Use of millimeter wave carrier frequencies in 5G

Stefano Tomasin

Abstract Electromagnetic signals with carrier lengths between 1 mm and 1 cm are commonly denoted as mm-waves, and they are going to be used in the fifth generation (5G) of mobile communications. This chapter will outline the main features of mm-waves transmissions. We first discuss the drivers and opportunities of using mm-waves in 5G mobile systems, underlining technical aspects and peculiar physical phenomena. Then we introduce signal processing techniques that are essential for mm-waves, indicating also relevant issues for 5G systems, namely: channel estimation, hybrid beamforming and initial access. We conclude the chapter with a description of most promising applications and some notes on regulatory aspects of 5G mm-wave systems.

1 Drivers and Opportunities for 5G Systems

An ambitious performance is expected from the fifth generation (5G) of cellular communication systems in order to accommodate a variety of applications (e.g., remote control, monitoring, intelligent transport systems, and tactile interaction), with user experienced data rates up to 1 Gbps (500 Mbps) in downlink (uplink) and latency as low as 0.5 ms. These targets can not be met by using only the spectrum available for 4G systems[1], but require the use of new frequencies. When the international telecommunication union (ITU) started as early as in 2012 the international mobile telecommunication 2020 (IMT-2020) standard[2], it also pushed for a new spectrum allocation to cellular systems worldwide. The world radiocommunication

Stefano Tomasin
Department of Information Engineering, University of Padova, via G. Gradenigo 6/B, 35131 Padova, Italy, e-mail: tomasin@dei.unipd.it

[1] In 4G systems the center frequencies are from 1 to 3 GHz, and the total bandwidth is up to 10 GHz.

[2] IMT-2020 will be defined by third generation partnership project (3GPP) as a *release*, finally commercialized as 5G system to the end user.

conference (WRC) in 2015[3] has identified various spectrum portions between 24 to 86 GHz for mobile communications. Tens of GHz are expected to be made available in the mm-wave band, according to specific spectrum assignments made by each country.

The use of these frequencies for mobile communications opens various technological opportunities and challenges. Among opportunities, mm-waves are particularly favorable to the 5G scenario of small-cells envisioned by ITU, as their strong attenuation naturally reduces interference. Moreover, the maturity of complementary metal-oxide semiconductor (CMOS) transistor production has allowed a cheaper implementation of the circuitry needed to handle millimeter wavelength signals. On the other hand, mm-waves also pose technical channels to overcome strong attenuations, provide a good channel estimate, and discover new users entering cells, as described in the following.

Before proceeding, we recall that, strictly speaking, the portion of spectrum carrying signals with wavelength between 1 mm and 1 cm (thus being more entitled to be named mm-waves) is denoted by ITU as the extreme high frequency (EHF) band and spans frequencies from 30 to 300 GHz. However, even frequencies below 30 GHz, down to 6 GHz (about 5 cm wavelength) are typically denoted as mm-waves, at least in a 5G context.

2 Physical Characteristics

The most important characteristic of the mm-wave band for radio communication is its significant path loss attenuation due exclusively to the distance between the transmitter and the receiver. Indeed, the specific attenuation in free space due to the atmosphere raises from $5 \cdot 10^{-3}$ dB/km at 2 GHz to about $2 \cdot 10^{-1}$ dB/km at 24 GHz to dramatically increase to 20 dB/km at 60 GHz, due the peak of absorption of oxygen: these numbers translate into an attenuation of 10 dB at 200 km, 50 km, and 500 m, respectively. In order to incorporate other propagation phenomena, various channel models have been proposed for mm-waves (see [1] for an overview).

Moreover, the mm-waves are subject to the blockage phenomenon, as their propagation is largely prevented by almost any physical object. This phenomenon is typically captured by either *shadowing*, modelling the presence of static objects, or *fading*, accounting for fast attenuations variations due to moving objects.

Within the 3GPP 5G standard the channel model is described in the technical report series TR 38.901 [2], which specifies various scenarios, including urban macro and micro cells, rural macro cells and indoor office.

[3] The WRC is held every three or four years to review and revise radio regulations, the international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits.

2.1 Integrated Circuits Advancements

The spectrum of mm-waves has been used for many years by astronomers and military, thus we may wonder why engineers working on mobile communications become truly interested in this portion of the spectrum only in the ’10s of the third millennium. Together with an economic push to obtain new spectrum that would allow higher data rates, we find also technological reasons.

The signals transmitted by smartphones and other consumer devices are generated and amplified by integrated circuits typically built with silicon-based technologies, like CMOS or bipolar CMOS (BiCMOS). Any active device has a maximum frequency of operation, called *transit frequency*, beyond which it does not provide any current gain. Practical amplifiers can actually be built only at a fraction of the transit frequency. As the transistor transit frequency is inversely proportional to its geometrical size, the continuous downscaling of the microelectronic technology favored systems operating at increasingly higher frequencies. Only in ’10s of the third millennium the industry has been ready to mass-produce transistors with a minimum feature down to 28 nm and below, providing a reliable platform for applications operating above 10 GHz.

Indeed, the advance of this technology has pushed the use of mm-waves in many fields, including communications (devices for HD transmission from digital set top boxes, Wi-Fi standards, satellite communications), sensors (road radars for cars, body scanners), and medical applications.

3 Signal Processing and Protocols

Due to the peculiarities of the mm-wave channel, special signal processing techniques and protocols must be adopted. Some surveys on mm-waves and their use for 5G communications have appeared in recent years and provide further insight into these and other topics [3, 4, 5]. Here we outline three relevant issues: the use of multiple antennas; the estimation of the channel characteristics; and the discovery of new users entering a cell.

3.1 Massive MIMO and Beamforming

The use of multiple antennas at both the transmitter and the receiver is an effective means to overcome the attenuation of the mm-wave channel. In fact, by sending the same signal over multiple omnidirectional antennas with proper delays and amplifications we ensure that the signals add up coherently in the specific position where the receiver is. The overall effect is to create a directional antenna which sends data much farther away in specific directions than a single omnidirectional antenna that disperses power in all directions. The reason of using different delays and amplifications per antennas is related to the fact that the distances between each transmit antenna and the receiver are different, thus determining arrivals with different delays and attenuations, which must be compensated before transmission. This transmission strategy is named *transmit beamforming*.

Similarly, when at the receiver multiple antennas are available, the signals collected by them can be suitably delayed and combined in order to obtain a stronger replica of the transmitted signal. Note that while the same data signal is received by all receive antennas, in general independent zero-mean noise samples are present on each antenna, that are averaged out by combining. This is named *receive beamforming*.

A communication system with multiple transmit and receive antennas is a multiple input multiple output (MIMO) systems. The more antennas are used, the more focused is the beamforming: a system with a very large (from hundreds above) number of antennas is a *massive MIMO* system. However, we can also use multiple transmit and receive antennas to transmit simultaneously multiple signals, each carrying different data in what is called *multiplexing* transmission.

Let us now consider the baseband representation of a MIMO system. In a narrowband transmission between N_T transmit and N_R receive antennas, $s_k(nT)$ is the baseband signal at time nT on transmit antenna $k = 1, \ldots, N_\mathrm{T}$, where T is the sampling time and n is the time index. Similarly, at the receiver $r_m(nT)$ is the sampled signal at time nT on antenna $m = 1, \ldots, N_\mathrm{R}$ after demodulation. In the baseband representation, the effect of delays and attenuations of the channel is represented by a matrix multiplication of vector[4] $\boldsymbol{s}(nT) = [s_1(nT), \ldots, s_{N_\mathrm{T}}(nT)]^T$ by the $N_\mathrm{R} \times N_\mathrm{T}$ matrix $\boldsymbol{H}$ with complex entries, providing the input-output relation

$$\boldsymbol{r}(nT) = [r_1(nT), \ldots, r_{N_\mathrm{R}}(nT)]^T = \boldsymbol{H}\boldsymbol{s}(nT) + \boldsymbol{w}(nT), \qquad (1)$$

where $\boldsymbol{w}(nT) = [w_1(nT), \ldots, w_{N_\mathrm{R}}(nT)]^T$ is a vector of N_R independent zero-mean complex additive white Gaussian noise (AWGN) variables with variance σ_w^2. The beamforming is obtained by digitally transforming the transmitted and received signal vectors. In particular, let $\boldsymbol{H} = \boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^H$ be the singular value decomposition (SVD) of $\boldsymbol{H}$, where $\boldsymbol{D}$ is a $M \times M$ diagonal matrix, $M = \mathrm{rank}\boldsymbol{H} \leq \min\{N_\mathrm{R}, N_\mathrm{T}\}$, $\boldsymbol{U}$ and $\boldsymbol{V}^H$ are unitary matrices of size $N_\mathrm{R} \times M$ and $M \times N_\mathrm{T}$, respectively, with

$$\boldsymbol{U}^H\boldsymbol{U} = \boldsymbol{I}_{N_\mathrm{R}}, \quad \boldsymbol{V}^H\boldsymbol{V} = \boldsymbol{I}_{N_\mathrm{T}}, \qquad (2)$$

and $\boldsymbol{I}_K$ is the identity matrix of size K. Then by transmitting $\boldsymbol{s}(nT) = \boldsymbol{V}\boldsymbol{d}(nT)$, with $\boldsymbol{d}(nT)$ a vector of M data symbols, and multiplying the received vector $\boldsymbol{r}(nT)$ by $\boldsymbol{U}^H$, from (2) we have

$$\tilde{\boldsymbol{d}}(nT) = \boldsymbol{U}^H\boldsymbol{r}(nT) = \boldsymbol{U}^H\boldsymbol{H}\boldsymbol{V}\boldsymbol{d}(nT) + \boldsymbol{U}^H\boldsymbol{w}(nT) = \boldsymbol{D}\boldsymbol{d}(nT) + \tilde{\boldsymbol{w}}(nT), \qquad (3)$$

where $\tilde{\boldsymbol{w}}(nT)$ is a vector of M independent zero-mean AWGN variables with variance σ_w^2. Therefore the MIMO channel has been converted into M parallel AWGN

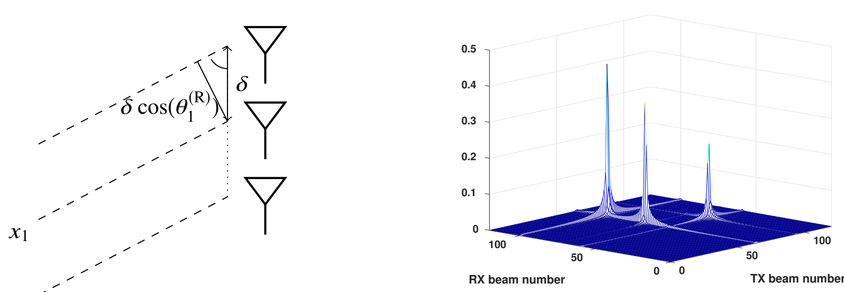
[4] ^{T} denotes the transpose operator. ^{H} denotes the Hermitian operator.

channels, as (3) can be written as $\tilde{d}_m(nT) = D_m d_m(nT) + \tilde{w}_m(nT)$, $m = 1, \ldots, M$, where $\tilde{d}_m(nT)$, $d_m(nT)$ and $\tilde{w}_m(nT)$ are the m-th entries of vectors $\tilde{\boldsymbol{d}}(nT)$, $\boldsymbol{d}(nT)$ and $\tilde{\boldsymbol{w}}(nT)$, respectively, and D_m is the m-th entry of the diagonal of $\boldsymbol{D}$. By this beamforming procedure at the same time we simplify the implementation of the transmitter and the receiver and maximize the data rate of the transmission, i.e., we achieve the capacity of the MIMO channel. Note that from the definition of M the number of antennas at either side of the communication system limits the number of data that can be simultaneously transmitted. In practice, experimental results have provided reduction of the attenuation by 40 dB with the transmitter and the receiver equipped with uniform planar array antennas with 64 elements [6].

3.2 Channel Model

Although the number of transmit and receive antennas can be large, the different paths from the transmitter to the receiver are related to the objects surrounding the devices, and they do not increase with the number of antennas. Moreover, mm-waves are subject to strong absorptions upon hitting most objects, thus only few reflections occurs before the signal is completely absorbed. Taking into account the strong free-space attenuation, typically the number of paths L over which a signal travels from a transmitter to a receiver is $L \approx 3$.

In this very simple scenario a simple model is available for the channel matrix $\boldsymbol{H}$, taking into account the multiple antenna geometry. Consider for example uniform linear arrays (ULAs) where antennas are uniformly spaced with δ spacing along a line and indicate with λ the carrier wavelength. The length of path $l = 1, \ldots, L$ from the transmit to the receive antennas is x_l. Assuming that $x_l >> \delta$, the *departure angle* $\theta_l^{(\mathrm{T})}$ is the angle between the line of the transmit antennas and the line connecting the transmitter to the reflecting object. Similarly path l is characterized by the arrival



(a) Single path received by a ULA.

(b) Example of channel inverse discrete Fourier transform (IDFT) of 3GPP channel.

Fig. 1 Example of mm-Wave received signal.

angle $\theta_l^{(\mathrm{R})}$ between the line of the receive antennas and the line connecting the receiver to the reflecting object. Fig. 1.a shows the incidence of the single path on a ULA with $N_\mathrm{R} = 3$ antennas. Then, the channel matrix has entries

$$[\boldsymbol{H}]_{p,q} = \sum_{l=1}^{L} \alpha_l e^{2\pi j \eta_\mathrm{R}^l p} e^{2\pi j \eta_\mathrm{T}^l q}, \quad p = 0, 1, \ldots, N_\mathrm{R} - 1, \; q = 0, 1, \ldots, N_\mathrm{T} - 1, \quad (4)$$

where $\eta_\mathrm{R}^l = \frac{\delta}{\lambda} \cos \theta_l^{(\mathrm{R})}$, $\eta_\mathrm{T}^l = \frac{\delta}{\lambda} \cos \theta_l^{(\mathrm{T})}$ and $\alpha_l = \frac{1}{x_l^2} e^{-j2\pi \frac{x_l}{\lambda}}$. The statistics of each parameter depend on the considered propagation scenario, and various relevant cases can be found for example in the 3GPP mm-wave channel model [2].

In conclusion, although the channel matrix $\boldsymbol{H}$ is large, it turns out to be defined by very few parameters, namely, the angles of arrival and departure and the length of L paths. These features can be exploited to simplify some procedures connected to the use of massive MIMO technology, such as channel estimation and initial access.

3.3 Hybrid Beamforming

For the technology of the '10s of the third millennium, digital to analog converters (DACs) are quite expensive and power consuming components. When N_T grows large, the N_T digital to analog conversions of vector $\boldsymbol{s}(nT)$ represent a problem. Therefore, it has been suggested to perform beamforming partially in the digital domain and partially in the analog domain. In fact we remember that multiplying a baseband signal by a complex number corresponds to attenuating and "delaying" the corresponding analog narrowband signal. Therefore, the matrix multiplication $\boldsymbol{V}\boldsymbol{d}(nT)$ can be performed in the analog domain by scaling, delaying and adding analog signals according to the entries of $\boldsymbol{V}$. For a transmit beaforming completely performed in the analog domain we need M DACs to convert the M symbols of vector $\boldsymbol{d}(nT)$ instead of the $N_\mathrm{T} >> M$ DACs required to fully digital represent $\boldsymbol{V}\boldsymbol{d}(nT)$.

On the other hand, the analog part should be reconfigurable since the channel matrix changes for different users and different scenarios. In practice, only a finite (small) set of delays are practically implementable, thus introducing quantization effects in the beamforming process. In order to rape the benefits of both analog and digital approaches, a significant effort has been done to develop *hybrid beamforming* structures, where a first digital matrix operation (beamforming) is performed on $\boldsymbol{d}(nT)$ generating an intermediate vector $\boldsymbol{y}(nT)$ of size $\tilde{M}$ with $N_\mathrm{T} > \tilde{M} > M$. Then $\boldsymbol{y}(nT)$ is converted into an analog signal and further processed by an analog beamforming structure to generate the N_T signals to be transmitted. Fig. 2 shows a general hybrid beamforming scheme.

Various solutions have been proposed, and for a survey on hybrid beamforming for 5G system refer to [7]. We only note that from (4) we have that for a large number of antennas matrix $\boldsymbol{U}$ can be written in part as a Fourier transform matrix that can be easily implemented both with analog circuits and with digital operations [8].

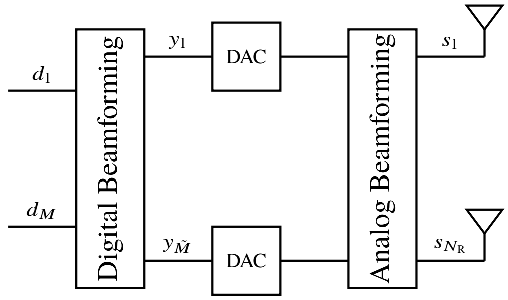


Fig. 2 Example of transmit hybrid beamforming structure.

3.4 Channel Estimation

In order to perform beamforming, matrix $\boldsymbol{H}$ must be known. The procedure used to obtain $\boldsymbol{H}$ goes under the name of *channel estimation*. In order to estimate it at the user terminal, the base station (BS) transmits a sequence of N_T *pilot symbols* represented by the $N_T \times N_T$ matrix $\boldsymbol{S}$, known also by the user, which collects N_T samples from each antennas. By exploiting the linear relation $\boldsymbol{R} = \boldsymbol{HS} + \boldsymbol{W}$, where we collected N_T received columns vectors $\boldsymbol{r}$ into $\boldsymbol{R}$, and solving the linear system in $\boldsymbol{H}$ we obtain the least squares (LS) estimate of $\boldsymbol{H}$, $\tilde{\boldsymbol{H}} = \boldsymbol{RS}^{-1}$, still affected by AWGN noise with variance σ_w^2 independent at each channel matrix entry, if $\boldsymbol{S}$ is unitary.

The LS method works for any MIMO system, and does not exploit the peculiarities of the mm-wave channel, where matrix $\boldsymbol{H}$ can be described by a reduced number of parameters and has the structure given in (4). In order to exploit these peculiarities we consider the *virtual channel*, or *angular domain representation*. This is obtained by taking the two-dimensional $M_1 \times M_2$ Fourier transform of matrix $\boldsymbol{H}$ as

$$[\boldsymbol{G}]_{f_1,f_2} = \frac{1}{M_1 M_2} \sum_{i_1=0}^{N_R} \sum_{i_2=0}^{N_T} [\boldsymbol{H}]_{i_1,i_2} e^{-\frac{2\pi f_1 i_1 j}{M_1}} e^{-\frac{2\pi f_2 i_2 j}{M_2}} = \sum_{l=1}^{L} \alpha_l [\boldsymbol{W}(\boldsymbol{\Omega}^l)]_{f_1,f_2}, \quad (5)$$

where $f_i = 0, 1, \ldots, M_i - 1$, $i = 1, 2$, $\boldsymbol{W}(\boldsymbol{\Omega}^l)$ is a matrix containing the two-dimensional (2D) sampled periodic sinc function[5] centered at frequencies $\boldsymbol{\Omega}^l = (\Omega_1^l, \Omega_2^l) = (M_1 \eta_R^l, M_2 \eta_T^l)$. Fig. 1.b shows an example of mm-wave channel in the

[5] The two-dimensional (2D) sampled periodic sinc function is defined as

$$[\boldsymbol{W}(\boldsymbol{\Omega}^l)]_{f_1,f_2} = \left[\frac{N_R}{M_1} I_{N_R}\left(\frac{N_R(f_1 + \Omega_1^l)}{M_1}\right) e^{j\pi(f_1+\Omega_1^l)\frac{N_R-1}{M_1}}\right] \times \left[\frac{N_T}{M_2} I_{N_T}\left(\frac{N_T(f_2 + \Omega_2^l)}{M_2}\right) e^{j\pi(f_2+\Omega_2^l)\frac{N_T-1}{M_2}}\right],$$

where $I_n(x) = \frac{\sin(\pi x)}{n \sin(\pi \frac{x}{n})}$ is the 1D-periodic sinc function.

angular domain: we can clearly distinguish a few peaks, corresponding to the small number of paths L.

The reason to move into this transformed domain is that the 2D-sinc functions that compose $\boldsymbol{G}$ are concentrated among their peaks, and the effect is more remarkable for a large number of antennas. In other words, from a full matrix $\boldsymbol{H}$ we obtain a sparse matrix $\boldsymbol{G}$. Note also that by the Fourier operation, the noise statistics are not altered, thus all points of the LS estimate of $\boldsymbol{G}$ are still affected by independent Gaussian noise.

In order to refine the LS channel estimate we find the peaks in the estimate of $\boldsymbol{G}$ and then reduce (or set to zero) all other values of the matrix that contain only noise. Lastly, by an inverse Fourier transform we obtain a new estimate of $\boldsymbol{H}$ with much reduced noise. Various solutions have been proposed for this purposes, and [5] provides a survey. For example, solutions based on the iterative detection and cancellation of the paths from the virtual channel estimation have been proposed in [8], also under the name of orthogonal matching pursuit (OMP). The sparsity of the channel can also be exploited by compressed sensing approaches, for example using fast iterative shrinkage-thresholding algorithm (FISTA), least absolute shrinkage and selection operator (LASSO), basis pursuit denoise (BPDN) and accelerated gradient descent with adaptive restart (AGDAR) [9] algorithms.

3.5 Initial Access

When a user enters a new cell, the user and the BS must find each other in space by turning their beamformers in the proper direction, in what denoted as *initial access* problem.

The basic solution provides that both BS and user sweep the space, the BS transmitting a pilot signal and the user detecting its direction of arrival. This corresponds approximately to estimating the strongest path of the mm-wave channel. Then the user transmits a pilot signal towards the BS that sweeps the space until it detects its direction of arrival.

This procedure can be refined in various ways (see [10] for a survey), in order to reduce the time by which a new user is discovered. For example, by exploiting positioning information coming from external sources (e.g., from a global navigation satellite system receiver) and exchanging this information over an existing communication channel at a lower frequency, the beamforming direction to be used at both terminals can be inferred. However, various phenomena can make the beamforming direction different from the line of sight: for example, obstructions may be present, while a good reflection path may be available; moreover, the rotation of the smartphone is typically not properly estimated by sensors, while being crucial for beamforming. Other approaches has focused on the optimization of sweeping, for example by introducing a hierarchical search starting from broader and less penetrating beams to then use more focused beams. Another solution is based on the observation that users typically enter the cell from particular directions (corresponding for example to streets), while other directions are not possible due to blockage effect toward the BS: by properly learning these typical patterns (also maybe related to commuting habits and changing over the day) and checking more frequently directions that are typically used for entrance, the duration of the initial access procedure can be significantly reduced [11].

4 5G Applications

As tracing the channel variations is complicated, the devices should not move fast while exchanging data over the mm-waves. In this context, two scenarios applications are particular promising for mm-waves: backhauling and fixed wireless access.

Backhauling refers to the communication among BSs of the same cellular system and is particularly useful in a mm-wave scenario, where cells are small for coverage purposes, and connecting all these BS to the fixed network may be expensive. On the other hand, mm-waves are ideal for backhauling, since they offer a huge spectrum and the connected devices are fixed, thus not posing channel tracking problems. Moreover, positions of BSs and antennas can be properly chosen in order to avoid blockage. For a survey on backhauling for 5G systems see [12]. A typical open issue in backhauling is the scheduling of transmissions to the backhaul BS and the user terminals. In this sense the spatial diversity experienced by the users with respect to the connected BS reduces interference and eases the resource allocation among the two sets of links.

A second important application of mm-wave for 5G is the fixed wireless access (FWA), where the wireless connection between the BS and the user terminal replaces the conventional broadband wired/fiber access at home or in office. Also in this case, the fixed position of the user is particular suitable for a mm-wave link. Typically the BS is serving many users (that can also be a mix of FWA users and conventional moving terminals) and suitable strategies for resources allocation between the two sets of users must be provided.

4.1 Regulatory Aspects

The ITU coordinates the spectrum allocation worldwide, in particular for the portions of the spectrum that are used for cross-country communications, for astronomy observations and for satellite observations. The use of the spectrum at a national level (which is the case for mm-waves within 5G systems) is instead in the hands of each state. Agreements among states (e.g., within Europe or the United States of America, USA) may partially or totally delegate the spectrum coordination to international bodies. In Europe various bodies are involved in the spectrum allocation, and since 2002 they are coordinated by European Regulators Group for Electronic Communications Networks and Services. In USA the responsible body is the Federal Communication Commission (FCC). Once portions of mm-wave spectrum is allocated to 5G systems, frequency blocks are then leased to operators, typically through auctions.

In Italy, in October 2018 the auction of groups of frequencies in the range 3600-3800 MHz and 26.5-27.5 GHz has been completed by the *Ministero per lo sviluppo economico* with total selling price of more than 4.5 bilions of euros. In USA an auction for portions of spectrum around 24 and 28 GHz will be started by FCC in mid November 2018.

References

1. Rappaport T.S., Xing Y., MacCartney G. R., Molisch A. F., Mellios E., Zhang J.: Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks-with a focus on Propagation Models. IEEE Transactions on Antennas and Propagation (2017) doi: 10.1109/TAP.2017.2734243
2. 3GPP (2018) Study on channel model for frequencies from 0.5 to 100 GHz. TR 38.901 Ver. 15.0.0 https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=3173
3. Niu, Y., Li, Y., Jin, and Vasilakos A. V.: A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges. Wireless Networks (2015) doi:1 0.1007/s11276-015-0942-z
4. Rappaport T., Sun S., Mayzus R., Zhao H., Azar Y., Wang K., Wong G. N., Schulz J. K., Samimi M. and Gutierrez F.: Millimeter wave mobile communications for 5G cellular: it will work! IEEE Access (2013) doi: 10.1109/ACCESS.2013.2260813
5. Heath R. W., González-Prelcic N., Rangan S., Roh W. and Sayeed A. M.: An overview of signal processing techniques for millimeter wave MIMO systems. IEEE Journal of Selected Topics in Signal Processing (2016) doi: 10.1109/JSTSP.2016.2523924
6. Roh W., Seol J., Park J., Lee B., Lee J., Kim Y., Cho J., Cheun K., Aryanfar F.: Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results. IEEE Communications Magazine (2014) doi: 10.1109/MCOM.2014.6736750
7. Ahmed I., Khammari H., Shahid A., Musa A., Kim K. S., De Poorter E., and Moerman I.: A Survey on hybrid beamforming techniques in 5G: architecture and system model perspectives. IEEE Communications Surveys & Tutorials (2018) doi: 10.1109/COMST.2018.2843719
8. Montagner S., Benvenuto N. and Tomasin S.: Taming the complexity of mm-wave massive MIMO systems: Efficient channel estimation and beamforming. IEEE International Conference on Communication Workshop (ICCW)(2015) doi: 10.1109/ICCW.2015.7247349
9. Soleimani H., De Donno D. and Tomasin S.: mm-Wave channel estimation with accelerated gradient descent algorithms. EURASIP Journal of Wireless Communications and Networks (2018)
10. Giordani M., Mezzavilla M. and Zorzi M.: Initial access in 5G mmWave cellular networks. IEEE Communications Magazine (2016) doi: 10.1109/MCOM.2016.1600193CM
11. Soleimani H., Parada R., Tomasin S. and Zorzi M.: Statistical approaches for initial access in mmwave 5G systems. Proc. European Wireless Conference (2018)
12. Jaber M., Imran M. A., Tafazolli R., Tukmanov A.: 5G backhaul challenges and emerging research directions: A Survey. IEEE Access (2016) doi: 10.1109/ACCESS.2016.2556011