Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
Use of Spectrum Bands Above 24 GHz For Mobile Radio Services	)	GN Docket No. 14-177
Amendment of the Commission's Rules Regarding the 37.0-38.6 GHz and 38.6-40.0 GHz Bands	)	ET Docket No. 95-183 (Terminated)
Implementation of Section 309(j) of the Communications Act – Competitive Bidding, 37.0-38.6 GHz and 38.6-40.0 GHz Bands	)	PP Docket No. 93-253 (Terminated)
Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42-43.5 GHz Band	)	RM-11664
Reassessment of Federal Communications Commission Radiofrequency Exposure Limits and Policies	)	ET Docket 13-84
Proposed Changes in the Commission's Rules Regarding Human Exposure to Radiofrequency Electromagnetic Fields	)	ET Docket 03-137

COMMENTS OF NYU WIRELESS

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TABLE OF CONTENTS

SUMMARY: THE WIRELESS INDUSTRY NEEDS MILLIMETER WAVE SPECTRUM

The FCC's recent Auction 97 is generating more than $40 Billion for 65 MHz of spectrum in the Advanced Wireless Service-3 (AWS-3) band. This is clear evidence that today's Cellular Mobile Radio Service (CMRS) licensees urgently require more capacity to meet consumer demand. Extensive studies and projections conducted by Cisco, Ericsson, and Intel all point to an even more dramatic demand for consumer data capacity in the coming years. These independent studies show the industry may expect between 60% and 100% annual increase in per-user data consumption by mobile consumers for the foreseeable future, and these are conservative projections that do not account for new applications and use cases that are sure to arise from the Internet of Things (IoT), the continued reliance on the cloud, the tactile internet, the increased provisioning of video and rich media content to mobile users, the introduction of driverless vehicles, and a vast array of machine-to-machine connections that will arise in the coming decade.[1]

The ability to increase mobile capacity, through four generations of cellular technology, has come primarily from shrinking the coverage distances of neighboring cell sites, thereby increasing capacity through greater spatial reuse of the allocated spectrum. Advances in digital signal processing, digital modulation and coding, multiple-input-multiple-output (MIMO) antenna technology, code division multiplexing, frequency domain equalization, and other technological advances now allow today's 4G *long term evolution* (LTE) cellular systems to provide tens of megabits per second data transfer rates to mobile users. However, as has been the case since the advent of the mobile communications industry, consumer demand for mobile content will continue to outstrip the technological capacities of current CMRS technology.

A remarkable fact is that over the past 40 years, as cellular services have evolved, the clock speeds and memory sizes of consumer devices have increased by many, many orders of magnitudes, yet the carrier frequencies of cellular mobile systems have been locked in between a relatively thin spectral band of approximately 450 to 2500 MHz (less than one order of magnitude) throughout the world.

Allocating new spectrum in the millimeter wave (mmWave) radio bands, in amounts that are *orders of magnitude* greater than available in today's CMRS service, is

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[1] T. S. Rappaport, " Defining the Wireless Future - Millimeter Wave Wireless Communications: The Renaissance of Computing and Communications," Keynote address, 2014 IEEE International Conference on Communications, Sydney, Australia, June 13, 2014, (http://icc2014.ieeeicc.org/speakers_28_4101586138.pdf)

one obvious way to assure that US consumers will enjoy internationally competitive mobile service for decades to come, while ensuring that the US mobile industry can reasonably keep up with ever-growing consumer data demand within a reasonable time frame[2]. As discussed below, America is far behind other countries when it comes to wireless R&D aimed at consumer usage, and an aggressive spectrum policy is a great equalizer at the disposal of the FCC. From a consumer or policy perspective, it is not prudent to expect that a new physical layer breakthrough or new cellular standard that offers orders of magnitude of increased end-user throughput using existing frequency allocations, could be developed rapidly (each generation of cellular technology requires about 10 years to develop from concept to product). Especially when one considers the onslaught of data consumption being brought about by technological advances and rapid consumer adoption of video and cloud applications, it becomes clear that new broadband spectrum allocations are urgently needed to foster development and rollout of new technologies that will support vastly greater data rates than what consumers have today.

Today, consumers are embracing unlicensed wireless local area network (WLAN) products where multi Gigabit per second (Gbps) transfer rates exist for indoor and low-mobility use through IEEE 802.11ac, IEEE 802.11ad and WirelessHD.[3] As more applications and web-based products continue to evolve, and as these multi-Gbps products proliferate, consumers will continue to expect higher data rates, and will embrace products and services that achieve massive connection speeds. This phenomenon was evident when early IEEE 802.11b WLAN systems were deployed as public hot-spots in restaurants and airports, where now WLAN has evolved to play a vital

[2] T. S. Rappaport, W. Roh, K. Cheun, "Mobile's Millimeter-Wave Makeover," *IEEE Spectrum*, Vol. *51*, No. 9, Sep. 2014.
[3] T. S. Rappaport *et al*., *Millimeter Wave Wireless Communications*, Pearson/Prentice Hall, 2015.

role in off-load for cellular customers in fixed or low-mobility scenarios.[4]

Consider the fact that future unlicensed WLAN standards will bond mmWave channels together to exceed 10-20 Gbps in the 60 GHz unlicensed bands, and similar speeds will be achieved in the 5 GHz unlicensed band with the IEEE 802.11ax standard.[5] Cellular mobile systems will need to be able to offer comparable capacity to mobile consumers, as the use cases and customer requirements drive the need for much greater data rates than what can be carried in today's CMRS. In short, the FCC must rapidly enable spectrum allocation in the mmWave bands to ensure that today's massive investment in CMRS is able to continue to meet consumer expectations and product evolution, as wireless communications enters its renaissance.

One of our goals in this filing is to show that, in light of the massive public and private investments being made by other countries in Europe and Asia, the US should use its mmWave spectrum policy to spur business formation and research and development incentives, to insure that US citizens and the US R&D community are not left behind in the move to 5G and mmWave frequencies.

Comments provided here explore how spectrum above 24 GHz can be made available to meet this growing consumer demand for mobile services, while enabling new technologies, use cases, and businesses that would benefit US citizens. All of the spectrum bands discussed in FCC 14-177 have existing (mobile) allocations, some bands have incumbent non-mobile users, and some bands have incumbent federal users. Further, all spectrum above 42.5 GHz is allocated for both federal and non-federal users

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[4] C. Na, et. al., "Measured traffic statistics and throughout of IEEE 80 2.11b public WLAN hotspots with three different applications", *IEEE Trans. Wireless Communications*, Vol. 5, No. 11, p. 3296-3305 (Nov. 2006)

[5] C. Cordeiro, "The Pursuit of Tens of Gigabits per Second Wireless Systems," *IEEE Wireless Communications Magazine*, February 2013

such that some accommodation with NTIA or Government/Non-Government (G/NG) sharing is needed.

We encourage the FCC to consider a future where CMRS carriers are not just a few nationwide carriers competing in particular markets, but where there is sufficient allocated bandwidth that many smaller entrants would be allowed to operate and thrive in particular geographic areas, or where carriers of different types could share or allocate wideband resources to meet different types of customers using the same spectrum license (e.g. enterprise customers, fixed access links, low mobility customers, and traditional mobile users). Fortunately, many new types of sharing methods, and new types of services, including G/NG sharing, are facilitated by the characteristics of mmWave technology and radio propagation. Thus, it is likely that no incumbents need be displaced by authorizing mobile use in some or all of the bands discussed, although careful attention is needed to the details of sharing and protecting incumbents.

We advocate here the use of flexible, permissive licensing with minimal restrictions on incumbent spectrum holders, so that they may rapidly and aggressively work with other constituents to implement new services and business models that may be mobile, fixed, or low-pedestrian in nature. We suggest that spectrum sharing not be disallowed, but not required, and we urge the FCC to consider auctioning off 5-10 GHz of new mmWave spectrum below 100 GHz, while also providing 5-10 GHz of unlicensed spectrum, including spectrum above 100 GHz (a technical playground of sorts), to spur economic development and new technological innovations, business, services, and use cases that will be suitable for mass consumer adoption, while providing a spectrum allocation that allows America to innovate while being technically ready to keep up with the onslaught of digital content over the next two decades.

We specifically point out, by way of an example, how current point-to-point regulations for incumbent mmWave licensees require very narrow, pencil beam antenna patterns with fixed antennas, even though future mmWave systems will use adaptive arrays that provide a spatially varying antenna beam and variable gain, based on specific operating conditions. Thus, the FCC should consider relaxing regulations, such as the antenna sidelobe requirements and spectral masks for incumbent mmWave point-to-point licensees, so that licensees may immediately support for mobile, low-mobility, as well as fixed wireless applications in currently licensed and future mmWave bands.

We also show that mmWave mobile communication raises some new radio frequency (RF) safety issues not addressed in present or proposed FCC rules. MmWave radiation is non-ionizing in nature, and hence does *not* pose new or increased RF safety risks. However, mmWaves operate at smaller wavelengths where the electromagnetic skin depth (depth of radio penetration into the body) is much smaller than at UHF or microwave frequencies. MmWave transmitters will employ adaptive antennas containing a large number of individual radiating elements, and may use new modulation and multiple access methods that excite the various antenna elements in a time-varying manner. These antenna structures will provide variable directivity and will require new measurement techniques and fine-tuning of safety standards, as the metrics used in other regulatory contexts to satisfy safety compliance are not directly applicable to these future multi-element mmWave devices. Also, present and proposed RF safety rules do not consider quantitative exposure limits above 100 GHz, and we believe it is critical for the US to look forward to these higher spectrum bands, and to remove regulatory uncertainties above 100 GHz, as spectrum use will inevitably move to these bands over time, just as clock speeds have increased from the MHz range to GHz range in personal computers.

INTERNATIONAL COMPETIVENESS ISSUES

We believe that in the global race to 5G, the US is falling behind other nations in R&D aimed at the mainstream wireless technology sector. Timely action by the FCC to make the mmWave spectrum available for commercial use, without prolonged regulatory uncertainty, will stimulate private capital formation for American product development that will result in new services and capabilities for American consumers, while also providing an influx of foreign investment and technical talent.

Figure 1 shows data from the Organization for Economic Cooperation and Development (OECD) on Information and Communications Technologies (ICT) basic R&D expenditures (BERD) as a fraction of Gross Domestic Product (GDP). Figure 1 illustrates that the US is #6 among OECD members. Major 5G researchers in the US include Qualcomm, Intel, Silicon Image, National Instruments, and Keysight Technologies.

Note that Taiwan and mainland China are not included in this data set, as they are not OECD members, yet are both very active in ICT research. In the specific area of 5G wireless communications, this *Notice* is one of the most significant activities launched by the US government, when compared to activities in other countries as discussed subsequently.

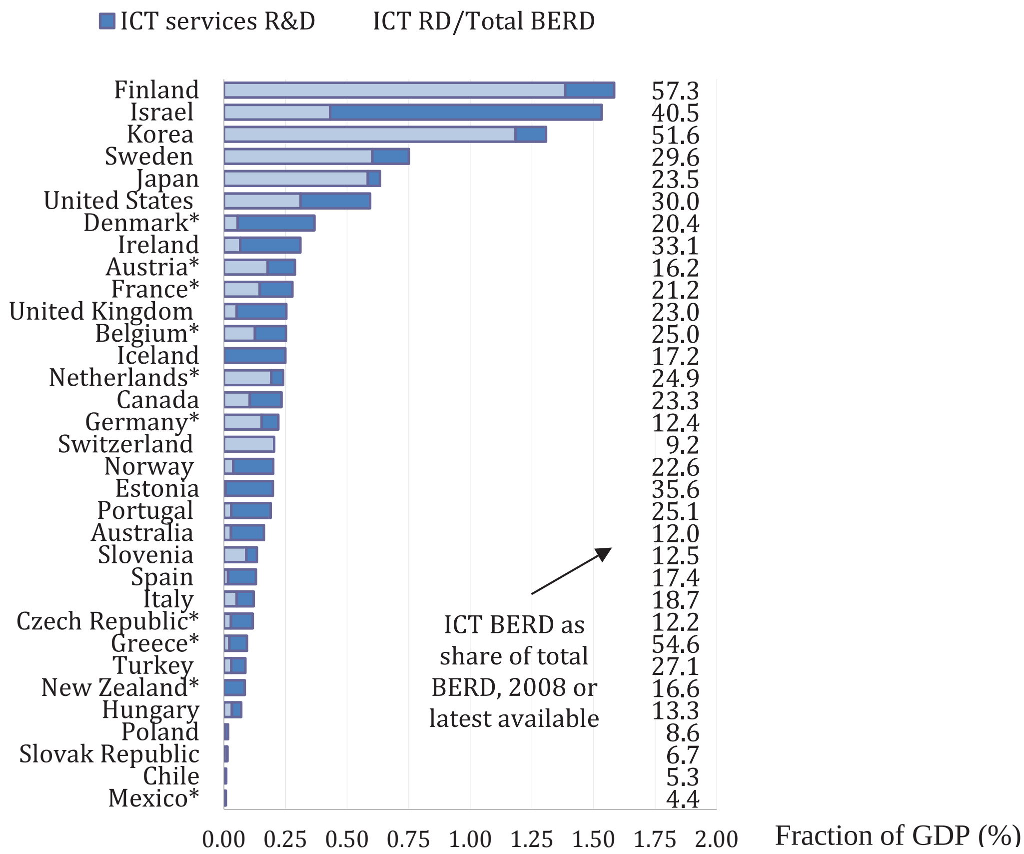

Figure 1: OECD Data on ICT Business R&D expenditures by selected ICT industries[6] (2012)

5G Support in China

As recently reported[7], China is the world's largest spender in ICT R&D, but does not appear in the OECD data. Another OECD report[8] indicates "China's intensity in research and development is driven by economic dynamism and its long-term commitment to science and technology innovation". Indeed, the *Notice* refers to "China

[6] http://www.oecd.org/sti/broadband/oecdkeyictindicators.htm
[7] http://www.universityworldnews.com/article.php?story=20141114112226407
[8] OECD Science, Technology and Industry Outlook 2014 (http://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-industry-outlook-2014_sti_outlook-2014-en)

Ministry of Science and Technology's National 863 Key Project in 5G".[9] It is reported that the Chinese Government

> … attaches great importance to the development of 5G. Ministry of Science & Technology has invested about CNY 300 million ($48M) and started the National 863 plan for major R&D projects of the fifth generation of mobile communication systems in an early stage, which attracted the participation of over 50 R&D enterprises, research institutes and universities, including Ericsson, Samsung and other international vendors.[10]

China-based Huawei alone plans to invest $600M in 5G R&D by 2020[11], although there is no public information about whether this includes national government support.

5G Support in Japan

A recent article on 5G overseas was entitled "China, South Korea commit to 5G leadership, while Japan and U.S. rely on private efforts".[12] While this was correct with respect to the US, it is not necessarily correct with respect to Japan. The Japanese counterpart of the FCC, the Ministry of Internal Affairs and Communications ("MIC"), like many of the FCC's overseas counterparts, not only is a telecom regulator but is also actively involved in communications R&D where it is "picking winners and losers". MIC has reportedly targeted the 2020 Tokyo Olympics as the roll out date for 5G, just as Japan launched the revolutionary *shinkansen*/"bullet train" at the 1964 Tokyo Olympic Games. While there do not appear to be any publicly available budgets for MIC's financial support of 5G R&D, it is clear that national government funds are involved.[13] The *Nikkei* newspaper reports "(t)he ministry may seek funds for development of 5G

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[9] *Notice* at para. 9
[10] http://www.cn-c114.net/575/a867030.html
[11] http://pr.huawei.com/en/news/hw-314871-5g.htm#.VLPE3UY8KJI
[12] http://www.fiercewireless.com/tech/story/china-south-korea-commit-5g-leadership-while-japan-and-us-rely-private-effo/2014-06-08
[13] "Japan said to plan 5G R&D investments", http://www.telecomasia.net/content/japan-said-plan-5g-rd-investments
"Japan eyes 5G mobiles by 2020 Olympic Games", http://digital.asiaone.com/digital/news/japan-eyes-5g-mobiles-2020-olympic-games

phones in the fiscal 2015 budget".[14] Other sources indicate that the use of the term "may seek funds" is a polite euphemism, and the funding will indeed be requested.[15] (Since MIC has direct access to the receipts of at least 500 yen/year (about $5) for a "spectrum usage fee"[16] on all radio transmitters in Japan, including cell phones, the availability of large R&D telecommunications support is different from present-day US-style budgeting). Japan's NTT DoCoMo maintains one of the most active and vibrant research arm of any wireless carrier on earth, and is a leader in 3GPP technology standardization.

5G Support in South Korea

It is reported that South Korea is planning to spend "1.5 billion dollars in a plan to roll out a next-generation 5G wireless network".[17] This is confirmed by other reports that the South Korean government will spend KRW 1.6 trillion or $1.46B on 5G.[18] Such expenditures dwarf any projections for R&D expenditures in the US, and demonstrate Korea's continued focus on being the most well connected country on the planet. Samsung has been one of the global leaders in pursuing 5G mmWave technologies, has conducted some of the earliest trials that demonstrate multi-Gigabit per second mobile data rates, and two of its US-based engineers, Z. "Jerry" Pi and Farooq Khan, published a landmark paper in 2011 regarding the concept of mmWave mobile communications[19]

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[14] http://asia.nikkei.com/Tech-Science/Tech/Japan-looking-to-launch-5G-mobile-service-in-2020
[15] http://www.telecomasia.net/content/japan-said-plan-5g-rd-investments
[16] http://www.tele.soumu.go.jp/resource/e/sys/fees/001.pdf
http://www.tele.soumu.go.jp/e/sys/fees/purpose/tectest/index.htm#4000249
[17] http://www.stofficeseoul.ch/13-february-2014-korean-government-investing-heavily-in-5g-technology/https://www.etno.eu/datas/press_corner/Speeches/ETNO%E2%80%99S%20CHAIRMAN%20SPEECH%20AT%205G%20EUROPE%20SUMMIT.pdf
[18] http://www.cnn.com/2014/01/22/tech/mobile/south-korea-5g/
[19] Z. Pi, F. Kahn, "An introduction to millimeter-wave mobile broadband systems," *IEEE Communications Magazine*, Vol. 49, No. 6, pp. 101-107, June 2011

5G Support in Europe

While the *Notice* mentions the European METIS program[20], it only does so in the context of the European Telecommunications Standards Institute (ETSI). While ETSI is involved, the European Union is also directly funding this effort with €50 million of funding in 2013.[21] Other EU statements show much greater funding levels being directed at R&D for future wireless technologies, where € 125 million will be awarded for the "first call for proposals" and "€ 700 million for research, development and innovation over the next seven years"[22] to be matched by another € 700 million from private firms.[23] Since this private matching funding is for a national government-supported project, the regulatory risk of this technology investment is much less than in the US, where the FCC has not yet made a specific commitment to this technology. Ericsson and Nokia are among industry leaders in 5G in Europe.

We say the above not to be critical of the FCC or US regulatory approaches, but rather as a factual statement on factors affecting private capital formation, and as motivation for the US to consider using its mmWave spectrum policy and our market access to accommodate and speed up development of new 5G wireless technologies that would benefit US consumers. While outside the scope of the present proceedings, the FCC and other US regulators and R&D agencies may wish to consider recommendations

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[20] *Notice* at para. 9

[21] European Commission Press Release, "Mobile communications: Fresh €50 million EU research grants in 2013 to develop '5G' technology", February 26, 2013 (http://europa.eu/rapid/press-release_IP-13-159_en.htm)

[22] http://ec.europa.eu/digital-agenda/en/news/5g-research-horizon-2020-webcast

[23] https://www.etno.eu/datas/press_corner/Speeches/ETNO%E2%80%99S%20CHAIRMAN%20SPEECH%20AT%205G%20EUROPE%20SUMMIT.pdf

in the 2006 National Academies Press publication “Renewing U.S. Telecommunications”[24], for ways to ensure US competitiveness in ICT R&D.

As noted above, many other countries that compete with the US ICT industry are financially supporting R&D in the mmWave area for 5G. We realize the FCC is not an R&D funding agency, and that the types of industrial R&D subsidies employed by other countries are not a part of US industrial policy. While there is some moderate NSF funding for 5G-related technologies, of which our organization has been one of the beneficiaries, it is dwarfed by government support overseas as discussed above.

In order for US wireless carriers, content providers, chip makers, network developers, internet providers, and equipment makers to compete globally, they will need access to private capital to fund R&D and to launch and try products and services in these promising multi-Gbps technologies. Access to such capital and markets depends critically on perceptions of the FCC’s support for this technology, and willingness to authorize it on a timely basis. Private sector investors do not expect 100% regulatory certainty, just as they do not expect certainly in any investments. But in order for wireless telecom R&D in the US to compete with other US industry sectors for private R&D capital, the investors need regulatory transparency and a clear understanding of when market access, in this case spectrum access, might be available.

We do not ask here for the FCC or other federal agencies to subsidize R&D as other countries do. As in the past, the US wireless industry can compete in the international arena with private capital, but only if regulatory risks are moderated and wireless spectrum is unleashed. The mmWave spectrum, as discussed below, already has mobile

[24] R.W Lucky and J. Eisenberg, editors, “Renewing U.S. Telecommunications,” National Academies Press, 2006

allocations and in some cases has incumbent licensees who offer great potential for this field. As shown below, the nature of mmWave bands makes band sharing much easier than at lower bands, and while we do not advocate the requirement of band sharing, we do advocate light-touch regulations that would foster rapid development and use of the mmWave spectrum by allowing incumbent license holders, and new future licensees, to aggressively try new wireless service models that are not specifically locked into "mobile" or "fixed". Thus, we urge the Commission to find that some or all of the bands discussed in the *Notice* for CMRS are vital for the public interest, and we suggest that the Commission begin timely rulemakings to make this spectrum available for CMRS use, and for other innovative uses, along the lines outlined herein.

INTRODUCTION TO NYU WIRELESS

NYU WIRELESS is a research center within New York University (NYU), founded in 2012 as one of the world's first academic research centers to combine wireless engineering, computing, and medical applications. But NYU is not new to the field of communications, and in fact, fostered the birth of the telecommunications era.

Samuel F. B. Morse, the inventor of the telegraph and the Morse Code, taught at NYU in its earliest days from 1832 to 1841, the period when he conceived the telegraph and extended the technology to a range of 16 km. He continued his association with the university until just prior to his death in 1872. One of his collaborators on this technology was NYU Professor Leonard Gale, who made breakthroughs in battery technology that made the telegraph practical.[25]

[25] http://en.wikipedia.org/wiki/Samuel_Morse
http://en.wikipedia.org/wiki/New_York_University
http://www.nyu.edu/greyart/information/Samuel_F_B__Morse/body_samuel_f_b__morse.html

NYU's Polytechnic School of Engineering is the nation's second oldest private engineering school and is descended from Brooklyn Polytechnic Institute. It includes the former Weber Research Institute (known prior to 1985 as the Microwave Research Institute – "MRI"), founded in 1945 by Ernst Weber at Brooklyn Polytechnic Institute as one of the world's first research centers on applications of microwave technology. MRI's annual symposia between 1952 and 1976 were key microwave technologies conferences, and their proceedings are key archives of the pioneering research of that era[26].

NYU WIRELESS was founded and is led by Prof. Theodore (Ted) Rappaport[27], a renowned expert in wireless communications who, earlier in his career, founded two academic wireless communications research centers that are among the largest in the world. His past two centers at Virginia Tech[28] and The University of Texas at Austin[29] have produced hundreds of MS and Ph.D. engineers who are employed by, and who in many cases have built and led, the wireless communications industry. NYU WIRELESS involves more than 100 students and 20 faculty members, and combines NYU's Polytechnic School of Engineering with NYU's Medical school and the Courant Institute, offering a depth of interdisciplinary expertise for the creation of new knowledge in wireless communications, computing, and medicine.

Most importantly for this proceeding, NYU WIRELESS has been a pioneer in research in terrestrial radio propagation, communication system design, and antenna technology at the millimeter wave frequencies that this proceeding deals with. With

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[26] http://en.wikipedia.org/wiki/Weber_Research_Institute#Publications
[27] http://en.wikipedia.org/wiki/Theodore_Rappaport
http://theinstitute.ieee.org/people/profiles/theodore-rappaport-at-the-forefront-of-5g
[28] http://wireless.vt.edu
[29] http://www.wncg.org

funding from the National Science Foundation[30] and with industrial funding provided by the NYU WIRELESS Industrial Affiliates program[31], NYU WIRELESS researchers have been conducting research in propagation measurements, radio channel modeling, system capacity analysis and simulation, antenna design, RF safety measurement and modeling techniques, and network design for use at mmWave frequencies. Many other research activities not related to this NOI are also underway as a routine part of NYU WIRELESS.

Part of our research activities germane to this proceeding involve the creation and dissemination to our students, faculty and Industrial Affiliate sponsors of a massive database of mmWave radio channel measurements collected from Manhattan and Brooklyn. Thus far, over 150 Gigabytes of radio channel impulse responses have been collected based on extensive radio propagation experiments in New York City. These extensive experiments and channel measurements were initiated in 2012 and are still on-going, where the campus of NYU in Manhattan and Brooklyn is used as a “living laboratory” to emulate realistic operating scenarios and real-world channel effects for base stations, mobile users, and backhaul devices in mmWave networks. Measurements are collected by customized state-of-the art ultrawideband radio transmitters and receivers (channel sounders) having spread spectrum chip rates of 400 to 800 Megachips per second, and RF bandwidths in excess of 1 GHz while using steerable directional antennas over a wide range of operating scenarios between the frequencies of 28 and 73 GHz. NYU

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[30] Recent NSF grants include:
Award Number 1320472 - NeTS Small: Collaborative Research: Exploring the 60 GHz Spectral Frontier for Multi-Gigabit Wireless Networks — Start Date 9/1/13
Award Number 1302336 - NeTS Medium: Massive Mobile Broadband Communications with Millimeter Wave Picocellular Networks — Start Date 9/1/13
Award Number 1237821 - PFI-AIR: Architectures for the Future Cellular Networks — Start Date 7/1/12

[31] Industrial Affiliate sponsors of NYU WIRELESS include: AT&T, Ericsson, Huawei, Intel, Keysight Technologies (formerly Agilent Technologies), L-3, National Instruments, Nokia, Qualcomm, Samsung, Silicon Image, and Straightpath (http://nyuwireless.com/industrial-affiliates/)

WIRELESS maintains an active measurement and propagation database dissemination program, manned by over a dozen graduate students and staff members, and measurements are used by our graduate and undergraduate students, faculty, and industrial affiliate sponsors to produce new knowledge and reliable models about mmWave wireless communication. Some of the attachments show the world's first measurements and analysis and simulation results that prove multi-Gigabit per second mobile data rates are possible in heavy urban environments like New York City, and this has spurred interest in the mmWave field. The results of our research are disseminated through technical conferences and journals, through an annual spring forum known as the *Brooklyn 5G Summit*, and through regular dialogue with our Industrial Affiliate sponsors and academicians throughout the world.

NYU WIRELESS propagation measurements are carried out with utmost of care, and the experimental approaches and operating scenarios are vetted through peer review and with experts in academia and industry. Recent publications coauthored by NYU WIRELESS researchers listed in Attachment 1, including representative technical papers[32] (see Attachments 2-5) and a new textbook[33], document key technology issues related to the subject of this NOI. The attached contributions prove that mmWave radio propagation and associated radio technologies can easily provide multi-Gigabit per second transmissions in CMRS scenarios. There is an imminent need to open up mmWave

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[32] S. Rangan, et. al., "Millimeter Wave Cellular Wireless Networks: Potentials and Challenges, *Proceedings of the IEEE*, Vol. 102, No 3, March 2014 (Attachment 2)
T. S. Rappaport, et. al., "State of the Art in 60 GHz Integrated Circuits and Systems for Wireless Communications", *Proceedings of IEEE*, pp. 1396-1430, Aug. 2011 (Attachment 3)
T. S. Rappaport, et. al., "Millimeter Wave Mobile Communications for 5G: It will work", *IEEE Access*, vol. 1, pp. 335-349, May 2013 (Attachment 3)
M. R. Akdeniz, et. al, "Millimeter Wave Channel Modeling and Capacity Evaluation," *IEEE JSAC* June 2014.

[33] T. S. Rappaport, et al., *Millimeter Wave Wireless Communications, op. cit.*

spectrum to support the evolution of this technology in the marketplace. The four attached papers are included here with the kind permission of the Institute of Electrical and Electronic Engineers ("IEEE"), the publisher and copyright holder of those works.

OVERVIEW

In the early 1980s it was generally assumed that mobile radio communications were impractical at frequencies above 1 GHz. Thus, Docket 85-172 explored increased sharing of UHF TV spectrum as a way to meet growing land mobile requirements. Wireless technologies, including reasonably priced components that are now implemented in silicon integrated circuits (many of which are a byproduct of military R&D through agencies such as SEMATECH, DARPA's Electronics System Technology Office, and the DARPA MIMIC program[34]) have now made mobile use up to the 2 GHz frequency bands an everyday occurrence, enabling devices that are ubiquitous, affordable and pocket sized.

The "conventional wisdom" that spectrum above 24 GHz, often called millimeter-wave or "mmWave."[35] could not be used for mobile communications, is challenged by new technical developments, many pioneered at NYU WIRELESS and its 12 industrial affiliate sponsors[36]. The classic wide beam sector antenna used in base stations, and omnidirectional mobile antennas used in today's CMRS systems[37] simply do not work at higher frequencies because they would be physically too small (on the order of centimeters

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34 http://www.compoundsemiconductor.net/article/85012-darpa-rattles-up-a-half-century.html

35 The formal definition of millimeter wave frequencies are where the free space radio wavelength is between 1 to 10 mm, which implies a frequency band of 30 to 300 GHz, but colloquial usage of the term "millimeter wave" implies frequencies ranging from 10 GHz to 100 GHz or above

36 *See* fn. 27, *supra*

37 Some early exploration into directional antennas at UHF/Microwave frequencies showed the potential for directional antennas in peer-to-peer networks as discussed in: G.D. Durgin, et. al., "Wideband measurements of angle and delay dispersion for outdoor and indoor peer to peer radio channels at 1920 MHz," *IEEE Trans. Ant. Prop.*, Vol. *51*, No.5, p. 936-944, May 2003

or millimeters) at 24 GHz and above, and would lead to excessive propagation path losses such that uplinks and downlinks could not be established in realistic environments with plausible transmit powers.[38] However, as frequency increases, wavelength decreases proportionally, and the small wavelengths in these bands permit multiple antenna radiating element configurations (phased array antennas) that are of small physical form factor, while also permitting antennas that are the same physical size as today's antennas but which have vastly greater gain (e.g. directional patterns) compared to today's CMRS. This is evident since for a given physical size footprint, many more antenna elements may be implemented as the wavelength is decreased[39] MIMO (multiple-input and multiple-output) technology is now widely used at lower frequencies for both CMRS and unlicensed wireless local area network (Wi-Fi) systems, and uses real time computation to adjust the power and phases of power going to and coming from antenna elements to maximize radio channel capacity or Signal to Noise Ratio.

The NOI in this proceeding contains 176 questions on a wide variety of issues relating to mobile mmWave technology and applications. To simplify the discussion, we focus on discussing a few fundamental questions, and answer other questions in the process (often without identification), and we use the question numbering scheme proposed in a

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[38] RF safety issues, battery capacity issues, and component technology all limit practical power levels in CMRS systems. For the mobile unit case, battery and RF safety issues are especially important limitations. Also, higher antenna gain is possible at base stations than at mobile units due to less size constraints on antennas. However, in practical systems without relays or cooperative multiple processing points, effective radiated power at both mobile units and base stations for a given link must be comparable.

[39] T. S. Rappaport, et. al., "State of the Art in 60 GHz Integrated Circuits and Systems in Wireless Communications", *Proceedings of IEEE*, pp. 1396-1430, Aug. 2011 (Attachment 3)
F. Gutierrez, K. Parrish, T. S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," IEEE Journal on Selected Areas in Communications, Vol. 27, Issue 8, October 2009, pp. 1367-1378.
T. S. Rappaport, et al., *Millimeter Wave Wireless Communications, op. cit.*
S. Sun, et. al, "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," IEEE Communications Magazine, Vol. 52, pp. 110-121,,December, 2014

previous filing in this proceeding.[40]

NOI QUESTIONS

Question Number	NOI Para.	Question
1	17	Will it be feasible to provide mobile services in bands above 24 GHz?

Research at NYU WIRELESS and elsewhere show that the propagation channel can be used by low cost mmWave mobile devices if cell sizes are in the 200 m range, and if adaptive beamforming or MIMO-like technology is used in base stations and mobiles. With beam combining, where receivers are able to couple energy from multiple beams simultaneously from more than one direction simultaneously, viable ranges can often be increased to 300 - 400 m.[41] In experiments conducted in New York City in 2012 and 2013 at 28 and 73 GHz, and earlier work in Austin, Texas at 38 and 60 GHz, all using our specialized 800 MHz or 1.5 GHz (first null-to-null) RF bandwidth spread spectrum channel sounding system, outage probabilities at below 40 GHz were found to be less than 15% for a wide range of random base station and receiver locations, and less than 18% at 72 GHz, and we often found no outage whatsoever at random locations throughout non-line of (NLOS) obstructed locations within a 200 meter coverage distance. Normal deployment

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[40] *Ex parte* statement of Marcus Spectrum Solutions, Docket 14-177, November 6, 2014 (http://apps.fcc.gov/ecfs/comment/view?id=60000976603)

[41] S. Sun and T. S. Rappaport, "Multi-beam antenna combining for 28 GHz cellular link improvement in urban environments," in *Proc. IEEE Global Telecommun. Conf.*, pp. 3754-3759, (Dec. 2013)
S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter wave multi-beam antenna combining for 5G cellular link improvement in New York City," *Proc. 2014 IEEE International Conf. Comm.* , pp. 5468–5473, June 2014
S. Sun and T. Rappaport, "Wideband mmwave channels: Implications for design and implementation of adaptive beam antennas," *Proc. Int. Microwave Symp. (IMS)*, pp. 1–4, June 2014.
T. S. Rappaport, "Millimeter Wave Cellular Communications: Channel Models, Capacity Limits, Challenges, and Opportunities, IEEE Communications Theory Workshop, Curacao, June 2014. (http://www.ieee-ctw.org/2014/slides/session1/Ted_Rappaport_CTW2014.pdf).

methods by carriers would ensure even better performance.[42] It should be noted these outage results were for random transmitter and receiver locations using wideband transmitter power levels of 1 Watt or less, using a single steerable beam horn antenna (with antenna gains ranging from 15 dB to 27 dB) at both the base station transmitter and mobile receiver, where the antennas were pointed to "find" the viable propagation paths. For coverage distances out to 425 m, the outage probability increased to 20% to 50% for randomly selected sites, but surprisingly good outage statistics (less than 17%, and often 0%) were found in both Austin and New York City over a wide range of locations within 200 m. Outage likelihood would be reduced, and range increased, using site-specific deployment guidelines and adaptive beam, phased array antennas with beam combining at the transmitter and receiver.[41, 43]

While rain and atmospheric attenuation are factors at larger distances and near 60 GHz, these effects will be less deleterious over shorter coverage distances, where propagation factors dominate path loss. Foliage and shadowing by people and objects will play a role in blocking signals, but early work indicates reflections and scattering paths from various directions may be quickly formed using electrical beamsteering, thus allowing a mobile link to be maintained at high speeds.

Figure 2 shows path loss at three different bands, 2.5 GHz, 28 GHz, and 73 GHz, using omnidirectional antennas. The propagation models for omnidirectional antennas at both 28 and 73 GHz predict omnidirectional path losses that, for most of the distances, are

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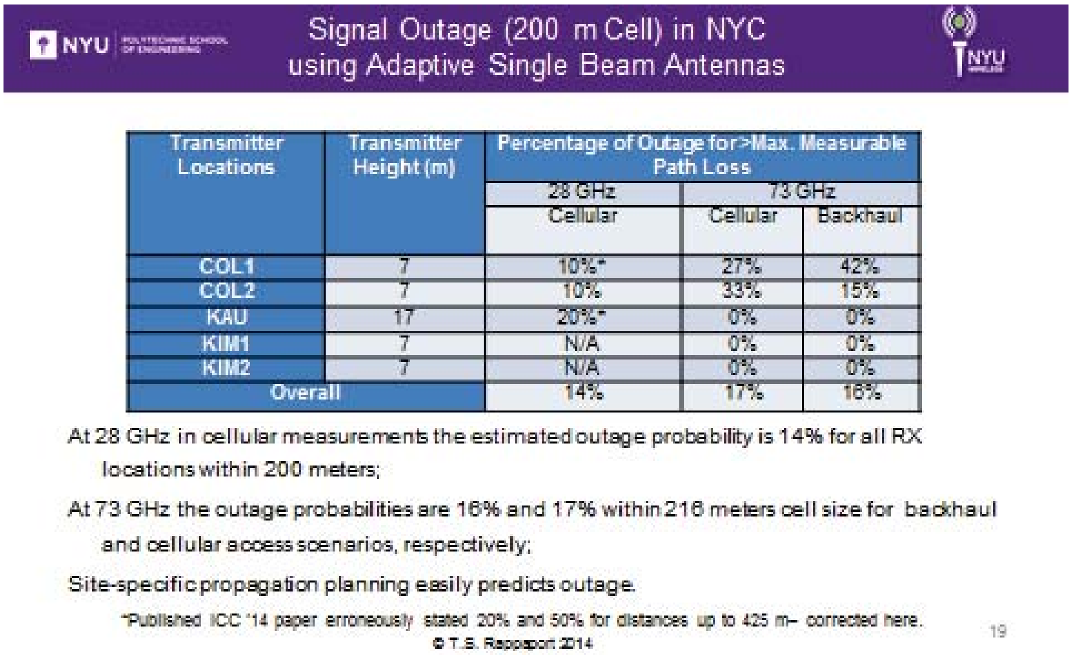
[42] T.S. Rappaport, F. Gutierrez, E. Ben-Dor, J.N. Murdock, Qiao Yijun, J.I. Tamir , " Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications, *IEEE Trans. on Antennas and Propagation*, Vol. *61*, No.4, pp.1850-1859 April 2013

[43] S. Nie, G. R. MacCartney, S. Sun, T. S. Rappaport, "28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications," 2014 IEEE Int. Conf. on Comm. (ICC), Sydney, Australia.

approximately 20-25 dB higher than the common 3GPP UMi model at 2.5 GHz.



Signal Outage (200 m Cell) in NYC using Adaptive Single Beam Antennas

Transmitter Locations	Transmitter Height (m)	Percentage of Outage for>Max. Measurable Path Loss		
		28 GHz	73 GHz	
		Cellular	Cellular	Backhaul
COL1	7	10%*	27%	42%
COL2	7	10%	33%	15%
KAU	17	20%*	0%	0%
KIM1	7	N/A	0%	0%
KIM2	7	N/A	0%	0%
Overall		14%	17%	16%

At 28 GHz in cellular measurements the estimated outage probability is 14% for all RX locations within 200 meters;

At 73 GHz the outage probabilities are 16% and 17% within 216 meters cell size for backhaul and cellular access scenarios, respectively;

Site-specific propagation planning easily predicts outage.

*Published ICC '14 paper erroneously stated 20% and 50% for distances up to 425 m– corrected here.

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19

Figure 2: Signal Outage (200 m Cell) in NYC using Adaptive Single Beam Antennas[44]

Recent work[45,46] shows that there is only about 8 dB more channel path loss for omnidirectional, unity gain 28 GHz and 73 GHz channels as compared to 1.9 GHz channels, *when all path losses are referenced to a free space path loss reference distance of 1 m at their respective frequencies.* However, note that the wavelengths at 28 and 73 GHz are approximately 10–30 times smaller than at 1.9 to 2.5 GHz. Since, for a fixed antenna area, the antenna gain grows with λ^{-2}, the increase in path loss at mmWave

[44] S. Nie , G.R. MacCartney; S. Sun, T.S. Rappaport, "28 GHz and 73 GHz signal outage study for millimeter wave cellular and backhaul communications", *Proc. 2014 IEEE Int. Conf. on Comm.*, pp. 4856 – 4861, June 2014.

[45] T. S. Rappaport *et al*., *Millimeter Wave Wireless Communications*, Pearson/Prentice Hall, 2015, ch. 3.

[46] G. R. MacCartney and T. S. Rappaport, "73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City," in *2014 IEEE International Conference on Communications (ICC)*, pp. 4862-4867, June 2014.

frequencies (the Friis loss factor of 20 log f2/f1) can be entirely overcome by applying directional antennas and beamforming at either the transmitter or the receiver. In fact, the mmWave path loss relative to today's cellular systems can be more than overcome, when beamforming is applied at both ends[47].

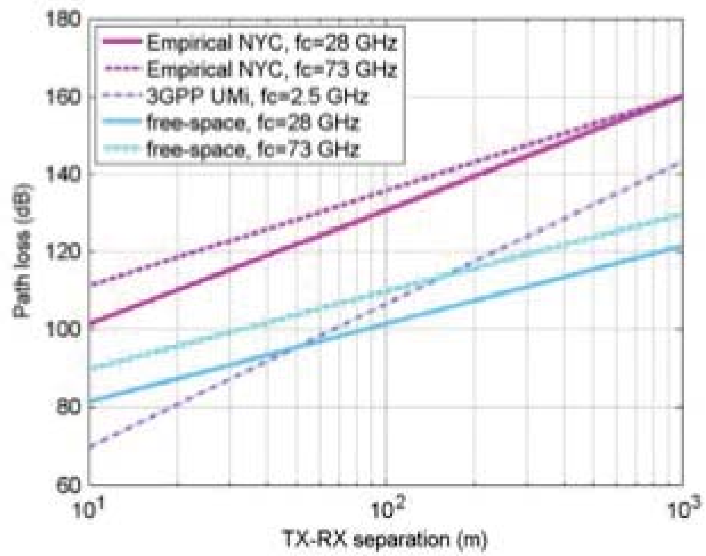

Figure 3: Comparison of distance-based path loss models with unity gain antennas. The curves labeled ''Empirical NYC'' are the experimentally derived mmWave models based on the NYC propagation measurement data. These are compared to free space propagation for the same frequencies and the 3GPP UMi model for 2.5 GHz[48].

We conclude that, barring outage events and maintaining the same physical antenna size, mmWave propagation does not lead to significant reduction in path loss relative to current cellular frequencies (our work shows, at most, no more than 8 dB more path loss above free space, on average, over 200 m propagation distances when compared to today's CMRS systems), and, in fact, path loss may be improved over today's CMRS systems using directional steered antennas. Moreover, further gains may be possible via spatial

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[47] T. S. Rappaport, et al., *Millimeter Wave Wireless Communications*, Ch. 3, 4, *op. cit*,
[48] *ibid*.

multiplexing[49]. Since Doppler speeds scale proportionally with frequency, frame and time slot durations will become smaller for mmWave systems. These time scales are much smaller than anything involving human motion, thus we are confident that adaptive beamforming, MIMO, and other signal and spatial processing methods will be easily implemented at mmWave frequencies, even at very high mobile speeds[50, 51].

2	17	To what extent will the viability of mobile service above 24 GHz be dependent on having complementary access to mobile services in lower frequency bands?

The surface area of the 50 states and the District of Columbia is 9,833,517 km^2.[52] While it is possible that the borough of Manhattan in New York City might be entirely covered by 5G systems, all at greater than 24 GHz, propagation factors limit the feasibility of nationwide coverage of larger US states or sovereign nations in the immediate future. As discussed above, with the appropriate antenna technology, mmWave spectrum can be constructively used for CMRS systems. However, this will inevitably require base station densities significantly greater than what is necessary at lower bands. The density of base stations will be exacerbated by tall vegetation, such as trees, that impact propagation. A recent published study considers the cellular network in a major city in Saudi Arabia[53]. Using propagation models from the NYU WIRELESS propagation measurement database,

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[49] S. Rangan, T. Rappaport, E. Erkip, *op. cit* at p. 373

[50] Rappaport, T.S., Shu Sun, Mayzus, R., Hang Zhao,"Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!", *IEEE Access*, May 2013 (http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6515173)

[51] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 32, pp. 1152-1163, June 2014

[52] http://water.usgs.gov/edu/wetstates.html

[53] A. I. Sulyman, A. T. Nassar, M. K. Samimi, G. R. MacCartney, T. S. Rappaport, and A. Alsanie, "Radio propagation path loss models for 5G cellular networks in the 28 GHz and 38 GHz millimeter-wave bands," *IEEE Communications Magazine*, vol. 52, pp. 78-86, September 2014

the study shows that approximately four times as many base stations will be needed per geographic area for a mobile system operating at 28 or 38 GHz to achieve comparable performance as compared to an existing CMRS system (albeit with hundreds of times greater capacity per user, given that 1 GHz channel bandwidths are provided at mmWave bands). Fewer base stations are required if beam combining techniques are used at the mobile and base station.

It is expected that mmWave mobile technology will initially be rolled out in dense urban areas, as an extension to existing 4G LTE systems, and later expand to less densely populated areas. However, the vast quantities of spectrum at mmWave also enable the use of new wireless systems that can pinpoint particular needs for pedestrian traffic, for example, within urban cores where users are largely ambulatory. Thus, it is likely that new mmWave spectrum could greatly support the off-loading of low-mobility users from smaller existing cellular channels, onto much wider bandwidth mmWave channels, thereby providing much higher user data rates. It will also be possible for mmWave to be used within buildings, with interior base stations functioning similarly to today's femtocells, where the greater wall absorption experienced at mmWave bands will actually improve the electromagnetic isolation and reduce interference between indoor and outdoor networks[54, 55]. It is not likely that mmWave spectrum will immediately support ubiquitous mobile technology over the entire USA; however, licensees of today's mmWave spectrum should be incentivized to bring this massive amount of spectrum into the marketplace

[54] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!," *IEEE Access*, vol. 1, pp. 335-349, May 2013

[55] S. Nie, G. R. MacCartney, S. Sun, and T. S. Rappaport, "72 GHz Millimeter Wave Indoor Measurements for Wireless and Backhaul Communications," *24th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, London, UK, Sep. 2013

through lighter regulation, that would allow spectrum licensees to explore new use cases, such as licensed off-loading that would help today's carriers, or to allow current licensees to implement their own "Wi-Fi like" network but in protected licensed bands, while also supporting their use for fixed backhaul (LMDS-like usage) as well as mobile use. Rules that foster immediate use and cooperation and collaboration for existing spectrum holders will help all US citizens by allowing rapid technology advances.

Today's CMRS industry generally views mmWave spectrum as a supplement to lower bands that would be particularly useful in areas where much faster data rates are needed than can be obtained with today's technologies in today's bands. The protection offered by a license ensures a long-term investment approach can be used, while assuring service quality to consumers.

While standards setting bodies such as 3GPP have not yet embarked on mmWave spectrum standardization, current thinking is that the phantom cell concept[56] is likely to be used. The phantom cell idea would uses today's incumbent UHF and microwave CMRS frequencies to carry today's extensive and increasing data communication needs, but would also provide a "control plane" to enable the use of a much higher data rate "user plane" at mmWave frequencies that could carry new types of traffic and applications far greater in bandwidth than anything used today.

We believe that new types of wireless services will evolve, beyond today's traditional licensed CMRS and unlicensed networks, if FCC policy gives new flexibility to incumbent mmWave spectrum licensees such that they could freely explore backhaul, mobility, and low-mobility services for new business models and markets for vastly greater data rates than today. We suggest that FCC policy attempt to unleash the potential of mmWave

[56] T. S. Rappaport, et al., *Millimeter Wave Wireless Communications, op. cit*., Chapt. 7,8

spectrum, so that the devices and know-how can be rapidly developed to ensure that America plays a key role in technology development and enjoys the resulting economic benefits.

The *Notice* notes that several of the bands under consideration have in excess of 1 GHz of bandwidth available:

Band	**Available Bandwidth (GHz)**
LMDS (27.5-28.35 GHz, 29.1-29.25 GHz, and 31-31.3 GHz)	1.3
39 GHz Band (38.6-40 GHz)	1.4
37/42 GHz Bands (37.0-38.6 GHz and 42.0-42.5 GHz)	2.1
60 GHz Bands (57-64 GHz and 64-71 GHz)	14.0
70/80 GHz Bands (71-76 GHz, 81-86 GHz)	10.0
24 GHz Bands (24.25-24.45 GHz and 25.05-25.25 GHz)	0.4

Table 1: Available bandwidth in various bands mentioned in *Notice*[57]

Over time, as adaptive antenna technology and low power mmWave circuits and systems are perfected for performance and low cost, it is *possible* that the lower cellular bands will become less important for future mobile systems, just as 150 MHz and 400 MHz systems of the 1950's-1970's are not used widely today in commercial consumer-based mobile communications. But total reliance on a solely mmWave frequency band for nationwide coverage appears to be unlikely for the next decade (or perhaps longer). Over time, however, say within 15 – 20 years, we are confident that nearly-ubiquitous mmWave coverage could eventually occur if FCC policy fosters investment and business formation.

[57] *Notice of Inquiry*, Docket 14-177, at para. 46-87 (October 17, 2014)

4	17	What characteristics of the anticipated technology are likely to inform the agency's determination of what regulatory framework (or frameworks) for mobile services in the mmW bands will best serve the public interest?

We believe that FCC regulation should be enabling, and not prescriptive. MmWave mobile communications technology is now cutting edge technology, and will soon become part of mainstream consumer technology. However, other mmWave technology is already in the consumer marketplace, due to previous visionary FCC actions. MmWave radar devices have been widely available for the past several years for automotive collision avoidance and sensing as well as "smart cruise controls' that maintain minimum distance from other cars. Consumer mmWave technology is also available now for the unlicensed use authorized by FCC since 1995 under the terms of § 15.255.[58] Examples include both the WirelessHD[59] and WiGig[60] standards for consumer equipment. IHS has pegged shipments of such consumer mmWave equipment at "an estimated 49 million units in 2013 (increasing) to 503 million by 2018".[61] Thus, the unlicensed consumer version of mmWave technology is already becoming a mainstream consumer item, and research for these products has influenced parallel developments for CMRS equipment.

Note when the FCC authorized ISM band technology in the 900, 2400, and 5700 MHz bands in 1985,[62] that technology was then cutting edge and without any consumer product precedent. By focusing on enabling issues in the rules for the ISM bands, the Commission allowed the later roll out, with only routine FCC equipment authorization actions, of innovative technologies such as Wi-Fi, Bluetooth, and ZigBee that were not even envisioned at the time, and were never even mentioned in the record of that

[58] 47 C.F.R. § 15.255
[59] http://www.wirelesshd.org/
[60] http://www.wi-fi.org/discover-wi-fi/wigig-certified
[61] http://www.fiercewireless.com/europe/story/high-speed-wireless-device-shipments-set-soar
[62] *Report and Order*, Docket 81-413 (May 9, 1985)

rulemaking.

Providing unlicensed spectrum for a "technical playground" for the creation of new technologies proved to have a tremendous outcome, as noted above. Thus, we advocate that the FCC allocate 10 GHz of unlicensed spectrum for the continuing evolution of life-changing wireless mobile technologies, including 5 GHz of unlicensed spectrum above 100 GHz. At the same time, the Commission should realize that mmWave technologies are being developed for commercial, licensed CMRS use, and the availability of licensed spectrum for these new mobile technologies should also be accommodated with spectrum auctions (we advocate 10 GHz of auctioned mmWave spectrum for flexible use).

One can never be certain when technology in a new frequency band will be economical, but one can be certain that if FCC forbids mobile, or low mobility, or simultaneous fixed or mobile use in a particular band, then there will be major disincentives to capital formation for such R&D due to regulatory uncertainty and regulatory risk. Thus, we would advocate for the FCC to create mobile service rules for some or all of the mmWave bands discussed in a way that does not preclude other uses now authorized, and to enable new uses of existing spectrum held by incumbent license holders, as long as they were not subjected to harmful interference and such that they did not create harmful interference for others.

It is possible that both mobile and fixed service, for backhaul and other uses, can coexist in the same band in the same area due to spatial processing (antenna beamforming) and the massive channel bandwidths that may be allocated at mmWave – something inconceivable in lower bands. The necessary fixed/mobile isolation might be achieved by approaches such as TDD/TDMA, physical separation of narrow beam antennas, adaptive beams that avoid particular radiation zones, frequency blocks within licensed bands, CDMA processing gain, interference cancellation, or a combination of such techniques. There are other methods that are well known, such as those discussed in some of the papers cited in the appendix. At this time, we believe the FCC should neither mandate such fixed/mobile sharing, nor preclude it. Rather, the FCC should allow and create an environment where licensees have the incentives and the flexibility to work out the technical details among themselves, as this will help spawn new business and use cases, as well as rapid technological advancement.

In bands where there are incumbents with area licenses, these should be given flexibility and time to expand their present systems to include CMRS mobile use, and to administer, within their own spectrum holdings, approaches that could support both backhaul, fronthaul[63], and wireless local area network use.

In bands without incumbents, area licenses should allow both fixed and mobile use subject only to interference and RF safety limits, and new spectrum should be both auctioned off (with primary protections for the spectrum license), and new mmWave unlicensed bands should be contemplated (to spur investment and new use cases, such as the Internet of Things (IoT)). The Commission should enable capitalization and business partnerships that would allow for the transition of spectrum use for the highest and best value as deemed proper by the license holder. Marketplace forces should be relied upon to either facilitate the transition at the time it is economically practical, or to encourage the development of appropriate sharing techniques, but there should be minimal regulation regarding the use cases or implementation of wireless communication within the mmWave spectrum that a license holder enjoys today.

[63] http://www.huawei.com/en/about-huawei/publications/communicate/hw-327210.htm

We would also encourage the FCC to find multiple GHz of spectrum bands suitable for mobility above 24 GHz, and consider nationwide auctions with very light regulations for the winning bidders.

Thus, the focus should be on enabling mobile access and the spawning of new infrastructure and handset technologies, as well as new use cases and partnerships in specified bands subject to reasonable stated interference limits to adjacent bands and adjacent cochannel licensees, such as satellite users and federal government systems.

While the FCC did have detailed technical interoperability standards for 1G cellular in the early 1980s, since 1987 the FCC has not specified CMRS technologies for new systems[64]. This flexibility is what allowed *both* the 2nd generation US Digital Cellular (TDMA) and Qualcomm's CDMA technologies to be developed in the US while CDMA was shunned for 2G cellular by prescriptive overseas regulators as being immature. All early 3G technologies incorporated CDMA subsystems, and this generation of mobile technologies would likely not have been possible if the US (and South Korea) had not been the testbed for proving the effectiveness of this innovative technology, first through the ISM band regulations of 1985 that fostered widespread spread spectrum innovation, and then through a light-touch CMRS regulation for 2G cellular. We urge the FCC to consider a light-touch approach for existing spectrum holders, and to allow great flexibility for new spectrum that it would auction off above 24 GHz for licensees to provide mobile service as well as fixed services in its own license band.

When the "Wi-Fi rules"[65] were adopted in Docket 81-413, there was no mention of wireless LANs as a possible use of the ISM bands, most likely because all LAN use at that

[64] 47 C.F.R. § 22.917
[65] Now codified at 47 C.F.R. §15.247

time was limited to industrial applications, and LANs were then rare in the office environments. Indeed, even when the "founding fathers" of 802.11 began their first deliberations in the 1980's, the focus of WLAN application discussions was department store cash registers and warehouse bar scanners.[66] But the flexibility of the ISM band rules allowed them to serve as the basis for a revolutionary change in wireless technology, bringing about the applications of Wi-Fi, Bluetooth and ZigBee with only minor FCC fine tuning of the 1985 rules. This has also stimulated much private capital formation to develop innovative products permitted under these non-prescriptive enabling rules. An approach to mmWave mobile regulation that combines the non-prescriptive, interference preventions focused approaches of §15.247 and § 22.917 is likely to enable a similar spurt of technical creativity consistent with a statutory "policy of the United States to encourage the provision of new technologies and services to the public."[67]

We note that license holders will always rely on their ability to have primary access, and will pay for that right. We believe that mmWave licensed spectrum would incentivize carriers to invest in infrastructure and service provisioning, at a much faster rate than what is likely to occur in today's unlicensed 60 GHz band (where no user can be sure of interference conditions, and where air attenuation is somewhat greater (20 dB/km) due to oxygen absorption). Hence, we advocate for both licensed spectrum for CMRS and other flexible uses (we suggest 10 GHz new licensed spectrum, in 2.5 GHz blocks) as well as unlicensed spectrum to further spur technological developments and to create completely new business and use cases (with at least 5 GHz above 100 GHz).

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[66] W. Lemstra, V. Hayes, J. Groenewegen, *The Innovation Journey of Wi-Fi*, 2010
[67] 47 U.S.C. § 157(a)

The *Notice* discusses[68] both the existing unlicensed band at 57-64 GHz as well as a possible new licensed or unlicensed band at 64-71 GHz. While in the past, cellular carriers have used unlicensed bands, *e.g. Wi-Fi* offload[69], this was basically an afterthought to cellular system design. But in current 5G cellular thinking, incidental use of unlicensed spectrum when it is available will likely be a part of the basic system design. Thus, more cooperation will be needed between the CMRS community and the unlicensed community to assure that such sharing is efficient, fare, equitable, and useful for end-user service quality requirements. However, this will generally be best if handled among the affected parties without formal regulations that could easily become outdated as this rapidly developing technology evolves. By providing light touch rules focused primarily on interference limits and safety regulations, and by authorizing new flexibility in existing mmWave bands while providing copious quantities of new auctioned and unlicensed mmWave spectrum, capital formation and technological development will result for US consumers.

To be more explicit, we believe the FCC should provide sufficient flexibility such that today's mmWave spectrum license holders should be allowed to implement "Wi-Fi like" service along with mobile service, mesh backhaul and fixed access if they felt the business demand or unmet need was there, and similarly, the FCC should encourage the development of mmWave equipment through more spectrum licenses and more unlicensed spectrum blocks (we advocate 10 GHz of licensed mmWave spectrum, and 10 GHz of unlicensed mmWave spectrum, including 5 GHz of unlicensed spectrum above 100 GHz)

[68] *Notice* at para. 70-74
[69] Cisco, "Whitepaper: Architecture for Mobile Data Offload over Wi-Fi Access Networks", 2012 (http://www.cisco.com/c/en/us/solutions/collateral/service-provider/service-provider-wi-fi/white_paper_c11-701018.pdf)

in the near future.

Where there are incumbent fixed service area licensees, we believe a good path for timely implementation is to give them the rights for mobile transmissions, including low-mobility transmissions, relaying, and combined backhaul/mobile transmissions, as well as their presently authorized services in their service area (e.g. fixed point-to-point), subject to a buildout requirement. This approach is much more expedient than the alternative of having separate mobile and fixed licensees in the same service area and in the same spectrum, but with different owners who must clear the way for their intended uses over time. The resulting marketplace forces will facilitate licensee decision-making to determine the appropriate sharing details much faster than detailed FCC rulemaking would.

One particular regulatory area that could assist mmWave mobile services would be to provide MSA or RSA licenses, while relaxing the required minimum antenna directivity regulations, and by extending the sliding scale of the currently used rule of one dBi reduction in directivity for every two dB reduction in the EIRP (2 for 1 rule) currently used for fixed access at 70/80 GHz, where the lowest allowable directivity is 43 dBi. Similarly, current licensees of 28 and 39 GHz spectrum would benefit from the relaxation of current regulations that today require high directional beams (thus precluding mobile of low-mobility usage). As just one specific example in today's 70/80 GHz regulation, extension of the "sliding scale" would be useful for mobile access, where the required link budget may not be very high, depending on the particular propagation conditions or mobile equipment being used. Adaptive antennas will be able to rapidly adapt their gain and pointing angle, requiring relaxation of regulations for this technology to be used. Another possibility (particularly when considering future unlicensed allocations) would be to adopt the approach used in the unlicensed 60 GHz band, where no directivity requirement is given, and only a maximum is specified up to 82 dBm allowable EIRP for outdoor use.

To dig a bit deeper on this point, as an example of how the FCC could rapidly accommodate new products, services, and technology deployment at mmWave bands, the current nominal requirements for operating in the 70/80 GHz band are with minimum 43 dBi directivity, with maximum 71 dBm EIRP. For mobile access services, these requirements are too restrictive for the mobile handset, where directivities on the order of a few dB to as much as 40 dBi may be more likely, based on the form factor of the mobile device. It would be useful to have a sliding scale to reduce the requirement for directivity, thus supporting practical mobile phased array antennas that could implement a wide range of gains and patterns through beam steering, based on the locations of mobile users in relation to base stations or repeaters, and based on existing interference conditions. The FCC should reconsider removing the restrictions on pencil beams, or high directivity regulations that are typically used in fixed wireless applications.

5	17	What characteristics of the technology are relevant to the manner in which mobile services in the mmW bands might coexist without impact on incumbent services that occupy the relevant frequency bands?

The small wavelengths involved in the mmWave bands allow much more directional antennas for reasonable antenna sizes than at lower bands. This means that transmissions will be more noise-limited than interference-limited, since energy is beamed in specific directions using higher gain antennas – a major departure from today's CMRS services. The ability to electrically steer beams with great accuracy is a powerful technological capability that previous mobile and older Wi-Fi networks have not been able to exploit due to much larger wavelengths and thus much smaller gain (broader radiation pattern) antennas. Several NYU WIRELESS researchers and Industrial Affiliate companies have demonstrated prototypes or are shipping or using products that use adaptive antennas with beam steering agility at mmWave frequencies, thus this technology is maturing rapidly and will play a major role in the future of wireless communications above 24 GHz.

In addition, atmospheric absorption and poor diffraction around obstacles limit undesired power received at other users, much more so than at lower frequencies, such that spectrum sharing issues and interference avoidance are much easier to solve than at lower bands. Real time interference avoidance is much easier when adaptive antennas are used, thereby providing a completely new dimension that past consumer wireless networks have not been able to exploit.

8	17	In addition to seeking comment on mobile use of the mmW bands, we also seek comment on alternative uses of the mmW bands.

107	45	We specifically inquire about the utility of the mmW bands for backhaul.

110	45	Could the 5G technologies discussed above also provide backhaul capabilities?

111	45	Would it be possible to use "in band" service in which backhaul reuses frequencies that are also used for access?

It is likely that the same bands can be used for both mobile and fixed/backhaul in the same area, but at this point it is uncertain when this will become economically feasible and what will be the best technology to implement this sharing. FCC rules should permit such sharing but not require it at this time. Thus, when the technology becomes mature for commercial use, it can be implemented in a timely way without further FCC rulemaking or waivers.

We believe that simultaneous use of spectrum for mobile use and backhaul will be supported in the same spectrum, provided that spectrum allocations are sufficiently wide to justify the capital investments to bring such equipment to market. Channel allocations of 2.5 GHz or more per licensee (e.g. 4 license holders within a 10 GHz licensed block throughout the mmWave spectrum), and individual RF channel bandwidths of 500 MHz or more (with flexibility for smaller sub-channel bands as desired by the licensee), will likely be necessary for such efficient use and rapid development of the spectrum, as this represents about an order of magnitude increase in spectrum compared to the inventory of most incumbent 4G cellular operators. One way to share spectrum between fixed and mobile in the same band and with the same radio unit is to use time division duplexing ("TDD") and place mobile and fixed users in different time slots, an approach likely to be adopted because of the relatively small coverage range of low power mmWave devices. The smaller cells of future mmWave networks will readily lend themselves to TDD use due to the relatively small time delays between close-in mobiles and mobiles at the edge of the cell. Extensions of today's frequency-domain equalization methods used in OFDM and SC-FDE 4G cellular modulations could easily be used in mmWave systems[70, 71]. Also, CDMA with interference cancellation could be used in many mobile and fixed channels, due to the relatively benign multipath spread (leading to simple receivers that do not require the idle

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[70] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, S. Sun, and S. Nie, "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 32, pp. 1152-1163, June 2014

[71] T. S. Rappaport *et al*., *Millimeter Wave Wireless Communications*, Chap. 7 and 8, Pearson/Prentice Hall, 2015.

time of a cyclic prefix) and very wide channel bandwidths that appear flat when highly directional antennas are used to find the "right" directional pointing angles.[72] Another way to efficiently share spectrum between fixed links and mobile users is to use various multiple access techniques such as OFDMA, CDMA, etc. where the two classes of users are separated in time, frequency, code, sub-channel, etc, even when the two classes of signals happen to be on the same carrier and at precisely the same beam heading. Finally, it is likely that polarization diversity may be used on many links, or to place a mobile base station with a MIMO-like antenna at one height on a monopole support, and place a fixed antenna high on the same monopole. Adequate separation between the two systems could be implemented through a trade off between vertical separation of the two antenna systems, and separation of the beam patterns, or beam nulling between the two systems. In general, the lower mobile antenna would have downtilt that would increase the separation of powers while exploiting ground bounce for greater coverage.

Current incumbent licensees in various mmWave bands must presently meet stringent requirements of the Radio Pattern Envelop (RPE) for the purposes of fixed (backhaul) links. These FCC should consider reducing these requirements for some or all current licensees, to lighten the regulatory burden so that new network architectures (e.g., mobile access, mesh backhaul, cross-connects) and new technologies (e.g., phased array antennas with adaptive beams) could be accommodated in these bands. The FCC should also consider reviewing and adopting ETSI RPE requirements, which appear to be less restrictive (e.g., ETSI Class 2 in the 70/80 GHz E band).

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[72] S. Sun, et. al, "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," IEEE Communications Magazine, Vol. 52, No. 12, December, 2014;
J. Liberti, T. Rappaport, "Analysis of CDMA Cellular Radio systems employing adaptive antennas in multipath environments," *Proc. 1996 IEEE Vehicular Technology Conference*, Vol. *2* ,p. 1076 - 1080

Specifically, most operations in the mmWave band have been licensed exclusively for fixed systems (e.g., point-to-point backhaul using extremely narrow pencil beams with ~1 degree beamwidths using lenses or parabolic fixed beam antennas). As new phased array antennas are implemented for fixed links, and as mobile or low-mobility mmWave systems are implemented that can simultaneously provide backhaul communications, antenna patterns will exhibit greater antenna side lobes, as well as broadening of the main lobe due to amplitude tapering and beam steering. Practically, it would be extremely difficult to meet the FCC's current 50 dBi and 43 dBi 70/80 GHz RPE requirements in the 70/80 GHz E band using state-of-the-art electronic beam steering. The ETSI Class 2 requirements are more manageable and should be considered by the FCC, as an example of lightening the current regulatory requirements for mmWave spectrum users as today's fixed services are expanded to also allow mobile users and new technologies.

While the above discussion has contemplated backhaul fixed links as part of CMRS systems, non-CMRS Fixed Service links may well be able to share spectrum with CMRS systems. Such sharing should be allowed in order to encourage R&D of such technologies to increase spectrum utilization. However, there should be a primary licensee in each license area who has both the opportunity and incentive to authorize such sharing without the requirement for non-routine FCC action. Such an approach would both protect the primary licensee while allowing new sharing technology to have timely market access. Also, current spectrum holders and new auction winners should be allowed to partition their own spectrum in a flexible manner to support CMRS or non-CMRS services, in any manner they wish, as the market and technologies mature.

9	18	In the section that follows, we seek comment on the current development of antenna technology in the mmW bands.
10	18	What advanced antenna technologies are anticipated to be feasible in the mmW bands?

MIMO-like technology in both the base station and at the mobile is very plausible, and is a key way to deal with the difficult propagation paths encountered in mobile or backhaul use above 24 GHz. Prof. Gabriel Rabeiz gave a compelling presentation at the North American 5G Summit, hosted by Qualcomm and Ericsson at Asilomar in November 2014, wherein he demonstrated that the technology to implement extremely complex and high perfomring phased arrays in very small form factors, with very highly directional and adaptive gain, exists today and has been perfected over the past two decades in the military and aviation fields. In today's 4G LTE CMRS equipment, MIMO precoding is implemented by orthogonolizing (nulling out interference) without using classic beamforming (where RF power is directed with focused energy and low sidelobes). That is to say, today's cellular does not implement classic beamforming for high directivity because of lack of antenna gain at UHF/microwave frequencies.[73] Recently urban measurements in New York City show that mmWave systems could implement true beamforming, with single user MIMO, where multiple beams carry independent data streams, and can also implement massive MIMO when the channel coherence degrades among many users.[74] The potential for MIMO is very strong in mmWave systems, where antenna manifolds can be electrically large but relatively small in physical size compared to

[73] J. Liberti, T. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA*, Prentice-Hall, 1999
Sun, S. , Rappaport, T.S., Heath, R.W. Nix, A., Rangan, S., "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?"
IEEE Communications Magazine, Vol. *52* , No. 12. P.110 – 121 (Dec. 2014)
[74] *Ibid.*

today's cellular antennas, and the rich scattering supports diversity[75, 76, 77].

However, we believe FCC should not require any specific antenna technology and should focus on interference limits in the new regime of directional antennas, and not design techniques. Allowing flexible licensing that enables engineering solutions that exploit interference cancellation, beamforming, and new spatial processing should be allowed and encouraged for the US wireless industry to develop and expand rapidly.

43	25	How do commenters anticipate a transition from current LTE designs will occur?
44	25	As LTE networks are redesigned for a 5G environment, will 5G architectures be integrated into current LTE designs, or added as a separate system or module, requiring, for example, use of a dual handset capable of operating on both LTE and 5G networks?

For at least the next decade, CMRS use of spectrum above 24 GHz use will supplement other technologies such as LTE, not replace it. 5G mobile technology, unlike previous generations, will not be one monolithic technology in a specific band, but rather is likely to be a package of technologies in various bands that match the characteristics of the bands to the services required.

76	35	However, we encourage commenters to describe how to characterize coverage in comparison with today's networks that typically provide coverage over wide areas.

While most of the US geographic territory is now covered with lower frequency

[75] A. Adhikary, E. Al Safadi, M. Samimi, R. Wang, G. Caire, T. Rappaport, A. Molisch, "Joint Spatial Division and Multiplexing for mm-Wave Channels", *IEEE Journal on Selected Areas in Communications*, Vol. *32*, no. 6, (June 2014)

[76] M. K. Samimi and T. S. Rappaport, "Ultra-wideband statistical channel model for non line of sight millimeter-wave urban channels," in *2014 IEEE Global Telecommunications Conference (GLOBECOM 2014)*, Dec 2014

[77] G. R. MacCartney and T. S. Rappaport, "73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City," in *2014 IEEE International Conference on Communications (ICC)*, pp. 4862-4867, June 2014

CMRS signals, this is not a reasonable expectation for mmWave bands in the early deployment stages, where base stations covering several kilometers are unlikely to be feasible in suburban or highly dense forested areas. Thus, areas with low user density will likely be served primarily with low band services for at least the first 5 to 8 years of mmWave rollout.   As costs decrease and components are available for a mass market, it is likely that mmWave could be used to cover vast geographies using relays and backhaul modes that serve sparsely populated areas, much like how electrical power is now carried to rural areas. The speed of the buildout of very massive broadband connectivity depends, in part, on the speed at which the FCC enables broad swaths (many 10s of GHz) of mmWave spectrum to be used by license holders (both incumbents and new auction winners, and through new unlicensed allocations) to provide the grid of coverage that could connect even the most remote mobile or fixed users.

115	48	**What are the economic benefits of global harmonization within the bands above 24 GHz for these services?**

There are real benefits with economies of scale in R&D and production with global harmonization. However, such goals have been elusive in the past and probably will continue to be elusive. The desire to remain focused on frequencies below 6 GHz by some countries, including the USA, gave rise to a delay in consideration of mmWave technologies at the World Radio Conference 2015 convention. The FCC and NTIA should do all they can to harmonize mmWave spectrum allocation in the US, with band allocations in other parts of the world as rapidly as possible. Early rulemaking by the FCC that makes available spectrum listed in the NOI, as well as new frequency bands contemplated in other countries and at frequencies above 100 GHz, would help launch the capital formation and technology development needed.

The FCC should focus on enabling global harmonization, rather than mandating it. We suggest that the FCC continue its practice of almost three decades of not requiring specific physical layer standards, *e.g.* modulation and channel access mechanism, for CMRS bands, even if international standards do so. Overly rigidly regulatory standards slow technical innovation. FCC regulations would do best to focus on preventing interference between users, and on RF safety issues, and not interoperability, which is generally best left to market place forces.

Thus, as bands are identified for 5G harmonization, the FCC, in conjunction with NTIA, should examine feasibility in the US. Federal users have legitimate needs for spectrum in the bands under consideration for CMRS use, but in general, federal spectrum use and CMRS spectrum use are orthogonal in space and time -- with the San Diego area being a notable exception due to its urban military base locations.

Government/Non-Government (G/NG) sharing at above 24 GHz is very different than at VHF, due to the high directionality and the natural losses that occur due to obstructions, so G/NG sharing should be easier and should permit new approaches such as the existing novel 70/80 GHz sharing.[78] The online coordination available for 70/80 GHz allows quick confirmation that a specific location, frequency, and power combination does not pose an interference concern to federal users and thus can be used without lengthy traditional formal NTIA coordination. There were concerns during the original development of 70/80 GHz online coordination that licensees in these bands[79] might abuse the online inquiry process, and might be able to deduce the location of sensitive federal systems. However,

[78] 47 C.F.R. §101.1501,1527
[79] 70/80 GHz licenses are available on a nationwide basis with minimal cost to any entity meeting minimal licensing eligibility. *See* 47 C.F.R. §101.7,1501-1523

the rules and the online system were designed by FCC and NTIA to minimize this security risk, and this has not been a concern to date. The CMRS mmWave case is very different from VHF, so it should be much less of a concern due to a modest number of CMRS licensees who have clearly defined licensed areas, lower effective radiated powers for 70/80 GHz mobile antennas at ground level, and the fact that base stations will likely use down tilted antennas or over-the-horizon beam patterns that have little propagation distance potential beyond obstructions or into the sky.

The US has the largest, most technically advanced military in the world that depends greatly on IT for its advantage. It may not be reasonable to expect that US spectrum use above 24 GHz will be the same as countries with lesser national security problem, and the US is likely to be much more spectrally efficient in its use of spectrum than military counterparts in other countries. Creative sharing approaches could minimize such differences, and freeing up unused or extremely lightly used military or radio astronomy spectrum for mobile wireless use in the mmWave bands should be done to spur American competitiveness and to bridge the digital divide. Particularly in light of the massive global investment in other countries where national governments are partially supporting R&D[80], the US must rapidly allow light-touch regulation for incumbents to unlock the potential of mmWave technology while fostering a policy that enables new auctions and unlicensed allocations of many GHz of spectrum above 24 GHz. Spectrum used by astronomers, particularly above 100 GHz, should be partitioned off such that mobile communications can continue to expand as channel bandwidths become much greater than today.

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[80] *See* International Competitive Issues section, *infra*

88	41	Is the +55 dBW EIRP limit currently applicable in the 27.5-28.35 GHz band and 39 GHz band appropriate?

While this is an appropriate power level for fixed services, we also believe it is a useful value for base stations that support mobile devices, Wi-Fi hotspots, or backhaul. However, this value is too high for mobile terminals, due to RF safety considerations.

We believe the focus of regulation (from a base station or relay perspective) should not be EIRP limits, but rather power flux density (PFD) limits (far-field values) that protect cochannel and adjacent channel users, and RF safety-based limits that ensure heating effects do not cause human damage. The use of PFD will allow users of varying bandwidths and beamforming antenna arrays to trade off power and antenna beamwidth (gain) over a wide range of channel bandwidths. Alternatively, a standard EIRP level for a nominal 1 degree beamwidth and 1 GHz bandwidth could be used, and appropriate scaling could be used to allow spectrum users sufficient flexibility in partitioning their spectrum. The small antenna sizes, now feasible with small millimeter wavelengths, allow antenna pattern shaping in much more detail than at lower bands, making EIRP less relevant and more variable during a communication sequence.

Regarding safe exposure limits to mmWave radiation, we note that mmWave radiation is non-ionizing, and that the only noted health concerns to date are due to radio frequency heating. Current regulations for safety (e.g. radiation exposure limits) focus on a metric of power flux density (PFD), yet this is not a sensible or ideal metric for mmWave transmissions that are close to a human, where the skin depth is much less than at frequencies below 6 GHz. Indications are that for devices far from the human body, existing FCC limits on PFD should be adequate to ensure safety. However, in work to be published by NYU WIRELESS researchers in the March 2015 issue of *IEEE Microwave*

Magazine[81], we demonstrate how the change in temperature in the tissue of the human body, and not PFD or SAR, appears to be a more appropriate measure for safety than today's regulations. We believe new regulations for user equipment (mobile devices) that focus on *temperature changes induced by RF radiation* are the proper approach for devices above 24 GHz

93	41	What should the appropriate limits be for mobile units?

The controlling issues for mobile power limits should be both RF safety limits and interference-based limits. In general, we expect that interference-related factors will be secondary to decisions on power (battery) limits, owing to the noise-limited (not interference-limited) nature of highly directional mmWave communication. Given the high gain antennas likely to be used at the mobile handset, we expect that the RF safety issue will determine actual upper limits, although power efficiency for mmWave devices is currently not as great as today's UHF/microwave components, such that power drain might also play the limiting role.

As we discuss below, the use of mmWave adaptive antennas close to the user's body raise some novel issues of compliance measurement, and determinations will need to be addressed and resolved by the Commission. These RF safety issues are now being addressed, such as in Docket 13-84, although that rulemaking is silent on quantitative limits above 95 GHz[82]. We suggest the FCC immediately consider spectrum allocation, and RF safety regulations, above 100 GHz.

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81 T. Wu, T. S. Rappaport, C. M. Collins, "Biological effects of millimeter-waves: a review of current understanding", to appear in *IEEE Microwave Magazine*, March, 2015

82 *See* Reply Comments of Battelle Memorial Institute, Docket 13-84, Nov. 18, 2013 (http://apps.fcc.gov/ecfs/document/view?id=7520958221)

In the regime of non-ionizing radiation above 24 GHz, the distribution of heating is constrained more to the surface of the body than at lower frequencies. As discussed in our March 2015 IEEE Microwave Magazine article, the eye is unable to dissipate heat as well as other parts of the body, due to lack of blood flow in the eyes, but mmWave power levels typical for mobile CMRS operation have not been found to cause damage. Regulations will need to consider such issues where directional antennas are involved, to ensure that RF levels are safe for all possible pointing directions of adaptive arrays.

Some measurement issues that are unique for mmWave mobile handsets will nbeed to be resolved in either the ongoing RF safety NPRM in Docket 13-84 or in future FCC proceedings. Today's mobile handsets are subject to a specific absorption rate (SAR) determination "to evaluate the environmental impact of human exposure to RF radiation within the frequency range of 100 kHz to 6 GHz (inclusive)[83]." Thus, mobile handsets operating above 24 GHz would not be subject to SAR regulations, but only to a power density (PD), also called power flux density (PFD).[84] While we agree SAR is not appropriate for mmWave radiation, the problem with this regulation is that for mmWave bands, handsets will likely be close enough to the body of users to have the resulting fields on the users body be "near field" rather than "far field". For example, using the assumption of near field to far field transition of eight wavelengths (8λ), resulting from a square adaptive array with a dimension of 2λ per side, an 8x8 (64 element) antenna array of quarter wavelength antenna elements could be formed. The transition distances are:

Frequency - GHz	Distance - cm	Distance - inches
20	12.00	4.72
30	8.00	3.15

[83] 47 C.F.R. § 1.1310(a)
[84] 47 C.F.R. § 1.1310(e)

40	6.00	2.36
50	4.80	1.89
60	4.00	1.57
70	3.43	1.35
80	3.00	1.18
90	2.67	1.05
100	2.40	0.94
110	2.18	0.86
120	2.00	0.79
130	1.85	0.73
140	1.71	0.67

Table 2: Estimated near field/far field transitions as a function of frequency

Thus, many handset uses will be close enough that the far field assumptions of the present rules do not apply. While laptop use, or texting or video viewing, removes the handset sufficiently far away from the human user to allow far-field metrics, the handset will be in the near field of a human user when in the pocket pressed tightly to the body, or pressed to the ear. Indeed, radio waves at these frequencies barely penetrate the body, so effects on internal tissues and organs (beneath skin and subdermal fat, for example) are not likely to be of concern. Nonetheless, new methods may be needed to calculate near field power deposition in the outer few mm of the body.

Another new issue with RF safety and mmWave handsets is that today's handsets have low gain omnidirectional antennas that have a constant antenna pattern that can be used in SAR determinations. However, mmWave handsets will generally have multiple element antennas with adaptive beamforming, and thus will have radiation patterns that change with time depending on the multipath environment between the handset and the base station. Adaptive beamforming and MIMO algorithms are unlikely to optimize transmission paths by aiming most of the radiation towards the users body where diffraction (blockage) or reflection occurs at these frequencies, so estimating SAR based on worst case maximum gain beam direction is unrealistic, yet no present standard or generally accepted procedure exists for calculating SAR for mmWave handsets -- one will need to be developed. MmWave mobile units will be designed for high speed data transmission in the multi-Gbps range. Hence, it is very unlikely that such transmissions from a handheld unit will be continuous, since the necessary hundreds of Gbs of information are not likely to be in the handset's memory or collectable in real time (although games can generate continuous data streams). Thus, the 30 minute averaging time of § 1.1310(e) may not be appropriate for determining compliance in mmWave systems.

With regard to the use of beamforming, the ability to modify the pattern of a transmit antenna array significantly improves the flexibility and control over the gain of such devices. However, transmission with different amplitude and phase combinations in the adaptive array can result in the creation of constructive/destructive electric (E) field interference patterns inside the body (albeit only near the surface at mmWave frequencies). The power deposition in the body is then proportional to (roughly) the absolute value squared of the vector addition of the E fields generated by the different antenna elements. This capability of E field interactions, particularly with the small wavelengths involved, means that new quantification methods that account for all possible adaptive antenna amplitude and phase configurations (and perhaps using antenna steering algorithms in the handset that incorporate eye-avoidance beam pointing methods) will be needed to accurately model heating due to radiation.

Currently, PFD measurements for the cellular industry are not capable of accounting for these localized effects, and more advance methods for accounting for RF radiation at mmWave frequencies may be needed. MRI technology has been shown to be capable of measuring the distribution of temperature increase due to near field exposure in the microwave frequency range. In recent years, the cost of operation of MRI has been decreasing, and MRI-based systems for mapping thermal changes are becoming affordable to wireless manufacturers and regulatory bodies. They provide wide-band capabilities, high 3D resolution, safety, and scan speeds that are unparalleled to the current full SAR-measurement systems. Such technologies could perhaps be applied to mmWave safety, and this an area of ongoing research at NYU WIRELESS.

For far field regulations, there is some international debate with regard to “what should the appropriate limits be for mobile units,” because there is no international consensus with regard to the numerical limits posed by the different regulatory committees. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies basic restrictions in terms of power density starting from 10 GHz, and the limit value is intended to be spatially averaged over an area of 20 cm^2, while spatial peak power density averaged over 1 cm^2 should not exceed 20 times the given limit. For frequencies above 6 GHz, the FCC specifies a spatial peak power density of 10 W/m^2 for the general public. In the IEEE C95.1 standard, power density basic restrictions are specified from 3 GHz and above. These are intended to be spatially averaged values over an area of $100\lambda^2$ for frequencies below 30 GHz, and over 100 cm^2 for frequencies above 30 GHz. The peak PD limit in IEEE C95.1 is $18.56(f)^{0.699}$ for frequencies between 3 GHz and 30 GHz (where f is the frequency in GHz). Above 30 GHz, the peak power density in IEEE C95.1 is 200 W/m^2. The lack of consensus among the different standards indicates that further investigation and unification is needed to define accurate limits at these frequency bands, as these limits will have significant impact on the allowable power levels of mmWave devices.

Recent published papers question the suitability of the current limits at the mmWave frequencies, as there is an extremely large safety margin currently built into the regulations – significantly larger than those adopted for the basic restrictions at frequencies below 6 GHz. The temperature increase for the ICNIRP public 10g SAR limit is approximately 12 times higher than for the ICNIRP power density limit in the 6-10 GHz range[85]. In a different study, a power density of 2000-3000 W/m^2 was shown to increase the skin temperature by 10° C, corresponding to the temperature threshold for thermal pain[86]. The predicted skin temperature increase for a power density of 10 W/m^2 is only 0.05° C, not even detectable by a human. Since there is no harmonization between the various standardization bodies, further investigation is needed prior to arriving at the most appropriate limits for mmWave devices. Possibly, the aforementioned MRI technology or other advances based on thermal heating can assist in mmWave device evaluation, to gain better understanding of the desired and appropriate limits.

RF safety limit determination for mobile mmWave devices will necessarily be different than at lower bands. *This does not mean mmWaves are dangerous.* Rather the impact of much smaller skin depth and the potential near field use with directional antennas in many cases will raise new issues in testing standards to verify compliance with longstanding FCC protection goals.

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[85] McIntosh and Anderson, "SAR versus Sinc: What is the appropriate RF Exposure Metric in the Range 1- 10 GHz? Part 2: using complex human body models", Bioelectromagnetics, March 2010

[86] K. R Foster, R. Glaser. "Thermal response of tissues to millimeter waves: implications for setting exposure guidelines", *Health Physics*, December 2010

144	81	Could elements of the licensing model that presently applies to the 70/80 GHz bands be adapted to facilitate coordination with advanced mobile service if it were to be authorized in those bands?
145	81	Could the automated coordination and registration system that applies to fixed stations in this band be applied to advanced mobile service base stations, and, if so, would that adequately protect Federal government operations and other non-Federal government operators from interference from commercial base stations?
146	81	Alternatively, we seek comment on the advisability of allowing unlicensed Part 15 operations in the 70/80 GHz band segments.

The 70/80 GHz licensing model was designed for Fixed Service systems with point-to-point coverage only. CMRS services are area-based. The 70/80 GHz model is limited to "frozen rope" individual line of sight shots between fixed access points, and thus does not support the concept of CMRS or "Wi-Fi like" service. The 70/80 GHz model is basically first come/first served for link authorization, specifying just the endpoints and frequency (and not a coverage zone or region). In practice, a high fraction of the links already used (declared) in the data base are in Northern NJ, near data processing centers of the major US stock exchanges. It is probably unlikely that all of these links actually exist or will ever be implemented, and this shows the problems with "land rush" effects in which entities "stake claims" that may never be used.

Since the coverage of a mmWave cell site is likely to be on the order of 200 to 400 m when considering Cooperative Multipoint (CoMP)[87], spatial multiplexing, and multibeam combining, and possibly greater coverage distances if power levels of several watts are allowed, many base stations will be needed to cover an appreciable metropolitan area. Recent work based on NYU WIRELESS measurements and an existing cellular network in a major city in Saudi Arabia shows that the density is likely to be four to five times today's" 4G base stations[53]. It is worth noting that this increased density of base stations is

[87] R. Irmer, et. al., Coordinated Multipoint: Concepts,Performance, and Field Trial Results, *IEEE Communications Magazine*, Feb. 2011, pp. 101-108

very comparable to planned 4G LTE-Advanced small-cell deployments using CoMP[88]. Traditional licensing using small areas such as MSA, RSA, or BTAs[89], such as was done for the LMDS spectrum auctions of 1998,[90] is thus more appropriate for this case. Larger areas such as EAG or MEA are not meaningful for mmWave technology, given its short range and inability to serve a large areas with low (e.g. ~1 W RF transmitters in the mobile) in the foreseeable future.

However, automated coordination with NTIA will be a useful tool[91]. While it is important to protect federal users in this band, it appears that such federal users exist in only a small fraction of the land area of the US and most of them are not in the urban areas of greatest interest for mmWave systems. Further, the interference range from mmWave mobile systems to federal users will generally be small, a few km, due to low powers, low heights, and downtilt at base stations. The existing automated coordination system[92] quickly and efficiently identifies the few locations where detailed coordination is necessary, while allowing timely construction at most locations.

The issue of unlicensed use in 70/80 GHz was considered in Docket 02-146 and rejected at that time. We see no reason here to reopen that issue and create regulatory uncertainty for the existing licensees in the bands. However, the FCC would do well to

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88 "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Coordinated multi-point operation for LTE physical layer aspects (Release 11)," 3GPP TR 36.819, September, 2011

89 http://wireless.fcc.gov/auctions/default.htm?job=maps

90 http://wireless.fcc.gov/auctions/default.htm?job=auction_summary&id=17

91 Normal FCC licensing in bands shared with federal/"G" spectrum users involves an application to FCC that FCC must then coordinate with NTIA. NTIA in turn refers the application for the Frequency Assignment Subcommittee ,"FAS", of the Interdepartmental Radio Advisory Committee, "IRAC", which has representatives of most federal agencies that have significant spectrum use. While this coordination usually occurs within a few weeks, this is an awkward process if most of the applications are not within interference distance of federal users as has been the case in 70/80 GHz and will likely be the case for small cell mmWave mobile systems. Automated coordination, such as the existing 70/80 GHz system, allows the rapid approval of locations and frequencies that are interference risk free while allowing the interagency coordination process to focus on the small number of situations that pose realistic interference issues.

92 http://freqcoord.ntia.doc.gov/index.aspx

offer new wide bandwidth allocations, in excess of 5 GHz, for unlicensed use, at frequencies below and well above 100 GHz, in order to provide a complement to the 60 GHz band that suffers an extra 20 dB/decade oxygen absorption compared to 70/80 GHz bands. Opening up new unlicensed spectrum with such great bandwidths would further spur R&D investment, while creating a reservoir of technical experts who can engineer the future mmWave and THz wireless systems of the future.

148	82	Could the potential for interference be limited if the mobile subscribers were required to refrain from transmitting except when operating under the control of a nearby base station?
149	82	If such precautionary measures would not be sufficient by themselves, should we consider adopting a system of dynamic access control using databases similar to those used to control access to TV White Spaces, in this case to enforce exclusion zones around important Federal and radio astronomy sites?
150	82	We invite commenters to evaluate the extent to which such measures could prevent non-Federal subscriber units from causing interference to Federal government operations or to other non-Government operators in the 70 GHz and 80 GHz bands.

In general, CMRS mobile devices receive their frequency and power information from base stations. This requires mobile subscribers "to refrain from transmitting except when operating under the control of a nearby base station," and this is nothing new, and is not codified in present rules. Expected 5G mmWave usage will be different than existing CRMS use because the present thinking focuses on multiband handsets – in part due to the limited range and gradual buildout needed for mmWave coverage in the foreseeable future. Thus, initial contact between handsets and base stations to set up allowed transmission frequencies and powers could be handled in lower, more traditional bands. This might be a problem for new CMRS carriers that have only mmWave spectrum licenses, so there will be a need to assure that access to lower bands is available on reasonable commercial terms, to preclude anticompetitive practices from carriers with both mmWave and lower band spectrum licenses.

In mmWave bands where there are special interference concerns, such as satellite systems or federal systems in particular locations, it may be necessary to require initial contact between the mobile and the base station to be on an "order wire" channel in a band that is exclusively used by the terrestrial license holder (say, a CSMR-user, or a non-CSMR terrestrial licensee at mmWave frequencies), so that a verification can be performed to verify that spectrum in the shared band is available at that location, and to assure that the terrestrial (mobile) user is only using the spectrum when interference-free access is verified by a base station (either by the base station, itself, or through reporting by the mobile station or from a database) using knowledge of the mobile's location as well as the satellite or federal users (non-CSMR users) that might be interfered with. However, we would urge the Commission to avoid any requirement for mmWave spectrum holders to have to revert to using out of band, or lower-band frequencies, in order to resolve the conflict.

The approaches outlined above are comparable with the existing TV White Space provisions of §15.713[93]. In most locations, the base stations could authorize access in a shared band without any dynamic knowledge of the non-CMRS systems' present station because they are simply too far away to be of concern. However, in some locations, real time information could be needed on the status of the nonCMRS user with respect to frequency use and antenna directionality. For example, a satellite station's downlink use might be very intermittent. In that case, a wholesale version of the database would be needed by the CMRS licensees to convey updates on the timing of protected spectrum use at various locations.

In the case of sensitive federal systems, either the NTIA or FCC must allow sharing of information with a few carriers that is sensitive, or else the carriers will have to

[93] 47 C.F.R §15.713

overprotect the federal system at the public cost of spectrum lying fallow. However, in the near term, most new terrestrial CSMR or non-CSMR mmWave use will be in congested urban areas, where spectrum conflicts with primary federal users will be minimal.

CONCLUSIONS

NYU WIRELESS has shown, through extensive research in mmWave communications, that mmWave mobile technology is ready for commercialization, and the FCC has a valuable arsenal of spectrum at its disposal to help consumers enjoy the rapidly evolving access, while helping the US remain competitive in the ICT industry. Despite massive investments overseas in 5G technologies that far outweigh those being made in the US, the FCC has an opportunity to launch mmWave mobile development through the allocation of new mmWave spectrum for both auction (licensed) and unlicensed use. Given the new capabilities that adaptive antennas will permit at both the mobile station and base station, and given the remarkable capabilities of multi Gigabit/second data rates that have been proven recently, we recommend the FCC provide 10 GHz of new auctioned spectrum above 24 GHz, with a suggested minimum allowable channel bandwidth of 500 MHz (which may be further segregated by the license holder), with a suggested minimum spectrum block of 2.5 GHz per licensee, as this represents roughly an order of magnitude over today's CRMS spectrum inventory per major carrier. At the same time, we recommend the allocation of 10 GHz of unlicensed spectrum (5 GHz below 100 GHz, and 5 GHz above 100 GHz) to augment the current 60 GHz unlicensed band, and to foster rapid technological development and capacity for the documented data onslaught that will include the continued migration to the cloud, the Internet of things (IoT), and unforeseen business models and consumer applications.

We recommend that regulations for existing and future mmWave spectrum holders be enabling, and not prescriptive, and that existing mmWave licensees be given great latitude to implement new technologies and use cases, for mobile, fixed, and ambulatory (Wi-Fi like) service. We recommend licenses that encourage cooperation and sharing, while allowing market forces enable rapid development and deployment of new business cases, use cases, and technology implementations. Specifically, when many FCC regulations for mmWave spectrum were put in place, they considered traditional fixed point-to-point links that use very narrow, high gain fixed pencil beam antennas. They did not consider future new services (mobile access), new antenna technologies (phased arrays), adjustable beam patterns, and new network topologies (such as repeaters/relays, mesh connections, or offloading between unlicensed and licensed spectrum) that require and support dynamically reconfigurable communication links. We advocate for the FCC to lighten the mmWave regulations to allow rapid adoption of mmWave technologies and services.

We point out how typical mobile power levels at mmWave frequencies is non-ionizing and safe, yet different countries and organizations have different values established for safety levels above 6 GHz. Thus, we advocate that unification be done on an international level for safety standards, and we suggest that new regulations and measurement techniques that consider directional antennas at the mobile device should be developed. There is promising work already being done in this area, and this can be easily achieved if the FCC takes up the matter along with an enabling mmWave spectrum policy.

NYU WIRELESS welcomes this opportunity to participate in this key proceeding on moving the upper end of CMRS spectrum use into a new region - the millimeter wave (mmWave) regime, and encourages the FCC to also investigate the availability of unlicensed spectrum, including allocations above 100 GHz. The research we have performed and published has played a key role in the development of this exciting new technology. We plan to take an active role in this proceeding in order to speed the introduction of this exciting new technology to serve the public.

Based on research at NYU WIRELESS, and the recent research of many leading academicians and wireless communications engineers at leading companies throughout the world, we are certain that the technology exists to allow multi-Gigabit per second mobile networks to thrive in spectrum above 24 GHz. We urge the FCC to provide light-touch, flexible regulations that allow existing spectrum holders to spur the development of new technologies, networks, businesses and use cases. We also urge the FCC to consider allocating and auctioning off 10 GHz of mmWave spectrum for future licenses, while also creating new unlicensed spectrum (10 GHz), above 100 GHz.

The ability to use adaptive arrays with massive gains provides a new technical dimension that can be exploited in mmWave communications. Research results have shown that mobile networks with data rates on the order of 10 – 20 Gbps are viable in urban settings through the use of beamforming and MIMO-like techniques at frequencies above 24 GHz. The non-ionizing nature of mmWave radiation makes these transmissions safe to the human body, as long as heating is avoided. Thus, we believe new RF safety regulations, based on changes and temperature (and not power density or specific absorption rate) are needed to ensure that the reduced skin-depths of mmWave transmissions re properly accounted for when handsets using adaptive antennas are able to move their radiation patterns over time and space. NYU WIRELESS would be pleased to assist the Commission by arranging for presentation to its staff on key technical issues relating to this technology and the regulatory questions they raise.

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_____________/s/__________________

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ATTACHMENT 1

Selected NYU WIRELESS Publications on 5G mmWave Technologies

YouTube Video "NYU WIRELESS conducts pioneering 5G cellular measurements in New York City (5G millimeter wave)" http://youtu.be/pN_3Iek2jNw

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