Terahertz (THz) Wireless Systems for Space Applications

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***Abstract*—NASA has been leading the Terahertz (THz) technology development for the sensors and instruments in astronomy in the past 20 years. THz technologies are expanding into much broader applications in recent years. Due to the vast available multiple gigahertz (GHz) broad bandwidths, THz radios offer the possibility for wireless transmission of high data rates. Multi-Gigabits per second (MGbps) broadband wireless access based on THz waves are closer to reality. The THz signal high atmosphere attenuation could significantly decrease the communication ranges and transmittable data rates for the ground systems. Contrary to the THz applications on the ground, the space applications in the atmosphere free environment do not suffer the atmosphere attenuation. The manufacturing technologies for the THz electronic components are advancing and maturing. There is great potential for the NASA future high data wireless applications in environments with difficult cabling and size/weight constraints. In this study, the THz wireless systems for potential space applications were investigated. The applicability of THz systems for space applications was analyzed. The link analysis indicates that MGbps data rates are achievable with compact sized high gain antennas.**

Keywords- Terahertz (THz) communications, wireless communication, link analysis, Multi-Gigabits data rate, International Space Station.

I. INTRODUCTION

Previously, Terahertz (THz) technology has been driven by applications in astronomy. In the past 20 years, NASA has successfully launched and deployed scientific satellites with THz instruments and sensors for applications in astronomy [1,2]. The recent research and development activities in THz technologies are expanding into much broader applications such as security screening, medical imaging, and wireless sensors and communications [3-8]. There is no limit on the demand for the data rates and capacity of wireless communications for today's applications. Thus, new technologies for spectral efficient modulations and the reduction of interference were developed to achieve the growth of data rates in recent years. To meet the demand, new technologies are needed to offer data capacity and to reduce energy consumption requirements in the future wireless networks. One possibility is the exploitation of new frequency spectrum for the radio systems. In the THz range of the frequency spectrum (from 300 GHz to 3000 GHz), multiple gigahertz channel bandwidths are available, shown in Figure 1. This provides the possibility to transmit multi-gigabits per second (MGbps) data rates with less power consumption and higher channel capacity of the network.

The millimeter wave (MMW) technologies have been successful demonstrated at 220 GHz carrier frequency with 25 Gbps data rates [9]. The semiconductor devices and photodiodes for the THz frequency band between 300 and 500 GHz have been demonstrated [10]. The manufacturing technologies for the THz electronic components are advancing and maturing. THz-band wireless systems have some desired advantages over currently available wireless systems. Much higher bandwidths are available than the conventional microwave and millimeter wave systems. The THz system efficiency is higher than laser systems. The THz-band signals have smaller attenuations than the optical/laser signals. The capability of transmission and reflection off the dielectric materials could be useful in many non line of sight indoor applications for the THz waves.

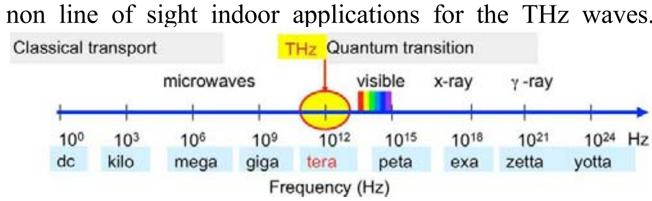

Figure 1. In the THz range of the frequency spectrum, multiple gigahertz channel bandwidths are possible.

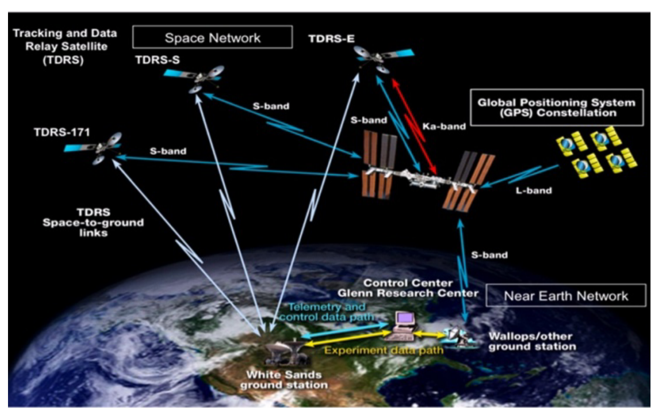

Figure 2. The current communication systems for human spaceflight missions at S-band, Ku-band, and Ka-band.

An important advantage of the THz wireless system is the potential low complexity system design with the simplest modulation schemes coupled with the multiple GHz channel bandwidth to achieve the multi-gigabit throughput performance. This simple system architecture could have a comparative advantage to the traditional spacecraft S-band, Ku-band, and Ka-band systems that use high complexity radio architectures to achieve high data rate due to limited available channel bandwidth. The small form factor and light weight nature of the THz radio and antenna could be attractive to the NASA human space exploration applications.

The spacecraft Radio Frequency Interference (RFI) could be a challenge for space flight missions involving multiple spacecrafts such as the future commercial spaceflights to the International Space Station. The THz system could be used to mitigate the potential RFI for multiple spacecraft operations. Operation in THz spectrum with very few existing space systems could minimize operational constraints due to RF interference. The THz spectrum property provides inherent isolation from terrestrial RF systems (through atmospheric attenuation), thus eliminating the potential RF interference from the ground systems.

A. *Antenna Technology Challenge*

In the THz systems, antenna is an important component affecting the system performances and required link budget. This is because the free space propagation loss is very high at THz frequencies. The system link budget could be improved by a high gain antenna, such as an array or reflector antenna. A high gain antenna could also ease the requirements for the low-noise amplifier and bandpass filter.

System planning for THz radio must take into account the propagation characteristics of the THz signals at this frequency band. While microwave radio systems can be used for very long distance communications, THz signals can travel much shorter distances due to the higher free space propagation loss. The higher space loss of THz system has to be compensated in the link design. Figure 3 shows the Free Space propagation loss at frequencies from microwave to THz. For every octave increase in frequency, the propagation loss increases by 20 dB. As a result, the propagation loss at 1 THz is 60 dB higher than that at 1 GHz. Note that even for short distance communication of 100 m, the free space loss can be very high (132 dB at 1 THz) for the THz system. This indicates that for the practical applications of the THz radio system, high gain antenna will be required even for the short range communications links.

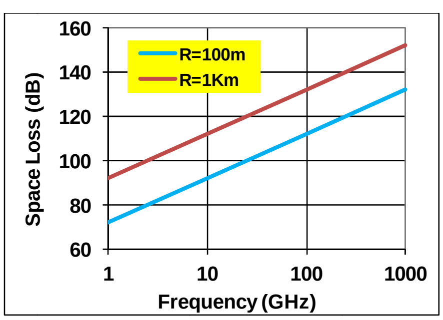

Figure 3. Free space propagation loss versus frequency.

A state-of-the-art antenna technology at THz frequency could reduce the cost of design and improve the system performance. The achievable data rates in couple with practically feasible sized high gain antennas should be analyzed for system feasibility study. The higher antenna gain increases the system capability. However, the narrower antenna beamwidth could also be technically challenging for the applications requiring precision antenna tracking and pointing. The antenna beamwidth is 1.7 degrees for a 40 dB antenna. The antenna beamwidth decreases to 0.105 degree for a 70 dB antenna. Thus, the antenna tracking and pointing accuracy requirements will be higher for the high gain antenna.

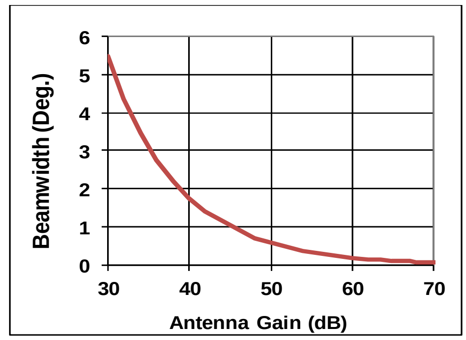

Figure 4. Antenna half-power beamwidth versus antenna gain.

Since the wavelength of the THz-band antenna is in the sub-millimeter range, a high gain antenna could be designed with a compact sized aperture, which is typically required for the spacecraft applications. Recently, a wideband and high gain reflector antenna system was introduced [11]. The design was based on a reflector antenna system with a 20 cm diameter dish centrally fed by a broad band lens antenna. The simulation results show a 60-65 dB gain is achieved at frequencies between 1 and 2 THz with the proposed design. A mechanically scanned confocal ellipsoidal reflector antenna system was reported [12]. The simulation results show to achieve 75 dB gain at 0.67 THz with a 1 m diameter dish.

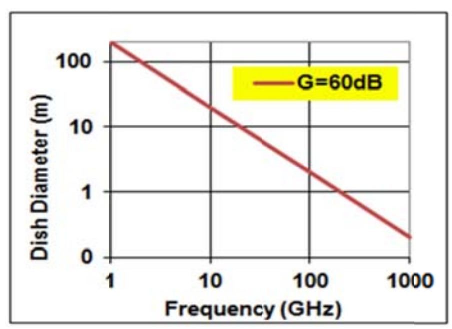

Figure 5. Reflector antenna diameter versus frequency.

Figure 5 shows the required reflector antenna diameter versus frequency to achieve a 60 dB gain based on the reference design reported in [11]. At 10 GHz, a 20 m dish is required to have 60 dB gain. At 100 GHz, the dish size reduces to 2 m. At 1 THz, 0.2 m dish could achieve 60 dB gain. The THz radio system has an advantage for compact sized high gain antenna design. However, technical challenges still exist in the practical THz antenna system design and fabrication.

Recently, a breakthrough on nano phased array (NPA) design was reported [13]. It demonstrated a large-scale two-dimensional array antenna in which 64×64 (4,096) elements are densely integrated on a silicon chip with all of the nanoantennas precisely balanced in power and aligned in phase to generate a designed, sophisticated radiation pattern in the far field. A phased array antenna could electronically steer the antenna beam at the target with high precision, which is an advantage over the conventional reflector antenna. This technology breakthrough could greatly increase the THz system applications in the future for non point to point fixed wireless network.

II. Spacecraft Link Analysis

Wireless communication is an enabling technology for both manned and unmanned spacecraft; it enables un-tethered mobility of crew and instruments, increasing safety and science return, and decreasing mass and maintenance costs by eliminating cabling.

Terahertz wireless system links for potential space applications are theoretically analyzed in this section. The wireless link is assumed to have an additive white Gaussian noise (AWGN) channel. In such an AWGN channel the theoretical maximum data rate is defined by its capacity which can be calculated with the Shannon formula

$$C=B\log_2(1+SNR) \qquad (1)$$

where SNR is the signal-to-noise ratio and B is the available bandwidth in the channel. The noise power can be calculated from the thermal motion of the charges in the receiver. The additional noise due to the non ideal receiver is defined by the noise figure F. Hence, the signal-to-noise-ratio is

$$SNR=P_r/(FkTB) \qquad (2)$$

where P_r is the received power, k is the Boltzmann constant, and T is the ambient temperature. According to the Farri free-space path-loss model, the received power is

$$P_r = P_t\, G_t\, G_r\, L_s \qquad (3)$$

where P_t is the transmitted power, G_t and G_r are antenna gain for transmitter and receiver, and L_s is the space loss. Therefore, with (2) and (3) in (1) we can calculate the maximum achievable data rate for the proposed wireless THz links. Note that this maximum data rate is the theoretical upper limit. The following parameters were assumed in the following data rate calculations. The frequency is 0.5 THz (500 GHz); the bandwidth is 10 GHz or 50 GHz; the transmit power is 10 mW or 1 W; the noise figure is 10 dB; the ambient temperature is 300 K.

A. Interior WLAN

Due to the atmospheric attenuation of THz signals, the practical THz indoor communication distances are limited to 50 meters. Since the diffracted fields or creeping wave at THz frequency are insignificant compared to microwave signals, THz signals could not overcome the structure blockage. THz systems would require line of sight operations between transmitter and receiver. Crews moving in the module could block and disrupt the communication links.

A THz wireless system could provide Gbps high data rate WLAN services to the crew modules of the Space Station, as shown in Figure 6 [14]. A 10 dB additional path loss due to the atmospheric attenuation is assumed for the 0.5 THz signals traveling a 10 m distance.

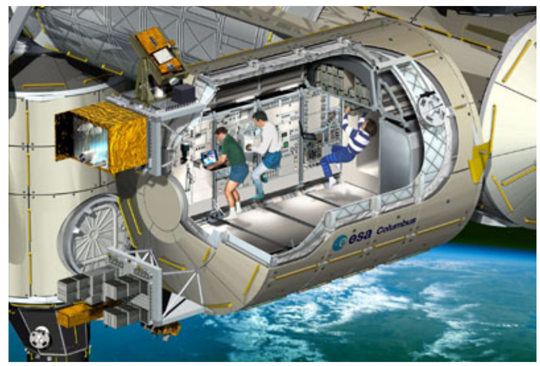

Figure 6. Interior WLAN applications inside a module.

Figure 7 shows the achievable data rate versus required antenna gain for 10 m range interior WLAN applications. A 30 dB gain antenna is needed to compensate for the free space path loss and atmospheric attenuation. The data rate increases with the allocated bandwidth as well as the noise. From (1) the receiver power and the maximum achievable data rate can be calculated. A maximum data rate of 55 Gbps is achieved with a moderate 30 dB gain antenna and 10 mW transmit power, as shown in Figure 7. The rate could be higher with higher channel bandwidth and higher gain antenna, as shown in Figure 8.

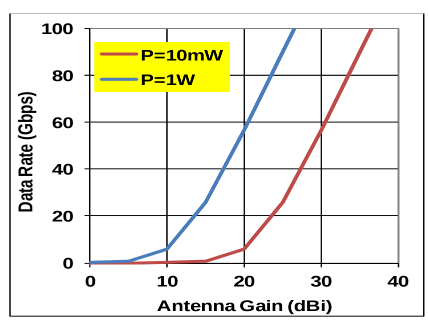

Figure 7. The maximum achievable data rates for the interior WLAN applications with 10mW or 1W transmit power.

This high gain antenna requirement for the THz system is quite different from the conventional 2.4 GHz and 5.8 GHz indoor WLAN systems on the ground. The microwave

WLAN on the ground is typically equipped with low gain and broad beam monopole or patch antennas. This is because the propagation loss and atmospheric attenuation at 0.5 THz is 40-50 dB higher than the microwave WLAN at 2.4 or 5.8 GHz. The high gain antenna is required to compensate the loss in the link budget. As for most indoor applications, the signals could have a time delay in the indoor environment due to multipath. The data rate may be limited to avoid the intersymbol interference (ISI) between data received along the multiple propagation paths. Adaptive smart antenna system and modulation schemes could be used to mitigate the ISI concern. This sheet of dielectric reflectors may be used to improve indoor THz communications by providing alternative propagation paths for non line of sight links [15].

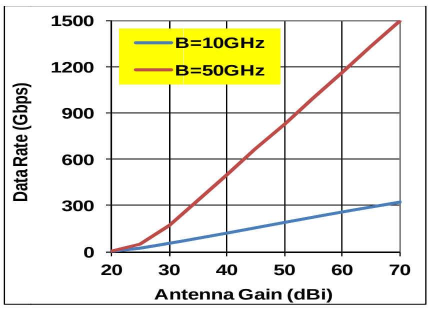

Figure 8. The maximum achievable data rates for interior WLAN applications with 10 and 50 GHz channel bandwidths.

B. *Planet Surface Applications*

High data rate wireless systems would support high rate science and public outreach applications such as real time hyperspectral imaging, radar, and high definition television [16].

The maximum achievable data rate for a range distance of 1 km for planet surface wireless communications is shown in Figs. 10 and 11. The transmitter and receiver antennas are required to have a gain greater than 40 dB to compensate the path loss to close the link budgets. The required antenna aperture size could be compact for the THz system, as shown in figure 12.

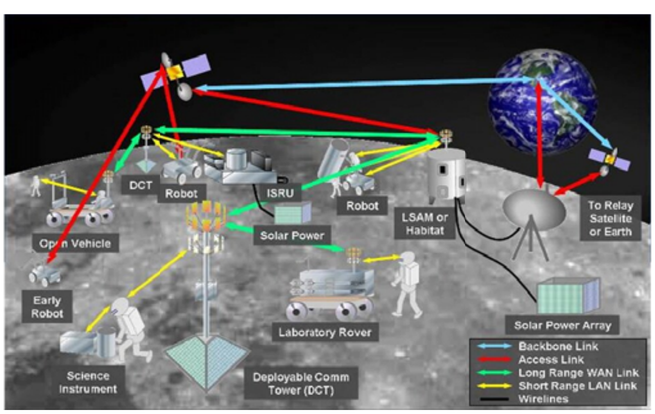

Figure 9. Surface communication network architectures for the future human space exploration missions [16].

At 20 GHz, a 40 dB antenna needs an aperture with a diameter of 2 ft. It could be only 2 inches for a frequency of 0.5 THz. The required antenna aperture size will be 1.2 m for a 70 dB gain at frequency of 0.5 THz based on the reference design [11,12]. The achievable data rate could be 100 Gbps or higher with a 5" diameter antenna with a 50 dB gain and a moderate 10 mW transmit power. The rate could be increased to 300 Gbps with 50 GHz channel bandwidth. This would not be possible for the conventional wireless systems at microwave frequency band.

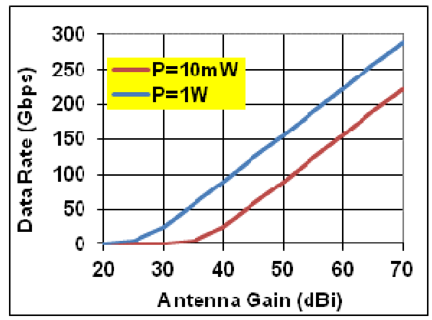

Figure 10. The maximum achievable data rates for the planet surface wireless applications with 10 mW and 1 W transmit power.

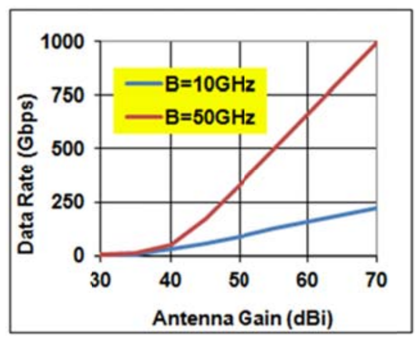

Figure 11. The maximum achievable data rates for planet surface applications with 10 and 50 GHz channel bandwidths.

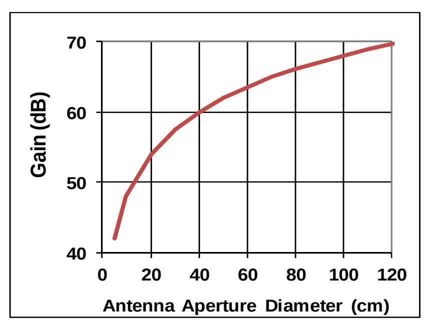

Figure 12. Antenna gain versus aperture size at 0.5 THz.

III. CONCLUSION

Terahertz wireless system links for potential interior WLAN and planet surface wireless communication applications were investigated. The results indicated that the maximum achievable data rate is more than 10 Gbps per 1 GHz channel bandwidth. High gain antenna is required to overcome the high space loss at THz band. High gain antenna could be compact size at THz band. It's a technical challenge for long range applications at THz band. In addition to high gain antenna, high power transmitters would be required for long range communications to be feasible.

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