State-of-the-Art and Research Challenges for Consumer Wireless Communications at 60 GHz

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Abstract — *The demand on performance of wireless networks is constantly increasing. To date, conventional sub 6 gigahertz (GHz) bands were able to keep up with the requirements through continuous spectral efficiency improvements. Consequently, advancing this area further became exceptionally costly. Therefore, despite the industry resistance towards changing the already established communications spectrum and unavailability of sufficient number of suitable frequency bands for typical communication purposes, carrier frequency, hence operation bandwidth, increase method is chosen as an alternative. In this paper, the first spectrum chosen for utilization, the 60 GHz band, is surveyed. Detailed explanations of the standards and their processes are provided, in addition to the characteristics of the channel and 60 GHz technologies, devices and consumer applications. As its initial standards are already complete and widespread communications usage expected to start in 2016, the 60 GHz band is a genuine candidate for the next generation of mass market wireless communication systems*[1].

Index Terms — 5G mobile communication, communication standards, millimeter wave communication, millimeter wave propagation, millimeter wave devices.

I. INTRODUCTION

Since Marconi's first wireless transmission at the end of 19th century, wireless communication technology has advanced to peak data rates on the order of 1 gigabits per second (Gb/s) with ever-increasing adoption. According to International Telecommunication Union (ITU), since 2009 internet users have increased from 25.6% of the world's population to 43.4% in 2015, corresponding to a nearly 1.4 billion rise from 1.75 billion. Subscriptions of mobile cellular, which is the quickest adopted technology in human history, also rose from 4.64 to 7.09 billion within the same period, and the latter value represents a 96.8% global penetration rate [1], [2].

Internet usage continues to steadily increase. However, mobile cellular market reaches towards saturation, as its latest growth rates are 1.88% for the world, and 2.17% and 0.88% for the developing and developed countries, respectively. In view of the current states of the two main telecommunications services, another major technology was needed to continue the expansion of the sector, and that emerged to be the mobile broadband. Since 2007, the number of mobile broadband subscriptions nearly thirteenfolded to 3.46 billion [2].

Network convergence has been a central theme in the telecommunications industry for more than a decade. In 1997, ITU Radiocommunication Sector (ITU-R) classified six service information types, i.e., audio, data, image, speech, text and video, with different design constraints for the third generation of mobile telecommunications technology with the Recommendation ITU-R M.1034-1. Whereas, 11 years later a single set of technical performance criteria was identified for the radio interface of the fourth generation (4G) mobile systems [3]. As all types of communication narrow down to a mere exchange of data streams, the competition between wireless standards concentrates on the transmission properties such as peak data rate, spectral efficiency, total throughput, coverage area, mobility and energy efficiency.

With the ever increasing human mobility and mobile broadband usage, the performance expectations from wireless communication networks are rising towards the upper limits of their wired counterparts. Average mobile network connection speed for smartphones was 0.614 megabits per second (Mb/s) in 2009, and 1.038 Mb/s in 2010 [4]. The most recent forecast presents the global average mobile downstream speeds of tablets and smartphones as 11.6 and 7.5 Mb/s in 2015, and predicts compound annual growth rates of 7% and 11% until 2020, respectively, rising the rates to 16.2 and 12.5 Mb/s [5].

Users constantly demand higher data rates, and continuous rise in subscriber numbers inherently necessitates greater network capacity, which causes growth in corresponding research efforts. The methods to improve peak data rate are commonly known: Increasing the operation bandwidth or spectral efficiency or decreasing the signaling overhead. Spectral efficiency, arguably, is the most investigated area of telecommunications. Therefore, any new improvements, albeit minor, come with sizeable investigation costs. Signaling overhead, on the other hand, has a secondary effect on the data rate, and thus cannot originate significant enhancements. Consequently, the most practical approach is increasing the operation bandwidth. However, accommodating any new service requests within the conventional frequency bands that are already overcrowded is problematic [6].

Currently, the vast majority of wireless data traffic is conveyed over the customary sub 6 GHz bands. Both the

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telecommunications industry and academia are aware of the anticipated spectrum crunch and started taking actions. One possible solution is increasing the carrier frequency to the industrial, scientific and medical (ISM) radio band centered at 61.25 gigahertz (GHz), not just for small cell networks [7]-[9], but for beyond 4G (B4G) mobile systems too [10]. In line with these, this paper investigates the forthcoming utilization of the 60 GHz ISM band for the next-generation of consumer wireless communications products. This is the first work comprising both the industrial and institutional 60 GHz standards in time for the expected launch of 60 GHz mass market communication systems in 2016, and complete with channel characteristics and device electronics.

The rest of this paper is organized as follows: In Section II, the 60 GHz standardization efforts are discussed. Section III focuses on the electromagnetic (EM) wave propagation properties of these new transmission channels. Following a description of the 60 GHz device technologies, state-of-the-art transceivers (TRXs) enabling consumer millimeter wave (mm-wave) communications are introduced in Section IV-A, and the facilitated 60 GHz mass market wireless communication applications are presented in Section IV-B. Subsequently, the paper concludes with summarizing remarks.

II. 60 GHz STANDARDIZATION ACTIVITIES

The higher data rate objective requires higher spectral efficiency, bandwidth, or preferably both. Since the legacy bands are already crowded, wider bandwidth is not an option for those spectra. The 2.4 GHz ISM band cannot even accommodate one 80 megahertz (MHz) channel of the IEEE 802.11ac, whereas at most three 160 MHz channels can be supported within the 5 GHz band, which number is lower than the user limit of downlink multi-user multiple input, multiple output (DL-MU-MIMO) defined in the standard [11].

Spectral efficiency increase is another option, but because the techniques used are already advanced, the yields of the more complex and costly modulations are becoming insignificant. Furthermore, modulation rates cannot be infinitely improved. Receiver (RX) minimum input sensitivity increases with higher modulation rates: For 3/4 forward error correction (FEC) coding rate, minimum sensitivities of a 160 MHz IEEE 802.11ac channel are defined to be -61, -56 and -50 dBm, for 16-ary quadrature amplitude modulation (16-QAM), 64-QAM and 256-QAM, respectively. Taking into account the link budget equations presented by Yilmaz et al. [12], unless there is a significant margin between the received power and minimum sensitivity, the rise in the sensitivity has to be countered via either escalated transmitting power or antenna gains. However, this also cannot be done at will. Radio frequency (RF) output powers are regulated, and in the case of Europe, European Telecommunications Standards Institute restricts the mean equivalent isotropically radiated power (EIRP) to 20, 23 and 30 dBm for the 2.4-2.484, 5.15-5.35 and 5.47-5.725 GHz bands, respectively.

Considering all of these, the need for new frequency bands becomes clear. Since wireless local area networks (WLANs) operate in the unlicensed spectrum, ISM bands at frequencies above 6 GHz were the primarily anticipated targets. Table I lists the ITU-R designated ISM bands. Frequency allocations are carried out up to 275 GHz, and there are four ISM bands in this range, with the center frequencies (f_{center}) of 24.125, 61.25, 122.5 and 245 GHz. The first three are very close to the local maxima of gaseous attenuation (γ). Therefore, it can be argued that ISM bands were assigned to the spectra possessing poor EM properties, and thus little financial value [13].

TABLE I
ISM BANDS

Frequency Range			f_{center}	Bandwidth	
6.765	6.795	MHz	6.78	30	kHz
13.553	13.567		13.56	14	
26.957	27.283		27.12	326	
40.66	40.70		40.68	40	
433.05	434.79		433.92	1.74	MHz
902	928		915	26	
2.4	2.5	GHz	2.45	100	
5.725	5.875		5.8	150	
24	24.25		24.125	250	
61	61.5		61.25	500	
122	123		122.5	1	GHz
244	246		245	2	

The first ISM band above 6 GHz, starting at 24 GHz, would be the expected choice. However, it lacks sufficient bandwidth, which is the primary requirement. Only the 100 MHz between 24.15 and 24.25 GHz is assigned for non-specific short-range devices, with an EIRP limit of 20 dBm [14]. On the other hand, as per the same Decision, 9 GHz of continuous spectrum between 57 and 66 GHz is assigned for wideband data transmission systems with 40 dBm EIRP constraint. Similar broader allocations around the stated ISM band are also true for the rest of the world [15]. Taking into account this vast amount of open spectrum, the ISM band centered at 61.25 GHz, which is referred to as the 60 GHz band, is selected for wireless personal area network (WPAN) and WLAN expansions. 60 GHz standards and standardization efforts are explained in the remainder of this section.

A. WirelessHD

WirelessHD special interest group was formed in late 2006 to originate a specification targeting data rates over 1 Gb/s in the 60 GHz ISM band for point-to-point (PP) audio/visual (A/V) networks. The first version of the specification was published a year later than expected, in April 2008, and the final issued version, 1.1, was completed in May 2010 [16].

From an application point of view, data rates on the order of 1 Gb/s are needed principally for high-quality video streams [17]. An uncompressed 1080p video, advertised as full high-definition (HD), displaying 60 frames per second (f/s) and using 3 bytes (B) information to denote the color of each pixel requires a data rate of 2.781 Gb/s. If the graphic resolution is increased to the subsequent common frames of

2560 to 1440 or 3840 to 2160, which are marketed as quad HD and ultra HD (UHD), respectively, data rate requirements, keeping the f/s and color depth the same, increase to 4.944 and 11.124 Gb/s.

TABLE II
GENERAL PARAMETERS OF WIRELESSHD PHYSICAL LAYERS

Quantity	LRP	MRP	HRP
Bandwidth (MHz)	92	890	1760
Sampling rate (Ms./s)	317.25	1269	2538
Number of subcarriers	128	256	512
Number of data subcarriers	30	168	336
FFT period (ns)	403.47	201.73	201.73
Guard interval (ns)	88.26	25.22	25.22
Symbol duration (ns)	491.73	226.95	226.95
Highest modulation	BPSK	16-QAM	64-QAM
Peak data rate (Mb/s)	40.673	1904	7138

The WirelessHD specification is composed with the video requirements prioritized. The term “wireless video area network” is coined and used throughout the standard. This arrangement can also be directly observed from the coordinator handover priority order table, within which device types are listed in terms of suitability for the coordinator role. Coordinator resembles access points within the IEEE 802.11 architecture, and the list, which also illustrates the equipment targeted by the WirelessHD, is ordered as follows: digital TV, set-top box (STB), DVD/BD player, DVD/BD recorder, A/V RX, personal computer, video projector, game console, digital video camera, digital still camera, personal digital assistant, portable media player, MP3 player, cell phones and other.

There are 3 physical layers (PHYs) defined in the specification: Low rate PHY (LRP), for discovery and control tasks, medium rate PHY (MRP), intended for low power applications and universal bidirectional data transmission, and high rate PHY (HRP), for top quality video streaming. Some of the important parameters of the PHYs are detailed in Table II. Only for HRP an optional spatial multiplication mode is identified, which enables 4 concurrent streams, and thus the opportunity to quadruple the HRP data rate.

Beginning with the 2009 Consumer Electronics Show, products including WirelessHD TRXs started to be introduced, such as TVs, home cinema projector and personal 3-D viewer. However, WirelessHD specification could not gain the momentum necessary for vast adoption. The specification was not comprehensive enough and compatible with the other main WLAN standards, and at the time there was not an actual demand for the devised technology. A new specification is not released since May 2010 and any kind of activity related to the technology has not occurred since the beginning of 2013, making the WirelessHD effectively obsolete.

B. Wireless Gigabit Alliance

Wireless Gigabit (WiGig) Alliance is the second and final industrial organization established to contribute to the 60 GHz standardization processes. Founded on 7 May 2009 with 13 board of director and 4 contributor member companies, unlike WirelessHD, the support to the WiGig Alliance continually grew over time. The initial specification was completed by the end of 2009 and in May 2010, both the cooperation with the Wi-Fi Alliance and contribution of the specification to the IEEE 802.11ad task group were declared.

TABLE III
FREQUENCY PLAN AND SPECIFIC ATTENUATIONS OF 60 GHZ CHANNELS

	Frequency (GHz)			Attenuation (dB/m)		
	f_{start}	f_{center}	f_{end}	γ_{fstart}	$\gamma_{fcenter}$	γ_{fend}
1	57.24	58.32	59.4	0.011	0.0132	0.0144
2	59.4	60.48	61.56	0.0144	0.0154	0.0151
3	61.56	62.64	63.72	0.0151	0.0125	0.008
4	63.72	64.8	65.88	0.008	0.0044	0.0022

In 2011, on top of the release of version 1.1 of the standard, three protocol adaptation layer (PAL) specifications, namely WiGig Bus, Display and Serial Extensions, were published. However, the technical details of the specifications were not made available to the public. Following nearly 2.5 years of partnership, at the beginning of 2013 the Wi-Fi and WiGig Alliances agreed for unification of activities under the former consortium, and this procedure was completed on 5 March 2013. WiGig interoperability certification program is still not unveiled, as of 2016. Though, unlike the WirelessHD's activity period, industry now has a consensus on the need for 60 GHz communications. Consequently, mass market WiGig hardware is expected to be available for purchase in 2016.

C. ECMA-387

ECMA is historically involved in formation of standards for modern technologies. Technical Committee 48 of Ecma International, titled “High Rate Wireless Communications”, was assigned to work in three fields, i.e., TV white spaces, ultra wideband and the 60 GHz band, and the ECMA-387: “High Rate 60 GHz PHY, MAC and HDMI PALs” is the first issued standard for WPAN operation in the 60 GHz ISM band. Its first edition was finalized in October 2008 and approved two months later, and the initial draft of the second and current version of the standard was completed in June 2010, with the publication taking place in December 2010 [18].

Albeit not formally defined, 10 m can be considered as a conventional range limit for WPANs, and ECMA-387 was structured for high data rate requiring applications operating within that limit, such as wireless uncompressed or lightly compressed video, wireless docking station and short-range sync-n-go file transfer. For these purposes two device types are defined: Types A and B. Type A is positioned as the high-tech device with antenna training and non-line-of-sight (NLoS) operation capabilities, whereas Type B is planned to cover low-cost equipment and only supports LoS links over shorter distances. Both types support coexistence and interoperability.

Channelization of all the 60 GHz ISM band specifications and standards are the same, and explained as follows: There are 4 channels defined between 57 and 66 GHz, each covering a bandwidth of 2160 MHz and having starting, center and stopping frequencies as listed in Table III. The atmospheric attenuation for the 9 GHz spectrum, calculated for the standard ground-level atmospheric conditions of 15.15°C temperature, 1013.25 hPa pressure and 7.5 g/m^3 water vapor density (ρ), and according to the Recommendation ITU-R P.676-9 [19] is given in Fig. 1, with particular values of the frequency plan provided, again, in Table III. Even though the losses are much greater than the surrounding spectrum, deterioration over a typical WPAN link is negligible.

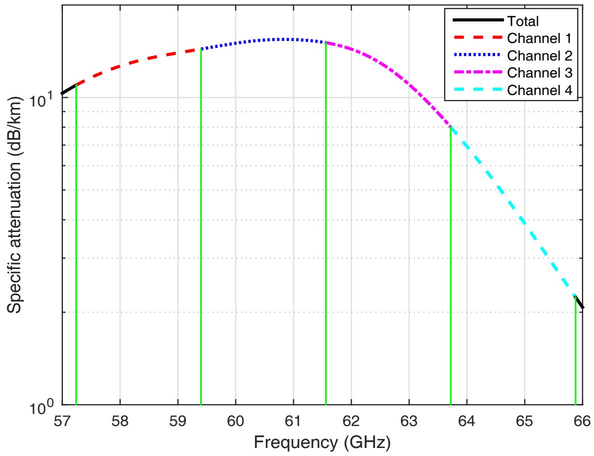


Fig. 1. Specific attenuation due to atmospheric gases, calculated under the standard ground-level atmospheric conditions and between 57 and 66 GHz at 1 MHz intervals, with the 60 GHz channels indicated.

There are 22 and 4 transmission modes defined for Type A and B devices, respectively. The mandatory mode of Type B employs differential binary phase-shift keying (DBPSK) with Reed-Solomon (RS) and differential encodings, and without the optional channel bonding, 0.794 Gb/s data rate is achievable. Other described modulation types are differential quadrature PSK (QPSK) and unequal error protection (UEP)-QPSK, both allowing communications at the peak rate of 3.175 Gb/s. Besides the possibility of supporting Type B modes, options specific to the Type A devices are split into two categories: 14 single carrier block transmission (SCBT) and 8 orthogonal frequency division modulation (OFDM) modes. The constellations for these range from BPSK to 16-QAM, and the encoding is either only RS or RS and one of the convolutional code (CC), trellis coded modulation and UEP-CC. This way, data rates of 6.350 and 4.032 Gb/s are possible with SCBT and OFDM, respectively.

Prior to communication link formation, devices need to detect each other, and this is performed using the discovery mode over the channel 3. Interoperability configuration and antenna training follows this step. A common physical layer convergence protocol (PLCP) protocol data unit (PPDU) frame is formed of 4 main sections, which are PLCP preamble, PLCP header, PPDU payload and antenna training sequence (ATS). The last two are optional, and the antenna training symbols are sent within the ATS field. A device trains its RX antenna by including training symbols in the ATS field of a single frame, whereas its transmitter (TX) antenna can use the same antenna weights of the RX, or calculate according to the feedback from the receiving device. These modes are termed as open- and closed-loop, respectively.

As amendments to the IEEE 802.11 are executed over the core standard, ECMA-387's medium access control (MAC) specification is obtained through necessary revisions made to the ECMA-368: “High Rate Ultra Wideband PHY and MAC Standard” [20]. There are 3 acknowledgment policies defined for different application requirements: No, immediate and block. Active and hibernation modes are described for power management. Security is also offered through the use of Advanced Encryption Standard-128 Galois/counter mode.

D. IEEE 802.15.3c

Being IEEE standards, 802.15.3c and 802.11ad, which were ratified in October 2009 and December 2012, respectively, are widely covered in the literature [21]-[23]. Since it is a WPAN standard, anticipated use cases of 802.15.3c are mostly for distances shorter than 30 m. One group of applications aim to replace short-range cabled communication links such as the IEEE 1394 serial bus and 802.3 Ethernet links with mm-wave. Another group tries to accomplish 60 GHz vertical wireless connections, and one other set focuses on the multimedia potentials and explores data distribution methods [24].

IEEE 802.15.3c mm-wave PHY defines 3 PHYs: Single carrier (SC PHY), high speed interface (HSI PHY) and A/V (AV PHY) modes. 3 modulation and coding scheme (MCS) classes are stated for SC PHY, targeting inexpensive user equipment with operation data rates up to 1.5 Gb/s, top-quality products offering communications at 3 Gb/s and above, and the rest of the devices in between. Timing-related parameters are common for all the classes, and chip rate and subblock length are set at 1760 Mchip/s and 512 chips, respectively. HSI PHY is dedicated to bidirectional data transfer and all its MCSs exclusively use OFDM and low-density parity-check (LDPC) code for FEC. Finally, AV PHY makes use of the asymmetric data transfer nature of the commonplace A/V applications and implements 2 modes: HRP and LRP. The highest attainable data rates for SC PHY's classes 1, 2 and 3 are 1650 Mb/s using the MCS 3 of π/2 BPSK and RS(255,239), 3300 Mb/s with the MCS 11's π/2 QPSK and RS(255,239) and 5280 Mb/s by applying the MCS 13 of π/2 16-QAM and LDPC(672,504), respectively [25]. Moreover, Table IV presents the MCS and timing-related parameters comparatively between the HSI PHY, AV PHY and directional multi-gigabit (DMG) PHY, which is the general term for the PHYs of the IEEE 802.11ad [26].

There are 5 types of acknowledgment: No, delayed, implied, immediate and block. No particular security mechanism, apart from the ones already existent in the core 802.15 standard, is specified. UEP is supported as well as equal error protection, primarily for the tasks where the most significant bits are more important than least significant bits, like video transmission.

A beam forming procedure, albeit optional, is also provided in the standard, supporting many antenna types, including switched antennas and antenna arrays. Of the two defined protocols, pro-active beam forming is used when a piconet coordinator (PNC) transmits data to any number of devices, and on-demand beam forming is used between two devices or a device and a PNC. After the two stages of beam forming, which are the coarse sector and fine beam level trainings, high resolution tracking step is, again, optional.

TABLE IV
General Parameters of IEEE 802.15.3c and 802.11ad OFDM PHYs

Quantity	HSI PHY	AV HRP PHY	AV LRP PHY	DMG PHY
Sampling rate (MHz)	2640	2538	317.25	2640
FT size	512	512	128	512
Data subcarriers	336	336	30	336
Pilot subcarriers	16			16
DC subcarriers	3			3
FT period (ns)	193.94	201.73	403.47	193.94
Guard interval (ns)	24.24	25.22	88.26	48.48
Symbol duration (ns)	218.18	226.95	491.73	242.42
Modulation	64-QAM	16-QAM	BPSK	64-QAM
Code rate	5/8	2/3	2/3	13/16
Peak data rate (Mb/s)	5775	3807	10.2	6756.75

E. IEEE 802.11ad

802.11ad is the only WLAN standard for the 60 GHz band. Taking advantage of the wider coverage of WLANs, specified usage models include some of the WPAN services, such as short-range video streaming, in addition to the newly possible ones like outdoor campus, auditorium and manufacturing floor functions and point-to-multipoint (PMP) backhaul links [27].

There are 32 MCSs identified, divided into four categories: MCS 0 for control PHY, MCSs 1-12 for SC PHY, MCSs 13-24 for OFDM PHY and MCSs 25-31 for low-power SC PHY. Compulsory control PHY PDDU communication is performed with DBPSK modulation at 1/2 coding rate, resulting in a data rate of 27.5 Mb/s. SC and OFDM PHYs solely use LDPC encoder, whereas an RS(244,208) outer code and a shorter inner code, which is either block code or single parity check, are employed in the case of low-power SC PHY. The highest stated data rate for SC PHY is 4620 Mb/s, using the MCS 12 consisting of $\pi/2$ 16-QAM and LDPC(672,504).

The basic service set (BSS) particularly designed for the standard is named personal BSS (PBSS). This is comparable to the independent BSS (IBSS), which is the simplest type and labelled ad hoc network, since devices communicate directly with each other. The main difference between IBSS and PBSS is, in IBSS all stations (STAs) transmit beacons, whereas in PBSS one STA undertakes the duties of PBSS control point.

Many new MAC functions are also defined in the standard. Beam forming is again described; however, unlike 802.15.3c, there is a single mechanism. It begins with a sector-level sweep where sectors, or antenna patterns, are limited to 64 per antenna and 128 per STA. Two kinds of relay operation are identified: Link switching and link cooperating. The first type includes the relay DMG STA (RDS) forwarding data from source relay endpoint DMG STA (REDS) to destination REDS in case of a link disruption, whereas in the second type data is transmitted both directly and over the RDS to the destination REDS. Finally, DMG Block Ack is the additionally defined acknowledgment policy [26].

III. 60 GHz Channel Characteristics

9 GHz wide unlicensed spectrum comes at a price. The gaseous attenuation up to 275 GHz, which is the upper limit of the ITU allocated spectrum, is calculated for the standard ground-level atmospheric conditions using ITU-R P.676-9 [19] and given in Fig. 2. Two separate components, water vapor and dry air, make up the total. Oxygen, nitrogen and Debye-Waller factor cause the dry air attenuation. The frequencies and values of the local extrema of the atmospheric attenuation are also explicitly denoted in the figure.

Furthermore, 60 GHz WLANs are not constrained to indoor operation, as outdoor purposes were listed in detail during the IEEE 802.11ad standardization process [27]. Therefore, meteorological phenomena can generate additional losses on top of the gaseous attenuation. Fig. 2 also demonstrates the specific attenuation due to rain, calculated for rain rates of 1, 4, 8, 16, 25 and 50 mm/h assuming horizontal polarization and according to the Recommendation ITU-R P.838-3 [28].

Rain attenuation curves all exhibit a similar form, which escalates with a decreasing rate and stays approximately constant following its maximum as frequency increases. Attenuation due to rain also increases in line with the rain rate and can be severer than atmospheric attenuation. To present an example, for 50 mm/h rain rate, which is the lowest limit of the violent rain shower category, at 60.829 GHz where gaseous attenuation reaches its local maximum with 15.474 dB/km, the rain attenuations are 0.876, 2.522, 4.278, 7.258, 10.201 and 17.308 dB/km, respectively, for increasing rain rates.

Three principal parameters affect the atmospheric attenuation: Water vapor density, temperature and air pressure. Fig. 3 illustrates the effect of each factor as the other two are kept constant at the standard ground-level values.

In Fig. 3a, water vapor density is given the values 0, 2.5, 7.5, 12.5, 20 and 30 g/m^3, where 0 and 7.5 g/m^3 correspond to the "dry air" and "total" cases in Fig. 2, respectively. Attenuation increases in relation to the ρ, and as an example, the maximum attenuation is reached by the 30 g/m^3 instance at 183.394 GHz with 108.111 dB/km. The local maxima in the 60 GHz band are also 15.451, 15.453, 15.474, 15.532, 15.683 and 16.007 dB/km, in the ascending ρ order, respectively. Because many of the oxygen absorption lines emerge around 60 GHz, that particular local maximum is originated by oxygen. Therefore, the water vapor density has restrained impact on the outcome, causing the comparatively close attenuation values around the 60 GHz band.

Fig. 3b illustrates the effect of temperature, and the values of 248, 268, 288, 298, 308 and 328°K are evaluated. Contrary to the ρ, increasing the temperature reduces attenuation. The local maxima of the gaseous attenuation in the 60 GHz band are 21.791, 18.269, 15.474, 14.293, 13.233 and 11.423 dB/km, in the ascending temperature order, respectively.

The results for air pressure are available in Fig. 3c. Only three quantities, 973, 1013 and 1037 hPa, are computed, since even a substantial pressure change of 40 hPa does not translate to a significant attenuation shift. The local attenuation maxima within the 60 and 122 GHz ISM bands are 14.951, 15.474 and 15.784 dB/km, and 2.038, 2.061 and 2.074 dB/km, respectively, for increasing air pressure values.

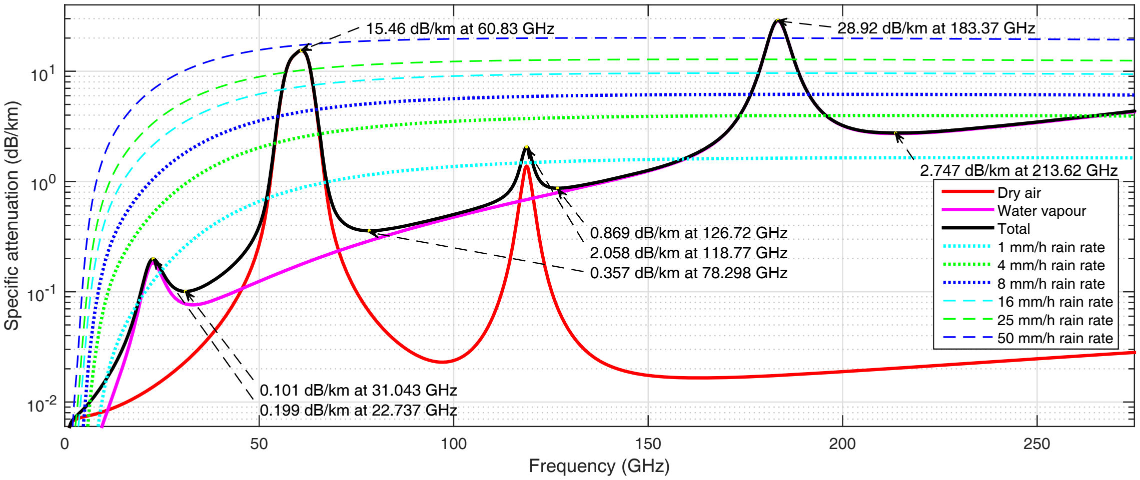
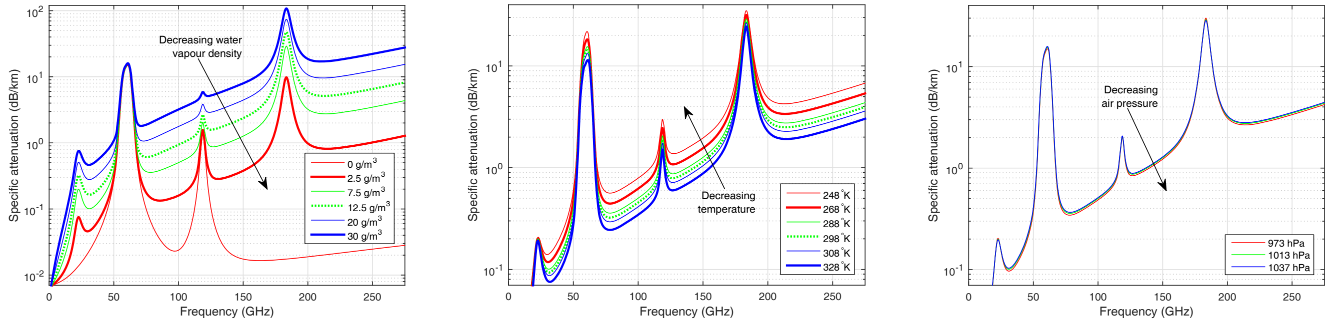


Fig. 2. Specific attenuation due to atmospheric gases and rain, calculated at 1 MHz intervals with local extrema of the gaseous attenuation indicated.



(a) (b) (c)

Fig. 3. Specific attenuation due to atmospheric gases, calculated up to 275 GHz and for (a) water vapor densities of 0, 2.5, 7.5, 12.5, 20 and 30 g/m^3, (b) temperatures of 248, 268, 288, 298, 308 and 328°K, and (c) total air pressures 973, 1013 and 1037 hPa.

The main differences of EM wave propagation mechanisms between the legacy spectrum and proposed 60 GHz band are:

- Free-space path loss (FSPL) increases by 28 and 21 dB for the 60 GHz band compared to the 2.4 and 5 GHz bands for the same distance, *d*, as per the Friss equation

$$FSPL = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \tag{1}$$

- Atmospheric attenuation (AA) is higher but not preventative within the range of 60 GHz small cell communications, since it is expressed as

$$AA = \gamma d \tag{2}$$

- Refractive indices of a diverse range of materials remain practically constant with frequency [29]. Yet, due to the general Kirchhoff solution for scattering, reflection coefficient reduces as the frequency increases [30].
- Absorption coefficients of materials rapidly grow with escalating frequency [31].
- Diffraction is almost entirely negligible at 60 GHz [30].

The combination of these form a channel different than the typical bands where multipath propagation is evident. Thus, either high-gain antenna techniques or high output power TXs are required for stable communication links [32]. In fact, the channel models developed for the IEEE 802.11ad consider second order reflections at most. Because many of the signal attenuation sources intensify with rising frequency, upper limit for reflections can be set to 2 at the entire mm-wave band. This reduces the complexity of a complete, deterministic solution, which then should be the channel modelling method [33], [34].

To illustrate the feasible network capacity improvements, comparative capacities of the 40 MHz IMT-Advanced, 160 MHz IEEE 802.11ac and 2.16 GHz IEEE 802.11ad channels with respect to the signal-to-noise ratio (SNR) are presented in Fig. 4. The channel parameters are selected as per the authors' previous work [35]. Even though 6.79 dB of SNR is required for BPSK transmission with 10^{-3} symbol error ratio (SER) [23], which is indicated in the figure and can reasoned to be one of the options for the lowermost limit for practical wireless communications, the SNR range is chosen to be between -30 and 50 dB. These bounds are in line with the outcomes of the realistic 4G and 60 GHz indoor simulations existing in the literature, where the SNR values are shown to change between 30 to 50 dB in the 4G case, and between 8 to 19 dB for the 60 GHz LoS simulations. Higher material absorption also drove the respective 60 GHz NLoS SNR values below -22 dB [13].

Coverage areas of indoor mm-wave networks are restricted to a single room for the currently used building materials and access network architectures [36]. If this hindrance is accepted and performance comparisons are conducted over one room, the lowest practical SNR limit of 6.79 dB, which is below the calculated achievable quantity range for the 60 GHz band, generates a channel capacity of 4.756 Gb/s for the 802.11ad, which is nearly double and one order higher of 2.624 and 0.664 Gb/s, the capacities of the 802.11ac and IMT-Advanced for the maximum SNR result of 50 dB, respectively. However, bit rate analysis is more informative for the real-world use cases. 27.2 dB SNR is needed for 64-QAM with an SER of 10^{-6}. So, if stable PP communication links employing BPSK for the 802.11ad and 64-QAM for the 802.11ac and IMT-Advanced channels are assumed, peak data rates become 1.88, 0.948 and 0.24 Gb/s, respectively, still clearly displaying the minimum anticipated return from the carrier frequency switch.

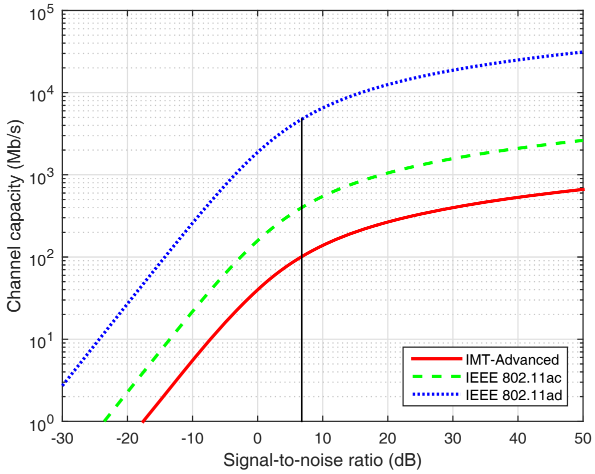


Fig. 4. Channel capacities of IMT-Advanced, IEEE 802.11ac and IEEE 802.11ad, calculated from -30 to 50 dB SNR.

IV. 60 GHz CONSUMER DEVICE ELECTRONICS AND WIRELESS APPLICATIONS

A. 60 GHz Devices

60 GHz is an unoccupied territory for consumer electronics. However, like most sections of the mm-wave band, it is already in use by other fields. For example, 57 to 59.3 GHz spectrum is also assigned for passive Earth exploration-satellite services, and actively utilized for atmospheric monitoring. One specific device operating in this band is the advanced microwave sounding unit-A (AMSU-A), which is a total-power microwave radiometer currently functioning in multiple NASA and NOAA satellites. AMSU-A monitors 15 channels, 6 of which are within the 57-59.3 GHz band [37].

At 100 kg and working with a DC power of 100.5 W, AMSU-A from the early 1990s possesses no use for present communication instruments. The mm-wave band is defined to be between 30 and 300 GHz, or 10 and 1 mm wavelengths, and this spectrum is situated between the legacy microwave and optical bands. The main methods to develop mm-wave devices thus have been increasing the operation frequency of microwave electronic circuitry, and the inverse for optical devices. Owing to the proximity to the already industrialized sub 6 GHz electronics market and the ease of integration to other components of the same type, semiconductors are the definitive choice for the 60 GHz devices.

Escalated losses within the 60 GHz band forces the use of amplifiers, hence transistors. The two foremost semiconductor transistor technologies are silicon (Si) and III-V compounds. The latter, in theory, comprises all binary compounds made up of one group III and one group V elements, and their ternary and quarternary alloys. However, the prominent elements are aluminium, gallium and indium from group III, and nitrogen, phosphorus, arsenic and antimony from group V.

The performance criteria of the newest semiconductors are so diverse that the structural properties of semiconductors separately contain only partial information. Large band gap is what differs an insulator from a conductor, though to enable high-temperature functioning without complete impact ionization, even higher band gap is preferred in semiconductors. Greater thermal conductivity enables high-power device applications, since it is inversely proportional to self-heating. The boundary before avalanche breakdown, that is the critical breakdown field, is also useful for high-voltage duties. Carrier mobility, which can be defined as the easiness of motion within the semiconductor and specified for both electrons and holes, is pursued for high-frequency tasks.

III-V compounds, in general, perform better at the figures of merit and fundamental material properties. However, the most important parameter for a technology targeting billions of end-user wireless communication equipment is cost. The immensely abundant Si and complementary metal-oxide-semiconductor (CMOS) is unrivalled in manufacturing expenses as a result of its current market dominance, and thus is the primary 60 GHz band semiconductor technology [38].

To the best of authors' knowledge, the most recent entirely integrated 60 GHz CMOS TRX publication that digitally executes at least the PHY tasks is the work of Saito et al. [39]. The RF integrated circuit (IC) is able to communicate in all 4 of the defined channels, and the baseband (BB) IC is proclaimed to implement both the PHY and MAC layer of the IEEE 802.11ad. RF IC has separate antennas for TX and RX, which are made of four patch elements and supply 6.5 dBi gain over 50° beamwidth. The reference temperature compensated crystal oscillator clock can vary between 26 and 40 MHz and is connected to the fractional-N phase locked loop (PLL), which drives the quadrature modulator (QMOD) of the TX and quadrature demodulator (QDEM) of the RX. Signal is generated in 110 MHz steps within the digital BB IC domain, and then passes through a digital-to-analog converter, variable-gain amplifier (VGA), QMOD and four-stage power amplifier (PA), before getting transmitted over the antenna. RX circuitry, on the other hand, starts with a four-stage low-noise amplifier (LNA) and followed by the QDEM and VGA.

Main technical features of the TRXs that are reviewed in this section are presented in Table V. The first TRX realizes the MCSs 0-9 of the IEEE 802.11ad, which constitute the control PHY and SC PHY operating with BPSK or QPSK modulations, omitting 16-QAM. Using the MCS 9 and emitting a TX EIRP of 8.5 dBm, MAC layer throughputs of 1.8 Gb/s up to 0.4 m and 1.5 Gb/s up to 1 m are measured, whereas the PHY data rate is 2502.5 Mb/s [39].

TABLE V
TECHNICAL FEATURES OF THE STATE-OF-THE-ART 60 GHZ CMOS TRXS

Quantity	Saito [39]		Mitomo [40]		Okada [41]	
	RF	BB	RF	BB	RF	BB
Process (nm)	90	40	65	65	65	40
Chip size (mm x mm)	3.6 x 3.75	6.3 x 7.4	2.2 x 1.3	3.4 x 3.9	4.2 x 4.2	3 x 3
TX power (mW)	347	441	160	432	319	196
RX power (mW)	274	710	233	523	223	427

Another recent associated TRX chipset is published by Mitomo et al. [40]. It also provides the PHY and MAC layer functionalities for all of the 60 GHz channels, whereas these do not mirror any of the 60 GHz standards. For the PHY, an OFDM-QPSK modulation with RS(240,224) outer and 3/4 CC inner codes for FEC is executed. MAC is based on CSMA/CA and retransmission using acknowledgment techniques.

There is a single, 0 dBi gain antenna connected to a TX/RX switch to reduce the size. The TX path consists of QMOD, up-conversion mixer and PA, and the RX contains LNA, down-conversion mixer, QDEM and VGA. QMOD and QDEM use the 20 GHz local oscillator PLL output, which is based on a voltage-controlled oscillator. However, the TX and RX mixers require a frequency doubler prior to usage. The TRX reaches data rates of 2.62 and 2.07 Gb/s at the PHY and MAC layer, respectively, though up to a maximum distance of 0.04 m [40].

The final complete 60 GHz CMOS TRX available in the literature is implemented by Okada et al. [41]. This TRX also operates in all 4 of the channels, but only PHY tasks are realized. Modulation choices are QPSK and 16-QAM, whereas just LDPC(1440,1344) is available for FEC. Maximum output powers of the RF IC are 5.6 and -4 dBm, for normal and low-power modes, respectively, and the independent TX and RX antennas each have gains of 6 dBi.

Architectures of the TX and RX circuitries are similar to the corresponding blocks of the previously explained TRXs: Mixer, differential preamplifier and PA for the TX, and LNA, differential amplifier and mixer for the RX. The local synthesizer is based on a 20 GHz integer-N PLL working with a 36 MHz reference clock. This part is directly connected to an injection-locked oscillator, which triples the frequency. With the technical attributes illustrated in Table V, the RF IC and BB IC achieve data rates of 3.1 Gb/s up to 1.8 m and 6.3 Gb/s over 0.05 m using QPSK and 16-QAM, respectively [41].

B. *60 GHz Applications*

Wireless communication is the enabler of numerous novel user activities. Hence, the 60 GHz ISM band that offers exalted data rate and network capacity is valuable for many applications. A number of these are associated to network architecture enhancements such as single or multi-hop backhauling, mobile fronthauling and data offloading, whereas some have specific use cases like inter-rack communication at data centers. Consumer electronics related applications can be grouped under the following usage model categories:

- **Rapid file transfer:** The exceptionally wide bandwidths of the 60 GHz band channels can be very effectively utilized in ultra short range communication settings. The 6756.75 Mb/s peak data rate identified in the IEEE 802.11ad transfers 591 MB data every second at 70% MAC layer efficiency, thus enabling the download of a 1.5 GB standard definition movie in less than 3 seconds at a kiosk or toll-gate. This solution can also lead to cordless computing in home or office scenarios [27].
- **Wireless display:** An essential high throughput requiring application is video or mass data distribution over PP or PMP network topologies. Performance requirements are lower than the sync-n-go case: 1 Gb/s data rate over a single link is sufficient for uncompressed video, and a fraction of this quantity is needed for the compressed file. However, connection can be LoS or NLoS, RX can be moving and the range covers the room for projection to TV or projector and augmented and virtual realities, and the entire occupied area for the PMP environments such as classroom, airplane and exhibition [42], [43].
- **UHD video streaming:** Similar to data rate, consumers continuously demand higher image resolution from their video monitors. 8K UHD display devices, having a graphic resolution of 7680 to 4320 pixels, are next in succession. Using 4:2:0 chroma subsampling, 8K UHD video at 60 f/s and 3 B color depth requires a data rate of 28.51 Gb/s, which is significantly higher than even the maximum total throughput of the up to date HDMI 2.0a specification. This data transfer would also require the latency and jitter to be less than 5 ms. Therefore, by channel bonding, higher order modulation and MIMO, 60 GHz band is the main technology to provide UHD video stream between a TV and an STB [44], [45].

V. CONCLUSION

This paper is focused to the efforts on the utilization of the 60 GHz ISM band for consumer wireless communications. Standardization activities that began in 2006 are completed by the end of 2012 for both WPAN and WLANs. During these actions, EM wave transmission properties and channel models of the 60 GHz band are developed. Low-cost 60 GHz devices are also produced, as commercial products are expected to go on sale in 2016. Overall, the 60 GHz ISM band is ready for both widespread adoption and further use in B4G systems.

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