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# ENABLING FREQUENCY-AGILE ULTRA-BROADBAND AIRBORNE NETWORKS IN THE THZ BAND

RESEARCH FOUNDATION FOR THE STATE UNIVERSITY OF NEW YORK

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FINAL TECHNICAL REPORT

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#### **1 SUMMARY**

The objective of this research is to develop the first network architecture and protocol stack to support ultra-broadband airborne networks in the Terahertz (THz) band (0.1-10 THz), by following a bottom-up approach and through a closed-loop combination of mathematical modeling, numerical simulation and experimental evaluation. During this five-month period, contributions have been made along two thrusts. First, the development of the Ultra-Broadband Networking Systems Testbed or UB NeST, i.e., state-of-the-art platform to test the performance and refine the networking solutions to be developed as part of this effort has been significantly advanced. Initial functionalities, including successful data transmission and reception with singlecarrier modulations following a time-division multiplex, have been demonstrated. Second, the concept of hierarchical bandwidth modulation, which can make the most out of the distancedependent bandwidth of the THz channel resulting from molecular absorption by water, which on its turn changes across altitudes, has been proposed. The modulator and demodulator blocks have been designed, and the achievable performance has been numerically investigated. The outcomes of this project will contribute to realize the vision of the Air Force Future Operating Concept, and are well aligned with the recent report by NIST on Future Generation Wireless Research and Development Gap.

#### **2** INTRODUCTION

Terahertz (THz)-band communication [1–5] is an emerging technology that can address three relevant challenges for the U.S. Air Force. First, THz-band frequencies (0.1 to 10 THz) remain almost completely unutilized for communication; hence, being the first to exploit this band provides an unmatched technological advantage. Second, the very high propagation loss at THz frequencies can be leveraged to create intrinsically secure air-to-air communication channels. On the one hand, the high spreading loss requires the utilization of ultra-directional systems, which enable ultra-low probability of intercept & detection (PI/PD) communications. On the other hand, atmospheric absorption at THz-band frequencies drastically limits the ability to intercept or disrupt air-to-air communications from ground systems, thus, further enhancing the security of the air-to-air links. Third, the THz band supports huge transmission bandwidths (from hundreds of GHz up to a few THz, depending on the transmission distance and medium composition). This enables wireless Terabit-per-second (Tbps) links and opens the door to transformative applications, such as in-air big-data sharing for real-time monitoring and control with unmanned aerial vehicle networks.

For many decades, the lack of compact high-power signal sources and high-sensitivity detectors able to work at room temperature has hampered the use of the THz band for any application beyond sensing. However, many recent advancements with different technologies is finally closing the so-called THz gap. In an *electronic approach*, the limits of standard silicon CMOS technology [6], silicon-germanium BiCMOS technology [7], and III-V semiconductor HEMT [8], mHEMT [9], HBT [10], and Schottky diode [11] technologies are being pushed to reach the 1 THz mark. In a *photonics approach*, uni-traveling carrier photodiodes [12], photoconductive antennas [13], optical downconversion systems [14] and quantum cascade lasers (QCLs) [15] are being investigated for high-power THz systems. More recently, the use of nanomaterials such as graphene is enabling the development of novel plasmonic devices for THz communications [16]. These devices are intrinsically small, efficiently operate at THz frequencies, and can support very large modulation bandwidths. Moreover, graphene is "just the first" of a new generation of 2D materials (such as MoS2 or Hb-N), which can be stacked to create new types of devices and leverage new physics.

In parallel to the development of new device technologies, there is a need to develop new communication and networking solutions which can reliably support wireless Tbps mobile networks. Existing communication algorithms and networking protocols cannot be simply reused, because many of the underlying assumptions in lower-frequency-band communications do not longer hold when moving to the THz band, especially those arising from the capabilities of THz devices and the peculiarities of the THz channel. For the last ten years, and with the support of the AFOSR (Award # FA9550-16-1-0188) and the AFRL (Award FA8750-15-1-0050), we have worked towards establishing the theoretical foundations of THz communications, by designing and developing innovative THz transceivers [17] and antennas [18], THz-band channel models [19–21], and new physical layer solutions (including modulation [22, 23], coding [24], synchronization [25, 26] and ultra-massive MIMO communications [27]) to support ultra-broadband THz links, even in the presence of multi-user interference [28, 29]. These works have been focused on short-range (under one meter) and medium-range (up to tens of meters) communications in indoor and outdoor on-the-ground scenarios with stationary nodes.

Starting from our aforementioned preliminary works as well as our NSF-funded state-of-theart experimental platform, the objective of this research is to develop the first network architecture and protocol stack to support ultra-broadband airborne networks in the THz band, by following abottom-up approach and through a closed-loop combination of mathematical modeling, numerical simulation and experimental evaluation. During this five-month-long reporting period, we have made the following contributions:

- We have advanced the development of the Ultra-broadband Networking Systems Testbed or UB NeST, by working towards the integration of the National Instruments (NI) 2-GHz digital baseband system of the X60 testbed [30] with the up and down converters to 1 THz in the TeraNova testbed [31].
- We have theoretically developed and numerically tested the performance of hierarchical bandwidth modulations, which can make the most out of the distance-dependent bandwidth of the THz channel resulting from molecular absorption by water, which on its turn changes across altitudes.

In the following sections, we provide more details of our progress in each of these thrusts.

#### **3 ULTRA-BROADBAND NETWORKING SYSTEMS TESTBED DEVELOPMENT**

#### 3.1 Methods, Assumptions and Procedures

To demonstrate the potential of THz-band communication for airborne networks and to validate the networking solutions developed as part of this effort, we are developing a unique experimental platform, namely, the Ultra-Broadband Networking Systems Testbed or UB NeST. The UB NeST will be the first software-defined-radio testbed in the world spanning the 60 GHz, 240 GHz and 1 THz bands, with baseband bandwidths ranging from 2 GHz to 32 GHz. This platform will be the result of integrating and enhancing two testbeds already available to the team, namely, the X60 testbed (NSF CRI Award CNS-1629929) and the TeraNova testbed (NSF CRI Award CNS-1730148), and increasing the capabilities through collaboration with VDI and the NASA JPL.

During this reporting period, the focus has been on integrating the NI 2-GHz baseband system in the X60 testbed with the 1-THz front-ends in the TeraNova testbed.



Fig. 1: Ultra-broadband Networking Systems Testbed.

#### 3.1.1 National Instruments 2 GHz Baseband System

The NI 2-GHz baseband system consists of two PXIe-1085 chassis, each housing 11 processing modules. Of these 11 processing modules, we have nine FPGA modules performing essential functions including modulation, demodulation, encoding, and decoding. Their functionality depends on the LabVIEW program implemented. The other three non-programmable processing modules implement Analog to Digital Conversion (ADC), Digital to Analog Conversion (DAC), Up and Down conversion. Communication between these modules is achieved using First In First Out (FIFO) memory blocks or Direct Memory Access (DMA) blocks.

The system blocks mostly affecting the capabilities are:

- **NI PXIe-3610:** The PXIe-3610 is a 14 bit DAC with a sampling rate of 3.072 GSa/s and can support 2 GHz bandwidth. At the transmitter, this module along with the PXIe-3620 acts as an arbitrary waveform generator.
- **NI PXIe-3630:** The PXIe-3630 is a 12 bit ADC with a sampling rate of 3.072 GSa/s and can also support 2GHz bandwidth. At the receiver, this module along with the PXIe-3620 acts as a digitizer.
- **NI PXIe-3620:** This module provides an IF interface operating in the range of 10.5 GHz to 12 GHz frequencies. The IF OUT port supports a linear power in the range -40 dBm to 7 dBm and the IF IN port supports -25 dBm to +20 dBm linear power. It is capable of working in a full-duplex mode with 2GHz of instantaneous bandwidth.
- NI PXIe-7902: The NI chassis has two NI PXIe-7902 modules, each housing Xilinx Virtex 7 485T FPGA, one acting as modulator and one as demodulator. The Modulator FPGA modulates the signal and sends it to the PXIe-3610 (DAC) for transmission, whereas the Demodulator FPGA demodulates the signal received from the PXIe-3630 (ADC). Currently, the system supports conventional phase and amplitude modulations, including BPSK, QPSK, 8PSK, 16QAM and 64QAM. Later in the project, these modules will be reprogrammed according to our newly designed modulations.
- **NI PXIe-7976R:** The NI chassis incorporates several NI PXIe-7976R modules, in charge of error control and any additional required digital signal processing. In terms of error control, Turbo Codes and Cyclic Redundancy Check are currently implemented. Additional signal processing might be related to, among others, the implementation of multi-carrier modulations including OFDM, which is part of this project too.

The control of the system and programming of reconfigurable modules (NI PXIe-7902 and -7976R) is performed through NI LabView.

#### 3.1.2 Up- and Down-converting System at 1 THz

We currently have access to an up-converter and a down-converter at 1 THz, which are utilized at the transmitter and the receiver respectively. On the transmitter side, an analog signal generator (PSG, Keysight E8257D) with very low root mean square (RMS) jitter (21 fs) is utilized to synthesize the Local Oscillator (LO) at a frequency between 41.67 GHz and 43.75 GHz. A Schottky-diode-based chain of frequency multipliers, custom designed by Virginia Diode Inc. (VDI), is utilized to upconvert the LO to the target radio frequency (RF) between 1 THz and 1.05 THz. A mixer based on the same technology is utilized to mix an Intermediate Frequency (IF) signal. The maximum input power at IF in the mixer is 0 dBm and the maximum output power is -15 dBm or 30  $\mu$ W. On the receiver side, a second PSG and a frequency multiplier chain with mixer based on the same technology is utilized to generate the LO frequency and RF carrier, respectively, needed to down-convert the received RF frequency to IF band. Furthermore, for transmitting and receiving the RF signal, two directional diagonal horn antennas (by VDI) are utilized. Both antennas exhibits 26 dBi gain and 10 degree angle half-power bandwidth at the 1 THz design frequency. Coaxial

(2.4 mm male to male) and RoHS (restriction of hazardous substances) compliant cables are utilized to interconnect the different testbed elements.

#### 3.1.3 Interconnection of the two Systems

The following hardware and software modifications have been implemented (Figure 1). On the transmitter side, the NI LabView software project has been modified for the NI baseband to output the IF signals through the NI PXIe-3610 and the output of the NI PXIe-3620 has been interfaced with the VDI mixer. On the receiver side, the VDI mixer output has been connected to the NI PXIe-3630 and the software has been modified accordingly to process the received signals at IF.

#### 3.2 Results and Discussion

Currently, 2-GHz-wide signals following a TDMA scheme are transmitted and received. The system uses a 10 ms frame with 100 slots. Each slot is 100  $\mu$ s long and contains 150 blocks. Different blocks can serve different purposes, including synchronization, channel estimation and uplink and downlink data (the current system is half-duplex only). At the time this report is written, successful data transmission has been accomplished utilizing single-carrier modulations (see Figure 2), but only for the data slots transmitted immediately after a synchronization slot (Figure 3). We are currently exploring the trade-offs between synchronization, channel estimation and data-slots.



Fig. 2: Successful data blocks transmission following a synchronization block.



Fig. 3: Periodic successful and unsuccessful blocks transmission within one frame.

#### 4 HIERARCHICAL BANDWIDTH MODULATION DESIGN

#### 4.1 Methods, Assumptions and Procedures

The peculiarities of the THz-band channel [19] motivate the development of new modulation schemes. While traditional modulations (e.g., m-PSK, m-QAM) can be utilized, these cannot make the most of the unique behavior of the available bandwidth at THz frequencies. More specifically, in airborne networks, the available bandwidth changes with both the distance between the transmitter and the receiver as well as their absolute and relative altitude. This phenomenon leads to different types of communication links, including, *horizontal links* between planes at the same altitude and *vertical links* between planes at different altitudes. Therefore, in order to maximize the utilization of the air-to-air channel, distance- and altitudeadaptive dynamic-bandwidth modulations are needed. During this reporting period, we have established the fundamental theoretical basis of hierarchical bandwidth modulations. Partially related to the concept of hierarchical or concatenated modulations [32], the fundamental idea in this case is to embed multiple binary information streams on the same carrier signal while adjusting the symbol time according to the available bandwidth. Hierarchical modulations are traditionally used in video transmission over the air, as a way to guarantee that receivers with different capabilities and channel conditions can display the content to the best of their resources. In our case, not only the modulation order can be adapted to the received signal strength, but, more importantly, the symbol transmission rate is set in light of the available

bandwidth.

Next, we describe the modulator and demodulator designs and provide preliminary performance results.

#### 4.1.1 Modulator and Demodulator Block Diagrams

The conceptual block diagram of the hierarchical bandwidth modulator is shown in Fig. 4. The figure depicts an M-level modulator in which a QPSK modulation is chosen to be the base layer modulation and  $r_1 > r_2 > r_3 > ... > r_M$ , where  $r_i$  is the distance between the transmitter and the *i*th receiver.



Fig. 4: Block diagram for the hierarchical bandwidth modulator.

The outputs of the first block are the I and Q components of the base modulation, which are held constant for a total symbol time of  $m_1T_s$ , where  $m_1$  is an integer and  $T_s$  is the inverse of the bandwidth available at the closest receiver. The second mapping block further modulates the I and Q components according to the second level of information. In other words, each QPSK symbol is further mapped to a local QPSK modulation. In this case, the information bits are held for a total symbol time of  $m_2T_s$ . Note that,  $m_1$  must be an integer multiple of  $m_2$ . This is applied successively until the highest level modulation, M, whose symbols are held only for Ts. For a fixed transmission power, the fact that higher level modulations are held for shorter times results into a lower transmission energy per bit Eb. However, over the shorter distances

at which these symbols are expected to be received, the channel path-loss is lower, which results in still high  $E_b N_0$  values at the receiver.

On the receiver side, as shown in Fig. 5, the first step is to estimate the bandwidth  $\frac{1}{78}$  of the

received signal, which in the simplest case could be done by means of a training pulse sequence. Based on the estimated factor  $m = T_s/T_s$ , the received signal is then demodulated as a  $4^{(M-m+1)}QAM$  at  $a\frac{1}{mT}$  rate. A traditional M-level hierarchical modulator maps all the layers at the

same rate that is suitable for the farthest receiver. In the considered scenario, this rate would be

$$\frac{1}{MT_s}$$
, where  $\frac{1}{T_s}$ 

is the rate available for closest receiver. On the receiver side, the demodulator would estimate the bandwidth  $\frac{1}{T_s}$  to get an estimate of the distance ( $m = T/T_s$ ) and in turn to decide on the demodulator

 $(4^{(M-m+1)}QAM)$ . However, the symbol duration would still be  $MT_s$  for all of the M receivers.



Fig. 5: Block diagram for the hierarchical bandwidth demodulator.

#### 4.2 Results and Discussion

We next numerically illustrate and analyze the performance of hierarchical bandwidth modulations. The carrier frequency is chosen to be 1.025 THz. Considering that the channel bandwidth is chopped almost to half from 1 m to 30 m distance, we place two receivers at distance 1 m and 30 m. The bandwidth available at the closer and farther receivers is 92 GHz and 45 GHz respectively. We set the transmission power to 1 mW, in light of the existing compact THz sources at room temperature. We consider the transmitter and the receiver to be equipped with directional antennas with 30 dB, which enable meeting the SNR requirement at the furthest receiver. The THz channel is numerically implemented by following our model in [19].

In Fig. 6, we illustrate the time and frequency domain representation of the transmitted signal, the received signal at 1 m and the received signal at 30 m, respectively. From this figure, it is clear that not only the received signal power is much lower, but its bandwidth has been drastically reduced. This is due to the high frequency components being chopped by the molecular absorption of THz channel. This phenomenon is clearer from the frequency domain plot of the signals in fig. 6d, 6e, and 6f. As a result, the user at 30 m distance can not receive the enhancement layer information, rather bound to demodulate the base layer information at rate $\frac{1}{2}$ .

The symbol error rate (SER) for the closer and the farther users are shown in Figure 7 as function of the SNR for farther receiver. It is relevant to note that, when the SNR requirement for the farther user is met, it is also being met for the closer user. As can be seen from this figure, the closer receiver has no error until the SNR for farther receiver goes as bad as -6 dB which would never be the target. To see this better, the received constellation diagrams at the closer and farther receiver is shown in Fig. 8a and Fig. 8b respectively for an SNR of 18 dB at the farther node.

For the full detailed analysis, we point the reader to our work in [33]. Our next steps involve the implementation of this modulation and testing in the experimental platform described in Sec. 3.



Fig. 6: Time and frequency domain plot of the transmitted signal, received signal at 1 m and received signal at 30 m.



Fig. 7: SER of both closer and farther receiver as a function of SNR of farther receiver.

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Fig. 8: Received constellations.

#### **5** CONCLUSIONS

THz communications will contribute to realize the vision of the Air Force Future Operating Concept in different ways [34]. On the one hand, the addition of a new spectral band can relieve the overcrowded spectrum at lower frequencies and, thus, increase the performance of legacy systems. On the other hand, THz communication enables new high-bandwidth applications that are not feasible with current narrow-band wireless technologies, such as inair big-data sharing among networks of unmanned aircrafts for real-time monitoring, decision and actuation. Ultimately, this will help to diversify the portfolio of capabilities needed to achieve operational agility. Beyond the US Air Force, and as highlighted in the recent report by the National Institute of Standards and Technology (NIST) on Future Generation Wireless Research and Development Gap ([35], Section 2.2.2, Higher Frequencies), *future generation networks will need to leverage higher frequencies (above 6 GHz and up to THz) in conjunction with existing technologies (below 6 GHz) in order to meet the performance expectations of seamless user connectivity, improved speed, and ultra-reliability.* 

Within the first five months of the project, the focus has been on developing the experimental platform to be utilized for the testing and refinement of the new networking protocols for airborne THz networks as well as on the theoretical and numerical analysis of new modulations that can make the most of the THz channel and its distance-dependent bandwidth. Moving forward, contributions will be made along the theoretical design and experimental implementation and testing oftailored

networking protocols for mobile airborne THz communication networks.

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#### 7 LIST OF ACRONYMS

ADC	Analog to Digital Converter
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AWG	Arbitrary Waveform Generator
BiCMOS	Bipolar CMOS
BPSK	Binary Phase Shift Keying
CMOS	Complementary Metal-Oxide-Semiconductor
CCF	Computing and Communication Foundations
CNS	Computer and Network Systems
CRI	Computer and Information Science and Engineering Research Infrastructure
DAC	Digital to Analog Converter
DMA	Direct Memory Access
DSO	Digital Storage Oscilloscope
FPGA	Field-Programmable Gate Array
Hb-N	Hexagonal Boron Nitride
HBT	Heterojunction Bipolar Transistor
HEMT	High-Electron-Mobility Transistor IF Intermediate Frequency
LO	Local Oscillator
mHEMT	Metamorphic High-Electron-Mobility Transistor
MIMO	Multiple-Input Multiple-Output
MoS2	Molybdenum disulfide
NASA JPL	National Aeronautics and Space Administration Jet Propulsion Laboratory
NI	National Instruments
NSF	National Science Foundation
OFDM	Orthogonal Frequency-Division Multiplexing
PSK	Phase Shift Keying
PXIe	Peripheral Component Interconnect eXtensions for Instrumentation
PD	Probability of Detection
PI	Probability of Intercept
PSG	Performance Signal Generator
QAM	Quadrature Amplitude Modulation
QCL	Quantum Cascade Laser
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SER	Symbol Error Rate
SNR	Signal-to-Noise Ratio
TBPS	Terabit-per-second
TDMA	Time-Division Multiple Access
USAF	United States Air Force
VDI	Virginia Diodes Inc.