words, since the network equally distributes resources between the two users, the network throughput of 5.5 Mbps is equally divided between the two users as (5.5 Mbps/2= 2.75 Mbps).

In our simple example, the network throughput *is reduced by almost 50%* (i.e., from 10 Mbps to 5.5 Mbps) in Scenario 2 compared to Scenario 1! Just imagine what would happen to the business models of service operators if the cost of supporting their customers doubles overnight? While the scheduler has optimized network performance in Scenario 1, User 1's throughput and User 2's throughput are also better in Scenario 1 compared to Scenario 2 (e.g., 5 Mbps in Scenario 1 compared to 2.75 Mbps in Scenario 2). *Better network performance enables the service operator to cost-effectively provide services to many users simultaneously*. Subscription plans for users can then be relatively inexpensive, promoting growth of cellular subscribers and services. ***The comparison of network performance in Scenarios 1 and 2 shows that differentiation is best for the network and for all users.***

Combined service and user differentiation is also quite important. Assume that User 1 has an ongoing email application and has in the past been promised a maximum data rate of 10 Mbps, and assume further that all the network resources are being consumed by such a user. Suddenly, ten users start making voice calls. The network simply lacks the resources to simultaneously support ten voice users and an email user with a 10 Mbps data rate. If the network's resource management algorithms downgrade the email data rate to perhaps 9 Mbps, then the network can accommodate both the email user and all ten voice calls. If the network fails to differentiate between the voice users and the email user, all ten voice calls would be blocked. *In summary, user and service differentiation is essential to service fairness for the average consumer.*

Differentiation based on resource consumption is also inherent in a wireless network and facilitates network efficiency and fairness. The network management algorithms must differentiate between users based on the amounts of network resources each user is consuming. For example, current wireless networks commonly limit the amount of resources a single user can consume. If one user consumes an excessive amount of network resources due to a hostile radio environment for other users and/or he is using bandwidth-intensive data applications, that user may dominate the network so much that no other user can get any service in the absence of pro-active network management.

User differentiation based on pricing for varying levels of service (e.g., platinum level vs. gold level) will also be enabled in modern wireless networks such as LTE. Higher data rates could be allowed for a premium user, who pays more in exchange for using more network resources. This difference in pricing level is logical since more of the limited network resources are needed to support higher data rates. The 3GPP standard suggests that QCI 8 and QCI 9 could potentially be used to separate premium and non-premium subscribers [3GPP_23.203]. In addition, the "nondiscrimination" rule also prohibits an access provider from charging application and content providers for premium services. Since premium services would require specific and varying qualities of service (e.g., high-definition video streaming requires more resources and toll-quality VoIP calls require stringent performance), differentiation may be necessary here as well. Premium services strain wireless networks, so allowing the access provider to charge application or service providers for such premium services is only fair.

Different categories of devices exist in today's wireless networks. For example, HSDPA has a dozen categories of devices defined, some low-end devices with fewer capabilities and some high-end devices with more capabilities. For example, a Category 10 HSDPA device can support about 14 Mbps peak data rate, and Category 5 and Category 6 devices can support about 3.6 Mbps [3GPP_24.306]. In emerging 4G LTE technology, a Category 1 LTE device supports up to 10 Mbps, and a Category 5 device can support up to 300 Mbps [3GPP_36.306]. When a scheduling algorithm is trying to allocate resources, it must consider the device's capabilities and differentiate to optimize the device-specific user experience. As a simple example, the scheduler would not allocate a data rate higher than what the device can handle. Furthermore, additional *specialized terminals* continue to emerge (e.g. smart meters, heart monitors, e-readers, vehicle telemetry). The diverse nature of customized devices makes differentiation necessary for relevant applications.

New applications and services for wireless networks have been rapidly emerging. More than 100,000 applications are available just for Apple's iPhone. Example categories of applications include voice, video, gaming, navigation, banking, health monitoring and many others. The number of Google applications is expected to hit about 150,000 in 2010![14] According to the research firm IDC, major U.S. carriers are expected to increase capital spending from $19.3 billion in 2009 to $28.7 billion in 2011 to meet the surge in wireless data demand [DataSurge_BusWk_122309]. Such applications' resource requirements cannot be accurately predicted due to the lack of experience with such services. This mind-boggling quantity and diversity of applications adds yet another element of surprise to highly-dynamic wireless networks. Some form of traffic differentiation (e.g., higher or lower priority and higher or lower data rates) may be needed to strike an optimal balance between network performance and user experience

[14] [GoogleApps]

(e.g., individual application experience, overall experience of multiple applications perceived by a given user, and overall service experiences of multiple users).

New *service architectures*, such as *IMS and PCC*, will facilitate QoS implementation across dissimilar radio access technologies, although IMS and PCC will not be used on a large scale for quite some time. Furthermore, IMS and PCC will help provide *relative* QoS (e.g., VoIP getting higher priority than email); the user's *actual* QoS experience (e.g., how fast an email can be downloaded) will vary significantly due to the technology, the operator's network configuration, the existence of other users and their applications, and the radio environment.

In summary, a nondiscrimination rule for wireless networks is simply impractical. Any such rule will actually work *against* the FCC's goals of promoting innovation and benefiting consumers.

4.5 The Sixth Principle: "Transparency"

The general concept of transparency is a good one if it is *consumer*-focused. Some practical issues must be addressed, however. Determining how much information and what type of information consumers need to make informed purchasing decisions should be the focus. Consumers do not need highly proprietary technical data to make those decisions, and requiring it to be published could threaten both commercial interests and the security of the system.

As discussed in Section 3, many network management algorithms, such as the scheduling algorithm, are implementation-specific and are intellectual properties of network equipment manufacturers. Furthermore, some strategies related to network deployment and optimization are intellectual properties of access providers. Revealing the details of network management approaches may jeopardize those intellectual properties and hamper innovation. Furthermore, excessive transparency would undermine the competitive advantage gained from significant investments in R&D. Finally, excessive transparency may jeopardize the security of wireless networks. For instance, broadly disclosing the technical details of the interfaces and security mechanisms used in a wireless network poses a serious security threat.

In summary, deviation from a customer focus in implementing transparency could interfere with intellectual property rights and could undermine innovation and security in wireless networks.

5. Conclusion

For the reasons explained above, applying net neutrality principles to wireless networks would be a grave mistake and would cause irreparable harm to innovation, network performance, and user experience. The after-the-fact, *ad-hoc* “reasonableness” approach proposed in the NPRM would be particularly unworkable. Wireless engineers must respond to complex and dynamic performance issues on a real-time basis and they need maximal flexibility in terms of experimentation and innovation to achieve the best possible network performance and user experience. The application of the proposed net neutrality regulations would severely limit the flexibility currently available to engineers. We strongly recommend against the implementation of net neutrality principles in wireless networks in the best interest of wireless consumers and the entire wireless industry ecosystem, from network operators to content, device and application providers.

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Member of **Phi Kappa Phi Honor Society**

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IEEE Transactions on Signal Processing
IEEE Transactions on Circuits and Systems
IEEE Transaction on Communications
IEEE Transactions on Selected Areas of Communications
IEEE Signal Processing Letters
IEEE Communications Magazine
International Journal on Wireless Information Networks

Funding Agency Reviewer:

NSF
University of California, MICRO
Kansas 2000

Section II: Funded Research
(Principal Investigator or Co-Principal Investigator)

VT-Cornet: Virginia Tech Congitive Radio Network, ICTAS, 7/1/08 – 6/30/09 $142,580

Cryptographic API and Subsystem Simulator, SCA Technica, 1/1/09 – 9/26/09 $39,000

Cognitive Radio Network Testbed Instrumentation, Office of Naval Research, 4/15/09 – 4/14/10 $347,979

VT-Cognet: Virginia Tech Cognitive Radio Network Testbed Phase 2, ICTAS 1/12/09 – 1/11/10 $149,959

Nets Prowin: An Open Systems Approach for Rapid Prototyping Waveforms for Software Defined Radio**,** National Science Foundation, 8/1/08 – 7/31/09 $12,000 (asking for additional REU funding)

Enhancements to OSSIE: (Open Source SCA Implementation: Embedded), Science Applications International Corporation, 4/1/07 – 90/07 $75,000

Collaborative Research: CT-T TRIESTE: A Trusted Radio Infrastructure For Enforcing Spectrum Etiquettes*,* NSF, 10/01/07 – 9/30/10, $150.000 (Reed Co-PI)

Development Design of a Cognitive Engine and Anyalysis of WRAN Cognitive Radio Algorithms, ETRI, 7/01/07 – 12/31/07 $119,999

An Integrated Tool for SCA Waveform Development, Testing, and Debugging and A Tool for Automated Estimation of DSP Resource Statistics for Waveform Components, US-Army-CERDEC Office, 6/12/07 – 6/11/08, $326,125

Software Defined Radio Waveform and Device Development and Component Deployment Using OSSIE, DOD, 7/19/07 – 7/18/10, $975,639 ($184,744 awarded to this point)

Reasoning and Learning in Adapative Wireless Networks, BBN Technologies, 10/1/07 – 12/31/10, $913,196 (Reed-Co-PI)

US/Ireland International Workshop on Next Generation Open Architectures for Software-Defined Radio, NSF, 9/15/07 – 8/31/08, $35,963

VT-CogNet: Virginia Tech Cognitive Radio Network, ICTAS, 1/1/08 – 6/30/09,$160,170 (Reed, Bose PIs)

Trade Study Of Implementation of SDR: Fundamental Limitations and Future Prospects (DARPA SEED), US Army Aviation & Missile Command, 9/11/07 – 6/30/08 (Reed PI) $115,364

CT-ISG: Assuring Security in Spectrum Agile Radio Networks, NSF, 01/01/07 - 12/31/09 $499,997 (Reed Co-PI).

Distributed Computing for Collaborative Software Radio, Office of Naval Research, 02/05/07 - 02/04/10, $533,722 ($108,728 awarded first year)

A Panel of Commercial GSM Experts For Supporting JIEDDO Operations, JIEDDO, 12/18/06 - 2/28/07 $38,275

Cognitive Radio Test-bed, Virginia Space Grant Consortium, 08/16/06 - 08/15/07 $5,000

Emerging Wireless Technologies (EWT) Technology Assessment, Rosettex, 07/03/06 - 12/31/07 $91,000

Development of a Cognitive Engine and Analysis of WRAN Cognitive Radio Algorithms, ETRI, 06/16/06 - 12/31/06 $175,554.

Wireless@Virginia Tech Group Start-up, Institute for Critical Technology and Applied Science – ICTAS, 01/01/06 - 06/30/07 $500,000.

A Low-Cost All-Band/All-Mode Radio for Public Safety, National Department of Justice (Dept. of Justice), 10/01/05 - 09/30/08 $399,816 (Reed Co-PI)

Applying Artificial Intelligence Techniques to the Development of a Cognitive Radio Engine: Assessment, Evaluation, and Implementation, Army Research Office, 10/01/05 - 06/30/06 $49,995.

Analysis of WRAN Algorithms, ETRI, 10/01/05 - 12/31/05 $86,275

NeTS PROWIN: An Open System Approach for Rapid Prototyping Waveforms for Software Defined Radios, 08/15/05 - 08/14/09 $999,995 (Reed Co-PI)

Cognitive Radios, Virginia Space Grant Consortium, 08/10/05 - 08/09/06 $5000

A Software Defined Ultra Wideband Communication System Testbed, Virginia Space Grant Consortium, 08/10/05 - 08/09/06 $5,000

Advanced Wireless Integrated Network: AWINN, Office of Naval Research, 12/20/04 - 06/24/06 $484,200 (Reed portion)

Software Defined Radios: Evolution and Application Areas, Booz Allen Hamilton, 1/1/05 - 3/15/05 $74,497

Ossie and Harriet, SAIC, 08/16/04 - 12/31/05 $300,519

CDMA 2000 System Modeling and Simulation Program, Magnolia Broadband, Inc.**,** 12/15/03 - 12/14/04 $84,500

Policy-based Resource Management in a Vehicular Ad-Hoc Network for First Responders, Naval Postgraduate School, 09/24/03 - 09/30/04 $25,431

System Level Design Approach and Methodologies For Software Defined Radios, National Imagery and Mapping Agency, 7/25/03 - 7/24/06 $189,282

Smart Antennas Research At The MPRG, Army Research Office, 06/01/03-12/31/04 $37,500

Proposal for GDDS Cluster X-SCA-Lite Architecture, General Dynamics, 05/01/03-10/31/03 $85,691.

Game Theoretic Analysis Of Radio Resource Management For Ad-Hoc Networks, Office of Naval Research, 04/01/03-03/31/06 $589,411.

Game Theory in Radio Resource Management*,* Motorola University Partnership in Research, 09/01/02 - 05/31/04 $60,000

Software Radios and Smart Antennas: Challenges for Creating Seamless Networks, Samsung Electronics, 04/08/03 - 05/15/04 $520,785

UWB Propagation Measurements, Modeling, and Communication System Enhancements, DARPA, 08/16/01 - 12/31/03 $688,620

Tactical Communications Architecture and Implementation Plan for the U.S. Customs Service, Naval Surface Warfare Center, Dahlgren, 8/16/01 - 8/15/02 $402,000

ACN Independent Innovative Research Component, Raytheon Systems, 12/1/01 - 11/30/02 $11,250

Foundation Wireless Network for Medical Applications, Carilion Biomedical Institute, 8/6/01 - 8/10/02 $75,000

Interference, Propagation, and Antenna Placement Issues for XM Radio, GM, 3/26/01 - 9/25/02 $583,527

AOL Fellowship in Wireless Home Networking Technologies, AOL, 01/01/01 - 05/15/03 $84,583

Reconfigurable Apertures and Space-Time Processing, Raytheon Systems, 05/00 - 09/02 $841,350

Advanced Wireless Technology for Aerospace Communications, Virginia Space Grant Consortium, 08/00 - 05/03 $15,000

Research and Development for IMT-2000, LG Electronics, 05/15/00 - 09/31/01 $350,000

Motorola University Partnership in Research: Overloaded Array Processing, Motorola, 09/01/00 - 08/31/02 $84,944

Multiuser Detection for Overloaded Antenna Arrays, Raytheon, 05/00 - 05/02 $1,126,194

An Investigation of Base Station Diversity For Cellular Applications - Phase II, Metawave, 02/29/00 - 02/28/01 $104,000

Broadband Channel-Adaptive Radio Modem for NGI Network Extension and Access, Hughes Research Laboratory, 10/01/99 - 11/30/01 $81,412

Research Into Signal Recovery Algorithms in Support of Spectral Spatial Interference Cancellation System (SSICS) – Phase II Research Effort, Raytheon Company, 02/01/00 - 05/15/01 $149,756

Navy Collaborative Integrated Information Technology Initiative (NAVCIITI), Office of Naval Research, 04/00 - 06/04 $9,651,087 (Reed portion $534,089)

Research into Spatial Signal Recovery Algorithms in Support of Spectral Spatial Interference Cancellation System - Phase I (SSICS), Raytheon Company, 080/2/99 - 01/10/00 $97,857

Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting, Texas Instruments, 07/01/98 - 06/30/00 $331,993

An Investigation of Base Station Diversity for Cellular Applications, Metawave Communications, 03/01/99 - 02/28/01 $179,706

International Wireless Communication Research Program, Virginia Tech Research and Graduate Studies' SEED Program, 01/01/99 to 06/30/00 $7,500

Navy Collaborative Integrated Information Technology Initiative (NAVCIITI), Office of Naval Research, 11/14/98 - 09/30/00 $2,700,000.

Enhancing the Capacity of IMT-2000 Through Turbo Coding and Smart Antennas, LGIC, 10/01/98 - 09/30/99 $122,904

Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting, Texas Instruments, 07/01/98 - 06/30/99 $132,000

Techniques for Evaluating Location Technologies, Comcast, 05/01/98 - 12/31/98 $112,154

Development of Tools for CDMA Cellular Network Planning, Innovative Global Solutions (IGS), 04/01/98 - 01/31/99 $42,889

Configurable and Robust Wireless Communications Nodes, DARPA, 07/01/97 - 12/30/00 $2,015,431

Support of Telelink System Test, Global-Net, Inc., 09/25/96 - 09/24/97 $50,000

Sprint RFI and Evaluation, Sprint Spectrum L. P., 09/26/96 - 12/31/96 $31,158

Rural MayDay/800 Call-in System Feasibility, I-95 Corridor Coalition/ Virginia Department of Transportation, 02/01/96 - 01/31/97 $299,176 (MPRG share $157,988)

A Study of Reconfigurable Receivers for Cellular and PCS, Texas Instruments, 08/25/95 - 08/25/96 $35,000

CDMA/FM Evaluation Effort, Comdial Corporation/Sigtek, 08/28/95 - 12/31/95 $25,000 (plus $7,500 CWT match)

Measured DECT System Performance in Actual Radio Channels, National Semiconductor, 10/01/94 - 2/15/96 $35,024

Investigation of BMP Impacts on Nonpoint Source Pollution Using System Analysis Procedures, Virginia Water Resource Center/U.S. Dept. of Interior, 04/01/95 - 04/30/96 $9,963

Development and Implementation Of Interference Rejection Techniques for Cellular Communications, SAIC, Center for Wireless Telecommunications (CWT), $50,000 (SAIC, 03/22/95 to 12/31/95) $25,000 (CWT, 07/01/95 to 06/31/96)

Expanded Testing of a High Capacity Adaptive Wireless Receiver, ARPA/AASERT, 08/01/95 - 07/31/98 $125,522

Co-Channel Interference Rejection for FM Mobile Phone Systems, Motorola, 01/16/95 - 09/15/9, $33,000

A High Capacity Wireless Receiver Implemented with A Reconfigurable Computer Architecture, ARPA/WAMIS, 09/94 - 08/30/97, $1,727,230 ($533,250 for the first year, $586,750 second year)

Development of a Low Power High Data Rate Spread-Spectrum Modem**,** Grayson Electronics, Virginia's Center for Innovative Technology (CIT), Center for Wireless Telecommunications (CWT), $29,833 (Grayson, 03/01/94 - 11/30/94), $13,204 (CIT, 03/01/94 - 10/31/94) and $16,000 (CWT matching funds, 04/01/94 - 06/30/95)

Rejection of Interference in AMPS Cellular Communication, ARGO Systems, VA's Center for Innovative Technology (CIT), $25,000 (ARGO Systems, 12/10/93 - 05/10/94) and $12,500 (CIT, 04/01/94 - 07/31/94)

Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz Band, Southwestern Bell Mobile Systems, 10/01/93 - 08/15/94 $70,007

University Road Connection - A Smart Highway, Virginia Dept. of Transportation, 07/01/94 - 11/01/94 $19,523.79

Development of a Spread Spectrum Transceiver for the DECT System, National Semiconductor, 07/01/94 - 06/30/95 $30,000

Investigation of a Dynamic Range Enhancer for an Electro-optic Interface, Southwestern Bell Technology Resources, Inc., 08/01/93 - 06/01/94 $45,000

IVHS Research Center of Excellence, Federal Highway Administration (FHWA), 1993 - 1998, $1 million/year for 5 years (MPRG total approximately $390,000 over performance period, $330,000 received in 93-94, 94-95, 95-96, 96-97 contract years)

Center for Wireless Communications, Center for Innovative Technology, 09/01/93 - 08/31/98, $300,000 for first year. (Anticipated total funding approximately $1,490,835 plus an additional $357,551 of cost sharing by Virginia Tech)

The Performance and Feasibility of Time-Dependent and Non-Linear Adaptive Filters for Rejecting High-Power Co-Located Co-Channel Interference, US Navy via Systems Research Center, 05/15/93 - 09/01/93, Amount: 1/2 summer session support (value approximately $3,750)

Evaluation of an NTP-Based Protocol for Paging and Advanced Data Services, MobileComm, 07/01/93 - 09/30/93 $39,986

Section III. Teaching and Advising

Classes Taught:

Graduate Courses

Cellular and Personal Communications (ECE6644)
Software Radios: A Modern Approach to Radio Engineering (ECE5674)
Digital Signal Processing (ECE5624)
Cellular (ECE 5664)

Undergraduate Courses

Implementation of Communication Systems (ECE4654)
Signal Processing (ECE4624)
Communication Systems (ECE3604)

Courses Developed:

Major Revision of ECE course 5664 to focus on systems level description and design considerations of cellular standards this will take two more years to complete and result in a textbook.
Implementation of Communication Systems (ECE 4654)
(Lab materials also developed)
Software Radios (ECE 5674)
Major Revisions on over half of lecture material (ECE 5664)

Advising: **Completed Ph.D. Dissertations**

Kyou Woong Kim, "Exploiting cyclostationarity for radio environmental awareness in cognitive radios," May 2008

Youping Zhao, "Enabling cognitive radios through radio environment maps," May 2007

Rekha Menon, "Interference avoidance based underlay techniques for dynamic spectrum sharing," April 2007 (co-advised with Dr. Michael Buehrer)

Jong-Han Kim, "On the impact of MIMO implementations on cellular networks: An analytical approach from a system perspective," March 2007

Ramesh Chembil Palat, "Performance analysis of cooperative communications for wireless networks," December 2006

Jody Neel, "Analysis and design of cognitive radio networks and distributed radio resource management algorithms," September 2006

Chris Anderson, "A software defined ultra wideband transceiver testbed for communications, ranging, or imaging." September 2006

James Hicks, "Novel approaches to overloaded array processing," August 2003

Raqibul Mostafa, **“**Feasibility of smart antennas for the small wireless terminals,” April 2003

William Newhall, “Radio channel measurements and modeling for smart antenna array systems using a software radio receiver,” April 2003

Pablo Max Robert, “Reduction in coexistent WLAN interference through statistical traffic management,” April 2003

Tom Biedka, “Analysis and development of blind adaptive beamforming algorithms,” August 2001

Srikathyayani Srikanteswara, “Design and implementation of a soft radio architecture for reconfigurable platforms,” July 2001

Rich Ertel, “Antenna array systems: Propagation and performance,” July 1999

Nitin Mangalvedhe, “Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems,” July 1999

Nishith Tripathi, “Generic handoff algorithms using fuzzy logic and neural networks,” November 1997

Paul Petrus, “Novel adaptive array algorithms and their impact on cellular system capacity,” April 1997

Jeff Laster, “Robust GMSK demodulation using demodulator diversity and BER estimation,” January 1997

Rong He, “AMPS co-channel interference rejection techniques and their impact on system capacity, August 1996

Section IV. Publications List

Books Authored or Co-Authored

1. J. H. Reed, ed., *An Introduction to Ultrawideband Communications Systems*, Prentice Hall, March 2005, ISBN: 0-13-148103-7.

2. J. H. Reed, *Software Radio: A Modern Approach to Radio Design*, Prentice Hall, May 2002, ISBN: 0-13-081158-0.

3. N. D. Tripathi, J. H. Reed, and H. F. VanLandingham, *Radio Resource Management in Cellular Systems,* Kluwer Academic Publishers, Spring 2001.

Books and Proceedings Edited

1. W. H. Tranter, B. D. Woerner, J. H. Reed, T. S. Rappaport, and P. M. Robert, *Wireless Personal Communications – Bluetooth and Other Technologies,* Kluwer Academic Publishers, 2000.

2. W. H. Tranter, B. D. Woerner, T. S. Rappaport, and J. H. Reed, *Wireless Personal Communications – Channel Modeling and Systems Engineering*, Kluwer Academic Publishers, 1999s.

3. W. H. Tranter, T. S. Rappaport, B. D. Woerner, and J. H. Reed, eds., *Wireless Personal Communications: Emerging Technologies for Enhanced Communications*, Kluwer Press, 1998.

4. T. S. Rappaport, B. D. Woerner, J. H. Reed, and W. H. Tranter, eds., *Wireless Personal Communications: Improving Capacity, Services, and Reliability*, Kluwer Press, 1997.

5. J. H. Reed, B. D. Woerner, and T. S. Rappaport, eds., *Wireless Personal Communications: Advances in Coverage and Capacity*, Kluwer Press, 1997.

6. T. S. Rappaport, B. D. Woerner, and J. H. Reed, eds., *Wireless Personal Communications: The Evolution of PCS*, Kluwer Press, 1996.

7. B. D. Woerner, T. S. Rappaport, and J. H. Reed, eds., *Wireless Personal Communications: Research Developments*, Kluwer Press, 1995.

8. T. S. Rappaport, B. D. Woerner, and J. H. Reed, editors, *Wireless Personal Communications: Trends and Challenges*, Kluwer Press, 1994.

Book Contributions

1. Y. Zhao, S. Mao, J. Neel, and J. H. Reed, “The Radio Environment Map” (Book Chapter) in Cognitive Radio Technology, B. Fette, ed., 2nd ed., Elsevier, April 2009.

2. J. Neel. J. Reed, and A. MacKenzie, “Cognitive Radio Network Performance Analysis” (Book Chapter) in Cognitive Radio Technology, B. Fette, ed., 2nd ed., Elsevier Inc., April 2009.

3. Y. Zhao, B. Le, and J. H. Reed, “Network Support: The Radio Environment Map” (Book Chapter) in *Cognitive Radio Technology*, by B. Fette, Elesvier Inc., pp. 337-363, August 2006, ISBN: 978-0-7506-7952-7.

4. J. O. Neel, J. H. Reed, and A. B. MacKenzie, “Cognitive Radio Performance Analysis” (Book Chapter) in *Cognitive Radio Technology*, by B. Fette, Elesvier Inc., pp. 501-579, August 2006, ISBN: 978-0-7506-7952-7.

5. B. M. Donlan, R. M. Buehrer, and J. H. Reed, “Ultra-wideband Wireless Systems,” in the *Encyclopedia of RF and Microwave Engineering*, pp. 5411-5423, Spring 2005, ISBN: 0-471-27053-9.

6. N. D. Tripathi, J. H. Reed, and H. F. VanLandingham, “Application of a Neurofuzzy System to Handoffs in Cellular Communications” (Book Chapter) in *Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications (Signals and Communication Technology)*, by P. Stavroulakis, Springer Publishing, May 2004, ISBN: 3540407596.

7. J. H. Reed and C. J. Rieser, "Software Radio: Technical, Business and Market Implications," in *World Market Series Business Briefing Wireless Technology 2001,* WMRC *PLC – World Markets Research Centre*, pp. 146-150, October 2000, ISBN 1-903140-36-1.

8. P. Petrus and J. H. Reed, "Co-channel Interference in Wireless Communication Systems," in *Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons, Inc., February 1999 (invited paper).

9. N. R. Mangalvedhe and J. H. Reed, "Analysis of an Eigenstructure Technique for DSSS Synchronization," in *Wireless Personal Communications: The Evolution of PCS*, Kluwer Press, 1996 (also appears in *Virginia Tech's Sixth Annual Symposium on Wireless Personal Communications*, June 1996), pp. 201-214.

10. J. D. Laster and J. H. Reed, "A Survey of Adaptive Single Channel Interference Rejection Techniques for Wireless Communications," in *Wireless Personal Communications: Research Developments*, Kluwer Press, 1995 (also appears in *Virginia Tech's Fourth Annual Symposium on Wireless Personal Communications*, June 1994), pp.29-54.

11. I. Howitt, J. H. Reed, V. Vemuri, and T. C. Hsia, "Recent Developments In Applying Neural Nets to Equalization And Interference Rejection," in *Wireless Personal Communications: Trends and Challenges*, Kluwer Press, 1994 (also appears in *Virginia Tech's Third Symposium on Wireless Personal Communications*, June 1993), pp.49-58.

Papers in Refereed Journals

1. R. Menon, A. B. MacKenzie, R. M. Buehrer, and J. H. Reed, "Interference avoidance in networks with distributed receivers," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 3078-3091, October 2009.

2. C. R. Aguayo Gonzalez, C. B. Dietrich, F. E. Kragh, S. Sayed, H. I. Volos, J. D. Gaeddert, P. M. Robert, and J. H. Reed, "Open-source SCA-based core framework and rapid development tools enable software-defined radio education and research," *IEEE Commun. Mag.*, October 2009.

3. C. R. Aguayo Gonzalez, C. B. Dietrich, and J. H. Reed, "Understanding the software communications architecture," *IEEE Commun. Mag.*, vol. 47, no. 9, September 2009.

4. S. Haykin, D.J. Thomson, J.H. Reed, "Spectrum Sensing for Cognitive Radio," *Proceedings of the IEEE,* Vol. 97, Issue 5, May 2009, pp. 849-877.

5. R. Menon, A. B. MacKenzie, J. Hicks, R. M. Buehrer, and J. H. Reed, "A game-theoretic framework for interference avoidance," *IEEE Trans. Commun.*, vol. 57, no. 4, pp. 1087-1098, April 2009.

6. J. Gaeddert, K. Bae, T. Newman, J. Reed, I. Morales, and C. H. Park, "Development of a case-based reasoning cognitive engine for IEEE 802.22 WRAN Applications," *ACM SIGMOBILE Special Issue on Cognitive Radio Technologies and Systems*, vol. 13, no. 2, pp. 37-48, April 2009.

7. A. B. Mackenzie, J. H. Reed, P. Athanas, C. W. Bostian, R. M. Buehrer, L. A. DaSilve, S. W. Ellingson, Y. T. Hou, M. Hsiao, J. M. Park, C. Patterson, S. Raman, and C. R. C. M. da

Silva, "Cognitive radio and networking research at Virginia Tech," *Proceedings of the IEEE*, vol. 97,no. 4, pp. 660-688, April 2009.

8. Y. Zhao, S. Mao, J. O. Neel, and J. H. Reed, "Performance Evaluation of cognitive radios: Metrics, utility functions, and methodology," *Proceedings of the IEEE*, vol. 97, no. 4, pp. 642-659, April 2009.

9. R. Chembil Palat, A. Annamalai, and J. H. Reed, "Accurate bit error rate analysis of bandlimited cooperative OSTBC networks under time synchronization errors," *IEEE Trans. Veh. Technol.*, vol. 58, no. 5, pp. 2191-2200, June 2009.

10. R. Menon, R. M. Buehrer, and J. H. Reed, "On the impact of dynamic spectrum sharing techniques on legacy radio systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, part 1, pp. 4198-4207, November 2008.

11. D.-K. Park, T. Saba, and J. H. Reed, "Technical Standard for unlicensed radio device on DTB band in U.S.A.," *IEICE Trans. Commun.*, (Japanese Edition), vol. J91-B, no. 11, pp. 1351-1358, November 2008.

12. R. Chen, J.-M. Park, Y. T. Hou, and J. H. Reed, "Toward secure distributed spectrum sensing in cognitive radio networks" (cognitive radio communication and networks), *IEEE J. Select. Areas Commun.*, vol. 46, no. 4, pp. 50-55, April 2008.

13. R. C. Patat, A. Annamalai, and J. H. Reed, "An efficient method for evaluation information outage probability and ergodic capacity of OSTBC systems," *IEEE Commun. Lett.*, vol. 12, no. 3, pp. 191-193, March 2008.

14. R. Chen, J.-M. Park, and J. H. Reed, "Defense against primary user emulation attacks in cognitive radio networks," *IEEE J. Select. Areas Commun.*, vol. 16, no. 1, pp. 25-37, January 2008.

15. S. Mao, X. Cheng, Y. T. Hou, H. D. Sherali, and J. H. Reed, "On joint routing and server selection for MD video streaming in ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 338-347, January 2007.

16. C. A. Gonzalez, F. Portelinha, and J. H. Reed, "Design and implementation of an SCA core framework for a DSP platform," part 1, *Military Embedded Systems Mag.*, March/April 2007 issue. Part 2 in May/June 2007 issue.

17. J. O. Neal, R. Menon, A. B. MacKenzie, J. H. Reed, and R. P. Gilles, "Interference reducing networks," *MONET Special Issue - Cognitive Radio Oriented Wireless Networks Commun.*, February 2007.

18. N. Ryu, Y. Yun, S. W. Choi, R. Chembil Palat, and J. H. Reed, "Smart antenna base station open Architecture for SDR networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 58-69, June 2006.

19. L. daSilva, G. E. Morgan, C. W. Bostian, S. F. Midkiff, J. H. Reed, C. Thompson, W. G. Newhall, and B. D. Woerner, "The resurgence of push-to-talk technologies," *IEEE Commun. Mag.*, vol. 44, no. 2, pp. 48-55, January 2006.

20. V. Srivastava, J. Neel, A. Mackenzie, J. Hicks, L. DaSilva, J. H. Reed, and R. P. Gilles, “Using game theory to analyze wireless ad hoc networks,” *IEEE Commun. Surveys Tutorials,* pp. 46-56, December 2005.

21. B. Le, T. W. Rondeau, J. H. Reed, and C. W. Bostian, “Analog-to-digital Converters,” *IEEE Signal Processing Mag.*, pp. 69-77, November 2005.

22. R. Mostafa, R. Gozali, P. M. Robert, R. Chembil Palat, B. D. Woerner, and J. H. Reed, “Design and implementation of a DSP-based MIMO system prototype for real-time demonstration and indoor channel measurements,” *Eurasip J. Applied Signal Processing*, vol. 2005, no. 16, pp. 2673-2685, September 2005.

23. R. Mostafa, A. Annamalai, and J. H. Reed, “Performance evaluation of cellular mobile radio systems with adaptive interference nulling of dominant interferers,” *IEEE Trans. Commun.*, vol. 52, no. 2, pp. 326-335, February 2004.

24. S. Srikanteswara, R. Chembil Palat, J. H. Reed, and P. Athanas, “Overview of configurable Computing machines for software radio handsets,” *IEEE Commun. Mag,*, pp. 134-141, July 2003.

25. J. D. Laster, J. H. Reed, and W. H. Tranter, “Bit error rate estimation using probability density function estimators,” *IEEE Trans. Veh. Technol.*, vVol. 52, no. 1, pp. 260-267, January 2003.

26. P. Petrus, J. H. Reed, and T. S. Rappaport, “Geometrical-based statistical macrocell channel model for mobile environments,” *IEEE Trans. Commun.*, vol. 50, no. 3, pp. 495-502, March 2002.

27. R. Mostafa, F. Alam, K. K. Bae, J. H. Reed, W. H. Tranter, and B. D. Woerner, “3G-around the world and back again,” *RF Design*, February 2002.

28. J. Hicks, S. Bayram, W. H. Tranter, R. J. Boyle, and J. H. Reed, “Overloaded array processing with spatially reduced search joint eetection,” *IEEE J. Select. Areas Commun.*, vol. 19, no. 8, pp. 1584-1593, August 2001.

29. T. Li, Y. M. Vasavada, B. D. Woerner, and J. H. Reed, “A novel direct sequence spread spectrum CDMA system with analog frequency modulation,” *International J. Wireless Inform. Networks*, vol. 7, no.1, pp. 43-53, 2000.

30. M. Majmundar, N. Sandhu, and J. H. Reed, “Adaptive single-user receivers for direct-sequence spread-spectrum CDMA systems,” *IEEE Trans. Veh. Technol.,* vol. 49, no. 2, pp. 379-389, March 2000.

31. T. E. Biedka, W. H. Tranter, and J. H. Reed, “Convergence analysis of the least squares constant modulus algorithm in interference cancellation applications,” *IEEE Trans. Commun.*, vol. 48, no. 3, pp. 491-501, March 2000.

32. S. Srikanteswara, J. H. Reed, P. Athanas, and R. Boyle, “A soft radio architecture for reconfigurable platforms,” *IEEE Commun. Mag.,* pp. 140-147, February 2000.

33. R. B. Ertel and J. H. Reed, "Angle and time of arrival Statistics for circular and elliptical scattering models," *IEEE J. Select. Areas Commun., Wireless Commun. Series*, vol. 17, no. 11, pp. 1829-1840, November 1999.

34. N. Tripathi and J. H. Reed, “Handoffs in cellular systems,” *IEEE Pers. Commun.*, pp. 26-37, December 1998.

35. R. B. Ertel and J. H. Reed, “Generation of two equal power correlated Rayleigh fading envelopes,” *IEEE Commun. Lett.*, vol. 2, no. 10, pp. 276-278, October 1998.

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3. J. H. Reed, “Distributed computing in collaborative software radio,” presented to the Office of Naval Research, May 1, 2007.

4. J. H. Reed, “Issues in cognitive wireless networks,” talk presented at the *Intel Research Forum Seminar Series*, Portland, OR, March 28, 2007.

5. J. H. Reed, “Issues in cognitive wireless networks,” talk presented at NIST, March 2, 2007.

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11. J. H. Reed, "Open architecture bridging the gap in emergency communications," guest speaker at the *International Wireless Communications Expo – IWCE Conf. Tektronix Symposium,* Las Vegas, NV, May 19, 2006.

12. J. H. Reed, "An introduction to cognitive radio and some research trends in cognitive radios," talk presented at *ETRI Cognitive Radio Workshop*, Seoul, Korea, April 2006.

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43. J. H. Reed, “Adaptive antenna arrays,” Dresden University of Technology Guest Lecture, Dresden, Germany, November 26, 1997.

44. J. H. Reed, “Overview of fundamental wireless systems in today’s telecommunications technology,” *46th Annual International Wire Cable Symposium*, Philadelphia, PA, November 17-20, 1997. (Invited tutorial.)

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60. K. Khan, J. H. Reed,and I Howitt, "Interference mitigation in AMPS/NAMPS and CMP using artificial neural networks," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

61. N. Tripathi, J. H. Reed, and H. VanLandingham, "Neural net & fuzzy logic approaches to handoffs in cellular systems," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

62. K. Saldanha and J. H. Reed, "Performance evaluation of an AMPS digital base station with automatic gain control," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

63. R. He and J. H. Reed, "System capacity improvement by ysing DSP interference rejection techniques," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

64. B. D. Woerner, T. S. Rappaport, and J. H. Reed, "Improved spectral efficiency for CDMA systems," *Wireless Technology Conf. Exposition Proceedings*, Stamford, CT, September 1995.

65. P. Petrus and J. H. Reed, "New blind multichannel filtering techniques," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

66. N. Zecevic and J. H. Reed, "Comparative study of adaptive CDMA interference rejection techniques," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

67. M. Majmundar and J. H. Reed, "Interference rejection for IS-54," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

68. D. Bailey and J. H. Reed, "MPRG: Signal processing and communications laboratory," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

69. R. He and J. H. Reed, "Co-channel interference for AMPS and NAMPS signals," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

70. N. Mangalvedhe and J. H. Reed, "An Eigenstructure technique for soft synchronization of DSSS signals," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

71. M. Welborn and J. H. Reed, "Interference rejection using model-based spectral estimation," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

72. A. Amanna, R. James, and J. H. Reed, "Communications on the smart road," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

73. F. Dominique and J. H. Reed, "Development of a frequency hopping system for the 902-928 MHz ISM band," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

74. S. Elson and J. H. Reed, "Modeling CDPD," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.).

75. P. Petrus, F. Dominique, and J. H. Reed, "Spectral redundancy exploitation in narrowband interference rejection for a PN-BPSK system," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

76. F. Cheng and J. H. Reed, "Dynamic range enhancement techniques for RF and fiber optic interface," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

77. P. Petrus and J. H. Reed, " Blind adaptive arrays for mobile communications," *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

78. R. He and J. H. Reed, "Spectral correlation of AMPS signals with applications to interference Rrejection," *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

79. R. Zheng and J. H. Reed, "System modeling and interference rejection for spread spectrum CDMA automatic vehicle monitoring systems," *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

80. N. Mangalvedhe and J. H. Reed, "An eigenstructure technique for soft spread spectrum synchronization," *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

81. R. Holley and J. H. Reed, "Time-dependent filters For CDMA interference rejection," *3rd Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1993. (Poster session.)

Technical Reports

1. Y. Zhao, "Enabling cognitive radios through radio environment maps," MPRG-TR-07- Ph.D. dissertation, May 2007.

2. R. Menon and J. H. Reed, "Interference avoidance based underlay techniques for dynamic spectrum sharing," MPRG-TR-07-, Ph.D. dissertation, April 2007.

3. J.-H. Kim and J. H. Reed, "On the impact of MIMO implementations on cellular networks: An analytical Aapproach from a system perspective," MPRG-TR-07-, Ph.D. dissertation, March 2007.

4. R. Chembil Palat and J. H. Reed, "Performance analysis of cooperative communications for wireless networks," MPRG-TR-06-, Ph.D. dissertation, December 2006.

5. J. O. Neel and J. H. Reed, "Analysis and design of cognitive radio networks and distributed radio resources management in algorithms," MPRG-TR-06-14, Ph.D. Dissertation, September 2006.

6. C. R. Anderson and J. H. Reed, "A software defined ultra wideband transceiver testbed for communications, ranging, and imaging," MPRG-TR-06-13, Ph.D. dissertation, September 2006.

7. C. R. Anderson, S. Venkatesh, D. Agarwal, R. Michael Buehrer, P. Athanas, and J. H. Reed, "Time interleaved sampling of impulse ultra wideband signals: Design challenges, analysis, and results," MPRG-TR-06-12, technical report, August 2006.

8. J.-H. Kim and J. H. Reed, "Efficacy of transmit smart antenna at mobile station in cellular networks," MPRG-TR-06-09, Ph.D. preliminary, May 2006.

9. J. A. DePriest and J. H. Reed, "A practical approach to rapid prototyping of SCA waveforms," MPRG-TR-06-06, M.S. thesis, April 2006.

10. B. M. Donlan, R. M. Buehrer, and J. H. Reed, "Ultra-wideband narrowband interference cancellation and channel modeling for communications," MPRG-TR-05-02, M.S. thesis, January 2005.

11. S. Vasudevan and J. H. Reed, "A simulator for analyzing the throughput of IEEE 802.11b wireless LAN systems," MPRG-TR-05-01, M.S. thesis, January 2005.

12. A. M. Hebbar and J. H. Reed, "Empirical approach for rate selection in MIMO OFDM," MPRG-TR-04-11, M.S. thesis, December 2004.

13. C. R. Anderson, A. M. Orndorff, R. M. Buehrer, and J. H. Reed, "An introduction and overview of an impulse-radio ultrawideband communication system design," MPRG_TR-04-07, technical report, May 2004.

14. J. Hicks and J. H. Reed, "Novel approaches to overloaded array processing," MPRG-TR-03-19, Ph.D. dissertation, August 2003.

15. R. Mostafa and J. H. Reed, "Feasibility of smart antennas for the small wireless terminals," MPRG-TR-03-12, Ph.D. dissertation, April 2003.

16. S. Krishnamoorthya and J. H. Reed, "Interference measurements and throughput analysis for 2.4 GHz wireless devices in hospital environments," MPRG-TR-03-10, M.S. thesis, April 2003.

17. P. M. Robert and J. H. Reed, "Reduction in coexistent WLAN interference through statistical traffic management, MPRG-TR-03-09, Ph.D. dissertation, April 2003.

18. W. G. Newhall and J. H. Reed, "Radio channel measurements and modeling for smart antenna array systems using a software radio receiver," MPRG-TR-03-08, Ph.D. dissertation, April 2003.

19. Y. Ahmed and J. H. Reed, "A model-based approach to demodulation of co-channel MSK signals," MPRG-TR-02-24, M.S. thesis, December 2002.

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20. R. Chembil Palat and J. H. Reed, "VT-STAR design and implementation of a test bed space-time block coding and MOMI channel measurements," MPRG-TR-02-19, M.S. thesis, October 2002.

21. W. Newhall and J. H. Reed, "Radio channel measurements, modeling, and characterization for antenna array Ssystems," MPRG-TR-02-16, Ph.D. preliminary, August 2002.

22. B.-L. Cheung and J. H. Reed, "Simulation of adaptive array algorithms for OFDM and adaptive vector OFDM systems," MPRG-TR-02-15, M.S. thesis, September 2002.

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26. P. M. Robert and J. H. Reed, "Reduction in coexistent WLAN interference through statistical traffic management," MPRG-TR-02-01, Ph.D. preliminary, August 2001.

27. R. Mostafa, R. Gozali, W. Newhall, I. Akbar, J. H. Reed, B. D. Woerner, and W. H. Tranter, "Navy collaborative integrated information technology initiative," report # 16, MPRG-TR-01-17, technical report, October 2001.

28. M. Soni, P. Athanas, and J. H. Reed, "Computing engine for reconfigurable software radio," MPRG-TR-01-15, M.S. thesis, October 2001.

29. T. E. Biedka and J. H. Reed, "Analysis and development of blind adaptive beamforming algorithms," MPRG-TR-01-14, Ph.D. dissertation, August 2001.

30. R. Gozali, R. Mostafa, P. M. Robert, R. Chembil Palat, W. Newhall, B. D. Woerner, and J. H. Reed, "Design process of the VT-STAR multiple-input multiple-output (MIMO) test bed," MPRG-TR-01-12, technical report. August 2001.

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32. S. Srikanteswara and J. H. Reed, “Design and implementation of a soft radio architecture for reconfigurable platforms,” MPRG-TR-01-10, Ph.D. dissertation, July 2001.

33. R. Mostafa and J. H. Reed, “Feasibility of transmit smart antenna at the handset,” MPRG-TR-01-07, Ph,D. preliminary, December 2000.

34. J. Hicks and J. H. Reed, “Overloaded array processing with spatially reduced search joint detection,” MPRG-TR-00-08, M.S. thesis, May 2000.

35. T. Biedka and J. H. Reed, “A general framework for the analysis and development of blind adaptive algorithms,” MPRG-TR-OO-O5, Ph.D. preliminary, April 2000.

36. S. Srikanteswara and J. H. Reed, “Design and implementation of a soft radio architecture for reconfigurable platforms,” MPRG-TR-00-02, Ph.D. preliminary, November 1999.

37. R. B. Ertel and J. H. Reed, "Antenna array systems: Propagation and performance,” Ph.D. dissertation, July 1999.

38. N. R. Mangalvedhe and J. H. Reed, “Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems,” Ph.D. dissertation, July 1999.

39. K. Phillips and J. H. Reed, “Probability density function estimation for minimum bit error rate equalization,” MPRG-TR-99-04, M.S. thesis, May 1999.

40. Z. Hu and J. H. Reed, “Evaluation of joint AOA and DOA estimation algorithms using the antenna array systems,” MPRG-TR-99-02, M.S. thesis, December 1998.

41. R. B. Ertel and J. H. Reed, "Antenna array systems: Propagation and performance," MPRG-TR-98-12, Ph.D. preliminary, December 1998.

42. N. R. Mangalvedhe and J. H. Reed, "Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems," MPRG-TR-98-13, Ph.D. preliminary, December 1998.

43. P. M. Robert and J. H. Reed, "Simulation tool and metric for evaluating wireless digital video systems," MPRG-TR-98-11, M.S. thesis, September 1998.

44. S. F. Swanchara and J. H. Reed, “An FPGA-based multiuser receiver employing parallel interference cancellation,” MPRG-TR-98-06, M.S. thesis, July 1998.

45. N. Tripathi and J. H. Reed, “Generic handoff algorithms using fuzzy logic and neural networks,” Ph.D. dissertation, MPRG-TR-97-18, November 1997.

46. D. Breslin and J. H. Reed, “Adaptive antenna arrays applied to position location,” MPRG-TR-97-14, M.S. thesis, August 1997.

47. S. Nicoloso and J. H. Reed, "Investigation of carrier recovery techniques for PSK modulated signals in CDMA and multipath mobile environments," MPRG-TR-97-11, M.S. Thesis, May 1997.

48. N. Tripathi, J. H. Reed, and H. VanLandingham, "An adaptive direction biased fuzzy handoff algorithm with unified handoff candidate selection criterion," MPRG-TR-97-08, April 1997.

49. N. Tripathi, J. H. Reed, and H. VanLandingham, "An adaptive algorithm using neural encoded fuzzy logic system," MPRG-TR-97-07, April 1997.

50. N. Tripathi, J. H. Reed, and H. VanLandingham, "A new class of fuzzy logic based adaptive handoff algorithms for enhanced cellular system performance," MPRG-TR-97-06, April 1997.

51. B. Fox and J. H. Reed, "Analysis and dynamic range enhancement of the analog-to-digital interface in multimode radio receivers," MPRG-TR-97-02, February 1997.

52. A. Alexander, S. Panchapakesan, D. Breslin, J. H. Reed, T. Pratt, and B. D. Woerner, "The feasibility of performing TDOA based position location on existing cellular infrastructures," MPRG-TR-96-37, December 20, 1996.

53. N. Tripathi and J. H. Reed, "Handoffs in cellular systems: A tutorial," MPRG-TR-96-35, November 1996.

54. N. Zecevic and J. H. Reed, "Interference rejection techniques for the mobile unit direct-sequence CDMA receiver," MPRG-TR-96-27, August 1996.

55. K. J. Saldanha and J. H. Reed, "Performance evaluation of DECT in different radio environments," MPRG -TR-96-28, August 1996.

56. R. He and J. H. Reed, "AMPS co-channel interference rejection techniques and their impact on system capacity," MPRG-TR-96-25, July 1996.

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59. J. H. Reed, T. S. Rappaport, and B. D. Woerner, "What you should know before returning to school," *RF Design*, pp. 67-69, March 1996.

60. T. Biedka and J. H. Reed, "Direction finding methods for CDMA mobile wireless systems," MPRG-TR-96-20, June 1996.

61. Y. M. Vasavada and J. H. Reed, "Performance evaluation of a frequency modulated spread-spectrum system," MPRG-TR-96-13, February 1996.

62. M. V. Majmundar and J. H. Reed, "Adaptive single-user receivers for direct sequence CDMA systems," MPRG-TR-96-12, January 1996.

63. R. He and J. H. Reed, "Co-channel interference rejection techniques for AMPS signals using spectral correlation characteristics," MPRG-TR-96-11, January 1996.

64. J. S. Elson and J. H. Reed, “Simulation and performance analysis of cellular digital packet data,” MPRG-TR-96-08, February 1996.

65. J. D. Laster and J. H. Reed, “Improved GMSK demodulation emphasizing single channel interference rejection techniques,” MPRG-TR-96-05, February 1996.

66. M. Welborn and J. H. Reed, “Co-channel interference rejection using model-based demodulator” MPRG-TR-96-04, January 1996.

67. F. Dominique and J. H. Reed, “Design and development of a frequency hopper based on the DECT system for the 902-928 MHz ISM band,” MPRG-TR-96-02, January 1996.

68. P. Athanas, I. Howitt, T. S. Rappaport, J. H. Reed, and B. D. Woerner, “A high capacity adaptive wireless receiver implemented with a reconfigurable computer architecture,” MPRG-TR-18, November 1995.

69. N. Mangalvedhe and J. H. Reed, “An eigenstructure technique for direct sequence spread spectrum synchronization,” MPRG-TR-95-04, April 1995.

70. Y. M. Kim, N. Mangalvedhe, B. D. Woerner, and J. H. Reed, “Development of a low power high data rate spread-spectrum modem,” MPRG-PPR-95-01, February 1995.

71. Y. M. Kim, N. R. Mangalvedhe, B. D. Woerner, and J. H. Reed, “Development of a low power high data rate spread-spectrum modem,” MPRG-PPR-95-02, June 1995.

72. P. Petrus and J. H. Reed, “Blind adaptive antenna arrays for mobile communications,” MPRG-TR-95-01, December 1994.

73. S. Yao and J. H. Reed, “Differential detection of GMSK signals,” MPRG-TR-94-27, October 1994.

74. R. Zheng, J. Tsai, R. Cameron, L. Beisgen, B. D. Woerner, and J. H. Reed, “Capacity and interference resistance of spread-spectrum automatic vehicle monitoring systems in the 902-928 MHz ISM Band,” MPRG-TR-94-26, final report to Southwestern Bell Mobile Systems, October 1994.

75. F.-S. Cheng and J. H. Reed, “A new approach to dynamic range enhancement,” MPRG-TR-94-25, October 1994.

76. R. S. Zheng and J. H. Reed, “Channel modeling and interference rejection for CDMA automatic vehicle monitoring systems,” MPRG-TR-94-21, November 1994.

77. R. He and J. H. Reed, “AMPS interference rejection: Blind time-dependent adaptive filtering - Volume I,” final report to ARGO Systems Inc., MPRG-TR-94-19, July 1994.

78. T. H. Qazi and J. H. Reed, “Model-based demodulation of FM signals - Volume II,” MPRG-TR-94-17, final report to ARGO Systems, August 1994.

79. M. Subramanian and J. H. Reed, “Noncoherent spread-spectrum communication systems,” MPRG-TR-94-14, August 1994.

80. F. Cheng, A. Kelkar, I. Jacobs, and J. H. Reed, "Performance evaluation for the dynamic range enhancement technique (DRET)," MPRG-TR-94-10, final report to Southwestern Bell Technology Resources, September 1994.

81. V. Aue and J. H. Reed, "Optimum linear single user detection in direct-sequence spread-spectrum multiple access systems," MPRG-TR-94-03, March 1994.

82. R. Holley and J. H. Reed, "Time dependent adaptive filters for interference cancellation in CDMA systems," MPRG-TR-93-15, September 1993.

Other Papers and Reports

1. P. M. Robert and J. H. Reed, "Va. Tech finds soft radio's missing link," *EE Times*, August 2004.

2. J. H. Reed, T. C. Hsia, and H. Etemad, "Differential demodulation of BPSK using time dependent adaptive filtering," final report to California MICRO Program, 1992.

3. J. H. Reed, "Adaptive filters and their application to interference rejection," *Defense Electronics*, pp. 85-86 and 89-90, May 1989.

4. W. Gardner, B. G. Agee, W. A. Brown, C. K. Chen, J. H. Reed, and R. S. Roberts, "A comparison of Fourier transformation and model fitting methods of spectral analysis," Signal and Image Processing Lab Report No. SIPL-86-4, Department of Electrical and Computer Engineering, University of California, Davis, 1986. (Also in *Statistical Spectral Analysis — A Non Probabilistic Theory*, Prentice-Hall.)

Journal Papers in Review

1. J. O. Neel, J. H. Reed, R. P. Gilles, and A. B. MacKenzie, "A low complexity dynamic rrequency selection algorithm for cognitive radio," submitted to IEEE *J. Select. Areas Commun. - Special Issue: Cognitive Radio*, March 2007.

2. C. R. Anderson, S. Venkatesh, J. Ibrahim, R. M. Buehrer, and J. H. Reed, "Performance and analysis of a time-interleaved ADC array for a software-defined UWB receiver," submitted to *IEEE Trans. Circuits, Signals, Syst.*, March 2007.

3. R. Chembil Palat, A. Annamalai, and J. H. Reed, "Efficient bit error rate analysis of bandlimited cooperative OSTBC networks under time synchronization errors," submitted to *IET Commun.*, January 2007.

4. R. Menon, R. M. Buehrer, and J. H. Reed, "On the impact of dynamic spectrum sharing technologies on legacy radio systems," submitted to *IEEE Trans. Wireless Commun.*

5. J. H. Reed, A. B. MacKenzie, et al., "Cognitive radio and networking research at Virginia Tech," submitted to *Special Issue - IEEE Spectrum*, September 2006.

Selected Corporate Report Topics:

- Software Radios
- A DSP-Based Receiver for the New North American Digital Cellular Standard

- Spread Spectrum Detection Techniques
- Cyclic Spectral Analysis of Modulated Signals
- Projection of Future High-Volume Digital Communication Systems
- A High Speed Digital Filter for Sample Rate Conversion
- A Least-Squares System Identification Method
- Cyclic Adaptive Filtering for Interference Rejection
- Implementation Issues of Adaptive Interference Rejection Techniques
- Investigation of Modern Spectral Analysis Techniques
- The Performance of Time-Dependent Adaptive Filtering of Real Data
- A Maximum-Likelihood Estimator for Tracking and Detecting Frequency Hopping Signals
- Digital Signal Processing Algorithms for Squelch Control
- A Low-Cost Whitening Filter for Jammer Applications
- Time-Dependent Single Channel and Multi-Channel Interference Rejection Algorithms

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Section V. Public Service/Outreach

Industrial Affiliate/
Outside Agency Contacts:

Co-Leader for the SDR Forum and Object Management Group of Smart Antenna API standardization efforts 2008-2009

Co-Leader for workshop on SDR held in Ireland on May 12 – 16, 2008.

Session chair or co-chair at regional, national or international conferences 2007-2008

DARPA panel member to identify and create new programs for DARPA to support NSA. This activity is expected to result in $60 – $80m in new DARPA programs

Session Chair for the SDR Forum 2007, Denver, CO, November 5 – 9, 2007

Keynote Speaker at the *Communications Technology Program Review, Planning Assessment Meeting*, "Distributed computing for collaborative software defined radio," Naval Research Laboratory, May 2007.

Advisory Board member for the *IEEE International Conf. Ultrawideband (ICU)*, September 2005.

Moderator for the paper session "Ultrawideband Design Approaches," at the *Communications Design Conf.*, March - April 2004.

Moderator for the panel, "UWB Panel on Communication Systems Design," at the *Communications System Design Conf.*, October 2003.

Chair of session titled, "Mobile Computing and Software Defined Radios," at the *International Conf. Engineering Reconfigurable Systems Algorithms (ERSA)*, June 2003.

Presentation titled "Software radio: The key for enabling 4G wireless networks," at the *International Forum - 4th Generation Mobile Commun.*, Centre for Telecommunications Research, May 2003.

Co-technical program chairman for the *SDR Forum Conf.*, November 2002.

General Chair for the *UWBST Conf.*, November 2003.

Technical program chairman for the *SDR Forum/MPRG Workshop Smart Antennas*, June 2003.

Strengthened relationship with CIT via collaboration with Jean Woods on venture capital funding mission.

World International Disaster Risk Management Institute - collaborated with W. H. Tranter, A. Phadke, and S. Midkiff on a position paper which led, in part, to the establishment of the new International Disaster Risk Management Institute, a partnership among the Swiss Federal Institutes of Technology, Virginia Tech, and the World Bank Disaster Management Facility to enable countries to use applied research in wireless systems and critical infrastructure support to mitigate loss of life and property from disasters.

Invited to help DARPA define a new program in bio-mimesis, the imitation of living organisms through electronics and mechanics.

Assisted the Army Research Office in developing their five year research plan for communications.

Sponsorship:

Ahmed Darwish from Cairo University, June-September 1999
Yeongjee Chung from Korea, January-August 1999
Shinichi Miyamoto from Kobe, Japan, April 2001-March 2002
Young-Soo Kim from Seoul, Korea, February 2002-February 2003
Friedrich Jondral from Karlsruhe, Germany, April-June 2004

Francisco Portelinha from Brazil, October 2004-February 2006
Seuck Ho Won from Korea, February 2005-January 2006
Duk Kyu Park from Seoul South Korea, January 2007-February 2008
Marojevic Vuk from Spain, September 2007-January 2008
Francisco Martins Portelinha from Brazil, February 2008-March 2008
Jeong Ho Kim from South Korea, July 2008 – February 2010
Stefan Werner Nagel from Germany, August 2009 - October 2009

External Professional Service:

IEEE Transactions on Signal Processing
Associate Editor for Proceedings of the IEEE, Issue on Cognitive Radio
Associate Editor for IEEE Journal on Select Area of Communications, Issue on Cognitive Radio
Technical Program Committee for IEEE DySpan
Technical Program Committee for IEEE Conference on Communications
Technical Program Committee for CrownCom

IEEE Transactions on Antennas and Propagation
IEEE Transactions on Wireless Communications
IEEE Transactions on Communications
IEEE Transactions on Aerospace and Electronics Systems
IEEE Transactions on Selected Areas of Communications
IEEE Signal Processing Letters
IEEE Communications Magazine
IEEE Communications Letters
Army Research Office Strategic Plan
NSF Proposal Reviewer
Workshop on Biomimic (sponsored by DARPA to define a new program)
Member, Advisory Board for TechContinuum
Member of Samsung Technical Advisory Board
Reviewer for the International Journal of Electronics
Faculty Advisory Committee, Information Technology
IEEE International Conference Advisory Board Member

State/University Professional Service:

Committee/Task Force Assignments:
Participation within the Center for Wireless Telecommunications (CWT)
Department Computing Committee
Faculty Advisor to the Honor System
EE Graduate Administrative Committee (Grad AdCom)
Communications Area Committee
US Student Recruitment Strategy Task Force
Course supervisor of ECPE 5674 and ECPE 4654
ECE Department Head Search Committee
ECE Executive Committee
ECE Resource Committee
Deputy Director, MPRG
ECE Recruiting Committee

Section VI. Industrial Experience

Industrial Experience:

March 2000 - 2001

Co-founded Dot Mobile, Inc.
(Company specializes in mobile data applications including wireless-internet based applications.)

March 1986 – present

Founded Reed Engineering
(Company performs consulting in wireless communications and signal processing.)

Selected past projects:

- Samsung Technical Advisory Board (Future Forum)
- Software Architecture for Radios
- Expert witness in wireless location systems
- Evaluation of a wireless high-speed internet access system
- Evaluation of wireless/signal processing companies for acquisition
- Tutorials on software radio issues
- Adaptive interference rejection techniques
- Spread spectrum signal detection
- Expert witness for wireless power sources

August 1980

Member, Technical Staff Signal Science, Inc., Santa Clara, CA

Areas of Specialization:

- Spread spectrum detection
- Foreign technology analysis
- Computer systems administration

Nishith D. Tripathi, Ph. D.
419 Stone Bridge Circle, Allen, TX 75013
Tel.: 214-477-3516 and E-mail: nishith_t@yahoo.com

EDUCATION

VIRGINIA TECH **Blacksburg, VA**
Ph.D., Wireless Communications, August 1997, Overall GPA: 3.8/4.0
Dissertation: Generic adaptive handoff algorithms using fuzzy logic and neural networks
M.S., Electrical Engineering, November 1994, Overall GPA: 3.8/4.0

GUJARAT UNIVERSITY **Ahmedabad, India**
B.S., Electrical Engineering, September 1992
Graduated among the top 2% of the class.

TEACHING & COURSE DEVELOPMENT EXPERIENCE

(AWARD SOLUTIONS) *March '04 to Present*
Instructor
- Taught *first-time offerings* of courses at various clients to acquire new training business.
- Taught *in-person* and *web-based* (i.e., *distance-learning* via **WebEx** and **LiveMeeting**) courses at major chip-set manufacturers, infrastructure & device vendors, service operators, and tool vendors.
- Delivered in-depth LTE bootcamp multiple times using LiveMeeting for a major LTE infrastructure vendor.
- **Examples of Courses Taught**: LTE Network Planning & Design, Interworking of LTE with (1xEV-DO, 1xRTT, UMTS, and GERAN), LTE Protocols & Signaling, LTE Air Interface, WiMAX Networks and Signaling, 1xEV-DO Optimization, 1xEV-DO Rev. 0 and Rev. A, IP Fundamentals, HSDPA/HSUPA/HSPA+, UMTS R4/R5 Core Networks, UMTS Network Planning and Design
- Strived to make the training experience full of *relevant* knowledge and fun and to maximize the value of training to students.

Course Developer
- Developed an in-depth LTE Bootcamp Series for an infrastructure vendor (**Topics**: EPS Network Architecture, OFDMA/SC-FDMA, Radio Channels, System Acquisition & Call Setup, DL & UL Traffic Operations, Handover, and Antenna Techniques).
- Developed numerous instructor-led and web-based training courses by working in a team environment (**Examples**: Interworking of LTE with 1xEV-DO & 1xRTT, LTE Air Interface, WiMAX Essentials, WiMAX Network Planning, UMB, 1xEV-DO, HSUPA, Multiple Antenna Techniques, and IP Convergence).
- **Typical Course Contents**: Network architecture, air interface features, DL & UL data transmission, call setup, handover/handoff, resource management, and interworking.
- Designed outlines for several new courses.

SME Trainer
- Mentored other SMEs at Award Solutions to prepare them to teach technologies such as LTE, WiMAX, UMB, OFDM, and Advanced Antennas.
- Designed tests to evaluate readiness of other instructors and to identify areas where additional instructor efforts are required before facing the students.

Product Development Program Director
- Acquired, managed, and guided resources for timely and quality-controlled completion of following course development projects: LTE/1xEV-DO Interworking, EPC Overview, HSPA+ Overview, Fundamentals of RF Engineering, IP Convergence Overview, and Advanced Antenna Techniques.

- Devised and implemented strategies to maximize the quality of project deliverables and to accelerate the completion of the deliverables.

NORTEL NETWORKS September '97 to September '01

Educator and Presenter

- Taught "Introduction to Wireless" class at Nortel.
- Presented papers at several IEEE conferences such as VTC and ICC.
- Made presentations on topics such as data modeling, fixed wireless systems, and AI tools.
- Prepared tutorials on the standards such as 1xRTT, 1xEV-DO, and UMTS.

VIRGINIA TECH *January '93 to August '97*

Research/Teaching Assistant, MPRG, ECE

- Developed and co-taught ***a new wireless communications course*** **(DSP Implementation of Communication Systems**) as part of an **NSF** sponsored curriculum innovations program. Implemented different subsystems of a communication system (e.g., a digital transmitter, a carrier recovery system, a code synchronizer, and a symbol timing recovery system) using the **Texas Instruments** TMS320C30 DSP development system.
- Refined the class material for undergraduate and graduate signal processing classes.

PRODUCT DEVELOPMENT & RESERCH EXPERIENCE

HUAWEI TECHNOLOGIES *October '01 to March '04*

Product Manager and Senior Systems Engineer

- Designed advanced RL MAC and Power Control algorithms for a 1xEV-DO System.
- Designed various high-performance radio resource management (RRM) algorithms for the **CDMA2000** base station and base station controller. Major designed features include adaptive forward link and reverse link call admission control algorithms, dynamic F-SCH rate and burst duration assignment algorithms, R-SCH rate assignment algorithm, F-SCH burst extension and termination mechanisms, schedulers, forward link and reverse link overload detection and control algorithms, SCH soft handoff algorithm, F-SCH power control parameter assignment mechanism, adaptive radio configuration assignment algorithm, load balancing algorithm, and cell-breathing algorithm.
- Worked on the design of an RRM simulator to evaluate the performance of call admission control, load control, and scheduling algorithms for a **CDMA2000** system.
- Designed system level and network level simulators to evaluate the capacity gain of the smart antenna-based **UMTS** systems employing multiple beams.
- Resolved numerous field trial issues for **CDMA2000** systems.
- Reviewed **UMTS** RRM design and proposed enhancements related to call admission control, cell breathing, load balancing, soft capacity control, potential user control, and AMR control.
- Educated engineers through presentations to facilitate development of the **1xEV-DO** product.
- Led a team of engineers to define a comprehensive **simulation tool-set** consisting of link level simulator, system level simulator, and network level simulator to evaluate performance of CDMA systems including **IS-95**, **IS-2000**, **1xEV-DO**, **1xEV-DV**, and **UMTS**.
- Managed a group of engineers, prepared project plans, and established efficient processes to meet the requirements of the **CDMA2000** BSC product line.

NORTEL NETWORKS *September '97 to September '01*

Senior Engineer

Radio Resource Management, July '99 to Sept. '01

- Developed a comprehensive RRM simulator that models data traffic and major features of the MAC layer and physical layer. Analyzed various aspects of the RRM for several test cases. The performance results such as capacity and throughput were used in educating the service providers on the RRM for IS-2000 systems.
- Proposed a generic call admission control algorithm and filed a patent with the U.S. Patent Office.

Management of Supplemental Channels, June '00 to Sept. '01

- Designed and analyzed supplemental channel management for enhanced data performance and filed a patent with the U.S. Patent Office.

Data Traffic Modeling, Jan. '99 to Sept. '01

- Prepared a common framework for data traffic models for analysis of systems carrying data (e.g., 1xRTT and UMTS). Types of analysis include RF capacity, end-to-end performance, and provisioning. The data models for telnet, WWW, ftp, e-mail, FAX, and WAP services are considered.

Multi-Carrier Traffic Allocation, June '99 to Sept. '01

- Provided MCTA capacity improvements (compared to non-MCTA systems) that proved to be identical to the ones observed during the field-testing. Developed a method to estimate the MCTA capacity using the field data. This method was used in estimating MCTA capacity gains by RF engineering teams.

SmartRate and Related Vocoder Designs (e.g., SMV), June '99 to Sept. '01

- Provided estimates of SmartRate capacity improvements that were found to be close to the observed capacity gains in the field tests.

CDMA Based Fixed Wireless Access Systems, Sept. '97 to Dec. '98

- **Capacity Estimates**. Determined the system capacity for a variety of configurations using an IS-95 based simulator. These configurations include different rates such as 9.6 kbps and 13 kbps, different deployment scenarios such as 2-tier embedded sector and border sector, and different diversity techniques such as switch antenna diversity and phase sweeping transmit diversity. These capacity estimates were used for various project bids. The simulator utilizes propagation channel models extracted from the actual field measurements.
- **Handoff and Power Control Algorithms**. Analyzed existing handoff and power control mechanisms for fixed wireless systems and proposed new approaches.
- **Bridge between the Simulator and a Deployed System**. Developed a procedure to estimate the loading level for the simulator so that the capacity estimate from the simulator is close to the achieved capacity in real systems.
- **Switch Antenna Diversity Schemes**. Proposed three algorithms to exploit mobile switch antenna diversity. These schemes provide a low-cost solution that significantly enhances RF capacity.
- **Combined Overhead Power and Handoff Management**. Proposed a method of combined management of overhead channel power and handoff to improve capacity.

VIRGINIA TECH *January '93 to August '97*

Research/Teaching Assistant, **MPRG**, ECE

- Developed adaptive intelligent handoff algorithms to preserve and enhance the capacity and the Quality of Service of cellular systems.
- Investigated different aspects involved in dual-mode adaptive reconfigurable receivers as part of a project sponsored by **Texas Instruments**.

Research Assistant, Control Systems Group, ECE

Worked on a project sponsored by American Electric Power (AEP) to control drum level in a boiler system. Developed a process simulator to simulate the process. Applied neural and fuzzy control techniques to replace the existing 3-element PID control to mitigate the effects of process disturbances.

PHYSICAL RESEARCH LABORATORY (PRL), AHMEDABAD, INDIA Sept. '91 to Sept. '92

Research Assistant

Developed an integrated console for a distributed control system in a simulated environment using Pascal. The interactive Pascal code has an AutoCAD interface.

MAJOR PUBLICATIONS

- Author of an upcoming **book** (with Jeffrey H. Reed), "Cellular Communications: A Comprehensive and Practical Guide," ***Accepted for Publication by IEEE/Wiley***, 2010. (**Book Chapters**: Introduction to Cellular Communications, Elements of a Digital Communication System, Radio Propagation, IP Fundamentals, GSM, GPRS, EDGE, IS-95, CDMA2000 1xRTT, R99 UMTS/WCDMA, 1xEV-DO Rev. 0, HSDPA, 1xEV-DO Rev. A, HSUPA, IMS, Emerging 4G Technologies)
- Author of a **book** (with Jeffrey H. Reed and Hugh F. VanLandingham), "Radio Resource Management in Cellular Systems," Kluwer Academic Publishers, 2001.
- Author of one chapter in the book, "Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications," Editor- Peter Stavroulakis, Springer, April 2004.

RESEARCH PUBLICATIONS

- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, "Handoffs in Cellular Systems," *IEEE Personal Communications Magazine*, December 1998.
- Nishith D. Tripathi and Sarvesh Sharma, "Dynamic Load balancing for CDMA Based Wireless Systems," IEEE VTC'2001.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, "Fuzzy Logic Based Adaptive Handoff Algorithms for Microcellular Systems," IEEE VTC'99.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, "Adaptive Handoff Algorithms for Cellular Overlay Systems Using Fuzzy Logic," IEEE VTC'99.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, "Pattern Classification Based Handoff Using Fuzzy Logic and Neural Nets," Proc. of *IEEE ICC'98 (International Conf. on Communications)*, Atlanta, Georgia, vol. 3, pp. 1733-1737, 1998.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, " An Adaptive Direction Biased Fuzzy Handoff Algorithm with Unified Handoff Candidate Selection Criterion," Proc. of *IEEE VTC'98 (Vehicular Technology Conference)*, Ottawa, Canada, vol. 1, pp. 127-131, 1998.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, " An Adaptive Handoff Algorithm Using a Neural Encoded Fuzzy Logic System," Proc. of *ANNIE* (*Artificial Neural Networks in Engineering*), St. Louis, Missouri, 9-12 November, 1997.
- Nishith D. Tripathi, Jeffrey H. Reed, and Hugh F. VanLandingham, " A New Class of Fuzzy Logic Based Adaptive Handoff Algorithms for Enhanced Cellular System Performance," Proc. of the 9th International Conf. on Wireless Communications, *Wireless '97*, Calgary, Alberta, Canada, Vol. 1, pp. 145-164, 9-11 July, 1997.
- Hugh F. VanLandingham, and Nishith D. Tripathi, " Knowledge-Based Adaptive Fuzzy Control of Drum Level in a Boiler System," *Conference Record, IEEE Southcon'96*, pp. 454-459, Orlando, Florida, 1996.
- R. Krishnan, R. Monajemy, and N. Tripathi, " Neural Control of High Performance Drives: An Application to the PM Synchronous Motor drive," ***Invited Paper***, *IEEE Industrial Electronics Conf.*, Nov. 1995.
- N. Tripathi, A. Nerves, H. VanLandingham, and K. Ramu, " An Adaptive Fuzzy Controller for Damping Wind-induced Building Oscillations," *Proc. of the 10th VPI & SU Symposium on Structural Dynamics and Control*, pp. 335-344, May 8-10, 1995.
- Nishith Tripathi, Michael Tran, and Hugh VanLandingham, " Knowledge-based Adaptive Neural Control of Drum Level in a Boiler System," *Proceedings of SPIE*, vol. 2596, pp. 160-171, 1995.

PROFESSIONAL MEMBERSHIPS

Senior Member of **IEEE**. Reviewed research papers for the *IEEE Transactions on Vehicular Technology*, *IEE Electronics Letters* and the *IEEE Control Systems Magazine*.

AWARDS/RECOGNITION/HONORS

Received numerous spot awards in recognition of quick learning and exceptional teaching.
Recognized as a top-performer in the organizations in end-of-the-year evaluations.
Awarded **National Merit Scholarship** in 1986 and 1988.
Ranked in Top 15 in the statewide board exams in 1988.
Ranked in Top Ten on Subject Brilliance Search Tests in three out of four subjects in India in 1983.

PATENTS/DRAFTS (AUTHOR/CO-AUTHOR)

- Enhanced Power Control Algorithms for CDMA-Based Fixed Wireless Systems, Patent Number 6,587,442, Filed Date: October 28, 1999.
- Method and apparatus for managing a CDMA supplemental channel, Patent Number 6,862,268, Filed Date: December 29, 2000.
- Dynamic Power Partitioning Based Radio Resource Management Algorithm, Patent Disclosure No.: 11942RR, Filed Date: August 23, 2000.
- Switch Antenna Diversity Techniques at the Terminal to Enhance Capacity of CDMA Systems, Patent Disclosure No. RR2544, Filed Date: June 19, 1998.
- Adaptive Radio Configuration Assignment for a CDMA System, October 2003.
- Multi-carrier Load Balancing for Mixed Voice and Data Services, October 2003.
- Methodology for Hierarchical and Selective Overload Control on Forward and Reverse Links in a CDMA System, October 2003.
- A New Predictive Multi-user Scheduling Scheme for CDMA Systems, November 2003.
- A New Method for Solving ACK Compression Problem by Generating TCK ACKs based on RLP ACKs on the Reverse Link, October 2003.