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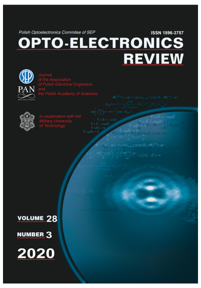

# Digital communication – optical *vs.* THz links

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**Abstract**

The paper presents a comprehensive look at the perspectives on the use of THz in digital communication systems. The publication aims to focus on arguments that justify a significant increase in the frequency of radio links and their integration with fibre-based networks. Comparison of THz links with their microwave and optical counterparts is discussed from basic physical limitations to technological constraints. Main attention is paid to the available channel capacity resulting from its bandwidth and signal-to-noise ratio. The short final discussion is about technology platforms that seem to be crucial to the availability of suitable THz sources. According to the author, the biggest advantage of using bands in the range of several hundred GHz for a digital data transmission is their use for mobile communication over short distances, as well as for broadband indoor links. However, these applications require a development of compact electronic THz sources with low noise and power reaching single watts. This is beyond the range of the most popular silicon-based technology platform, although a significant progress can be expected with the development of technologies based on wide bandgap semiconductors. Fibre optic connections remain the unquestioned leader in communication over long distances and permanent links.

## 1. Introduction

This article does not provide a complete overview of optical and THz data networks. This is an author's review aimed at comparing the advantages of both types of networks and indicating their synergy, visible especially in the case of radio links using very high frequencies. The author uses the arguments of a physical and technological nature that are understandable to both scientists and network engineers.

Many factors determine the choice of a data link. In the previous decade, a lot of discussions concerned the use of THz bands to send massive amounts of data over relatively short distances. Nowadays, the THz frequency range has become more technology available. This includes both detectors, and to a lesser extent, sources. Moreover, the THz part of the frequency spectrum is largely free from the allocation of various services using wireless communication but at the World Radio Conference in October/November 2019 a preliminary consensus towards future allocations from 275 GHz to 450 GHz was reached [1]. The bands of 275-296 GHz, 306-313 GHz, 318-333 GHz, and 356-450 GHz would be usable in the future for land mobile and fixed services. This would allow to use a much wider bandwidth to transfer data than is possible in congested microwave bands. It is an important factor because the amount of information that can be sent is directly proportional to the available bandwidth of a link.

In a so-called noisy-channel coding theorem (Shannon-Hartley theorem), referred to the maximum rate of error-free data for a particular noise level, Shannon defined in 1948 [2] a parameter called channel capacity $C$ (in bit/s). The theorem states that for any transmission at a rate slower than $C$ defined by Shannon limit formula, Eq. (1), there exist codes allowing the probability of transmission error to be infinitely small (however, using highly efficient codes may be economically or technically unjustified). Some recently used codes nearly reach the theoretical limit of $C$ and the equation itself was proven several years after it was published:

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$$C = B_W \log_2(1 + SNR), \tag{1}$$

where $B_W$ is the link bandwidth in Hz and $SNR$ denotes the signal-to-noise ratio. Without noise, $C$ would be infinite. This formula shows also that for a low rate of transmission we can send data using a sufficiently wide channel even if the signal is much smaller than the noise. Certainly, that is not useful for the fast transfer of massive data but offers a good cellular network performance. There is a way to improve $C$ by a multiple input multiple output (MIMO) technology but this idea works only when each of its channels is independent of others. This is often used in mobile networks to eliminate signal fadings. An extended analysis of MIMO network capacity, taking into account distortions from physical transceiver impairments (typical for cellular networks), may be found in Ref. 3.

Next parts of the article will address the issues determining the pros and cons of communication links on THz frequencies with a particular emphasis on optical networks. Perspectives of increasing the frequency in relation to commonly used microwave frequencies were also discussed.

## 2. Bandwidth

The Shannon formula shows the importance of a large bandwidth that is easier to be obtained and allocated for THz bands as compared with its microwave counterparts used widely in mobile communication. For optical links, a lot depends on the medium used to propagate information. While optical connections (with a few exceptions including space communication and some terrestrial point-to-point links) apply mainly to fibre-based networks, the radio frequency (RF) links are mostly using a connection between two (or more) antennas located in free space (for lower speeds they can use a different type of cabling). Wiring is slowly losing importance because it leads to a relatively slow transmission and requires a previously installed infrastructure suitable mainly for transmission on premises.

As far as the optical fibre links are concerned, commonly used multi-mode fibres introduce a multimode distortion, which often limits the bandwidth and length of the link. Single-mode fibres fabricated in leading technologies can achieve a large bandwidth providing stunning communication speeds [4]. The equivalents of fibre optics in the microwave technology are waveguides but they have some disadvantages including the fact that they are usually rigid and in the metal version they have high attenuation for very high microwave frequencies. Dielectric waveguides on the THz range might be more appropriate but they are not widely used and they are most often manufactured for short interconnections between chips.

For the above reasons, it is difficult to compare the pros and cons of optical and RF communication, since the first one manifests its most advantages in a fibre optic transmission, while the latter uses predominantly wireless links or cabling for short-distance communication. For mobile applications, however, it should be pointed out that sending massive amounts of data by RF requires frequencies much higher than those currently used for Wi-Fi or cellular networks. The emerging 5G technology offers a much wider bandwidth than other mobile standards but, basically, the band is shared by many users. Using the THz band for mobile communication seems to be a remedy since it would increase the bandwidth several dozen times regardless of the protocol used. The Shannon formula shows that it is much easier to get a larger capacity of a channel increasing the bandwidth than by an increase of the signal-to-noise ratio. Attenuation related to the atmosphere [5] may be a limitation of THz outdoor links and that aspect will be discussed elsewhere.

It should be mentioned that there are some experimental solutions, such as using a so-called visible light communication (VLC) technology [6] that provides short-distance wideband communication using light-emitting diodes as transmitters. This technology can provide services up to 20 Gbit/s currently for indoor communication. It has been used already to create an optical broadcasting system for shopping malls. VLC in this case was integrated with lighting and was using smartphone cameras as the receivers. Essentially, obtaining a large bandwidth in specific optical techniques, even if possible, should be always economically justified.

A direct consequence of the high optical frequencies is making it possible to use very broad optical bandwidths. Even if the bandwidth cannot be fully used (there are theoretical and practical limits to the achievable spectral efficiency that is typical of the order of a few bit/s per Hz of the optical bandwidth), an optical link (particularly fibre-based) can have a capacity far beyond that of available for RF links.

In conclusion, the achievable bandwidth is a factor causing the superiority of transmissions at THz frequencies over microwave ones but optical links may offer a significantly wider channel. However, the band-width resulting from the passband of optical fibres is not an adequate parameter for assessing the performance of an optical link.

## 3. Signal-to-noise ratio

The second term in Eq. (1) concerns the signal to noise ratio (denoted $SNR$). The theory leading to the formula assumes that the noise is added to the signal in a form of a continuous random variable generated by a Gaussian process with a known variance that is equivalent to the power of noise. This is so-called ‘white noise’ - being independent of frequency within the entire bandwidth of a channel. Estimating or measuring $SNR$ is not a trivial matter. To calculate the channel maximal capacity, $SNR$ is defined as a ratio of the signal power to the noise power. For RF links, it is often assumed that the minimal noise at the link input is a thermal noise for a temperature of $T = 290$ K. For obvious reasons, this is an estimate of the lowest possible level of the white noise at the link first stage. The noise power within the given bandwidth $B_W$ can be calculated from Eq. (2), where $T$ denotes the absolute temperature, and $k_B = 1.380649\ 10^{-23}$ J/K is the Boltzmann constant:

$$N = k_B T B_W. \tag{2}$$

Then, every element of the link between a transmitter and a decoding device in the receiver introduces its noise (and gain/attenuation/conversion efficiency - depending to which parameter it applies) leading in the end to the total *SNR* value influencing the maximal channel capacity. Situation concerning optical signals is more difficult. Frequency of the light wave is much higher than any useful band used for communication. Then, the result of noise measurements depends on the filtration techniques used. A common trick for the sake of comparisons is to use the *OSNR* (optical *SNR*) that is the ratio between the signal power and the noise power in a given bandwidth. *OSNR* can be measured easily with an optical spectrum analyser. In general, there is no simple relation between *OSNR* and *SNR* since *OSNR* is proportional to the optical power ratio, while *SNR* is proportional to the electrical power ratio. That makes a significant difference. In optical links some parts of the signal path are optical and some (at least at both ends) electrical, so using Eq. (2) as the input noise limit could be justified but the noise of electrical amplifiers and optical ones are of a different physical nature, the latter are much less noisy. An example of the mechanism used in an optical amplifier can be the stimulated emission process used in erbium-doped fibre amplifiers. A medium (fibre, waveguide, traditional cables, or atmosphere) has also a very significant impact on the signal attenuation, therefore, the *SNR* level.

Modern fibre-optic networks provide a disproportionately larger communication channel capacity than networks based on RF transmission due to a much better *SNR* and their larger available bandwidth. Optical links based on fibres are also very resistant to any external interference and maintain transmission security. RF links though remain irreplaceable for mobile services. The method of processing information including modulation and coding is also essential especially in the case of mobile wireless transmissions including sharing a communication channel between many users. A rapid development of the cellular network technology is just related to the development of signal processing techniques (including multi-value modulation, spatial multiplexing, and coding) allowing users to approach the Shannon limit even in mobile working conditions. It should be emphasized that the modulation scheme choice depends on several factors. Some types of modulation make better use of the available bandwidth, while others use less energy to transmit a single bit of information. The Shannon-Hartley theorem leads to a trade-off between both desired parameters. A similarly important decision concerns algorithms for correcting transmission errors. The best of these require a powerful computing system and can be inefficient in terms of cost or speed.

In Ref. 7 a reader can find an experimental work concerning 1 Tbit/s transmission at D-band (110-170 GHz) showing the importance of every technique on a sub-THz link performance. The technology supported by photonics together with the use of 4x4 MIMO and advanced digital signal processing ensured the ultra-high bit rate. It should be noted that this experiment used all available techniques to achieve the highest transmission speed. A high error rate was accepted, a very short distance transmission provided a sufficient *SNR* despite the low THz source power. The optical transmitting part formed two sub-carriers encoded in a probabilistically shaped quadrature amplitude modulation format [8]. Additional advanced techniques have been applied to maximize the system performance.

It should be pointed out that the specificity of cellular networks means that their designers do not aim for the error-free transmission but for the use of the most effective methods of error correction to maintain an acceptable bit error rate (BER) [9]. Telecom engineers should be aware that some type of noise is the result of another human activity that interferes with the bandwidth used for communication. For 2.4 GHz, it could be Wi-Fi, Bluetooth, microwave ovens, or medical equipment. Shifting bands toward less crowded THz bands may partly solve this problem.

In addition to measuring or theoretical estimating the noise level, a necessary element of any communication link design is to ensure a sufficiently high *SNR* level. In a digital communication, $E_b/N_0$ (energy per bit to noise power spectral density ratio) is a normalized *SNR* measure (also known as the *SNR* per bit or power efficiency). The $E_b$ is defined as the signal energy required to send one bit. Using this value we can avoid mentioned earlier problems with estimation of the available $B_W$ for optical links. If the signal bandwidth is known, the $E_b/N_0$ ratio is equal to the *SNR* (in that bandwidth) divided by the optical link spectral efficiency expressed in (bit/s)/Hz units. Essentially, using *SNR* and $E_b/N_0$ in Eq. (1) is equivalent but the latter is more convenient for BER estimation. *SNR* per bit means the power efficiency of a link without taking into account its bandwidth and signal processing (modulation and coding methods). For a thermal noise $N_0 = k_B T = N/B_W$. It should be pointed out that the constant noise density was assumed for these considerations.

For an electrical channel, the minimum energy that will be needed to change the receiver state from logical zero to one (and, thus, receiving one bit) seems to be very small. If one assumes that a state-of-the-art CMOS logic gate represents the input capacitance $C_{in}$ of the order of single femtofarads, and the input voltage change of the order of $U = 1$ V to flip it, then, the required energy to decode one bit equals $C_{in}U^2/2$ (that is the order of several femtojoules or even less for deep submicron technologies). Unfortunately, a more realistic model must take into account the length (capacitance) of the interconnections (especially external) on the receiver side. In this case, we have already a capacitance of the order of picofarads even when only a small part of the connection (corresponding to a 1-bit length) needs to be re-charged. In this case, it turns out that the minimal energy required to send a bit, assessed only on the receiver side, is much bigger (of several picojoules). Then, one should take into account all other parts of the entire communication chain increasing the required energy by several orders of magnitude.

If one focuses on free-space communication, where electronic links may have a natural advantage over optical ones in connection with mobile applications, it becomes obvious that the total energy required to send one bit will be much higher since only a small fraction of emitted energy usually reaches the receiver. Therefore, the energy per bit spent on the transmitter side is usually enormous for mobile networks.

In the case of an optical link usually using fibre optics (a free-space case shall be discussed elsewhere), photons are converted into electrons in a very efficient quantum process at the photodetector. The problem of significant energy losses in internal connections in the form discussed for electrical networks is not adequate to describe optical ones in which the photon flux energy is not used to re-charge interconnections capacitance, but covers only minimal losses of short optical fibres. Therefore, the energy consumption $E_b$ required to change the receiver gate state is much lower. Then, one should add again the energy dissipated in other parts of the link. A suitable example of the noise budget for an optical physical layer hardware may be found in Ref. 10. The budget depends on several factors such as modulation format, fibre losses, system length, and the spontaneous noise in optical amplifiers (commonly used for longer routes). A significant part of this energy is consumed by optical transmitters which usually use lasers and some energy is spent on the receiver side. The detailed estimation of every contribution to the total energy results in values of the order of several picojoules per bit [11]. For extremely low values of $E_b/N_0$ one has to take into account a so-called 'Shannon-limit bound' limiting the available spectral efficiency and providing the channel capacity independent on bandwidth. The $E_b/N_0$ value is still clearly in favour of the optical links using negligible-loss fibres and, if the link is long, optical fibre-based amplifiers.

To conclude, the use of fibres and extremely low losses of optical amplifiers make fibre optic links unrivalled over long distances. It should be pointed out that specific applications like space communication may also favour optical links due to highly effective antenna systems with a very small beam convergence but this aspect will be discussed elsewhere. Each design of any link requires a detailed analysis of the *SNR* to check if it is possible to achieve the assumed link parameters within a bandwidth using adequate signal processing techniques and available equipment. One of the input parameters for such an analysis is the permissible error rate. Then, for most designs, the link should be economically viable. Many parameters affect the performance of digital communications systems, so there is often room for system optimisation. In the case of mixed (partly electrical and partly optical) links, it is fruitful to use photonic elements as wide as it is possible to get a better *SNR*. Particular attention should be paid to relatively large energy losses when converting an electrical signal into an optical one. Essentially, microwave links are advantageous for mobile applications, and increasing their frequency to the THz range allows us to expand the connection capacity several dozen times.

## 4. Point-to-point links

A situation where it pays to use high frequencies on wireless links is a communication between directional antennas. Microwave radio lines are using often a parabolic dish antenna. The main advantage of this antenna is that it has a high gain proportional to the square of frequency multiplied by the dish diameter. It has also a narrow beam-width inversely proportional to the frequency. If we increase the frequency ten times to reach a THz band leaving the same dish diameter, the free-space path loss remains the same since the loss associated with the increase in frequency will be compensated by an increase in antenna gain (one dish antenna considered). At the same time, the available bandwidth will be substantially larger. It makes the THz link using such an antenna favourable over one using a low microwave band. The beam convergence might be also of importance for systems using multiplexing in space. Moreover, the THz antenna might be considerably smaller than its microwave counterpart if both are designed for the same gain. A significant problem for radio-links using THz bands is their considerable attenuation by atmospheric gases, especially water vapour. For short distances (or indoor applications) the THz wireless link offers good performance and broadband transmission if one chooses a frequency band within so-called 'atmospheric windows' characterized by the smaller attenuation.

The situation concerning a similar antenna designed for focusing light (a parabolic mirror of the same size as the microwave dish) should be analysed here. The precision (and, thus, the cost) of making such a mirror would have to be very high. The light has a wavelength several orders of magnitude shorter than RF, therefore, one can expect the extremely high gain of the antenna. Unfortunately, the losses of free space are also proportional to the square of frequency and the extremely narrow beam makes antenna adjustment very difficult, so the use of light for a point-to-point communication is envisaged only for very special tasks like Earth-Mars link or communication between satellites [12].

In space communication, the channel capacity is not the most important but the *SNR* is a crucial factor that is very much in favour of optical links (see the discussion concerning Friis formula in the next section). Also, the influence of the atmosphere (dispersion and absorption) is of importance for optical communication, although not as critical as in the case of THz attenuation in a humid environment.

## 5. Technological constraints of a wideband THz communication - THz sources

Detection of microwave and optical signals is usually considered as a technologically mature field. In optical links, quantum detectors in the form of various semiconductor photodiodes are commonly used. This is possible because the energy of a photon is much greater than the semiconductor forbidden gap. In the case of THz, the energy of a photon is of the order of a few meV, so even the use (except for cryogenic systems) of narrow-band semiconductors, energy states associated with doping, and devices based on quantum wells, or dots is not a solution. If we ignore the design of low-temperature detectors and devices that are too slow, the choice is not so wide.

The recent years, however, have brought an unprecedented development of high-speed detectors in the THz band in the form of various field-effect transistors - FETs, high electron mobility transistors - HEMTs, and specialized Schottky diodes. It should be mentioned that some of these devices can serve as mixers and, thus, can be used for a coherent detection. The state-of-the-art parameters and an extended description of uncooled rectifier detectors can be found in Ref. 13 and many details on the detection and generation of THz in Ref. 14.

A modulator is one of the basic devices in any THz communication system. THz modulators are based on a variety of principles and materials, and their design often depends on specific applications. Research progress in this field is very rapid and now optical modulators have great modulation depth and they are fast. An extensive review of this topic was published two years ago [15].

The main problem, however, remains unresolved – how to generate enough strong THz signals in a way that ensures their stability and easy modulation. If we focus on point-to-point connections or cellular networks with a sufficiently dense network of base stations (designed for 5G in many large cities where the use of THz would bring the greatest benefits) - compact THz sources will be required (at least 1 W for the base station). One may use the Friis formula describing a power transfer between two antennas in free space, Eq. (3) [16], to assess the performance of THz link compared to the microwave one:

$$P_\mathrm{r}/P_\mathrm{t} = A_\mathrm{r}A_\mathrm{t}/(\lambda d)^2, \qquad (3)$$

where $P_\mathrm{r}/P_\mathrm{t}$ denotes the ratio between power received *vs.* transmitted; $A_\mathrm{r}$ and $A_\mathrm{t}$ are the apertures of receiving and transmitting antennas, respectively; $\lambda$ is the wavelength; and $d$ is the distance between antennas. Assuming the same physical size of both antennas - microwave and THz (and, in consequence, their similar apertures), the ratio of the power received by the receiver to the transmitted power increases with the square of the frequency. Therefore, THz bands should not be neglected also in cellular technology even if atmosphere attenuation for THz is unfavourable. Moreover, as it was discussed, THz links offer a significantly wider bandwidth enabling, for example, a quick upload of movies. Some indoor links in server rooms or hospital operating rooms could arouse interest.

There are many ways to generate THz. Solid-state sources should be analysed here. The classic (inefficient) way is to start with an RF oscillator controlled by a phase loop, and then to amplify the signal several times and multiply its frequency (using fast transistors and/or Schottky diodes) to the technically achievable limit. Besides, there are several semiconductor diodes including an impact ionization avalanche transit-time diode (IMPATT) and a Gunn diode that can oscillate in the sub-THz region. Unfortunately, their output power falls very steep for higher frequencies. Moreover, several types of IMPATT-like diodes have a high noise figure (they are using avalanche), and they reach a few percent efficiencies maximally. Then, they produce a lot of heat so many studies are currently focused on GaN and SiC diodes offering more power and accepting higher temperatures of junctions [17]. The main drawback of them regarding communication is a phase noise high level. Gunn diodes have similar limitations as IMPATT, however, they have been used already as local oscillators for millimetre-wave radio astronomy receivers. InP resonant tunnelling diodes (RTDs) offer the highest frequency among the others but material parameters indicate that GaN may be more promising [18]. RTDs are based on tunnelling that is a very fast process and offers a smaller noise than avalanche-based diodes. The maximum reported power of a sub-THz radiation with the help of InP RTDs does not exceed 1 mW with efficiency reaching 1% (in 2020) but, essentially, power combining technology using an array of RTDs may overcome the limitation of the output power [19]. Rx/Tx based on the use of the RTD with a double InGaAs/AlAs barrier achieved error-free signal transmission of 30 Gbit/s [20].

In this place semiconductor laser-based THz sources are not discussed. They are not cost-effective, require cooling, and do not offer optical power in the sub-THz range reaching hundreds of GHz (frequencies expected for communication links). However, it should be mentioned that optical mixing signals from two infrared lasers are often used in research installations as a tuneable low-noise source of THz radiation.

Nonetheless, a leading-edge Silicon-Germanium - heterojunction bipolar transistor - bipolar/CMOS (SiGe-HBT BiCMOS) technology concerning integrated extremely fast circuits offers new perspectives for THz communication. This technology provides very high-frequency devices operating even close to 1 THz [21]. In this way, it is possible to produce not only an efficient electronic source of THz radiation but to integrate it with a modulator and a signal processing unit on the transmitter side or to design a complete THz receiver for digital communication in one chip. Unfortunately, the power level achieved on THz frequencies using SiGe-HBT BiCMOS technology is insufficient (state-of-the-art of a few mW in the 300 GHz range) in the context of sources for THz transmitters intended for wider use.

A more promising platform for both higher frequencies and the level of THz power are circuits based on InP and GaN. GaN HEMTs offer not only high frequency but also a high breakdown voltage. Unfortunately, at the present state-of-the-art, no solid-state electronic power amplifiers are working at THz frequencies. A comprehensive study on, among others, the prospects of achieving by the modern technologies the level of power enabling the wide application of THz links may be found in Ref. 22. It should be mentioned that for some specific applications vacuum devices in a form of traveling-wave tubes may be considered. They work as signal amplifiers reaching sub-THz frequencies and offer enough high power even for base stations [23]. Besides, the beamforming technology can significantly reduce the power requirement for maintaining the link in mobile networks [24]. Beamforming is a signal processing technique that enables directional transmission or reception of a signal. Since THz antennas are relatively small, beam control in small mobile devices can be performed using an array of antennas placed, e.g., in the housing of a mobile phone.

## 6. Conclusions

The above considerations are not only about the theoretical possibilities and restrictions of using the THz band for commercial purposes. In recent years, many reports have been published regarding the broadband data transmission in laboratory conditions on several hundred GHz and above. An example is Ref. 25 regarding an error-free transmission in the 46-GHz bandwidth at the 400-GHz carrier frequency. During the Beijing Olympic

Games, NTT together with Fuji Network Television Inc. were sending television images from the transmission car to the studio in 4k standard using a THz link. The predicted development map of THz techniques can be found in Ref. 26.

Communication on THz bands makes it possible to significantly increase the capacity of links in comparison to the capabilities of microwave links working at lower frequencies. At short distances, THz communication becomes complementary with optical fibre connections that can provide support for the core network (e.g., in the form of the Internet backbone). Its advantages are evident in mobile short-distance connections, broadband point-to-point links, and the transmission of massive amounts of data indoors. The choice of a specific technology is driven by applications. A major advantage in favour of using THz bands is their smaller occupancy than one of crowded microwave bands. The most serious obstacle to the development of THz communication is the lack of efficient semiconductor radiation sources emitting a continuous wave on the frequency of several hundred GHz with a sufficient level of output power. For a widespread use, they should be compact, not noisy, and economically justified.

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## References

[1] Provisional Final Acts WRC-19 *World Radiocommunication Conference 2019 (WRC-19)*. Available at https://www.itu.int/en/ITU-R/conferences/wrc/2019/Documents/PFA-WRC19-E.pdf (Accessed 5th August 2020, see p. 60)

[2] Shannon, C. E. A Mathematical theory of communication. *Bell Syst. Techn. J.* **27**, 379–423 (1948). https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

[3] Bjornson, E., Zetterberg, P., Bengtsson, M. & Ottersten, B. Capacity limits and multiplexing gains of MIMO channels with transceiver impairments. *IEEE Commun. Lett.* **17** (1), 91–94, (2013). https://doi.org/10.1109/LCOMM.2012.112012.122003

[4] Li, M.-J. & Hayashi, T. Advances in low-loss, large-area, and multicore fibres. in *Optical Fibre Telecommunications VII*, (ed. Willner, A.), 3–50, (Academic Press, 2019). https://doi.org/10.1016/B978-0-12-816502-7.00001-4

[5] Tamosiunaite, M., Tamosiunas, S., Zilinskas, M. & Valusis G. Atmospheric Attenuation of the Terahertz Wireless Networks. in *Broadband Communications Networks - Recent Advances and Lessons from Practice*, 143–156 (INTECH OPEN book, 2018). http://dx.doi.org/10.5772/intechopen.72205

[6] Ndjiongue, A. R., Ferreira, H. & Ngatched, T. Visible Light Communications (VLC) Technology. in *Wiley Encyclopedia of Electrical and Electronics Engineering*, 1–15 (Wiley Online Library, 2015). https://doi.org/10.1002/047134608X.W8267

[7] Li, X. *et al.* 1-Tb/s millimeter-wave signal wireless delivery at D-Band. *J. Lightwave Technol.* **37** (1), 96–204 (2019). https://doi.org/10.1109/JLT.2018.2871472

[8] Buchali, F. *et al*. Experimental demonstration of capacity increase and rate-adaptation by probabilistically shaped 64-QAM. in *2015 European Conferenceon Optical Communication (ECOC)* (2015). https://doi.org/10.1109/ECOC.2015.7341688

[9] H2020 EPIC Project: Next Generation FEC for Tb/s and THz Systems Enabling Practical Wireless Tb/s Communications with Next Generation Channel Coding. Available at:https://mentor.ieee.org/802.15/dcn/18/15-18-0206-00-0thz-h2020-epic-project-next-generation-fec-for-tb-s-and-thz-systems.pdf. (Accessed 5th August 2020)

[10] Dahlgren R., Noise in fibre optic communication links. *Technical Report, SV Photonics 2000*. Available at: http://www.svphotonics.com/pub/pub029.pdf. (Accessed 5st August 2020)

[11] Tucker, R.S., Green optical communications—Part I: Energy Limitations in Transport. *IEEE J. Sel. Top. Quantum Electron.* **17** (2), 245–260 (2011). https://doi.org/10.1109/JSTQE.2010.2051216

[12] Hecht, J. Laser Links will link small satellites to Earth and each other. *LaserFocusWorld* (24 March 2020). Available at: https://www.laserfocusworld.com/lasers-sources/article/14104017/laser-links-will-link-small-satellites-to-earth-and-each-other. (Accessed 5th August 2020)

[13] Sizov, F. Terahertz radiation detectors: the state-of-the-art. *Semicond. Sci. Technol.* **33** (12), 123001, (2018). https://doi.org/10.1088/1361-6641/aae473

[14] Sizov, F. Detectors and sources for THz and IR, PDF eBook DRM Free. vol. 72 of MRS (edited by Materials Research Forum LLC, 2020). https://doi.org/10.21741/9781644900758

[15] Ma, Z. T. *et al.* Modulators for terahertz communication: the current state of the Art. *Research* **2019,** 1–22 (2019). https://doi.org/10.34133/2019/6482975

[16] Friis, H. T. A Note on a Simple Transmission Formula. *IEEE Proc. IRE* **34** (5), 254–256 (1946). https://doi.org/10.1109/JRPROC.1946.234568

[17] Tripathy, P., Mukherjee M. & Pati, S. P. Prospect and Issues of Diamond based IMPATT Diode at MM-wave Frequency. *17th International Workshop on the Physics of Semiconductor Devices, 10-14 Dec. 2013* in Physics of Semiconductor Devices (eds: Jain, V. K., Verma, A.) 235–238 (Springer International Publishing, 2014). https://www.springer.com/gp/book/9783319030012

[18] Ahi, K. Review of GaN-based devices for terahertz operation. *Opt. Eng.* **56** (9), 090901 (2017). https://doi.org/10.1117/1.OE.56.9.090901

[19] Kasagi, K., Suzuki, S. & Asada M. Large-scale array of resonant-tunneling-diode terahertz oscillators for high output power at 1 THz. *J. Appl. Phys.* **125** (15), 151601 (2019). https://doi.org/10.1063/1.5051007

[20] Nishida Y. *et al.* Terahertz coherent receiver using a single resonant tunneling diode. *Sci. Rep.* **9**, 18125 (2019). https://doi.org/10.1038/s41598-019-54627-8

[21] Chevalier, P. *et al*., SiGe BiCMOS current status and future trends in Europe. in *IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS)* 64–71 (2018). https://doi.org/10.1109/BCICTS.2018.8550963

[22] Hillger, P. *et al*., Toward Mobile Integrated Electronic Systems at THz Frequencies. *J. Infrared Millim. Terahertz Waves* **41**, 846–869 (2020). https://dx.doi.org/10.1007/s10762-020-00699-x

[23] Basu, R.., Billa, L. R., Letizia, R. & Paoloni, C. Design of sub-THz traveling wave tubes for high data rate long range wireless links. *Semicond. Sci. Technol.* **33** (12), 124009, (2018). https://doi.org/10.1088/1361-6641/aae859

[24] Kutty, S. & Sen, D. Beamforming for millimeter-wave communications: an inclusive survey. in *IEEE Commun. Surveys Tuts.* **18** (2), 949–973 (2016). https://dx.doi.org/10.1109/COMST.2015.2504600

[25] Ducournau, G. *et al*. Ultrawide-bandwidth single-channel 0.4-THz wireless link combining broadband quasi-optic photomixer and coherent detection. *IEEE Trans. Terahertz Sci. Technol.* **4** (3), 328–337 (2014). https://doi.org/10.1109/TTHZ.2014.2309006

[26] Dhillon. S. S. *et al*. The 2017 terahertz science and technology roadmap. *J. Phys. D* **50** (4), 043001 (2017). https://dx.doi.org/10.1088/1361-6463/50/4/043001