Hyper-Spectral Communications, Networking & ATM as Foundation for Safe and Efficient Future Flight: Transcending Aviation Operational Limitations with Diverse and Secure Multi-Band, Multi-Mode, and mmWave Wireless Links: Project Overview, Aviation Communications and New Signaling

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***Abstract*—NASA's Aeronautics Research Mission Directorate (ARMD) has recently solicited proposals and awarded funds for research and development to achieve and exceed the goals envisioned in the ARMD Strategic Implementation Plan (SIP). The Hyper-Spectral Communications and Networking for Air Traffic Management (ATM) (HSCNA) project is the only University Leadership Initiative (ULI) program to address communications and networking (and to a degree, navigation and surveillance). This paper will provide an overview of the HSCNA project, and specifically describe two of the project's technical challenges: comprehensive aviation communications and networking assessment, and proposed multi-band and multi-mode communications and networking. The primary goals will be described, as will be research and development aimed to achieve and exceed these goals. Some example initial results are also provided.**

Keywords—aeronautics, air traffic management, aviation communications, networking

I. Introduction

Aviation is growing rapidly, and authorities worldwide are investigating new technologies and techniques that will be required for future safe and efficient operation. The National Aeronautics and Space Administration (NASA) is one of the leading organizations involved in this work in the United States. To this end, NASA recently issued research awards for its University Leadership Initiative (ULI), in which university-led teams have proposed visionary research and development for improving multiple facets of aviation, aimed at the time period through the year 2035 [1].

By a number of measures, civil aviation link and network capacity is—or very soon will be—severely limited. Research into new aviation communications techniques has been active for over a decade, e.g., [2]-[4], but continues today, and is becoming more urgent. According to the NASA Aeronautics Research Mission Directorate's (ARMD's) Strategic Implementation Plan (SIP) [5], the large number (and types) of links used throughout aviation likely do not possess the diversity, reliability, or security required for a future airspace that will be more dense and more complex than ever before, with both piloted and unmanned aircraft systems (UAS). This pertains to communications (and associated navigation, surveillance) both above the earth for aircraft aloft, and at airports. Airports specifically may be considered "aviation system nodes," or "air traffic management (ATM) system nodes," where dense concentrations of communications applications exist for a variety of user communities, including for example air traffic control, airline operations, catering, baggage handling, airport security, airport authorities, etc.

To address these issues and lay foundations for a safer and more efficient worldwide aviation system, the ULI team led by the University of South Carolina will be conducting research across a range of areas within aviation communications and ATM. This project will address several areas within the ARMD's SIP [5].

The remainder of this paper is organized as follows: in Section II we describe the NASA ULI broadly, and provide a list of the five ULI projects. In Section III the overall HSCNA project is described, in the context of the SIP. This includes a brief description of all the project's technical challenges (TCs). Section IV provides a more in-depth discussion of two specific TCs: the comprehensive aviation communications and networking assessment, and the multi-band multi-mode aviation communications TC. Section V provides some example initial results, and in Section VI we conclude.

This work was supported by the National Aeronautics and Space Administration under Federal Award ID number NNX17AJ94A.

II. NASA's University Leadership Initiative

A. Overall ULI

The NASA ULI program comes under the Transformative Aeronautics Concept Program. This ULI program aims to "cultivate multi-disciplinary, revolutionary concepts to enable aviation transformation and harness convergence in aeronautics and non-aeronautics technologies to create new opportunities in aviation" [6]. The ULI is a new effort launched by NASA that is intended to be "less directive" than most recent NASA Research Announcements. The ULI approach is to let researchers explore their own well-defined technical challenges that must be overcome in order to meet key outcomes that help fulfill broadly defined ARMD Strategic Thrusts (STs).

The STs were actually derived from NASA ARMD analyses of global trends. The ARMD analyses identified what are termed "Mega-Drivers," which are believed will shape coming aeronautical research needs. These Mega-Drivers are as follows [5]:

- **Mega-Driver 1**, Global Growth in Demand for High-Speed Mobility: Reflects rapid growth in traditional measures of global demand for mobility.
- **Mega-Driver 2**, Affordability, Sustainability, and Energy Use: Presents severe challenges in maintaining affordability and sustainability.
- **Mega-Driver 3**, Technology Convergence: Points to convergence occurring in industry sectors such as materials, manufacturing, energy, and information and communication technologies that will transform aeronautical capabilities.

The ARMD SIP describes NASA's broad visions to improve aviation over the coming decades. It "encompasses a broad range of technologies to meet future needs of the aviation community, the nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation" [5]. The six STs within the SIP are as follows:

- *Strategic Thrust 1:* Safe, Efficient Growth in Global Operations
- *Strategic Thrust 2:* Innovation in Commercial Supersonic Aircraft
- *Strategic Thrust 3:* Ultra-Efficient Commercial Vehicles
- *Strategic Thrust 4:* Transition to Alternative Propulsion and Energy
- *Strategic Thrust 5:* Real-Time System-Wide Safety Assurance
- *Strategic Thrust 6:* Assured Autonomy for Aviation Transformation

Generally, ULI projects are structured with STs as the over-arching goals. These STs are supported by Research Objectives (ROs) that are outcomes of project Technical Challenges (TCs). Both ROs and TCs are specified by the university teams, whereas the STs are specified by NASA. The TCs are specifically linked to detailed project tasks.

B. ULI Projects

The NASA ULI selected five projects for support. These projects cover a variety of areas within five of the six STs. The following is a list of the selected project titles, along with names of project principal investigators, the STs that each project supports, and the NASA research center (RC) that is primarily responsible for working with the ULI project team.

1. Hyper-Spectral Communications, Networking & ATM as Foundation for Safe and Efficient Future Flight: Transcending Aviation Operational Limitations with Diverse and Secure Multi-Band, Multi-Mode, and mmWave Wireless Links, David W. Matolak, University of South Carolina (ST 1), Glenn RC
2. Adaptive Aerostructures for Revolutionary Civil Supersonic Transportation," Dimitris Lagoudas, Texas A&M Engineering Experiment Station (ST 2), Armstrong Flight RC
3. Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles," James Coder, University of Tennessee, Knoxville (ST 3), Langley RC
4. Electric Propulsion: Challenges and Opportunities," Mike Benzakein, Ohio State University (ST 4), Glenn RC
5. Information Fusion for Real-Time National Air Transportation System Prognostics under Uncertainty," Yongming Liu, Arizona State Univ. (ST 5), Ames RC

III. Overall HSCNA

The overall goals of the HSCNA project are to dramatically improve aviation link communication and networking performance by design and evaluation of novel communication techniques at the physical (PHY) layer, data link layer (DLL) and networking layer. The project will apply these techniques to detailed networking simulations and testbed prototypes, and the project team plans to build analytical, simulation, and measurement tools that will demonstrate significant gains to ATM capacity, efficiency, and resilience. The other investigators on the HSCNA project are Dr. Ismail Guvenc, of North Carolina State University, Dr. Hani Mehrpouyan, of Boise State University, and Benjamin Boisvert, of Architecture Technology Corporation.

The HSCNA project has created three Strategic Thrust Outcomes, denoted TOs [6]. These TOs are project-specific outcomes linked to ST1:

TO1: More robust, efficient, reliable, and secure aviation communication and networking.

TO2: An ATM system capable of handling *significantly* larger air traffic density (including UAS), with rapid and reliable, automated and collaborative air traffic control and management.

TO3: Highly efficient airport operations to remove delays, reduce costs, and increase situational awareness.

Beneath these TOs are the project ROs [6]:

RO1*: Develop strategies and CNS techniques* for increasing severely-limited aviation link and network capacity (TO2, also TO1);

RO2: *Develop strategies and CNS techniques* for enhancing severely-limited aviation link diversity, reliability, and security (TO1, also TO3);

RO3: *Develop strategies, CNS techniques, and comprehensive ATM simulations* for dramatically improving a current ATM system that will be severely inadequate for future air traffic density and complexity (TO2);

RO4: *Develop strategies and CNS techniques* for dramatically improving slow and inefficient airport operations, e.g., aircraft delays on runways, into and out from gates (TO3).

The technical challenges (TCs) the project team has developed to achieve these ROs are listed next. Longer descriptions appear in [7], and for TCs 1, 4, 5, and 6, in [8], [9], [10], and [8], respectively. In this list, after the TC number, the TC leader last names are indicated in parentheses:

- TC1 (Boisvert): development of *multi-band* networking Concept of Operations (ConOps) for multiple phases of flight and all communication link types and *modes*, e.g., air-ground (AG), air-air (AA), air-"anything" (air-X, or AX), etc.
- TC2 (Matolak): quantification of capacity/coverage/ performance of existing aviation (plus adjacent) frequency bands and technologies. Quantification of shortcomings and mid- to far-term (~2035) improvements, and assessment of growth potential.
- TC3 (Matolak): development of analysis/simulation software toolboxes and prototypes to assess adaptive link and network performance over multiple frequency bands with multiple communication modes in a *hyper-spectral* network.
- TC4 (Mehrpouyan): quantification of capacity/ efficiency gains of mmWave wireless airport subnetworks. Measurement and modeling of example channels and validation of prototype mmWave systems in example airport network operations.
- TC5 (Guvenc): development of novel jammer and unauthorized UAS detection/localization techniques to detect and track any unauthorized UAS or jammer that enters any restricted zone.
- TC6 (Boisvert): development of a realistic and comprehensive ATM simulation capability to assess gains of multi-band/multi-mode and mmWave networking in terms of data link performance per aircraft, supportable traffic density, multi-vehicle collaboration, and operational benefits.

Figure 1, from [7], illustrates the relationships among the strategic Thrust Outcomes, Research Objectives, and Technical Challenges.

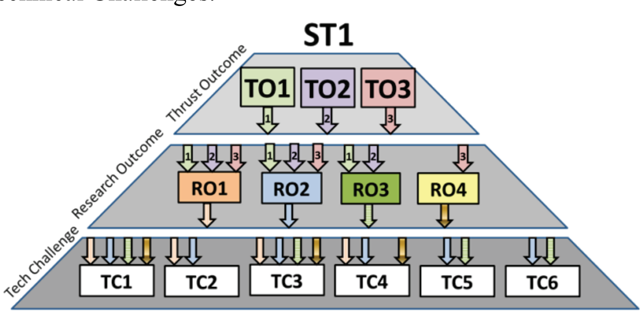

Figure 1. Mapping among strategic thrust outcomes (TOs), research objectives (ROs), and technical challenges (TCs), under Strategic Thrust 1, from [7].

IV. HSCNA Technical Challenges 2 and 3

The technical challenge number 2 is aimed at quantitatively assessing the current status of aviation spectral allocations and deployed communication technologies in those allocations, followed by identification of where and how improvements (in capacity, performance, etc.) can be made. This will be done from the physical layer (PHY) upward, and in conjunction with TC1. Technical Challenge 3 aims to employ results of TC2 and develop designs for both multi-band and multi-mode communication links that will support increased capacity and reliability of aviation networking. In the following sections we provide more detail.

A. *TC2: Aviation Communications and Networking Assessment*

Much in civil aviation communications lags behind current technology such as cellular radio and wireless local area networks. A prime example of this is the analog amplitude modulation (AM) employed for pilot-controller voice communication for air traffic control (ATC), and we elaborate further on this specific system via an example subsequently. In this technical challenge, we will be collecting information on all current and planned communication, navigation, and surveillance (CNS) systems applicable to civil aviation. The technical approach for this is straightforward for the information gathering and comparison construction portions. Example approaches we may follow include those in [11]-[13]. For the new system proposals, we will consider current (and planned, e.g., "5th-generation" cellular) technologies, existing aviation and other standards, plus revolutionary technologies, such as long-range free-space optical links [8]. We will assess potential link/system capacities, reliability, and role in the ConOps, while accounting for critical issues such as weather-induced trajectory deviations and link disruption recovery.

The proposed new systems will exhibit higher capacity, reliability, and expanded functionality (e.g., links used for communications *and* surveillance). Some example techniques to be investigated for improved new systems include use of spectrally, temporally, and spatially efficient modulations and advanced processing such as interference cancellation.

A long term goal is to also assess performance potential of truly revolutionary technologies. As previously noted, this includes the use of free-space optical wireless links, but also the following: a vast "Aeropedia[1]" aboard every aircraft; free and abundant energy sources for all aircraft; accurate and ubiquitous short-term numerical weather prediction, etc. These will be evaluated in terms of gains they can provide in ATM capacity, flexibility, and safety.

For an example illustration of analysis to improve system efficiency, we consider the analog AM voice communication system. Although inexpensive, the analog AM use of the very high frequency (VHF) band from 118-137 MHz could be

[1] By "Aeropedia" here we mean a comprehensive database of aviation and aeronautics related information usable by aircraft in ATM for CNS, which would contain, for example, information on ground sites and their locations and CNS capabilities, information on CNS capabilities of all known aircraft, all relevant flight regulations, etc.

made more efficient with modern multicarrier signaling, such as orthogonal frequency division multiplexing (OFDM) or filterbank multicarrier (FBMC). The former has been proposed for example in the L-band digital aeronautical communication systems, L-DACS1 [14].

Analog AM has a minimum signal to noise ratio (SNR) of approximately 10 dB due to the AM threshold effect [15]. With modern digital signaling, and forward error correction (FEC) coding, very good voice quality can be obtained with an SNR several dB less than this value. This reduced required SNR could either be used to increase range, or preferably, to lower transmission power levels—balanced of course with the need for pilot situational awareness as well as link closure margin. In either case this would improve system energy efficiency.

Also of interest is spectral efficiency. Based upon a 25 kHz VHF channel bandwidth, digital modulations could be used to improve spectral efficiency. If for example, a high quality voice encoder (vocoder) of bit rate approximately 6 kbps were employed with rate-1/2 FEC coding, the bit rate for a single user would be 12 kbps. Via well-designed FBMC filtering, using QPSK modulation, a subcarrier of 6 kHz width could be used to accommodate four users instead of one within a single 25 kHz channel. If higher order modulation such as 16 QAM are used—at least for shorter-range links with higher SNR—the per-user symbol rate for this example vocoder and FEC rate would be approximately 3 kHz, enabling up to 8 voice channels in the single 25 kHz allocation. The number of users per channel, N, is given by

$$N = \lfloor 25{,}000 / R_s \rfloor, \quad (1)$$

where R_s is the modulation symbol rate and $\lfloor \cdot \rfloor$ denotes the floor function, the largest integer less than or equal to the quantity inside. Additional examples appear in Table I, in which the basic vocoder rate is assumed to be 6 kbps, with R_b denoting bit rate after FEC. High-quality vocoders with lower bit rates, and including error correction, are also available, and these could be investigated to further increase VHF channel capacity.

We point out that this is of course a very preliminary set of results, and several other issues would require investigation before any implementation. One of these issues is Doppler shifts. For a civil aircraft traveling at a near maximum speed of 550 mph (222 m/s), at f_c=130 MHz, the Doppler shift is approximately 105 Hz. This is approximately 5% of the lowest symbol rate of 2 ksps in Table I, and this could be near tolerable limits.

TABLE I. SPECTRAL EFFICIENCY EXAMPLES FOR 25 KHZ CHANNEL

Modulation	FEC Rate	FEC R_b (kbps)	Rs (ksps)	# users/channel
AM	—	—	—	1
QPSK	1/2	12	6	4
QPSK	3/4	8	4	6
16 QAM	1/2	12	3	8
16 QAM	3/4	8	2	12

These two performance metrics—energy efficiency and spectral efficiency, are just two system characteristics that will be investigated. Other metrics include reliability, latency, and security.

B. *TC3: Multi-band & Multi-mode Communications & Networking*

The concept of multi-band communications is to simultaneously and/or alternately employ different spectral bands to achieve successful message transfer. Different frequency bands have different characteristics (attenuation, dispersion, available bandwidth, ambient interference, etc.), and knowledge of this can be employed judiciously to improve overall link and network performance. For example, the larger the difference in carrier frequency, the larger the differences in transmission characteristics, and these differences in transmission characteristics can be exploited to significantly increase the probability of successful message reception. The differences may also be used to adjust latency, reduce interference, or offload processing from congested links/bands, all of which improve overall network reliability.

Multi-mode communications here means communications among aeronautical and *non*-aeronautical entities. In addition to traditional aeronautical modes—air-ground, air-air, and air-satellite—aircraft may also connect to other platforms such as boats or trains, broadcast and public safety base stations, etc. The recent whitepaper by Uber, on their "Elevate" system [16], also incorporates multi-mode operation.

Work on this TC will explore designs for novel aviation communication links operating in a multi-band *hyper-spectral* multi-mode network, considering bands from HF to VHF to L-band, C-band, K-bands, mmWave bands, and higher. As noted in regard to TC1, existing and planned commercial technologies will be evaluated, as will military schemes and new state-of-the-art systems currently only in the conception stage.

Our work on multi-mode operation will address the improvement of network diversity as well as coverage. Initially we will analyze use of existing but non-aviation ground sites, then expand to other entities. For lower altitude operation, characterization of the AG channel will be especially important [18]: multipath propagation can become significant at lower altitudes. Figure 2, from [18], illustrates power delay profiles vs. link range for a C-band link in a near-urban environment. These profiles show the power in the AG channel impulse response versus delay in nanoseconds, over an approximately 0.5 km segment of flight. The link parameters are provided in [18], but the point here is that multipath components are prominent, time-varying, and may incur relatively long delays, all of which must be accounted for in physical layer link designs to ensure reliability.

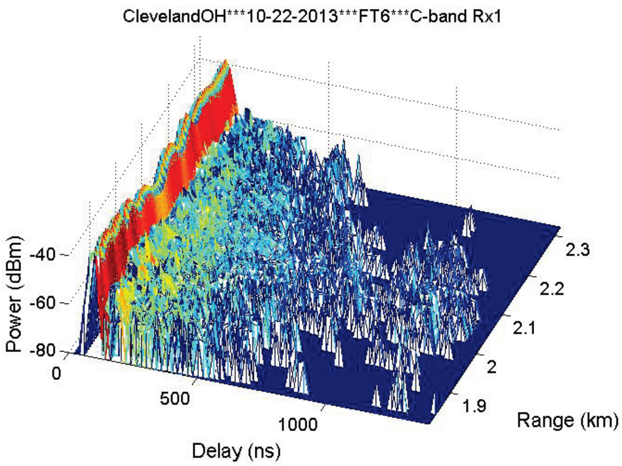

Figure 2. Sequence of power delay profiles for C-band AG channel in a near-urban setting, from [18].

The benefits of these new multi-band multi-mode networks, in terms of ATM capacity, flexibility, and efficiency, will also be evaluated via their incorporation into TC6 ATM simulations. We also plan development of a small UAS testbed with multiple networked UAS to validate some of our multi-band and multi-mode communication performance.

V. Example Results

For our initial example results here we consider the multi-band topic. We investigate the performance of a tri-band system using three aviation bands: the VHF band from 118-137 MHz, the L-band from 960-1164 MHz, and the C-band from 5030-5091 MHz. As noted, the VHF band is currently used for ATC voice communications, using 25 kHz channels (in some locations a further subdivision into 8.33 kHz channels is used). The L-band is used for aviation surveillance applications, including automatic dependent surveillance—broadcast (ADS-B), and the mode-S "secondary surveillance" radar transponders. This band also hosts military communication systems, and high-power ground-based distance measuring equipment (DME) [4]. The portion of C-band we employ has been allocated for UAS use.

We consider an AG link employing the three bands simultaneously, using a multicarrier transmission scheme FBMC [19]. The FBMC technique has been studied for some time, and is a contending scheme for some 5th generation cellular applications due to its extremely compact spectrum. Before specifically considering the FBMC aspects, we consider the actual AG channel effects. The scenario is shown in Figure 3. We assume the transmitter (Tx) is the ground site and the receiver (Rx) the aircraft (from the perspective of the channel this is immaterial).

Figure 3. Example communication scenario for tri-band AG FBMC links.

The link parameters are listed in Table II. The quantity L_{FS} denotes the free-space path loss or attenuation, and P_{Tx} denotes Tx power, P_{Rx} received power. Free-space path loss is given by

$$L_{FS} = 20\log_{10}\left(4\pi d f_c / c\right), (\text{dB}) \tag{2}$$

with d the link distance, f_c the frequency, and c the speed of light. Antenna gains are G_{Tx} and G_{Rx}. Higher-gain antennas are easier to deploy as frequency increases. The C-band antenna gains still correspond to moderate beamwidths of several tens of degrees, so we do not assume active beamforming here.

For these initial results we use the well-known "two-ray" (2R) channel, which consists of two components: the direct line of sight (LOS) component between Tx and Rx antennas, of length R_1, and the earth surface reflected component, of length R_2. We assume "broadbeam" antennas with identical gains for the 2R components at both Tx and Rx (it is easy to augment our analysis to generalize this). Each component itself incurs free-space path loss, and for our 2R path loss results we assume the earth surface is wet ground with surface height standard deviation 0.1 m. The 2R channel can be either a wideband or narrowband model, depending upon signal bandwidth and link geometry. Detailed computations for the 2R channel appear in [17].

TABLE II. Link Parameters for Tri-band Example.

Parameter	Frequency Band		
	VHF	*L*	*C*
P_{Tx} (dBm)	-20	0	10
f_c (MHz)	130	970	5000
G_{Tx} (dBi)	0	5	10
G_{Rx} (dBi)	0	5	10
L_{FS} at d=20 km (dB)	100.7	118.2	132.4
P_{Rx} at d=20 km (dBm)	-120.7	-108.2	-102.4

Pertinent link geometric parameters are the Tx and Rx antenna heights, h_T and h_R, respectively, and the link distance d. For our example we use h_T=20 m, and h_R=500 m. The well-known 2R channel attenuation, in linear scale, is given by

$$\ell_{FE2R} = \frac{(4\pi d / \lambda)^2}{4\sin^2\left(\dfrac{2\pi h_T h_R}{\lambda d}\right)}, \tag{3}$$

where in addition to identical antenna gains for the 2R components, a perfect reflection (reflection coefficient =-1) is assumed. Equation (3) is a very good approximation for small grazing angles that occur at large link distances, but is reasonably accurate even for moderate cases we consider here. In this equation, which neglects earth curvature, λ is the carrier wavelength, and subscript FE2R denotes the flat earth 2R model. Our work in [17] also incorporates earth curvature and earth surface roughness.

In Figure 4 we show 2R path loss vs. link distance from 1 to 20 km for our three frequency bands. Also shown is free-space attenuation for the VHF and L band frequencies for comparison. For the L-band case we also show the effects of earth curvature, which shifts the attenuation peaks along the distance axis. Although the attenuations follow those of free-space, the earth surface reflection yields significant variation. This is quasi-periodic via the sinusoid in (3), but the period varies with frequency and with distance for a given frequency. The relative free-space attenuation differs by approximately 17.5 dB between VHF and L-band, and by an additional 14.2 dB between L-band and C-band (so ~ 31.7 dB between VHF and C-band). Two ray attenuation peaks and nulls appear at different values of distance for the different bands, and in some cases, they may "counter-align," with the higher-frequency band exhibiting lower attenuation than that incurred in a lower frequency band, as happens here for the L- and C-band attenuations near d=16 km.

Also of potential interest in our studies for both reliability and capacity are diversity techniques such as spatial and frequency diversity. The 2R channel in particular provides some interesting behavior in this regard. Figure 5 shows a plot of the correlation coefficient between signals at two different frequencies in the L-band (received by the same antenna) as a function of link distance. This result pertains to an over-sea 2R link, with h_T=20 m, and h_R=792 m. The frequency separation is denoted Δf, and this correlation coefficient determines how similarly the channel affects the signals at the two frequencies: high correlation means very similar effects, whereas low correlation means distinct channel effects. Knowledge of this correlation can enable design of adaptive diversity techniques that can take advantage of this channel characteristic. Analysis and additional results on this phenomenon appear in [20].

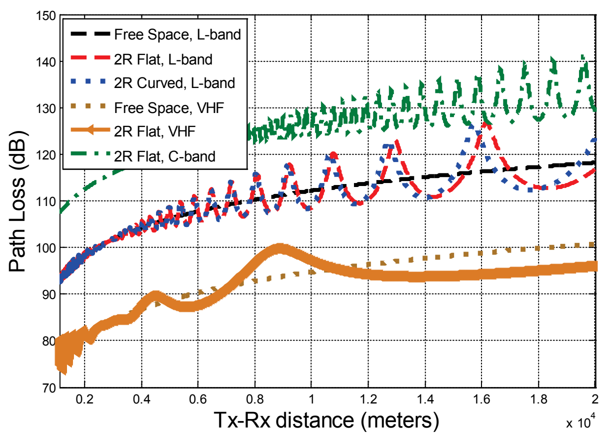

Figure 4. Two-ray channel path loss (dB) vs. link distance in meters, for the three frequency bands.

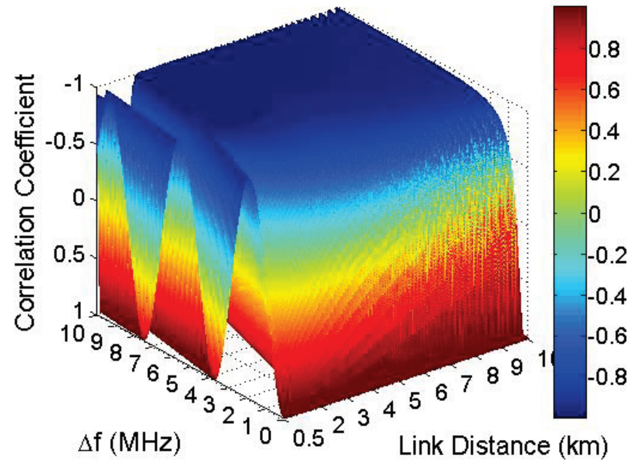

Figure 5. Cross correlation vs. Δf (relative to 968 MHz) vs. horizontal link distance (km), over-sea, h_T=20 m, h_R=792 m.

For our FBMC performance results we consider the tri-band spectral allocation depicted in Figure 6. We used the over-sea curved-earth 2R model from [17], which includes small-scale Ricean fading. Link parameters are those of Table II. For the FBMC multicarrier allocations we employ a VHF channel bandwidth of 25 kHz with 16 subcarriers, an L-band channel with 0.5 MHz bandwidth and 64 subcarriers, and a 5 MHz bandwidth C-band channel with 128 subcarriers. Resulting subcarrier spacings are 1.56 kHz, 9.76 kHz, and 39 kHz, and symbol durations are 2.56 ms, 409.6 µs, and 102.4 µs for VHF, L-band, and C-band channels, respectively.

Figure 7 shows the example bit error ratio (BER) versus link distance results for this case, using 64 QAM. Results are for uncoded modulation, and employ "instantaneous" Ricean fading, i.e., no averaging is done. The distance increment used here is 100 m. One can observe the 2R effects, primarily for the L-band results. These mimic results of the path loss in Figure 4, and would do so much more closely were averaging applied.

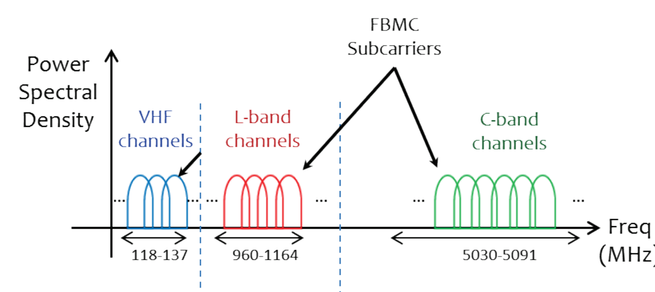

Figure 6. Filterbank multicarrier subcarrier spectral allocation for tri-band communication system example.

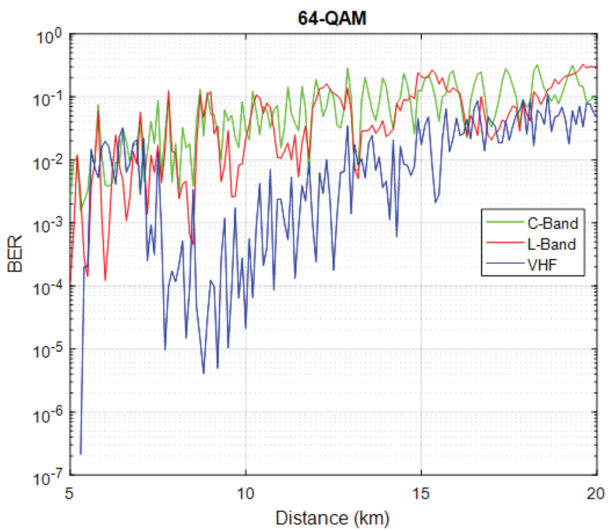

Figure 7. Tri-band example filterbank multicarrier uncoded bit error ratio (BER) vs. link distance (km) for an over-sea air-ground channel.

VI. Conclusion

In this paper we reviewed the structure and goals of NASA's University Leadership Initiative, driven by the Aeronautics Research Mission Directorate's Strategic Implementation Plan, in which university researchers set project goals to achieve Strategic Thrust Objectives laid out in the Strategic Implementation Plan. We then focused on the sole ULI project aimed at aviation communication and networking: the Hyper-Spectral Communications and Networking for ATM project. Two of the project's Technical Challenges were briefly described, and some example results for multi-band air-ground communications were provided.

Acknowledgment

The author would like to thank the NASA ULI program staff for their support. The author would also like to thank the project's co-investigators, Dr. Ismail Guvenc, North Carolina State University, Dr. Hani Mehrpouyan, Boise State University, and Paul Davis and Benjamin Boisvert of Architecture Technology Corporation. Finally, the author thanks his Ph.D. student Hosseinali Jamal for generating the FBMC simulation results.

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