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Corrected Link Budget Analysis for Terahertz Wireless Links

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Abstract: This presentation is a revised link budget analysis of the terahertz telecommunication wireless links. Attainability of the terabit capacity has been shown for the case of THz cryogenically cooled receivers to present a more optimistic evaluation of fundamental limits of maximal data rates for terahertz links. In addition, the well-known Shannon formula has been revised for the case of the receivers with cryogenic front-end components. We have also supplemented the analysis of the terrestrial horizontal channel operation by investigation of the cases of channels operating in diverse media which influence the channel capacity. Based on this investigation, the reasonable limits of the receiver own noise reduction have been estimated for different transmission media.

Keywords: Terahertz Telecommunication, Low Noise Receivers, Cryogenically Cooled Receivers, Noise Temperature, Noise Figure, Millimetre and Submillimetre Wave Communication

1. Introduction

The race for higher traffic-carrying capacities (>100 Gb/s) of wireless telecommunication links in both open space and on-land communication, and in the long view in a new generation of mobile telephone systems expectedly leads to considering application of the terahertz band (0.3 to 3 THz). At the moment, we are witnessing a growing interest in the THz telecommunication links [1], as the explorations in the sphere of telecommunication are getting confidently close to the THz bandwidth; a real boom of the interest in these explorations can be foreseen shortly to take place. Among other inhibitions are at the moment the high costs of the THz telecommunication hardware, but the prospective growth in the consumer demands, such as, for instance, the need for higher exchange rates, is anticipated to lower the costs considerably. Market analysts are already discussing the promising potentials of the THz communication links which are expected to come in existence quite soon [2] (Fig. 1).

The THz band potentials have already been estimated in Paper [1], wherein a structural diagram of the mobile client communication channel has been presented and also splitting of the terahertz band into five tentative sub-bands corresponding to the five known atmospheric windows has been suggested. The evaluation of the ultimate bandwidth capacity in Paper [1] has been done allowing for the atmospheric gas and hydrometeor absorption, the ground conditions, etc. This tentative evaluation is based on a number of fixed input conditions such as the power of the transmitter (*10 mW*), the size of the antenna, and the receiver noise (F_n = *10dB*). For the THz band, they have calculated the maximum data rate possible to be about 100 Gb/s. Increasing the transmitter power will boost the capacity, but presently, the only way to do it is to use highly-expensive gyrotrons [3, 4]. The given transmitter power (10mW) may not be increased by more than three orders of magnitude so as not to transgress health protection and electromagnetic compatibility standards, and it would not be reasonable to increase the dimensions of the antenna beyond certain limits either. However, the authors of Paper [1] failed to analyse one of the available resources of increasing the THz band capacity, that is, the receiver sensitivity. Strictly speaking, the only limitation to the THz receiver sensitivity is the quantum limit [5], or the fundamental Heisenberg formula. THz heterodyne receivers have already been designed [6] whose sensitivity nearly reaches the fundamental borderline. As is discussed below, a higher-sensitivity (one quantum per observation time) THz receiver will not be practical for telecommunication.

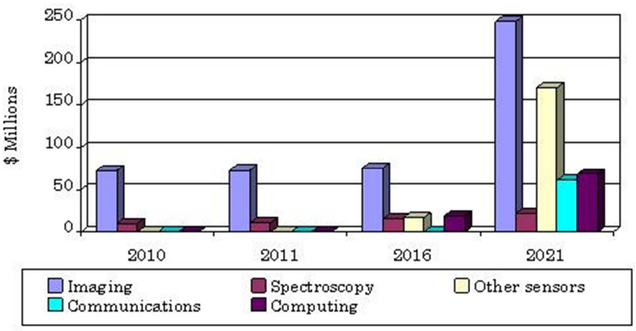

Fig. 1. *Forecast of the THz telecommunication market potential [1].*

2. Estimating the Link Budget

The theory-based capacity limit educed in Paper [1] has been calculated with the well-known Shannon formula which includes the signal-to-noise ratio (SNR) of the receiver. The ratio is calculated using Formula (1):

$$SNR = P_{rx} / F_n \, k \, T \, B \quad (1)$$

where F_n is the receiver noise factor, $T= T_o =300K$ is the receiver standard temperature, P_{rx} is the transmitter power, k is the Boltzmann constant, and B is the channel frequency band.

The table in Paper [1] shows that wireless THz data channels of the length of up to 1 km and capacity 100 Gb/s are technologically possible. Such channels would be a good match for the optical channels. The capacity of optical channels is quite high; for example, the respective capacities of Ethernet and Optical Transport Network (OTN) are 100 and 112 Gb/s as is set forth in the standards IEEE 802.3b and ITU-T G.709; however, all optical channels including IR channels are known for their susceptibility to interference and losses. The wireless THz channels of such capacity have experimentally been shown to be realisable in the most recent papers on THz telecommunication technologies [7, 8, 9, 10].

If we used the today's best receiver whose performance borders the fundamental limit of the signal-to-noise ratio, it is evident that we would be likely to get a higher capacity link than that described in Paper [1]. The creators of today's best THz receivers have reduced the noise level by an order of magnitude [6] if compared to the value assumed as fixed in Paper [1]. The link capacity as is shown in Paper [1] is related to the signal-to-noise ratio through the Shannon formula:

$$C = B \log2 (1+SNR) \quad (2)$$

It is evident that with the receiver noise reduced by an order of magnitude the link capacity becomes more than three times higher; therefore, attainable THz link capacities can be up to 300 Gb/s other things being equal.

It is theoretically possible and even practical, in view of radioastronomy and other similar applications, for the materialised and prospective receivers [6, 7] to achieve even further noise reduction down to the values below the quantum limit (the calculated sensitivity of a hypothetical receiver operating as a quantum counter, or, in other words, being able to register a quantum per observation time, will be below the radiation of a quantum), but this will have no sense for telecommunication. The quantum counters, although extremely sensitive, have a fundamental limitation of the power of the incoming signal, which makes them impractical for transmission of large volumes of information. Thus, what is really needed for telecommunication is not a quantum counter, but a heterodyne coherent detector which will, on the one hand, be sensitive enough to detect a singular quantum, and on the other hand, not be saturated by a powerful signal; that is, the desirable aim is a sensitive detector with a wide dynamic range. This is why there is no need to increase the receiver sensitivity up to the values that would permit to obtain the traffic-carrying capacity more than three times higher than the limit determined in Paper [1].

3. Revisiting the Shannon Formula

As we mention above, the authors of Paper [1] use the classic radio-engineering parameter, the noise factor F, for estimation of the receiver noise level. This parameter has been long and widely applied in radio-engineering; but it has long since been shown to be largely incorrect [10] (this is suggested even by the title of the paper we are referring to here). The receiver noise temperature, or T_n, would be a more accurate parameter. This value does not include the temperature T_o which for cooled receivers (to get extremely high sensitivity, receivers normally are incorporated into the cryogenic cooling system) may significantly differ from the standard T_o=300 K. T_n is related to F through the well-known formula:

$$F = 1 + T_n/T_o. \quad (3)$$

This is why we are suggesting the use of T_n and not F for estimation of the link capacity with a low-noise cryogenic receiver. A more precise formula for determining the signal-to-noise ratio of the receiver will therefore be as follows:

$$SNR = P_{rx} / k \, B \, (T_n+T_o) \quad (4)$$

thus yielding the developed Shannon formula for the link capacity estimation (instead of that used in Paper [1]):

$$C = B \log2 (1+ P_{rx} / k \, B \, (T_n+T_o)) \quad (5)$$

4. Discussion

In this section, we are supplementing some of the conclusions which were presented in Paper [12], to get a clearer view of THz communication channels operating in diverse media (open space, high elevation, and land-to-space channels), by the discussion of the limits to the sensitivity of the receiver. The atmospheric absorption will be different under particular conditions and, therefore, so will be the system signal-to-noise ratio and eventually the limit value of the channel capacity.

For the case of open space communication, for instance, exchange between space stations or satellites, the receiver sensitivity can be enhanced unrestrictedly but for the quantum limit. The sensitivity can be efficiently increased up to the fundamental limits by deep cooling alone.

Low-altitude terrestrial links are a substantially different case. Here, one has to deal with significant atmospheric absorption (0.4 to 10,000 dB/km for 0.1 to 1 THz). Even within the atmospheric windows, absorption, which defines the signal-to-noise ratio independently of the receiver performance, will be equivalent to the receiver noise temperature of 10 to ~150 K, and that makes it impractical to reduce the receiver noise to the values lower than tens of K. Due to this also, normal THz terrestrial links can reliably operate at distances of no more than 1 to 2 km.

Land-to-space communication is a somewhat intermediate case. If the transmitter is installed at the altitude of 3 to 5 km above sea level, this will be virtually the same as the case of open space communication since atmospheric absorption will have no significant effect on the channel capacity. For low altitudes, the limitations will be the same as for the case of the terrestrial link. For this case, the absorption of the zenith-pointing channel will be equivalent to that of a 2 or 3 km terrestrial link, since absorption takes place mostly in the lower part of the channel up to the altitude of 1 to 2 km, and is negligible beyond that point. The noise of the channel will be comparable to the receiver noise temperature of 10 to 100 K, and, therefore, extremely deep cooling of the receiver (to temperatures lower than 20 K) would be unreasonable.

5. Conclusion

The near-quantum limit receiver sensitivity allowing to make the capacity three times higher is impossible to achieve without a cryogenic cooling system. Cumbersome and expensive cryogenic hardware is at the moment a material hindrance for the THz technology on its way to the use in the consumer telecommunication. However, commercially feasible cryogenic systems like on-board refrigerators for air and space craft have already become available. Base stations can also be equipped with similar systems without much difficulty. A real breakthrough, though, is to be expected when the THz communication will become available for a mass consumer due to the new generation cryogenic systems based on thermodynamic processes of laser, thermoelectric, and thermomagnetic cooling instead of the present-day mechanical gas-based cryogenic equipment.

We would also like to emphasise that the authors of Paper [1] used a transmitter of mere 10 mW. The power of the transmitter can quite reasonably be raised by several watts (up to the values of the powers used in the present-day mobile communication systems) and still be below the health protection tolerable limits. This is a tangible opportunity to raise the capacity by another order of magnitude, and to get close to the THz terabit telecommunication channels.

Finally, we are being optimistic with respect to THz communication in general, since there are the new heterodyne technologies with a significant potential for further development, such as are, for example, quantum cascade lasers [11]. Thorough investigations of THz wave propagation in atmosphere also give definite hopes that not only space but also land-to-space and terrestrial THz communication links may soon become a reality [12].

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