6G Physical Layer: Recent Advances, Challenges, and Open Problems

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Abstract

6G is the sixth-generation mobile system currently under development and research. There is currently no clear definition of how the 6G final look will be, many vendors, commercial organizations, and researchers are racing to solve this considerable gap. We believe that it can be filled by surveying the existing emerging 6G technologies. In this paper, we present the latest 6G technology development, study the weaknesses and strengths, and highlight the current challenges and obstacles to help better envision 6G and how it will come about with a focus on the physical layer aspect of 6G technology.

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Keywords

6G, adaptive, Terahertz communication, Physical Layer, flexibility, VLC Communication, sensing, 6G Challenges.

1. Introduction

Wireless networks have evolved from the first generation (1G) till the current fifth generation (5G). Researchers are currently working on developing what is beyond 5G that is 6G six generation. 6G is the generic name for the next generation cellular wireless. It is expected to enhance and build upon the capabilities of the existing fifth generation, to provide a higher data rate (e.g., 100Gbps-1Tbps), higher connectivity density, higher energy efficiency and lower latency. At present, there are over 100 research papers and more that 12 white papers regarding the Sixth Generation (6G) of wireless communications. According to Gartner hype cycle for enterprise networking of 2022 [Gartner2022], 6G is still in the innovation trigger region, meaning that the technology is currently subject to significant media attention and industry interest.

There are currently certain trends that are expected to have a huge influence on 6G technology. One is that the current focus is shifted towards utilizing ultra-high frequency to achieve the promising ultra-high data rates and low latencies. The use of these very high frequencies will have a profound impact on system architecture, as at these frequencies the supported range is very small, resulting in cell sizes of reduced dimensions, overheating challenges, and low bandwidth issues. Therefore, new semiconductors and other materials need to be developed for these operating frequencies. It is expected thus that components for mm-wave and THz operation will be expensive. The commercialization of 6G is expected to be done by 2028[Gartner2022], and to be implemented by 2030 [Abdel2022].

In this paper we discuss the current obstacles facing 6G development, layout the current and most popular vendors who are currently working on this technology, later we provide our own critique and recommendations for future researchers.

The remainder of this paper is organized as follows. In Section 2 we present the 6G Vendors and commercial organizations. In section 3 we highlight 6G specifications and requirements. In Section 4 we discuss the physical layer challenges. In section 5 we present our conclusion and recommendations.

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2. 6G Vendors and Commercial Organizations

Research efforts on 6G are now being carried out in different countries and organizations. In this section we discuss the main players in what is called the "race to 6G". We discuss top contributor countries and vendors in this field.

Many commercial companies and academic organizations have started working on 6G. The competition for 6G leadership by local and international organizations has reached its peak by the beginning of this year. 6G is expected to become a sort of a national network supported and impacted by national regulations and policies. Corporations based in East Asia and China were found to be participating and collaborating in development consortium's.

The top 6G Vendors are Ericsson, Huawei, Nokia, NTT DOCOMO, Qualcomm, Samsung, SK Telecom, AT&T, T-Mobile and Verizon. Nokia is a founding member of the Next G Alliance, and also involved in the EU's flagship 6G initiative Hexa-X as project lead coordinating the effort, with Ericsson as technical manager. In terms of patents filed for 6G capabilities, around one-hundredth of the patents have been applied for on 6G vs 5G, with China-based Huawei in the lead. it is noted [jaun2021] that Huawei applications are mostly related to mobile infrastructure technology. Ericsson and AT&T executives are leading efforts on overall strategy and direction for the North American coalition, along with other members of the Next G Alliance [NextG] such as T-Mobile and Verizon.

According to Samsung Research 6G White Paper [Samsung2020] the 6G candidate technologies include, among others, terahertz (THz) communications and non-terrestrial networks (NTNs). It is believed that the THz-band communication will unlock huge swathes of contiguous available bandwidth in the 0.3-10 THz band for terabits per second (Tbps) wireless connectivity.

Figure 1 below, illustrates countries contribution in the current 6G patent applications.

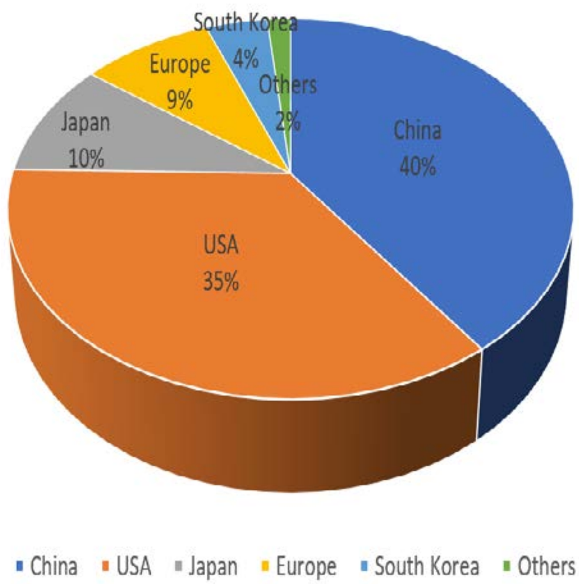

Figure 1: 6G Patent Applications.

According to [jaun2021] China accounts for 40% of 6G patent applications. Chinas' vendors and organizations are working in line with a government policy of leapfrogging other nations in the adoption of new technology. Chinas' government deployed a satellite exclusively for 6G research. The U.S. accounts for 35.2% of 6G patents, followed by Japan with 9.9%, Europe with 8.9% and South Korea with 4.2%.

A number of companies, policymakers, and academics in the USA are working to secure leadership for the country in 6G. U.S. companies with 6G-related patents include Qualcomm, Intel, IBM and Microsoft. Companies like Intel and Qualcomm have patented chips that will be used for mobile phones and computer hardware equipment for 6G networks. A new alliance called the Next 6 Alliance [Next6] has been initiated
As for Japan, Nippon Telegraph & Telephone (NTT) has many patents in the 6G space dealing with optical communications and mobile infrastructure networks in urban areas.

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3. Specifications and Requirements

In this section we discuss 6G Networks specifications and requirements along with physical layer charactarisitcs.

3.1 Network Characteristics Service Requirements

In the 6G era, human activity will dramatically expand from the ground to air, space, and deep sea. 6G network characteristics needs to satisfy the requirements of extremely broad coverage and ubiquitous connectivity. Therefore, a large dimensional network integrating non-terrestrial and terrestrial networks is needed to support various applications. The key performance indicators for evaluating 6G wireless networks include spectrum and energy efficiency,peak data rate, latency, network capacity, connectivity density, mobility.

For 6G to be a disruptive step forward from 5G it needs to present higher data rates, higher reliability and spectrum efficiency with a lower latency. Table 1 below illustrates the key differences in the requirements between 5G and 6G technologies.

Technology/Performance requirements	Peak data rate	Latency	Spectrum efficiency (bps/Hz)	Connectivity density	Reliability	Spectrum
5G	0.01 Tbit/s	1 ms	30	10^2 devices/100m2	99.999%	Above 24.25 GHz
6G	1 Tbit/s	0.1 ms	100	10^3 devices/100m2	99.99999%	95 GHz - 3 THz

Table 1: 6G/5G Specifications Comparison .

6G is expected to have a peak data rate of 1 Terabit per second, that is 100 times higher than what is in 5G, with a factor of 10 lower latency. An over-the-air latency of 10-100 Aus and high mobility larger than 1,000 km/h will provide acceptable quality of service for implementations such as high-speed rail (HSR) communications and airline systems. 6G is expected to operate within the range of 95GHz to 3 THZ compared to the 25GHz 5G spectrum.
The connectivity density refers to the potential number of connections within a certain network, it is expected that 6G will have 10 time the number of connections when compared to 5G, that is up to 10^7 devices per km square, with 3.3 times the spectrum efficiency. Hence spectrum efficiency is calculated by the amount of data transmitted over a given spectrum with a minimum number of transmission errors.

3.2 Physical Layer Characteristics

In this section we highlight the proposed 6G physical layer characteristics.

Figure 2 summarizes the proposed physical layer characteristics starting with Terahertz communications (THz), Visible light communications (VLC), and ending with Molecular communication.

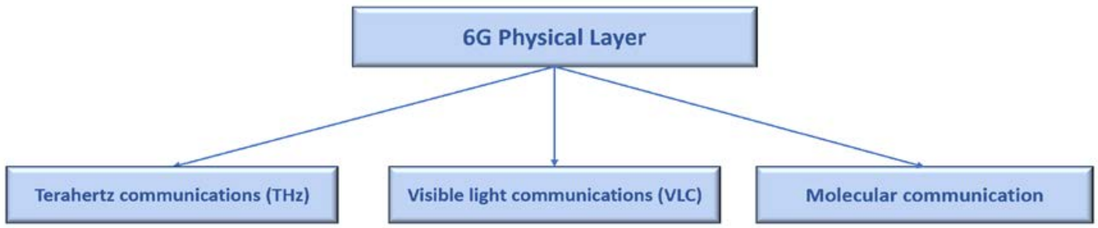

Figure 2: 6G Physical Layer.

4.2.1 Terahertz Communications (THC)

The Terahertz communication (THC) band for 6G is expected to between 0.1-10 THz. This frequency band supports high transmission rates, very high transmission speeds, pico-second symbol duration, immunity to interference, allows the integration of thousands of sub-millimeter long antennas, and allow a simpler integration of sensing and communications.

In addition, due to small antenna element dimensions and inter-element spacings, THz is also compatible with massive and ultra-massive multiple-input multiple-output (MIMO) antenna array technology that can provide significant beamforming and multiplexing gains for improved system performance [Basari2019]. However due to the high frequency, transmission within this band suffers from high attenuation rates, it is highly affected by molecules and dust in the air. Therefore, it will be used for short range communication with ultra-high speed and capacity transmissions. An example of that is the holographic communications. Holographic communications refer to the real time capturing, encoding and transmitting 3D videos where data needs to be transmitted in ultra-high speed with ultra-high capacity.

There are mainly three approaches to achieve the terahertz frequencies, one is the electronic approach which is sometimes referred to as the classical physics approach. Second is the photonic approach which is referred to as the quantum physics approach. We discuss the challenges in each approach later in section 4.

With the recent advancement in technology, researchers started to look into the adoption of nano materials to develop novel plasmonic devices for Terahertz communications. This technology differ from the aforementioned optical and electronic approaches as it doesn't depend on the up conversion of frequencies and millimeter wave signals nor depend on the down conversion of the optical signals, it relies on the material of the hybrid graphene/III-V that is still currently in an earlier stage of development.

An example of electronic technologies [Crowe2017] that relies on frequency up-conversion are the silicon-germanium BiCMOS technology, Heterojunction Biopolar Transistor (HBT) and standard silicon CMOS technology, metamorphic HEMT and III-V semiconductor-based High Electron Mobility Transistor (HEMT), Schottky diode technology. Photonic technologies [Nagatsuma2016] depends on an optical down-conversion based on photomixers or photoconductive antennas, quantum cascade lasers, uni-traveling carrier photodiodes.

Figure 3 summarizes the approaches currently being researched to achieve terahertz frequencies.

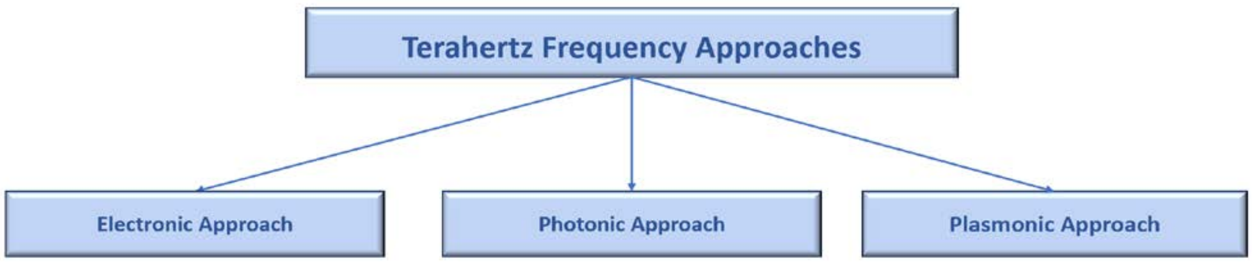

Figure 3: Terahertz Frequencies Approaches

4.2.2. Visible Light Communications (VLC)

Visible light communication (VLC) is a high-speed communication within a frequency range of 400-800 THz that can be down converted to produce the 6G Terahertz communications. The greatest advantage of VLC is that it can achieve ultra-high transmission rates when compared to other traditional wireless communication systems. Figure 4 below shows the three types of approaches used to generate VLC.

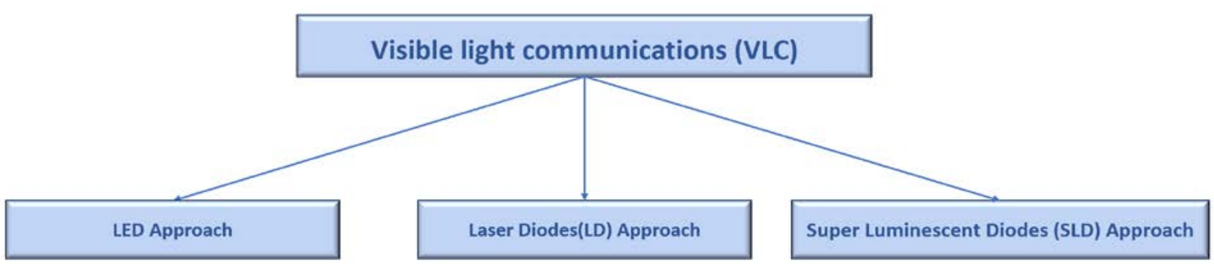

Figure 4: VLC Approaches

There are many advantages to VLC, one is that it is safe for human eyes, and it utilizes existing illumination systems, which can reduce the implementation cost with a good indoor coverage. There are commonly two types of used light sources for VLC systems, LEDs and laser diodes(LD). LED have a wider divergence; therefore, they can be used for short distance communications between point to point and point to multi point. In addition, LED is cheaper than LD therefore it can be integrated into a large scale arrays to achieve a very high illumination power.
LDs can be used for long distance transmissions, and can easily achieve high data rates due to the intrinsic large bandwidth of the LDs. One disadvantage of using LDs is that the system requires precise alignments between LDs and the corresponding receivers. Two methods are used to generate light illumination based on LEDs. The first is based on the use of blue emitters with a phosphor layer, while the second is based on the use of multicolor chip-integrated emitters, such as red-green-blue (RGB) and RGB-yellow (RGBY) emitters. The second method is preferred as it allows a higher bandwidth and allow wavelength division multiplexing (WDM) transmission, and thus can be used to improve data rates.
Gallium nitride (GaN) microLEDs (I1/4LEDs) are another type of commonly used LEDs that have a photoactive device area at the micrometer scale; therefore, the plate capacitance is relieved to allow higher bandwidth. Another types of LED are silicon based LEDs (Si-LEDs),surface plasmon-coupled LEDs (SP-LEDs), and off-the-shelf LEDs, which we refer to as commercially available off-the-shelf (COTS) products.
SP-LEDs are attractive solutions for high-speed VLC systems as it provides an effective way to increase the modulation bandwidth by increasing spontaneous emission rate, given that they afford high-modulation bandwidths and optical powers without the need of high current densities. Cheap off-the-shelf LEDs are available for less than half U.S. dollar and can be applied in free-space VLC systems with a record data rate of 15.73 Gb/s[Bian2019].
In recent years, with technology advancement, researchers were able to combine the benefits of LED and LD in what is called Super luminescent diodes (SLDs). SLDs combines the beam directionality of LDs with the wide divergence characteristics of LEDs. SLDs is the breakthrough that have a high bandwidth, increased brightness power and speckle-free characteristics.

4.2.3. Molecular Communication

Molecular communication (MC) is a rapidly advancing technology that has the potential to communicate in wave-denied environments. MC are signals that have the potential to deliver information by exploiting both new modulation mechanisms via chemical encoding and new multi-scale propagation physics. We have yet to realize its full potential in engineering.
Molecular communications systems use the presence or absence of a selected type of molecule to digitally encode messages. The molecules can be delivered into communications media such as air and water for transmission. The technique also is not subject to the requirement of using antennas that are sized to a specific ratio of the wavelength of the signal. The main advantage of molecular communication is that signals can be made biocompatible and require very little energy.

3.3 Summary

In this section we discussed the network characteristics and required specifications of 6G. Researches are currently working on finding ways to deliver the promise of high data rates, low latency and high density networks. Later in this section we discuss the physical layer characteristics where we discussed three approaches MC, THC and VLC. We discussed the basic principles of up conversion and down conversion methods of obtaining high frequencies to deliver the promise of high data rates and low latencies. In section 4 we continue to discuss the challenges and obstacles facing these approaches.

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4. Physical Layer Challenges

We have previously discussed the physical layer characteristics of 6G. In this section we discuss the challenges that are faced by the Terahertz communications, Visible light communications and Molecular communication.

4.1 Terahertz Communications Challenges

Manufacturing Terahertz devices is a major challenge. As Terahertz devices needs to be manufactured with a high-power transmitter, combined with a high-sensitivity receiver that can work in a room temperature without overheating. It is important to understand why terahertz frequencies are difficult to produce and detect, this is what is referred to as the"Terahertz Gap". The terahertz Gap refers to gap that exists in two approaches, the "electronic" and the "photonic" approaches, or sometimes can refer to the gap between modern physics (i.e. quantum) and classical physics. Terahertz frequencies can be generated using the forementioned two approaches, however both approaches encounter difficulties when trying to extend their frequencies to the terahertz. For example, using electronic approach to achieve shorter wavelengths and higher frequencies (i.e Terahertz waves) requires alternating current or high frequency alternating field issue.

High frequency alternating field comes the limitation of that the electrons may not be fast to travel far enough for a device to work before the polarity of the voltage changes and hence the electrons changes the direction. In addition to the unwanted effect of resistances and capacitances that reduces the power efficiency of the device. Generating terahertz frequencies using the photonic approach, faces many challenges due to the atomic structure of the materials, meaning that electrons exists at a discrete energy levels. Generating a terahertz frequencies requires electrons at energy level that is not available in many materials.

In addition to the difficulty to control electrons at the terahertz frequencies energy level, knowing that at room temperature, the electrons are already vibrating between energy levels vigorously. Working at a cooler temperature can help, but this makes the terahertz devices very expensive, larger in size and more complex to run. There have been significant efforts in research and development where novel techniques [TekbA+-yA+-k2019][Pang2022][Xu2022][Zheng2022] were proposed to combine the electronic and photonic approaches to overcome the terahertz gap.

THz communications face a severe blockage problem due to the huge reflection, scattering, and diffraction losses. On one hand, when frequency grows from 60 GHz to 1 THz, the reflection loss increases from 7 dB to 40 dB [Han2015]. On the other hand, the data rate requirement of the THz systems is much higher than the mmWave systems. In light of these, when the LoS path is blocked, the NLoS paths might be too weak to support high data rates and the THz link faces a more severe blockage problem than the mmWave link.

4.2 Visible Light Communications Challenges

The main challenge of LED-based VLC systems is the limited modulation bandwidth of LEDs. Thus, many researchers proposed efficient techniques to solve this issue. Multilevel carrier-less amplitude and phase modulation (CAP); pulse amplitude modulation (PAM); orthogonal frequency division multiplexing (OFDM); discrete multitone modulation (DMT); multiple-input, multiple-output (MIMO); and WDM are used to increase system data rates by improving bandwidth efficiency.

Meanwhile, analog pre-equalization circuits can also be applied to extend the modulation bandwidth of VLC systems and enhance overall transmission data rates. One type of LED-based VLC is the I1/4LEDs, where the photoactive device area is at the micrometer scale that results in a higher bandwidth. However, the reduction of the photoactive area results in a dramatic reduction of optical power and transmission distance. The optical power of I1/4LEDs is significantly less than that of standard phosphor-based LEDs. In general terms, propagation in optical wireless communications is quite like that in THz bands, with very short reach and signals being easily blocked by objects.

4.3 Molecular Communications Challenges

One of the main challenges facing molecular communications is that it is not yet well understood, especially by engineers and researchers in the field of telecommunications. We faced this issue while writing this paper. Molecular communications suffer from a fundamental transmission limits, meaning that there are established fundamental limits to how far a coherent MC signal can travel before it fully mixes into the atmosphere, making individual and sequential signal symbols indistinguishable. Here we define coherence as when the signal structure transmitted can still be recognized at the receiver.

4.4 Summary

In this section, we discussed the challenges and obstacles facing THC, MC and VLC communication. The common health concern is the use of an ultra-high frequency and its effect on health, it is proven by studies[Samuels2021] that high frequencies cause gene mutations that lead to cancer. Another technical issue is generating the ultra-high frequencies itself, with the complexities of short-range and high cost. In addition to the struggle to guarantee devices operate in room temperature.

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5. Conclusion and Recommendations

Although 6G is still in an early stage of development, there are certainly general trends expected to have a huge influence on the development of future communications systems. The most notable one is the gradual shift towards higher and higher frequencies. This move is motivated by multiple facts, one is the need for support of extremely high data rates, and the spectral congestion in lower frequencies.

In this paper, we discussed the main three approaches to achieve higher frequencies using Terahertz communications, Visible light communications, and Molecular communication. Despite the benefits of THz communication, it is characterized by challenging features such as high path loss, narrow beamwidth, and high directivity which pose critical challenges when employed for UAVs, with respect to channel estimation, beam tracking, and alignment, quality of service (QoS) constraints, etc. These challenges are subjects of an ongoing investigation in the research community.

VLC is an important component in the future 6G technology. Thus, research on VLC still should be carried out to further broaden its application scenarios and improve its communication performance. Future development of VLC requires more research on the evolution of its fundamental transmission devices. High-speed VLC systems are mainly restricted by the limited bandwidths of the light sources. Accordingly, this indicates that super-high-bandwidth light sources with new materials and mechanisms should be investigated.

Most of the current research on VLC is focused to demonstrate the capabilities of optical wireless communications that is detached from the fact that radio communication is the dominant way of transferring information wirelessly. We believe that optical and radio communications are highly complementary. The flexibility, scalability, and relative simplicity of radio can indeed be combined with the inherent security, safety, and privacy of VLC to create a high-performance and robust hybrid Terahertz communication system.

New semiconductors and other materials need to be developed for these operating frequencies. It is expected thus that components for mm-wave and THz operation will be expensive. Molecular communications (MC) are still not well understood, and experimental evidence to support models is still primitive. Therefore, it is important to lay out the challenges that motivate us to understand the underlying information theory and physical layer of MC through well-motivated experimentation. This is particularly missing in the macro-scale engineering and engineered systems, where there is a lack of application areas for MC.

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List of Acronyms

VLC	Visible Light Communications

5G	Fifth Generation
6G	Sixth Generation
NTNs	Non-Terrestrial Networks
UH	Ultra-High
THZ	Terahertz
HBT	Heterojunction Biopolar Transistor
HEMT	High Electron Mobility Transistor
LD	Laser Diodes
GaN	Gallium Nitride
I1/4LEDs	MicroLEDs
SP-LEDs	Surface Plasmon-coupled LEDs
Si-LEDs	Silicon-based LEDs
SLDs	Super Luminescent Diodes
PAM	Pulse Amplitude Modulation
CAP	Carrier-less Amplitude and Phase modulation
OFDM	Orthogonal Frequency Division Multiplexing
MIMO	Multiple-Input Multiple-Output
D2D	Device-to-Device
PL	Path Loss
QoS	Quality of Service
CFD	Computational Fluid Dynamics
COTS	Commercially available Off-The-Shelf

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