In the Matter of
Use of Spectrum Bands Above 24 GHz For Mobile Radio Services
Amendment of the Commission’s Rules Regarding the 37.0-38.6 GHz and 38.6-40.0 GHz Bands
Implementation of Section 309(j) of the Communications Act – Competitive Bidding, 37.0-38.6 GHz and 38.6-40.0 GHz Bands
Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42-43.5 GHz Band

GN Docket No. 14-177
ET Docket No. 95-183 (Terminated)
PP Docket No. 93-253 (Terminated)
RM-11664

REPLY COMMENTS OF STRAIGHT PATH COMMUNICATIONS, INC.

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FEDERAL COMMUNICATIONS COMMISSION
Washington, DC 20554

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Straight Path Communications, Inc. (“Straight Path”) submits these reply comments in response to the comments submitted by other parties on the Notice of Inquiry (“NOI”) issued by the Commission in the above-referenced proceedings. The record in this proceeding demonstrates broad support for allowing flexible services in the millimeter wave ("mmW") frequencies above 24 GHz, including for 5G mobile technologies, and for adopting a regulatory framework that preserves and expands the rights of incumbent licensees. Straight Path therefore urges the Commission to promptly issue one or more notices of proposed rulemaking to adopt regulations for the bands it has identified in the NOI, moving first on bands that are most suitable for mobile services such as the 39 GHz and Local Multipoint Distribution Service ("LMDS")

bands, to maximize the full potential of this spectrum and to help meet the growing demand for mobile broadband applications.

I. INTRODUCTION AND SUMMARY

As explained in its comments, Straight Path supports the flexible use of mmW spectrum, particularly the 39 GHz and LMDS bands, for a variety of applications, including mobile and fixed services.2/ In order to most effectively unlock the value of the mmW bands, Straight Path recommended that the Commission adopt both flexible technical and regulatory requirements.3/ Straight Path also expressed support for an exclusive licensing approach for mobile services in the 39 GHz and LMDS bands and for authorizing incumbents to provide flexible services.4/ If the FCC desires to create additional unlicensed spectrum opportunities, Straight Path suggested that the Commission consider doing so in the 60 GHz (57-64 GHz and 64-71 GHz) and 70/80 GHz (71-76 GHz and 81-86 GHz) bands.5/ It also recommended deploying hybrid approaches that involve sharing between licensed and either unlicensed or secondary operations in the 37/42 GHz (37.0-38.6 GHz and 42.0-42.5 GHz) bands.6/ Finally, Straight Path noted that while portions of the 39 GHz and LMDS bands have also been allocated domestically for satellite services, there is currently no satellite use of the 39 GHz band, very little use of the Ka-bands for satellite operations, and existing satellite use of those bands can otherwise be accommodated.7/

3/ See id. at 4-15.
4/ See id. at 22-24.
5/ See id. at 26-27.
6/ See id. at 27.
7/ See id. at 18-22.
Commenters join Straight Path in applauding the Commission’s efforts to make mmW spectrum available for flexible services. Commenters also widely agree that the 39 GHz and LMDS bands are particularly well suited for mobile services and that the Commission should move quickly to open up these bands for mobile operations. While some commenting parties expressed concern about preserving the use of the mmW bands for backhaul and other fixed services, these concerns can be addressed by adopting a flexible approach that allows a variety of services, including both fixed and mobile, to be deployed.

There is widespread agreement that an exclusive licensing approach for mobile services in the mmW bands has several benefits. Many commenters specifically support such an approach for mobile services in the 39 GHz and LMDS bands. Similarly, commenting parties agree with Straight Path that existing licensees’ rights should be protected and that incumbents should be authorized to provide flexible services in the bands for which they are already licensed. To the extent that unlicensed or hybrid licensing models are considered, commenters also agree with Straight Path that they can be deployed in other mmW frequencies. In any case, the Commission should not adopt a single licensing approach for all mmW bands.

While satellite interests assert that the FCC should protect and preserve their use of the mmW frequencies in the V-band (37.0-42.5 GHz) and Ka-band (28.35-28.6 GHz, 28.6-29.1 GHz, 29.1-29.25 GHz, 29.25-29.5 GHz and 29.5-30.0 GHz), their arguments, particularly with respect to the V-band, are speculative and should not block the potential 5G use of the mmW bands. As the satellite operators themselves recognize, there is no commercial use of the V-band today, making a straightforward separation of satellite and mobile uses of the V-band a feasible and practical solution that will best serve the public interest. Satellite operators’ use of the Ka-band may be more complicated, but their needs may be accommodated in other bands that may
not be appropriate for mobile 5G use. Nevertheless, such concerns need not delay FCC action on the 39 GHz or the LMDS bands.

II. THERE IS WIDESPREAD AGREEMENT THAT FLEXIBLE SERVICES SHOULD BE PERMITTED IN THE SPECTRUM BANDS ABOVE 24 GHz

As Straight Path explained, the time is ripe for the FCC to allow flexible services in the mmW bands – especially the 39 GHz and LMDS bands.8/ Not only has the Commission specifically contemplated allowing these bands to be used for mobile services,9/ but recent advances in wireless communications technologies now allow a variety of services to be deployed in mmW frequency bands. Since the 2011 pioneering study on mmW mobile broadband,10/ significant progress has been made that can enable 5G mobile services in mmW frequencies.11/ Those developments include extensive mmW channel measurement campaigns, multiple prototypes that demonstrate multi-Gbps throughput in different mmW frequencies, and numerous studies that provide a wide range of circuit, system, and network solutions for 5G.

Commenters widely agree.12/ T-Mobile USA, Inc. (“T-Mobile”), for instance, correctly points out that “as technologies continue to evolve, the frequency bands above 24 GHz have

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8/ See id. at 15-17.
9/ See id. at 16-17.
11/ See Straight Path Comments at 15.
12/ See, e.g., Notice of Inquiry Comment of Intel Corporation, GN Docket No. 14-177, et al., at 5 (filed Jan. 15, 2015) (“mmW mobile service in the bands above 24 GHz is now feasible.”); Comments of FiberTower Spectrum Holdings, LLC, GN Docket No. 14-177, et al., at 15 (filed Jan. 15, 2015) (“FiberTower Comments”) (“FiberTower supports the Commission’s goal of ‘develop[ing] rules that accommodate as wide a variety of services as possible’ and ‘promote coexistence between different services’ in bands above 24 GHz.”); Comments of NYU Wireless, GN Docket No. 14-177, et al., at 24 (filed Jan. 15, 2015) (“NYU Comments”) (“mmWave spectrum can be constructively used for CMRS systems.”); Comments of Mobile Future, GN Docket No. 14-177, et al., at 2-4 (filed Jan. 15, 2015) (“Mobile Future and its members strongly support the Commission’s efforts to help alleviate the spectrum...
potential for the provision of mobile radio services.”¹³/ Huawei Technologies, Inc. likewise believes that “future systems will allow for the utilization of a range of spectrum and access technologies for the best delivery of services” and that “future mobile services can operate in bands above 24 GHz.”¹⁴/ Nokia notes the importance of 5G technologies and explains that its ongoing research demonstrates that bands above 24 GHz “look promising for mobile services.”¹⁵/

Commenting parties also observe that the 39 GHz and LMDS bands are especially well suited for flexible services. Samsung Electronics America, Inc. and Samsung Research America (collectively, “Samsung”) explain that “there currently exist several swaths of spectrum in the 28 GHz [and] 39 GHz . . . bands that could support new 5G millimeter wave services” and recommends that “the 28 and 39 GHz bands should be the Commission’s top priorities at this time.”¹⁶/ XO Communications, LLC (“XO Communications”) highlights that “LMDS spectrum is well-suited for 5G commercial mobile operations” and “the 39 GHz band should successfully support 5G mobile operations.”¹⁷/

Some parties note that mmW frequencies have been successfully used for backhaul and other fixed point-to-point services and that they should continue to be available for those shortage facing mobile broadband consumers . . . . The Above 24 GHz NOI is a positive step toward employing new technological advances that can help provide services to consumers.”

¹⁴/ Comments of Huawei Technologies, Inc. (USA) and Huawei Technologies, Ltd., GN Docket No. 14-177, et al., at 5-6 (filed Jan. 15, 2015).
¹⁵/ Comments of Nokia (D/B/A Nokia Solutions and Networks US LLC), GN Docket No. 14-177, at 6 (filed Jan. 15, 2015) (“Nokia Comments”) (adding that it “applaud[s] the Commission for exploring new spectrum above 24 GHz to expand mobile broadband connectivity”).
¹⁶/ Comments of Samsung Electronics America, Inc. and Samsung Research America, GN Docket No. 14-177 and RM-11664, at 40-41, 45 (filed Jan. 15, 2015) (“Samsung Comments”) (emphasis added) (noting that “[t]he Commission has long envisioned the LMDS bands as playing host to mobile services” and that the 39 GHz band “also has a co-primary allocation for fixed and mobile services”).
applications. For example, the Wireless Innovation Forum observes that “the large total bandwidths possible in 5G mmW cells will require significant backhaul capacity” and urges the Commission to “allow [Commercial Mobile Radio Service] mmW licensees to also use their licensed spectrum for backhaul use.”

Allowing flexible services in the mmW bands would accommodate a variety of operations, both fixed and mobile alike. As NYU Wireless points out, “[i]t 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 Consumer Electronics Association emphasizes that “the FCC must accommodate a wide range of interests in the mmW bands, including incumbents, potential mobile broadband service providers, and other potential users of the mmW spectrum.” In addition, permitting flexible use in the mmW bands is more consistent with the Commission’s current licensing approach for commercial terrestrial services.

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18/ Comments of the Wireless Innovation Forum on the Notice of Inquiry in the Above-Captioned Proceeding, GN Docket No. 14-177, et al., at 5 (filed Jan. 15, 2015) (“WIF Comments”); see also Vivint Wireless, Inc. Comments, GN Docket No. 14-177, et al., at 2 (filed Jan. 15, 2015) (“Vivint Comments”) (“[T]he Commission should protect existing mmW band operations, which include access and backhaul services, by establishing priority rights for fixed services.”). Bluwan SA similarly asserts that use of the mmW should be restricted. It believes that “commercialization of mobile radio access networks, and associated devices is not practical in the short term, and recommends allocation of [the 39-42 GHz band] for the backhaul of heterogeneous networks, or fixed wireless access deployments in areas where the deployment of fiber optic last mile networks is economically or geo-demographically unachievable.” Bluwan SA Response to FCC Notice of Enquiry: Use of Spectrum Bands Above 24 GHz for Mobile Radio Services, GN Docket No. 14-177, at 3, 8-10 (filed Dec. 16, 2014).

19/ NYU Comments at 29.


21/ See, e.g., 47 C.F.R. § 24.3 (“PCS licensees may provide any mobile communications service on their assigned spectrum. Fixed services may be provided on a co-primary basis with mobile operations.”); id. § 27.2 (stating that licensees in the frequency bands allocated for wireless communications services “may provide any services for which its frequency bands are allocated”).
fixed and mobile services will enable it to self-manage its operations and respond to commercial needs, including backhaul, on a market-by-market basis. Because the provision of mobile and fixed operations by the same licensee is both technically feasible and consistent with sound spectrum management, the Commission should permit flexible services in the mmW bands.

The Commission should not, as some suggest, delay or avoid making any determinations about the future use of the mmW bands. As Straight Path explained, lack of regulatory certainty will only slow development of mmW technology in these bands. Conversely, regulatory certainty will help promote the use of the bands, allowing them to meet growing wireless capacity requirements. Moreover, the FCC should act to establish rules on which other administrations can rely in order for the United States to continue its leadership position in wireless technology and create a global 5G marketplace. As European and Asian regulatory bodies begin to examine making higher frequency bands available for 5G, it is imperative that the Commission take a proactive approach to provide strong spectrum and policy support so that the United States wireless industry – and ultimately wireless consumers – are well positioned to take advantage of 5G technologies. If not all bands are ripe for development, Straight Path agrees with Qualcomm Incorporated (“ Qualcomm”) that the FCC can and should act on some of

22/ See FiberTower Comments at 14 (“[L]icense holders are in the best position to self-protect fixed, fixed-portable, and mobile operations within their license border areas.”).

23/ See, e.g., Comments of Verizon, GN Docket No. 14-177, et al., at 2 (filed Jan. 15, 2015) (“The Commission should thus avoid making determinations at this time – even preliminary ones – about the appropriate regulatory framework or frameworks.”).

24/ See Straight Path Comments at 2.

25/ See Nokia Comments at 3 (“The U.S. can be a driving force in 5G.”).

the bands – *i.e.*, the 39 GHz and LMDS bands – now, while it continues to consider other mmW bands separately.  

**III. THE RECORD DEMONSTRATES THAT AN EXCLUSIVE LICENSING MODEL IS THE PREFERRED APPROACH FOR THE 39 GHz AND LMDS BANDS**

Straight Path recommended that the Commission – in areas where no licensees exist today – auction and issue exclusive authorizations in the mmW bands to entities for flexible services using geographic service areas.  

Straight Path explained that this approach is used for other mobile services in frequencies below 3 GHz and has the advantage of being a familiar, time-tested option that allows for flexible service deployment.

Several parties agree that an exclusive licensing approach based on geographic service areas, as a general matter, has many benefits for mobile services.  

CTIA – The Wireless Association, for instance, notes that exclusive licensing creates certainty that promotes investment and innovation as well as fosters efficient spectrum use. Qualcomm similarly correctly observes that “[t]he highly successful AWS-3 auction demonstrates the supremely high value of exclusively licensed spectrum.” Commenting parties also agree with Straight Path that an exclusive licensing model is the most appropriate approach for the 39 GHz and LMDS bands.

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28/ See Straight Path Comments at 22-23.

29/ See id. at 22-23.

30/ See, e.g., Comments of Motorola Mobility LLC, GN Docket No. 14-177, *et al.*, at 7 (filed Jan. 15, 2015) (“[E]xclusive allocations are preferred where possible.”); FiberTower Comments at 15 (urging the Commission to “license vacant spectrum by auctioning exclusive rights to geographic service areas”).

31/ See Comments of CTIA – The Wireless Association, GN Docket No. 14-177, *et al.*, at 8-10 (filed Jan. 15, 2015) (“CTIA Comments”); see also T-Mobile Comments at 6-7 (“Exclusive use licensing in the spectrum above 24 GHz would facilitate the greatest spectrum use.”).

32/ Qualcomm Comments at 4.
bands in particular. XO Communications asserts that an exclusive geographic area licensing regime would be “[t]he best regulatory approach for realizing a rapid, efficient 5G deployment above 24 GHz” by upper microwave band licensees.\footnote{XO Comments at 3-4.} Nokia agrees, noting that as the Commission pointed out, “[t]his option would extend to mobile services the status quo for the 24 GHz, LMDS, and 39 GHz bands.”\footnote{Nokia Comments at 31 (emphasis omitted).} As Straight Path has pointed out, the 39 GHz and LMDS bands in particular have already been exclusively licensed on a geographic area basis for fixed services with the expectation that mobile services would be allowed when technology is mature.\footnote{See Straight Path Comments at 16-17 (explaining that “[t]he Commission has already determined that the 39 GHz and LMDS bands can be used for mobile services” and that “[t]his proceeding is exactly what the Commission and mmW licensees like Straight Path anticipated when the Commission created the mobile allocation in both the 39 GHz and LMDS bands”).} Permitting existing licensees in these bands to provide mobile services is the most straightforward and expedient way to make exclusively licensed spectrum available for 5G.

On the other hand, commenting parties, like Straight Path, recognize that the Commission may also wish to create additional unlicensed or spectrum sharing opportunities.\footnote{See, e.g., CEA Comments at 9 (stating that “the Commissions should not foreclose the wide range of licensed and unlicensed uses for which the mmW bands are appropriate”); CTIA Comments at 9 (“Unlicensed spectrum also has an important role to play in the wireless ecosystem, and where spectrum is not easily used for mobile wireless services, it could be made available on an unlicensed basis.”).} Straight Path specifically recommended that the FCC consider an unlicensed approach for the 60 GHz and 70/80 GHz bands as well as a hybrid approach that includes sharing between licensed and unlicensed operations for the 37/42 GHz bands.\footnote{See Straight Path Comments at 26-27.} Many other commenters agree that an unlicensed approach would be more appropriate for the spectrum above 60 GHz. As T-Mobile observes, “spectrum above 60 GHz is unlicensed now,” making “[t]his portion of spectrum . . . a
good location to try out use of innovative spectrum access mechanisms.\textsuperscript{38/} Similar to Straight
Path, Samsung and Nokia recognize that the 37/42 GHz bands represent “clean slates” for
commercial services,\textsuperscript{39/} thereby making them ideal platforms for exploring hybrid solutions.\textsuperscript{40/}

The Commission should reject calls by Google and others to use a hybrid sharing
approach similar to the 3.5 GHz band for \textit{all} mmW spectrum.\textsuperscript{41/} While a sharing approach may
be appropriate for some of the frequencies above 24 GHz, \textit{e.g.}, the 37/42 GHz bands, spectrum
management cannot be approached as “one-size-fits-all,” particularly when there are incumbent
licensees. To the contrary, there is wide agreement that spectrum must be managed using an “all
of the above” philosophy.\textsuperscript{42/} Spectrum bands that already include several incumbents and/or do
not currently contemplate sharing – \textit{i.e.}, the 39 GHz and LMDS bands – are more suitable for
exclusive licensing. In contrast, the majority of the spectrum bands Google cites as support for
its proposal already permit sharing or have no existing licensees.\textsuperscript{43/} The record demonstrates that
the Commission has ample opportunities to satisfy demand for licensed, shared, and unlicensed

\textsuperscript{38/} T-Mobile Comments at 7-8; \textit{see also, e.g.}, Comments of Wi-Fi Alliance, GN Docket No. 14-177,
et al., at 4-6 (filed Jan. 15, 2015); Comments of IEEE 802, GN Docket No. 14-177, at 1-2 (filed Jan. 15,
2015); Comments of InterDigital, Inc., GN Docket No. 14-177, at 3-5 (filed Jan. 15, 2015); Comments of
SiBEAM, Inc., GN Docket No. 14-177, at 3-5 (filed Jan. 15, 2015); Comments of the National Cable &
Telecommunications Association, GN Docket No. 14-177 and RM-11664, at 4-7 (filed Jan. 15, 2015)
(“NCTA Comments”).

\textsuperscript{39/} \textit{See} Samsung Comments at 44; Nokia Comments at 32.

\textsuperscript{40/} \textit{See} Straight Path Comments at 27.

\textsuperscript{41/} \textit{See generally} Comments of Google Inc., GN Docket No. 14-177, \textit{et al.}, at 1-4 (filed Jan. 15,
2015) (“Google Comments”); \textit{see also} WIF Comments at 3-4; NCTA Comments at 2.

\textsuperscript{42/} \textit{See, e.g.}, NOI at Statement of Chairman Tom Wheeler (“An effective spectrum strategy requires
an all-of-the-above approach. This means making more spectrum available for not only licensed but
unlicensed uses; for both exclusive use and sharing.”); Keynote Presentation, FCC Commissioner Mignon
L. Clyburn, 4th Annual Americas Spectrum Management Conference, Washington, DC, at 1 (Nov. 13,
“all-of-the-above approach,” including “looking at both licensed and unlicensed use, exclusive use, and
sharing” must be employed to help meet the growing demand for spectrum).

\textsuperscript{43/} \textit{See} Google Comments at 7.
spectrum for 5G technologies in the bands above 24 GHz. Thus, there is no reason to adopt a single approach for all mmW bands.

IV. COMMENTERS RECOGNIZE THAT INCUMBENTS SHOULD BE AUTHORIZED TO PROVIDE FLEXIBLE SERVICES

As noted above, Straight Path prefers an exclusive licensing approach for the 39 GHz and LMDS bands in areas where no licensee exists today. In areas where the Commission has already issued a license to provide fixed services, Straight Path asserted that the FCC should authorize the incumbent to provide both fixed and mobile services. It explained that because incumbents acquired their authorizations at auction and paid for the spectrum with the expectation that the Commission would make the frequencies available for mobile services, the public interest dictates that they should be allowed to realize the full value of the spectrum for which they paid and the benefits associated with rule changes specifically contemplated by the Commission when it adopted service rules.

The record demonstrates widespread agreement that incumbents in the 39 GHz and LMDS spectrum bands should retain their authorizations and be able to take advantage of new rules permitting mobile wireless services. As T-Mobile correctly points out, “[t]hese licensees

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44/ See Straight Path Comments at 22-23.
45/ See id.
46/ See Amendment of the Commission’s Rules Regarding the 37.0-38.6 GHz and 38.6-40.0 GHz Bands; Implementation of Section 309(j) of the Communications Act – Competitive Bidding, 37.0-38.6 GHz and 38.6-40.0 GHz, Report and Order and Second Notice of Proposed Rulemaking, 12 FCC Rcd. 18600, ¶ 1, 18-23 (1997); Rulemaking to Amend Parts 1, 2, 21, and 25 of the Commission’s Rules to Redesignate the 27.5 GHz Frequency Band, to Reallocate the 29.5-30.0 GHz Frequency Band, to Establish Rules and Policies For Local Multipoint Distribution Service and For Fixed Satellite Services, Second Report and Order, Order on Reconsideration and Fifth Notice of Proposed Rulemaking, 12 FCC Rcd. 12545, ¶ 207 (1997).
47/ See Straight Path Comments at 22-23.
48/ See, e.g., Comments of EchoStar Satellite Operating Corporation, Hughes Network Systems, LLC, and Alta Wireless, Inc., GN Docket No. 14-177, et al., at 19-20 (filed Jan. 15, 2015) (“EchoStar/Hughes/Alta Comments”) (“By enabling existing licensees to offer a wider variety of
should not have to participate in another auction to use their existing spectrum.\textsuperscript{49} Moreover, new overlay mobile license rights in the 39 GHz and LMDS bands would, as XO Communications suggests, create a significant risk of interference to existing operations and diminish existing licensees’ rights.\textsuperscript{50} Straight Path stated before, and others agree,\textsuperscript{51} that only incumbents will be able to self-manage different applications – i.e., fixed and mobile – in the same spectrum in the same geographic areas.\textsuperscript{52} This is the same conclusion that the Commission reached with respect to AWS-4 spectrum,\textsuperscript{53} and it will alleviate concerns about the compatibility of fixed and mobile services in the mmW bands generally.\textsuperscript{54}

Qualcomm contends that because many LMDS and 39 GHz band licenses have been relinquished, there are large areas in the country where mobile deployments would not need to terrestrial services, the FCC would increase the efficient use of these frequencies and facilitate the introduction of more dynamic and diverse service offerings to current and prospective customers of LMDS operators.”); FiberTower Comments at 16-17 (“[T]o the extent mobile deployments in the 24 and 39 GHz bands are not currently permitted under Commission rules, the Commission should permit incumbent licensees to provide mobile services pursuant to their existing geographic licenses . . . .”); CEA Comments at 9-10 (“[T]he FCC should provide adequate protection to incumbents that are already using the mmW bands, as well as to promote their expansion of services, while facilitating the widest possible range of future uses.”); XO Comments at 7 (contending that “the Commission should not adopt any licensing mechanism that would enable other entities to operate 5G facilities in upper microwave licensees’ exclusively authorized frequencies”).

\textsuperscript{49} T-Mobile Comments at 7.

\textsuperscript{50} See XO Comments at 7.

\textsuperscript{51} See, e.g., T-Mobile Comments at 7 (“Incumbents are best positioned to determine how to achieve mobility by coordinating fixed and mobile uses of the spectrum in their license areas.”).

\textsuperscript{52} See Straight Path Comments at 23-24.


\textsuperscript{54} See Vivint Comments at 2-4 (claiming that “mobile transmissions are likely to be incompatible with existing fixed service in the same geographic area even with strict interference protection requirements”).
account for interference from or to these services.\textsuperscript{55} It thus proposes that in the limited areas where these licenses remain active, the FCC should explore moving those links to other bands.\textsuperscript{56}

This proposal should be strongly rejected. As Straight Path explained, the 39 GHz and LMDS bands are already licensed on an exclusive basis to a number of entities for fixed services.\textsuperscript{57} Straight Path has also already invested significant time and money into supporting and encouraging the advances and commercialization of 5G mmW technologies.\textsuperscript{58} While the Commission has cleared bands before, it was to auction spectrum for the use by licensees expected to provide incompatible services.\textsuperscript{59} In this case, the 39 GHz and LMDS bands have already been auctioned pursuant to Commission decisions that specifically contemplated future use of the bands for mobile services. Moreover, as noted above, 39 GHz and LMDS licensees can self-manage the band in order to provide existing fixed services and new mobile services. It would therefore be more efficient and promote greater use of spectrum if incumbent licensees are permitted to continue to hold their authorizations and grow their operations, rather than to reverse course and prevent existing licensees from recognizing the benefit of technical flexibility and relegating them to unspecified alternative spectrum. Straight Path agrees with NYU

\textsuperscript{55} See Qualcomm Comments at 8.

\textsuperscript{56} See id.

\textsuperscript{57} See Straight Path Comments at 23.

\textsuperscript{58} See id. at 2-3.

\textsuperscript{59} See, e.g., Amendment of Part 2 of the Commission’s Rules to Allocate Spectrum Below 3 GHz for Mobile and Fixed Services to Support the Introduction of New Advanced Wireless Services, including Third Generation Wireless Systems; Service Rules for Advanced Wireless Services In the 1.7 GHz and 2.1 GHz Bands, Ninth Report and Order and Order, 21 FCC Rcd. 4473 (2006) (establishing procedures for the relocation of Fixed Microwave Service operations from the 2160-2175 MHz band and modifying existing relocation procedures for the 2110-2150 MHz and 2175-2180 MHz bands to allow for Advanced Wireless Service operations); Amendment of the Commission’s Rules to Establish New Personal Communications Services, Second Report and Order, 8 FCC Rcd. 7700, ¶ 88 (1993) (designating UTAM as the coordinator for the transition of the 1890-1930 MHz band from fixed microwave service to unlicensed PCS).
Wireless that, in bands where there are incumbents with area licenses, those licensees “should be given flexibility and time to expand their present systems” to include a variety of uses. There is simply no need to clear the bands of existing licensees to promote 5G operations, and doing so would be punitive and contrary to the Commission’s anticipated development of the bands.

Where licenses have been surrendered, the Commission can conduct auctions for exclusive licenses in these areas. As the Commission and others recognize, this approach is already used in the 39 GHz and LMDS bands. To ensure that incumbent, as well as newly-auctioned, spectrum is used for 5G technologies, the Commission could adopt reasonable 5G-related performance requirements as it has for other spectrum bands in which mobile services are permitted. As Straight Path pointed out, even where a licensee met performance requirements, it is not unreasonable for the Commission to impose another reachable obligation if it allows additional use of existing spectrum. It should also ensure that licensees are allowed to use secondary market mechanisms such as leasing, partitioning, and disaggregation to encourage deployment.

V. THE FCC SHOULD ACT NOW RATHER THAN PROTECT SPECULATIVE SATELLITE OPERATIONS

Some parties note the existing allocation for satellite services in parts of the 39 GHz and LMDS bands and ask the Commission to preserve the use of the bands for those purposes. EchoStar Satellite Operating Corporation, Hughes Network Systems, LLC, and Alta Wireless, Inc. (collectively, “EchoStar”), for instance, claim that enabling 5G services in the V-band

60/ NYU Comments at 30.
61/ See NOI ¶ 92; FiberTower Comments at 17.
62/ See Straight Path Comments at 24-26; Samsung Comments at 36.
63/ See Straight Path Comments at 25.
64/ See id. at 10; Samsung Comments at 36; FiberTower Comments at 18.
“would unnecessarily jeopardize ongoing satellite investment and development in this band” because the V-band is a downlink band and “earth stations are vulnerable to receiving harmful interference from nearby 5G operations.”

ViaSat, Inc. (“ViaSat”) asserts that “the continually growing demand for satellite broadband services will require access to the full 2.5 GHz of the Ka band (in one form or another) to meet such demands.” And, Iridium Satellite LLC argues that care must be taken to avoid interference in the Ka-band that could interrupt the important communications that satellite operators carry. However, these satellite uses should not impede the use of the mmW bands for 5G operations. In the case of V-band spectrum in particular, continued reservation of the band for satellite applications where none has developed would frustrate the public interest.


The current allocation of the V-band for satellite use should not prevent or delay designation of the 39 GHz band for terrestrial 5G use. First, as satellite interests concede, use of

65/ See EchoStar/Hughes/Alta Comments at 25-26; see also id. at 19-20; Comments of the European Satellite Operators Association (ESOA), GN Docket No. 14-177, et al., at 2 (filed Jan. 15, 2015) (“ESOA Comments”) (explaining that satellite operators are designing solutions for services in the V-band and asserting that V-band frequencies that are already allocated for satellite services should be preserved); Comments of ViaSat, Inc., GN Docket No. 14-177 and RM-11664, at 11 (filed Jan. 15, 2015) (“ViaSat Comments”) (“[T]he V band will be an important expansion band for satellite networks.”).

66/ ViaSat Comments at 10; see also EchoStar/Hughes/Alta Comments at 18 (“Because satellite equipment and technology in the Ka-band has been developed and is widely in use for feeder links, it is critical that the FCC ensure that the Ka-band continues to remain available for the growing needs of the satellite community and their users.”); ESOA Comments at 2 (“Regulatory certainty is required by Ka-band satellite operators and their service providers to enable sustainable and viable access to Ka-band spectrum.”); Comments of Inmarsat, GN Docket No. 14-177, et al., at 4 (filed Jan. 15, 2015) (“Inmarsat Comments”) (arguing that there is currently significant satellite use of the 27.5-28.35 and 29.1-29.25 GHz bands and that “as the demand for Ka-band satellite services continues to grow, these bands will be more extensively used including for user terminal applications through coordination with existing users”).

67/ See Comments of Iridium Satellite LLC, GN Docket No. 14-177, at 7-9 (filed Jan. 15, 2015); see also Comments of O3b Limited, GN Docket No. 14-177, et al., at 5 (filed Jan. 15, 2015) (“O3b Comments”) (“As the Commission examines the possibilities of 5G, O3b urges the Commission to consider the role of incumbent services above 24 GHz, like Ka-band satellite services, in maintaining a healthy and balanced broadband ecosystem.”).
the V-band for satellite operations has not yet occurred, despite over 15 years of designation for that purpose.\textsuperscript{68/} Inmarsat reports that it is “examining the potential for deploying satellite networks in this band,”\textsuperscript{69/} and EchoStar acknowledges that any rules the FCC adopts in this proceeding would impact “future satellite broadband use” and that there have been “no successful commercial ventures” in the V-band.\textsuperscript{70/} Second, there is no industry agreement on the technical parameters that satellite operators need to deploy operations in the V-Band. For instance, there is no industry standard for “rain fade,” making it impossible for the FCC to adopt effective power limits or to allow satellite operators to take other ameliorative measures when that condition exits. In contrast, as this proceeding has demonstrated, there is a need for mmW spectrum for 5G technologies, and licensees are anxious for the authority to deploy it.

Rather than attempt to accommodate speculative satellite uses, the FCC should separate satellite services from mobile services and limit satellite operations to only a portion of the V-band. As the FCC has determined, it is not technically feasible for mobile services to coexist with Fixed Satellite Service ("FSS") operations in the same area. The Commission, for instance, declined to add a designation for Mobile Satellite Service ("MSS") in the 40.5-41.0 GHz portion of the V-band because that “would either relegate the existing designated service – FSS – to

\textsuperscript{68/} See Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5-38.5 GHz, 40.5-41.5 GHz, and 48.2-50.2 GHz Frequency Bands; Allocation of Spectrum to Upgrade Fixed and Mobile Allocations in the 40.5-42.5 GHz Frequency Band; Allocation of Spectrum in the 46.0-47.0 GHz Frequency Band for Wireless Services; and Allocation of Spectrum in the 37.0-38.0 GHz and 40.0-40.5 GHz for Government Operations, Report and Order, 13 FCC Rcd. 24649 (1998); see also Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5-38.5 GHz, 40.5-41.5 GHz, and 48.2-50.2 GHz Frequency Bands; Allocation of Spectrum to Upgrade Fixed and Mobile Allocations in the 40.5-42.5 GHz Frequency Band, Allocation of Spectrum in the 46.9-47.0 GHz Frequency Band for Wireless Services and Allocation of Spectrum in the 37.0-38.0 GHz and 40.0-40.5 GHz for Government Operations, Notice of Proposed Rulemaking, 12 FCC Rcd. 10130 (1997).

\textsuperscript{69/} See Inmarsat Comments at 6 (emphasis added).

\textsuperscript{70/} See EchoStar/Hughes/Alta Comments at 20, 25 (emphasis added); see also Inmarsat Comments at 6.
something less than predominant status, or . . . render the very use of ‘designations’ meaningless.”\textsuperscript{71/} The Commission suggested that “an MSS system would likely receive interference from FSS and BSS services under normal conditions,” particularly because MSS applications are generally mobile and, thus, require omni-directional antennas.\textsuperscript{72/} While the FCC has determined that satellite and mobile services can co-exist in the AWS-4 band, that determination was premised on ensuring that both services were operated by the same licensee.\textsuperscript{73/} It follows that the Commission should, as it previously proposed, limit satellite operations to the 37.5-38.6 GHz band and allow an increase in power levels for up to 12 dB for no more than 1.5 percent of the time.\textsuperscript{74/}

Not only would this solution represent the “best compromise,” as the FCC suggests,\textsuperscript{75/} but it would also create the regulatory certainty that both terrestrial and satellite service operators need to invest and develop spectrum in the V-band.\textsuperscript{76/} Straight Path agrees that the V-band issues that are unresolved in the FCC’s proceeding that has been pending for several years are

\textsuperscript{71/} Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5-38.5 GHz, 40.5-41.5 GHz and 48.2-50.2 GHz Frequency Bands, Second Report and Order, 18 FCC Rcd. 25428, ¶ 20 (2003) (“\textit{2003 V-Band Order}”).

\textsuperscript{72/} See id. ¶ 21.

\textsuperscript{73/} See generally \textit{AWS-4 Order}.

\textsuperscript{74/} See Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5-38.5 GHz, 40.5-41.5 GHz and 48.2-50.2 GHz \textit{Frequency Bands}; Allocation of Spectrum to Upgrade Fixed and Mobile Allocations in the 40.5-42.5 GHz \textit{Frequency Band}; Allocation of Spectrum in the 46.9-47.0 GHz \textit{Frequency Band for Wireless Services}; and Allocation of Spectrum in the 37.0-38.0 GHz and 40.0-40.5 GHz for Government Operations, Third \textit{Notice of Proposed Rulemaking}, 25 FCC Rcd. 15663, ¶ 46 (2010) (“\textit{2010 V-Band Third NPRM}”) (explaining that this proposal would not burden Fixed Services (“FS”) because, among other reasons, “1.5 percent of the time is the maximum that FS would experience any increase in [power flux density (‘PFD’)] from a single FSS satellite” and “[i]n most cases the PFD increases from FSS would not approach the maximum allowable level of 12 dB above clear-air PFD limits”); see also 47 C.F.R. § 25.208(q) (permitting a PFD limit of -105 dBW/m\textsuperscript{2} – i.e., a 12 dB power boost – during rain fade).

\textsuperscript{75/} See \textit{V-Band Third NPRM} ¶ 37.

\textsuperscript{76/} See \textit{2003 V-Band Order} ¶ 15 (determining that designating portions of the V-band for the Fixed Service and FSS “should promote investment and development throughout the V-band”).
tied to use of the 39 GHz band for 5G operations. The answer, however, is not to suspend action on both bands.\textsuperscript{77/} Instead, the Commission should adopt a notice of proposed rulemaking for the 39 GHz band and resolve its pending V-band proceeding at the same time. As O3b Limited recognizes, “it is essential that the Commission . . . carefully assess its rules for satellite services in the V-band, prior to or, at a minimum, in parallel with any proceedings addressing the potential for 5G in bands above 24 GHz.”\textsuperscript{78/}

Although some parties claim that satellite use of the V-band will “proliferate,”\textsuperscript{79/} there is no evidence that satellite operators require capacity in multiple segments of the bands above 24 GHz for their services. Satellite operators do not, as Inmarsat contends, “have just as much, if not more, invested in deployment of new services in the 39 GHz as any other services.”\textsuperscript{80/} Indeed, unlike existing incumbents in the 39 GHz band, satellite operators have not paid anything for authorizations in the V-band and have provided no services in the band. Because there are no existing satellite operations in the 39 GHz band, it should not prevent 5G operations in the band. The better approach is to allow FSS in the 37.5-38.6 GHz band with up to 12 dB power increase for 1.5 percent of the time and eliminate the FSS allocation in the 38.6-40.0 GHz band.

B. Concerns Related to the Ka-Band Can Be Addressed Separately.

Straight Path recognizes that satellite operations in the Ka-band are more complicated.\textsuperscript{81/} ViaSat suggests that the Ka-band “is intensively used today by a variety of satellite networks that

\textsuperscript{77/} See EchoStar/Hughes/Alta Comments at 25-26.
\textsuperscript{78/} O3b Comments at 11.
\textsuperscript{79/} See EchoStar/Hughes/Alta Comments at 25.
\textsuperscript{80/} Inmarsat Comments at 6.
\textsuperscript{81/} See Straight Path Comments at 21-22.
serve the United States.”  

Similarly, Echostar argues that “it is critical that, as part of any proceeding that considers making any part of the Ka-band available for 5G services, the FCC should ensure there is the ability for broadband satellite systems to expand.”

The Commission should therefore assess whether the Ka-band is still required for satellite services. Based on that evaluation, the Commission may wish to adopt several options which may permit use of 5G operations in some or all of the Ka-band spectrum. *First*, it may determine that existing satellite allocations are sufficient to meet the current and projected satellite requirements for the Ka-band. In that case, satellite operations may be migrated out of portions of the Ka-band to permit full use of the spectrum for terrestrial 5G use. *Second*, the Commission may determine that only some segments of the Ka-band are needed to support existing and future satellite needs. In that case, the Commission may wish to relocate certain satellite operations so that 5G and satellite use need not share the same spectrum. This study may delay, but should not ultimately prevent, mobile 5G operations in the LMDS bands. In any case, *issues related to satellite operations in the Ka-band should not prevent FCC action on the 39 GHz band.*

**VI. CONCLUSION**

The record in this proceeding demonstrates that the Commission can and should move expeditiously to open up the bands above 24 GHz – particularly the 39 GHz and LMDS bands – for flexible services. Accordingly, Straight Path respectfully urges the FCC to adopt one or more notices of proposed rulemaking that incorporates the proposals outlined above. Doing so will ensure that the FCC’s regulatory framework allows a variety of services to be deployed, recognizes the importance of and protects incumbents, accommodates the needs of satellite

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82/ ViaSat Comments at 10.
83/ EchoStar/Hughes/Alta Comments at 19.
84/ See Straight Path Comments at 22.
operators and most critically, provides the public with access to this largely untapped spectrum resource that can support the continued growth of the wireless communications ecosystem.

Respectfully submitted,

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Angela Y. Kung

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ATTACHMENT


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An Introduction to Millimeter-Wave Mobile Broadband Systems

Zhouyue Pi and Farooq Khan, Samsung Electronics

ABSTRACT

Almost all mobile communication systems today use spectrum in the range of 300 MHz–3 GHz. In this article, we reason why the wireless community should start looking at the 3–300 GHz spectrum for mobile broadband applications. We discuss propagation and device technology challenges associated with this band as well as its unique advantages for mobile communication. We introduce a millimeter-wave mobile broadband (MMB) system as a candidate next-generation mobile communication system. We demonstrate the feasibility for MMB to achieve gigabit-per-second data rates at a distance up to 1 km in an urban mobile environment. A few key concepts in MMB network architecture such as the MMB base station grid, MMB inter-BS backhaul link, and a hybrid MMB + 4G system are described. We also discuss beamforming techniques and the frame structure of the MMB air interface.

INTRODUCTION

Mobile communication has been one of the most successful technology innovations in modern history. The combination of technology breakthroughs and attractive value proposition has made mobile communication an indispensable part of life for 5 billion people. Due to the increasing popularity of smart phones and other mobile data devices such as netbooks and ebook readers, mobile data traffic is experiencing unprecedented growth. Some predictions indicate that mobile data will grow at 108 percent compound annual growth rate (CAGR) [1] with over a thousandfold increase over the next 10 years. In order to meet this exponential growth, improvements in air interface capacity and allocation of new spectrum are of paramount importance.

The current fourth-generation (4G) systems including LTE and Mobile WiMAX already use advanced technologies such as orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), multi-user diversity, link adaptation, turbo code, and hybrid automatic repeat request (HARQ) in order to achieve spectral efficiencies close to theoretical limits in terms of bits per second per Hertz per cell [2]. With limited room for further spectral efficiency improvement, another possibility to increase capacity per geographic area is to deploy many smaller cells such as femtocells and heterogeneous networks. However, because capacity can only scale linearly with the number of cells, small cells alone will not be able to meet the capacity required to accommodate orders of magnitude increases in mobile data traffic.

As the mobile data demand grows, the sub-3 GHz spectrum is becoming increasingly crowded. On the other hand, a vast amount of spectrum in the 3–300 GHz range remains underutilized. The 3–30 GHz spectrum is generally referred to as the super high frequency (SHF) band, while 30–300 GHz is referred to as the extremely high frequency (EHF) or millimeter-wave band. Since radio waves in the SHF and EHF bands share similar propagation characteristics, we refer to 3–300 GHz spectrum collectively as millimeter-wave bands with wavelengths ranging from 1 to 100 mm.

Millimeter-wave communication systems that can achieve multigigabit data rates at a distance of up to a few kilometers already exist for point-to-point communication. However, the component electronics used in these systems, including power amplifiers, low noise amplifiers, mixers, and antennas, are too big in size and consume too much power to be applicable in mobile communication. The availability of the 60 GHz band as unlicensed spectrum has spurred interest in gigabit-per-second short-range wireless communication. Several industrial standards have been developed, such as WirelessHD technology, ECMA-387, IEEE 802.15.3c, and IEEE 802.11ad. Integrated circuit (IC)-based transceivers are also available for some of these technologies. Much of the engineering efforts have been invested in developing more power-efficient 60 GHz RFICs [3]. Many of these technologies can be transferred to RFIC design for other millimeter-wave bands.

In this article, we explore the 3–300 GHz spectrum and describe a millimeter-wave mobile broadband (MMB) system that utilizes this vast spectrum for mobile communication. We describe the millimeter-wave spectrum and its propagation characteristics. We then discuss the network architecture, followed by the air interface design of the MMB system. After that, we conclude the article with a summary and brief discussion of future work.
Millimeter Wave Spectrum
Unleashing the 3–300 GHz Spectrum

Almost all commercial radio communications including AM/FM radio, high-definition TV, cellular, satellite communication, GPS, and Wi-Fi have been contained in a narrow band of the RF spectrum in 300 MHz–3 GHz. This band is generally referred to as the *sweet spot* due to its favorable propagation characteristics for commercial wireless applications. The portion of the RF spectrum above 3 GHz, however, has been largely unexploited for commercial wireless applications. More recently there has been some interest in exploring this spectrum for short-range and fixed wireless communications.

Within the 3–300 GHz spectrum, up to 252 GHz can potentially be suitable for mobile broadband as depicted in Fig. 1a. Millimeter waves are absorbed by oxygen and water vapor in the atmosphere. The frequencies in the 57–64 GHz oxygen absorption band can experience attenuation of about 15 dB/km as the oxygen molecule (O₂) absorbs electromagnetic energy at around 60 GHz. The absorption rate by water vapor (H₂O) depends on the amount of water vapor and can be up to tens of dBs in the range of 164–200 GHz [4]. We exclude these bands for mobile broadband applications as the transmission range in these bands will be limited. With a reasonable assumption that 40 percent of the remaining spectrum can be made available over time, millimeter-wave mobile broadband (MMB) opens the door for a possible 100 GHz new spectrum for mobile communication — more than 200 times the spectrum currently allocated for this purpose below 3 GHz.

LMDS and 70/80/90 GHz Bands
LMDS was standardized by the IEEE 802 LAN/MAN Standards Committee through the efforts of the IEEE 802.16.1 Task Group (“Air Interface for Fixed Broadband Wireless Access...
Millimeter-Wave Propagation

Free-Space Propagation

Transmission loss of millimeter wave is accounted for principally by free space loss. A general misconception among wireless engineers is that free-space propagation loss depends on frequency, so higher frequencies propagate less well than lower frequencies. The reason for this misconception is the underlying assumption often used in radio engineering textbooks that the path loss is calculated at a specific frequency between two isotropic antennas or $\lambda/2$ dipoles, whose effective aperture area increases with the wavelength (decreases with carrier frequency). An antenna with a larger aperture has larger gain than a smaller one as it captures more energy from a passing radio wave. However, with shorter wavelengths more antennas can be packed into the same area. For the same antenna aperture areas, shorter wavelengths (higher frequencies) should not have any inherent disadvantage compared to longer wavelengths (lower frequencies) in terms of free space loss [5]. In addition, large numbers of antennas enable transmitter and receiver beamforming with high gains. For example, a beam at 80 GHz will have about 30 dB more gain (narrower beam) than a beam at 2.4 GHz if the antenna areas are kept constant.

Penetration and Other Losses

For 3–300 GHz frequencies, atmosphere gaseous losses and precipitation attenuation are typically less than a few dB per kilometer [4], excluding the oxygen and water absorption bands. The loss due to reflection and diffraction depends greatly on the material and the surface. Although reflection and diffraction reduce the range of millimeter-wave, it also facilitates non-line-of-sight (NLOS) communication.

While signals at lower frequencies can penetrate more easily through buildings, millimeter-wave signals do not penetrate most solid materials very well. In Table 1, we provide attenuation values for common materials [6, 7]. High levels of attenuation for certain building materials (e.g., brick and concrete) may keep millimeter waves transmitted from outdoor base stations confined to streets and other outdoor structures, although some signals might reach inside the buildings through glass windows and wood doors. The indoor coverage in this case can be provided by other means such as indoor millimeter-wave femtocell or Wi-Fi solutions. It should be noted that next-generation Wi-Fi technology using 60 GHz millimeter waves is already being developed in IEEE 802.11ad [9].

Foliage losses for millimeter waves are significant and can be a limiting impairment for propagation in some cases. An empirical formula has been developed in [6] to calculate the propagation through foliage. In Fig. 2a, we plot penetration losses for foliage depth of 5, 10, 20, and 40 m. We note, for example, that at 80 GHz frequency and 10 m foliage penetration, the loss can be about 23.5 dB, which is about 15 dB higher than the loss at 3 GHz frequency.

Millimeter-wave transmissions can experience significant attenuations in the presence of heavy rain. Raindrops are roughly the same size as the radio wavelengths (millimeters) and therefore cause scattering of the radio signal. The attenuation (dB per kilometer) can be calculated from rain rates (millimeters per hour) [10], and the curves are plotted in Fig. 2b. For example, light

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<td>Drywall</td>
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<td>5.4</td>
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<td>1.9</td>
<td>0.5</td>
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<td>9.6</td>
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<tr>
<td>Clear glass</td>
<td>0.3/0.4</td>
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<td>7.7</td>
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<td>Chipwood</td>
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<tr>
<td>Mortar</td>
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<td>–</td>
<td>160</td>
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<tr>
<td>Brick wall</td>
<td>10</td>
<td>–</td>
<td>1178</td>
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<td>Concrete</td>
<td>10</td>
<td>17.7</td>
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Table 1. Attenuations for different materials.
rain at a rate of 2.5 mm/h yields just over 1 dB/km attenuation, while severe rain such as a monsoon at a rate of 150 mm/h can jeopardize communications with up to tens of dB loss per kilometer at millimeter-wave frequencies. Fortunately, the most intense rain tends to fall in selected countries of the world, and happen in short bursts and small clusters. A mechanism such as supporting emergency communications over cellular bands when millimeter-wave communications are disrupted by heavy rains should be considered as part of the MMB system design.

**DOPPLER AND MULTIPATH**

The Doppler of a wireless channel depends on the carrier frequency and mobility. Assuming a rich scattering environment and omnidirectional antennas, the maximum Doppler shift for carrier frequency of 3–60 GHz with mobility of 3–350 km/h ranges from 10 Hz to 20 kHz. The Doppler shift values of incoming waves at different angles at the receiver are different, resulting in a phenomenon called Doppler spread. In the case of MMB, the narrow beams at the transmitter and receiver will significantly reduce angular spread of the incoming waves, which in turn reduces the Doppler spread. In addition, as the incoming waves are concentrated in a certain direction, there will be a non-zero bias in the Doppler spectrum, which will be largely compensated by the automatic frequency control (AFC) loop in the receiver. Therefore, the time-domain variation of an MMB channel is likely to be much less than that observed by omnidirectional antennas in a rich scattering environment.

With narrow transmitter and receiver beams, the multipath components of millimeter waves are limited. Studies show that the root mean square (RMS) of the power delay profile (PDP) of a millimeter-wave channel in an urban environment is 1–10 ns, and the coherent bandwidth of the channel is around 10–100 MHz [11]. However, it is noted that the transmitter and receiver antenna gains used in these studies are higher than those used in MMB. Therefore, it is possible that in an MMB system a longer path can be observed and the coherence bandwidth is smaller than those reported in these studies.

**MMB NETWORK ARCHITECTURE**

**A STANDALONE MMB NETWORK**

An MMB network consists of multiple MMB base stations that cover a geographic area. In order to ensure good coverage, MMB base stations need to be deployed with higher density than macrocellular base stations. In general, roughly the same site-to-site distance as microcell or picocell deployment in an urban environment is recommended. An example MMB network is shown in Fig. 3.

The transmission and/or reception in an MMB system are based on narrow beams, which suppress the interference from neighboring MMB base stations and extend the range of an MMB link. This allows significant overlap of coverage among neighboring base stations. Unlike cellular systems that partition the geographic area into cells with each cell served by one or a few base stations, the MMB base stations form a grid with a large number of nodes to which an MMB mobile station can attach. For example, with a site-to-site distance of 500 m and a range of 1 km for an MMB link, an MMB mobile station can access up to 14 MMB base stations on the grid, as shown in Fig. 3a. The MMB base station grid eliminates the problem of poor link quality at the cell edge that is inherent in cellular systems and enables high-quality equal grade of service (EGOS) regardless of the location of a mobile.

With the high density of MMB base stations, the cost to connect every MMB base station via a wired network can be significant. One solution to mitigate the cost (and expedite the deployment) is to allow some MMB base stations to connect to the backhaul via other MMB base stations. Due to large beamforming gains, the MMB inter-BS backhaul link can be deployed in the same frequency as the MMB access link —

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**Figure 2.** Millimeter-wave propagation characteristics: a) foliage penetration loss; b) rain attenuation.
the downlink to and uplink from an MMB mobile station — without causing much interference. This greatly increases the deployment flexibility of MMB and allows MMB to achieve higher-density deployment than femtocells or heterogeneous networks deployed in sub-3 GHz spectrum.

Another challenge with millimeter-wave is the low efficiency of RF devices such as power amplifiers and multi-antenna arrays with current technology. A solution to avoid multi-antenna arrays at the MMB base station is to use fixed beams or sectors with horn antennas. Horn antennas can provide similar gains and beam widths as sector antennas in current cellular systems in a cost-effective manner [12]. The mobile station receiver still needs to use a multi-antenna array to form a beamforming pattern toward the base station. As the mobile station moves around, beamforming weights can be adjusted so that the beam is always pointing toward the base station.

**HYBRID MMB + 4G SYSTEM**

In the early deployment of MMB, there may be coverage holes in areas where the MMB base station density is low. However, it is expected that 4G systems will have good coverage and reliability when MMB systems start to deploy. A hybrid MMB + 4G system can improve coverage and ensure seamless user experience in mobile applications. In a hybrid MMB + 4G system, system information, control channel, and feedback are transmitted in the 4G system, making the entire millimeter-wave spectrum available for data communication. One example of a hybrid MMB + 4G system is shown in Fig. 3b. Compared with millimeter waves, the radio waves at < 3 GHz frequencies can better penetrate obstacles and are less sensitive to non-line-of-sight (NLOS) communication link or other impairments such as absorption by foliage, rain, and other particles in the air. Therefore, it is advantageous to transmit important control channels and signals via cellular radio frequencies, while utilizing the millimeter waves for high data rate communication.

**MMB AIR INTERFACE DESIGN**

**BEAMFORMING**

Beamforming is a signal processing technique used for directional signal transmission or reception. Spatial selectivity/directionality is achieved by using adaptive transmit/receive beam patterns. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter antenna to create a pattern of constructive and destructive interference in the wavefront. When receiving, signals from different receiver antennas are combined in such a way that the expected pattern of radiation is preferentially observed.

Beamforming is a key enabling technology of MMB. For MMB transceivers, the small size ($\lambda/2$ dipoles) and separation (also around $\lambda/2$) of millimeter-wave antennas allow a large number of antennas and thus achieve high beamforming gain in a relative small area (e.g., tens of antennas per square centimeter area at 80 GHz carrier frequency). Additionally, with a large number of antennas and high-gain (and thus narrow) beams, antenna technologies such as spatial-division multiple access (SDMA) can be implemented readily.

Beamforming can be achieved in digital base-
band, analog baseband, or RF front-end. With digital beamforming and multiple RF chains, it is possible to transmit multiple streams of data simultaneously, thus enabling SDMA or MIMO operation. However, the cost of implementing one RF chain per antenna can be prohibitive, especially given the large number of antennas in MMB. With analog baseband beamforming or RF beamforming, one or a few RF chains can be used. In that case, the number of data streams that can be transmitted is limited by the number of RF chains. These approaches require fewer RF components and are typically chosen for low-cost/low-power solutions.

Transmit beamforming is generally more challenging, requiring either antenna weights feedback from the receiver or antenna calibrations. Moreover, due to low efficiency of millimeter-wave power amplifiers with the current technology, battery power consumption is another issue for mobile station transmitter beamforming. To reduce the cost and complexity of mobile stations, a phased approach where initial deployments are hybrid MMB + 4G systems with downlink-only transmission in the millimeter-wave band can be considered. This removes the requirement for mobile stations to transmit in the millimeter-wave band.

**FRAME STRUCTURE**

OFDM and single-carrier FDM were chosen to be the multiplexing schemes of 4G systems due to a variety of reasons (e.g., flexibility in support of multiple bandwidths, simpler equalizer design, and ability to support efficient multiple access, etc.). In MMB, we also use OFDM and single-carrier waveform for largely the same reasons.

One configuration of MMB frame structure is shown in Fig. 4. The basic transmission time interval (TTI) of MMB is a slot, whose duration is 62.5 μs. In order to facilitate hybrid MMB + 4G operation, the durations of subframe, frame, and superframe are chosen to be 1 ms, 10 ms, and 40 ms, the same as those of LTE systems.

The OFDM/single-carrier numerology is carefully chosen according to a number of engineering considerations. For example, the sampling rate is chosen to be a multiple of 30.72 MHz, a popular frequency at which clocks with reasonable accuracy are readily available at low cost. The cyclic prefix (CP) is chosen to be 520 ns, which gives sufficient margin in accommodating the longest path, different deployment scenarios, and the potential increase of delay spread in the case of small antenna arrays (e.g., smart phones with small form factors) or wider beams (e.g., control channel transmissions). The subcarrier spacing is chosen to be 480 kHz, small enough to stay within the coherent bandwidth of most multipath channels expected in MMB. The corresponding OFDM symbol length (without CP) is 2.08 μs, resulting in 20 percent CP overhead. The subcarrier spacing is also wide enough to keep the size of fast/inverse fast Fourier transform (FFT/IFFT) small (2048 points for 1 GHz system bandwidth) and accommodate inaccuracies of low-cost clocks. For example, with a carrier frequency of 28 GHz and a clock with 20 ppm accuracy, the clock drift is at most 560 kHz, less than 2 times the subcarrier spacing. This enables simple design of synchronization and system acquisition.

Additionally, MMB also supports transmission with single-carrier waveform. Single-carrier waveform has lower peak-to-average-power ratio (PAPR) than OFDM. As the solid-state devices today only have a limited amount of output power rating (< 1 W) in 60–100 GHz frequency bands, it is beneficial to use single-carrier waveform to maximize the output power so that MMB can achieve the longest range possible. A lower PAPR also allows the receiver to use a low-resolution analog-to-digital converter (ADC). For single-carrier transmissions with binary phase shift keying (BPSK) or quaternary PSK (QPSK), an ADC with 2–4 bits would suffice, which greatly reduces the power consumption of the MMB receiver.

**LINK BUDGET**

The key factors that determine the downlink link budget of an MMB system are the base station transmission power, transmitter and receiver beamforming gains, and path loss.

Table 2 shows the link budget for four different MMB systems. A 20 dB margin is assumed to account for cable loss and losses due to penetration, reflection, or diffraction. A noise figure of 10 dB and an implementation loss of 5 dB are assumed at the receiver. As shown in Table 2, with 35 dBm transmission power, 1 GHz system bandwidth, 28 GHz carrier frequency, and realistic assumptions of transmitter and receiver antenna gains (case 1), more than 2 Gb/s can be achieved at 1 km distance.

**CONCLUSION**

Millimeter-wave spectrum with frequencies in the range of 3–300 GHz can potentially provide the bandwidth required for mobile broadband applications for the next few decades and beyond.
In this article, we have analyzed the suitability of different millimeter-wave frequencies for mobile communication. We have discussed the propagation characteristics of millimeter waves, including the propagation and penetration losses, Doppler, and multipath. Due to the narrow beam width of MMB transmissions, the interference among MMB base stations is a lot smaller than traditional cellular systems, and the coverage of neighboring base stations significantly overlap. As a result, the MMB base stations form a grid that can provide communication with good link quality regardless of the mobile station’s location within the coverage of the grid. The inter-BS backhaul link can be used to mitigate the cost of backhauling (and to expedite deployment). It is also possible to operate a hybrid MMB + 4G system such that existing 4G systems can be leveraged for reliable system information broadcast, packet data control, and feedback of MMB systems.

In order to operate in an urban mobile environment while keeping a low overhead, we chose the MMB subcarrier spacing to be 480 kHz and the CP to be 520 ns. We also designed the frame structure to facilitate hybrid MMB + 4G operation. In the link budget analysis, we show that a 2 Gb/s data rate is achievable at 1 km distance with millimeter waves in an urban mobile environment.

**ACKNOWLEDGMENT**

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**REFERENCES**


**Table 2. MMB link budget.**

<table>
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<tr>
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<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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<tr>
<td>TX power (dBm)</td>
<td>35.00</td>
<td>35.00</td>
<td>25.00</td>
<td>25.00</td>
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<tr>
<td>TX antenna gain (dBi)</td>
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<td>30.00</td>
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<td>Carrier frequency (GHz)</td>
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<td>72.00</td>
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<td>Distance (km)</td>
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<td>Propagation loss (dB)</td>
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<td>115.32</td>
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<td>Other losses</td>
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<td>RX antenna gain (dBi)</td>
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<td>Received power (dBm)</td>
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<td>Bandwidth (GHz)</td>
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<td>Thermal PSD (dBm/Hz)</td>
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<td>Noise figure (dB)</td>
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<td>Thermal noise (dBm)</td>
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<td>SNR (dB)</td>
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<td>Data rate (Gb/s)</td>
<td>2.77</td>
<td>0.91</td>
<td>1.74</td>
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</tbody>
</table>

**BIographies**

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