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Preliminary Analysis of the Spectral Requirements of Future ANLE Networks

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Abstract

The Federal Aviation Administration (FAA) is considering the use of the 5091-5150 MHz band for a future Airport Network and Location Equipment (ANLE) system. ANLE is visualized as a high-integrity, safety-rated wireless local area network (WLAN) for the airport surface, with terminals on the ground and on taxiing aircraft. In this analysis, The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has identified potential classes of sensors and other fixed and mobile applications that may participate in such networks. We have derived approximate upper bounds on the aggregate data rates and total bandwidth requirements of those potential applications. These upper bounds will provide a basis for estimating the total amount of radio spectrum that may be needed by an operational ANLE system.

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1 Introduction

The 5000-5250 megahertz (MHz) frequency band is allocated to the aeronautical radionavigation service (ARNS) on an international basis. The Federal Aviation Administration (FAA) is considering the use of the 5091-5150 MHz subband for the future Airport Network and Location Equipment (ANLE) system. ANLE is visualized as a high-integrity, safety-rated wireless local area network (WLAN) for the airport surface, with terminals on the ground and on taxiing aircraft. Figure 1-1 illustrates an airport environment for a potential ANLE network. This figure indicates how ANLE could provide the means of transporting data for fixed and mobile users such as sensors, taxiing aircraft, and other vehicles on the airport surface.

Figure 1-1. Airport Environment for a Potential ANLE Network

The FAA office of Air Traffic Control (ATC) Spectrum Engineering Services has requested the MITRE Corporation's Center for Advanced Aviation System Development (CAASD) to identify potential classes of sensors and other fixed and mobile applications that may participate in such networks, and to estimate data rates and bandwidth requirements for those potential applications. In addition, MITRE/CAASD was requested to review recent field-test measurement results, in order to determine their impact on the ANLE link budgets and interference estimates that MITRE provided in 2005. This report presents the results of the effort.

2 Potential Applications of ANLE

Figure 2-1 shows potential application classes that could be supported by ANLE. These include:

- Sensor data
  - Surveillance data
    - Airport Surveillance Radar (ASR) data
    - Airport Surface Detection Equipment Mode X (ASDE-X) data from remote units (RU) to the multi-processor
    - ASDE-X display data
    - Digital Bright Radar Indicator Tower Equipment (DBRITE) data
  - Weather data
    - Low Level Wind Shear Alert System (LLWAS) data
    - Automated Weather Observing System (AWOS) / Automated Surface Observing System (ASOS) data
    - Terminal Doppler Weather Radar (TDWR) data
    - Integrated Terminal Weather System (ITWS) data
    - Weather Systems Processor (WSP) data
  - Navigation and landing aid data
    - Terminal Navigational Aids (NAVAIDS) data
- Automation data
  - Enhanced Traffic Management System (ETMS) data
  - Center-TRACON Automation System (CTAS) data
- ATC voice (diversity path as a backup for existing facilities)
- Electronic Flight Bag (EFB) data
- Airport surface data transmission to taxiing aircraft and surface vehicles

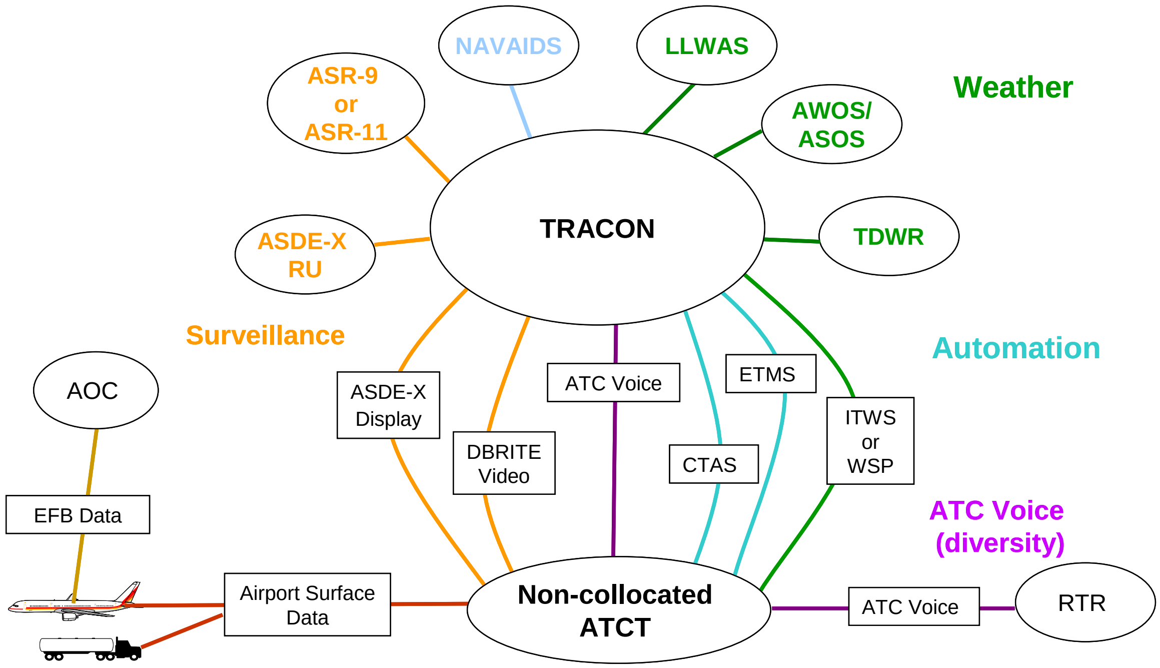

Figure 2-1. Potential ANLE Application Classes

Figure 2-1 shows an airport configuration with a Terminal Radar Approach Control facility (TRACON) and a non-collocated Air Traffic Control Tower (ATCT), which allows for the potential transmission of data between the two locations via the ANLE network.

This section discusses each one of these potential application classes that could be supported by ANLE. Data rate requirements for the various applications have been obtained primarily from references [1], [2], [3] and [4]. Reference [1] analyzed various types of applications at the Dallas Forth Worth (DFW) International airport. This airport has a special configuration with two ATCT towers that are separate from the TRACON. This doubles the amount of data rate transfer requirements between the TRACON and ATCT compared to an airport with only one non-collocated ATCT. Reference [1] also identified the numbers of stations required on the airport surface (at DFW) to support various types of fixed applications. These numbers will be airport-specific, but the large size of DFW allows us to regard the results derived from [1] as constituting an approximate upper bound on the expected number of fixed stations that might be served by ANLE at a single airport. Data from [4] was used to identify the maximum number of aircraft and surface vehicles that could be supported with ANLE mobile applications.

2.1 Potential Surveillance Data Application Classes

ANLE could potentially support the transport of surveillance data on the airport surface such as ASR data and ASDE-X RU data from the remote sites to the TRACON or ATCT. In the configuration shown in Figure 2-1, all the sensor data is transported to the TRACON [1]. ANLE could also transport ASDE-X display data and DBRITE data from the TRACON to one or more non-collocated ATCTs.

2.1.1 ASR Data

The ASR system provides medium-range (≈60 nautical miles radius) radar coverage of the airport vicinity. It provides primary radar information for ATC at the airport. The ASR-9 model is widely used at the busiest airports [5], [6]. The data rate requirement to transmit ASR-9 information to the TRACON is 62.4 kilobits per second (kbps) per radar [1]. Two ASR-9 radars are used at DFW [1].

The ASR-11 system [7], [8] consists of primary and secondary surveillance radars, monitoring equipment and interfaces to the TRACON and ATCT. The primary surveillance radar uses a continually rotating antenna mounted on a tower. The frequency range used by the primary radar is 2700 MHz to 2900 MHz. The secondary surveillance radar uses a frequency range of 1030 MHz to 1090 MHz. Data rates for the various interfaces are given in [3]. Data rate requirements will depend on the equipment and site configuration. Assuming that the radar site is away from the TRACON and that no fiber optics is available, five 56 kbps dedicated lines and three 19.2 kbps dial-up circuits are needed to transport the data from the radar site to the TRACON, for a total of 337.6 kbps. The DBRITE video system is used to transmit radar data between the TRACON and the ATCT. This system will be discussed in detail later in this section.

2.1.2 ASDE-X Data

The ASDE-X system provides air traffic controllers with aircraft and vehicle location on the airport surface. Figure 2-2 shows the block diagram of an ASDE-X system [9]. The main components are: the surface movement radar, the multilateration subsystem capable of receiving Automatic Dependent Surveillance – Broadcast (ADS-B) from equipped aircraft and ground vehicles, the multi-processor and tower displays [9]. The multi-processor performs the fusion of surveillance data from the various sources.

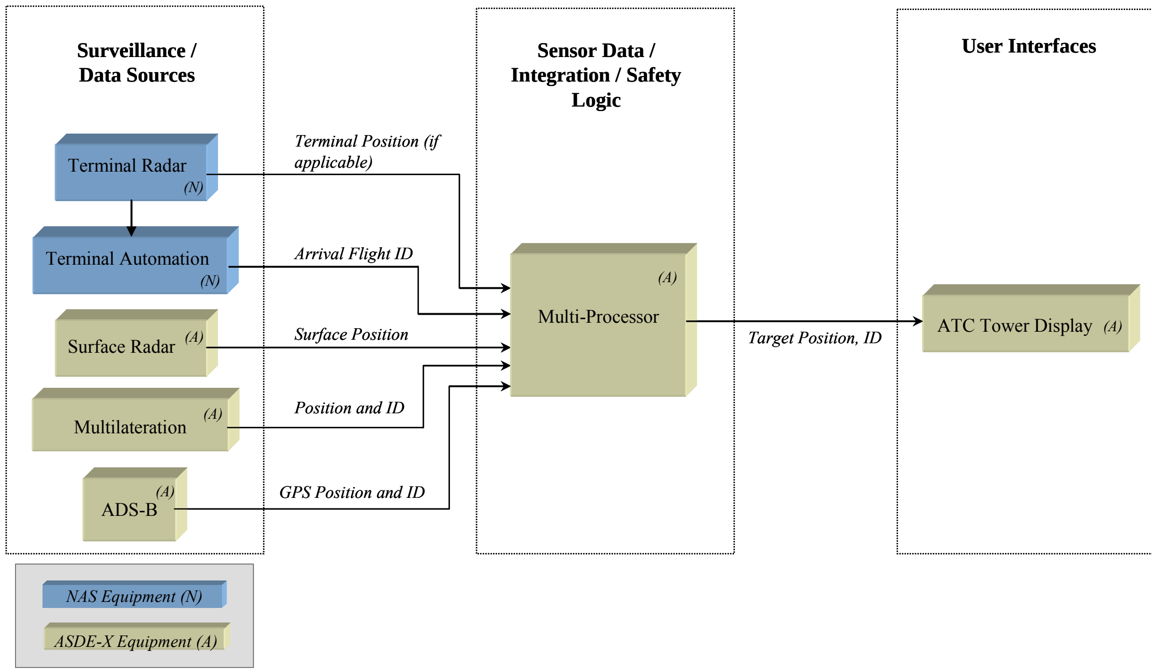

Figure 2-2. ASDE-X System Block Diagram

The multilateration subsystem provides position and identification information obtained from transponder-equipped aircraft and surface vehicles. The position information is obtained by using the time difference of arrival from transponder equipped targets after a signal is received by multiple remote units (RU). Each ASDE-X RU transmits information to a central location. The transmission data rate from the RU is 64 kbps [1]. The remote units are located on the airport surface so as to provide the requisite coverage and geometry for the multilateration function. The number of remote units is configuration-specific. For this analysis 10 RU are used [1].

A potential application for the ANLE network is to provide the transport of data from the ASDE-X RUs to the central location (which, for this analysis, is assumed located in the TRACON), using the ANLE base station (BS). This is illustrated in Figure 2-3.

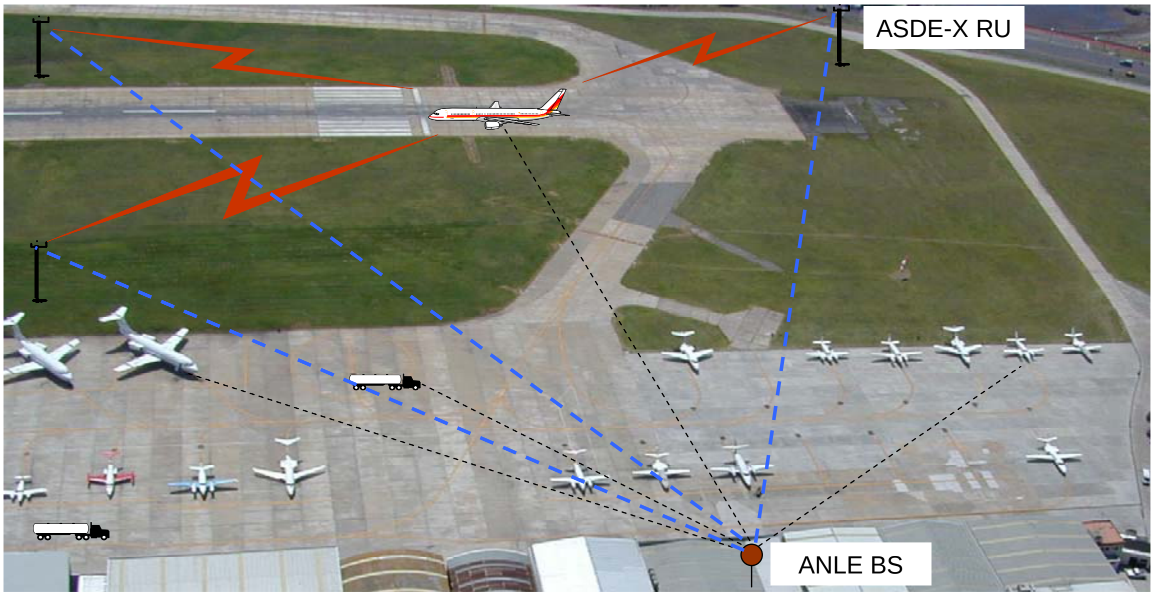

Figure 2-3. Potential ANLE Application for ASDE-X RU Data

The ASDE-X data from the multi-processor is transmitted for display at the ATCT and other (airline) displays. The required data rate for each display is 593 kbps [1]. Three display locations are considered in the analysis [1].

2.1.3 DBRITE Video System Data

The DBRITE video system provides wideband radar video and alphanumeric data from the TRACON to a remote ATCT. The system consists of a video compression unit, a video decompression unit, remote maintenance monitoring, and a tower display unit at the ATCT. The required data rate between the TRACON and ATCT is 1.544 megabits per second (Mbps) [3]. Four DBRITE connections are used in the analysis [1].

2.2 Potential Weather Data Application Classes

In this subsection, we examine weather data application classes that can potentially be supported by ANLE. ANLE could be used to transport sensor weather data, such as LLWAS, AWOS/ASOS, and TDWR data. In the configuration shown in Figure 2-1 all the weather data from the various sensors is transported to the TRACON [1]. ANLE could also transport ITWS or WSP display data between the TRACON and a non-collocated ATCT.

2.2.1 LLWAS Data

LLWAS is a network of wind sensors (anemometers) strategically located in and around an airport to measure the speed and direction of wind [10]. Data from wind sensors is transmitted to a master station. If microburst or wind shear conditions are detected, wind shear warnings and alerts are presented to controllers, who then issue warnings to pilots. Up to 32 LLWAS sensors can be located on the airport surface [11], [12]. The required data rate is 9.6 kbps/sensor [1], [13].

2.2.2 AWOS/ASOS Data

The AWOS system is a suite of sensors that collects and disseminates weather information [14]. The following types of data are measured:

- Wind speed, direction, and gusts
- Temperature and dew point
- Cloud height and coverage
- Visibility
- Present weather (rain, drizzle, snow)
- Rain accumulation
- Thunderstorms and lightning

An ASOS system has the same types of sensors as AWOS plus a freezing rain sensor [15]. A data rate of 19.2 kbps is needed to transmit AWOS/ASOS data to the TRACON [1].

2.2.3 TDWR Data

The TDWR system detects microbursts, gust fronts, wind shifts and precipitation intensity [16] and provides hazardous weather alerts in the terminal area. The system also provides a geographical situational display for traffic planning in the terminal area. Warnings are displayed on the ribbon display terminal. To transmit data from the radar site to the TRACON, multiple circuits with data rates of 4.8 kbps, 9.6 kbps and 56 kbps are used [1], for an aggregate data rate requirement of 175 kbps [1]. To support the generation of ITWS weather data, TDWR requires an additional data transmission capability of 1.544 Mbps [3], [17].

2.2.4 ITWS Data

The ITWS system uses data from several weather systems to produce weather products [2], [3]. The weather systems include:

- TDWR
- ASR
- LLWAS

- AWOS/ASOS
- National Lightning Detection Network

The ITWS system consists of a product generator, which processes all weather data, and situational displays. To display data to a remote ATCT situational display (from an ITWS system located in a TRACON), the required data rate is 256 kbps. As mentioned above, to support the ITWS product generator with TDWR data, an additional data rate of 1.544 Mbps is required for the TDWR to TRACON connection.

2.2.5 WSP Data

The WSP system processes data from ASR-9 and ASOS or LLWAS [3]. It displays weather conditions, forecasts gust front movements, and provides wind shear or microburst alerts at the ATCT and TRACON. The WSP system is used at airports with medium-density air traffic and exposure to thunderstorms or wind shear conditions. The required data rate from the WSP system to a display unit at a remote ATCT is 128 kbps [3]. Because the WSP application requires a lower data rate than ITWS, the analysis in this report uses the data rate requirements for an ITWS system instead.

2.3 Potential Navigation and Landing Application Classes

The potential use of ANLE to support the transport of data for control and monitoring of NAVAIDS is examined in this subsection. The NAVAIDS are monitored and controlled by the navigational monitor and control at the ATCT or TRACON.

NAVAIDS requirements vary with airport configuration. At DFW, the NAVAIDS are connected to the TRACON through fiber optics connections from NAVAID fiber optics shelters. Each NAVAID shelter is equipped with six 56-kbps channels (in addition to the NAVAID required channels) [1]. The aggregate required NAVAID data rate (including the six 56 kbps channels) is 767 kbps each for two NAVAIDS shelters, and 841 kbps each for the other two NAVAIDS shelters. Therefore the total aggregate required data rate for NAVAIDS is 3216 kbps, which is the value used in this report.

2.3.1 Instrument Landing System Data

The Instrument Landing System (ILS) equipment provides the pilot with an approach path aligned with the runway centerline. It consists of the following types of transmitters: localizer, glide slope, marker beacons, distance measuring equipment, and far field monitors [2]. Each element of the ILS system has connections to a link control unit (LCU) and a remote control and status unit (RCSU). These units allow for the control and monitoring of each subsystem. The data rates for the connections to LCU and RCSU are 2.4 kbps. There are also connections between the maintenance processor system and each element of the ILS system. The data rates for these connections are 19.2 kbps [1].

2.3.2 Runway Visual Range Data

The Runway Visual Range (RVR) equipment measures the visibility along the runway. There can be one to three RVRs at a runway. The data rate for the connection to the monitoring equipment is 19.2 kpbs [1].

2.3.3 Precision Approach Path Indicator Data

The Precision Approach Path Indicator (PAPI) systems consist of light units that provide visual descent guidance during non-precision approaches. The data rate for the connection to the monitoring equipment is 19.2 kbps [1].

2.3.4 High Intensity Approach Lighting System with Sequenced Flashing Lights Data

The High Intensity Approach Lighting System with Sequenced Flashing Lights is a visual guidance lighting system for category II/III runways. The data rate for the connection to the monitoring equipment is 19.2 kbps [1].

2.4 Potential Diversity Path for ATC Voice Application Classes

Data rate requirements needed to provide a diversity path for ATC voice transmission on the airport surface are presented in this subsection.

2.4.1 Diversity Path for ATC Voice to RTR

Remote Transmitters/Receivers (RTRs) are sites on the airport surface (remote from the ATCT and TRACON) that are used to carry critical ATC radio traffic between the ATCT/TRACON and pilots. The Low Density Radio Communications Link (LDRCL) provides microwave point-to-point communications between operational facilities, and is currently used at DFW for connections between the RTRs and the ATCTs [1]. At the interface between LDRCL and the RTR, the connection data rate is 1.544 Mbps [1]. The analysis in this report uses four RTR links, each having a data rate of 1.544 Mbps.

2.4.2 Diversity Path for ATC Voice between ATCT and TRACON

Our analysis also examines the supportability of a diversity path for ATC voice traffic between the TRACON and remote ATCTs on the airport surface. This analysis assumes four ATCT-to-TRACON links, each with a data rate of 1.544 Mbps [1].

2.5 Potential Automation Application Classes

Data rate requirements for the transport of automation data, such as ETMS data and CTAS data, between the TRACON and remote ATCTs are presented in this subsection.

2.5.1 CTAS Data

CTAS is planned as a set of tools to compute aircraft flight schedules and sequences in an ARTCC or TRACON using flight plans, aircraft characteristics, weather data, radar data and aircraft spacing rules [3]. CTAS currently consists of a Traffic Management Advisor (TMA) tool and a set of TMA displays at ARTCC, TRACON or ATCT. The data rate for a connection between CTAS and a remote TMA display is 512 kbps [1].

2.5.2 ETMS Data

The ETMS system provides national traffic management services such as:

- Flow sequencing of aircraft in controlled airspace
- Monitoring of current traffic flow
- Traffic management restrictions and delay advisories

ETMS obtains flight data from the host computers at each Air Route Traffic Control Center (ARTCC) processes this data at the ETMS traffic management computer complex, and then distributes Traffic Situation Display data to ETMS workstations located at ARTCCs, TRACONs, ATCTs, and other facilities [3]. All sites use 256 kbps circuits to connect to the ETMS traffic management computer complex. For ETMS connections between a TRACON and non-collocated ATCT(s), the required data rate is also 256 kbps [1].

2.6 Potential EFB Application Classes

Data rate requirements for the transfer of EFB data from Aeronautical Operational Control (AOC) to aircraft located at the gates are described in this subsection. The EFB is a portable electronic device [18] that can be used for the following:

- Electronic storage and retrieval of documents required for flight operations, such as:
  - Flight operations manuals
  - Operations specifications
  - Airplane flight manual and supplements
  - Maintenance manuals
  - Aircraft flight logs and servicing records
  - Aeronautical information manual
- Basic calculations
  - Takeoff, en route, approach, and landing performance calculations
  - Weight and balance calculations
- Electronic checklists
- Non-interactive electronic approach charts
- Weather and aeronautical data
- Applications for transfer of system maintenance data

- Camera displays for cabin-mounted video

Among the various types of applications that could be used with EFBs, the ones that require large data transfers have been chosen for this analysis. These applications are:

1. Software Loading

   This application consists of uploading new versions of software for non-safety related aircraft systems while the aircraft is at the gate.

2. Electronic Library Update

   This application enables the update of EFB data either automatically or by request while the aircraft is at the gate.

3. Graphic Weather

   This application enables the transmission of graphic weather data to the aircraft for display in the cockpit. This is advisory information that supplements or replaces the textual weather information available in current AOC services.

These applications are defined in [4], which also identifies message sizes, duration of aircraft position at the gate, and number of aircrafts located at gates in a high-density airport. Two sets of such values are presented in Table 2-1. Phase 1, as defined in [4], completes around 2020, when Phase 2 would start. Table 2-1 presents the characteristics of the EFB data applications and their respective estimated data rates averaged over the aircraft position durations.

Table 2-1. EFB Data Characteristics

Application		Aircraft Count	Message Size (bytes)	Aircraft Position Duration (sec)	Estimated Data Rate (kbps)
Phase 1	Software Loading	134	9000	2700	3.6
	Electronic Library Update	134	16500	2700	6.6
	Graphic Weather	134	27000	2700	10.7
Phase 2	Software Loading	194	25500	1800	22.0
	Electronic Library Update	194	99000	1800	85.4
	Graphic Weather	194	108000	1800	93.1

2.7 Airport Surface Data Transmission to Mobile Stations

In Section 2.2.1, it was mentioned that ASDE-X data from the multi-processor can be transmitted for display to various fixed locations (such as airline operations facilities). A potential ANLE application would be the transmission of such data to moving aircraft and surface vehicles.

For this analysis it is assumed that ANLE would use the IEEE 802.16e standard and the airport surface data would be broadcast, using the broadcast/multicast features in the standard. The data rate requirement depends on the airport configuration. For a large airport (such as DFW) nine simultaneous transmissions are assumed, each with a data rate requirement of 593 kbps (the value given earlier for ASDE-X display).

2.8 Summary of Potential Applications

Table 2-2 shows a summary of the potential application classes presented in this section.

Table 2-2. Summary of Potential ANLE Application Classes

Application Class Description	Estimated Data Rate (kbps)	Est. Number per Airport	Estimated Data Rate (kbps) per Airport
Surveillance Data			
ASR-9	62.4	1 - 2	62.4 - 124.8
ASR-11	337.6	1 - 2	337.6 - 675.2
ASDE-X RU to ASDE-X processor	64	3 - 10	192 - 640
ASDE-X Display	593	3	1779
DBRITE video to ATCT	1544	2 - 4	3088 - 6176
Weather Data			
LLWAS	9.6	1 - 32	9.6 - 307.2
AWOS/ASOS	19.2	1	19.2
TDWR	175	1	175
TDWR Data for ITWS	1544	1	1544
ITWS Display	256	1 - 2	256 - 512
WSP Display	128	1	128
Navigation and Landing			
NAVAIDS to TRACON	See Section 2.3		3216
ATC Voice (Diversity)			
RTR	1544	1 - 4	1544 - 6176
ATCT - TRACON (ATC Voice)	1544	1 - 4	1544 - 6176
Automation			
CTAS to ATCT	512	1 - 6	512 - 3072
ETMS to ATCT	256	1 - 2	256 - 512
EFB Data			
Software Loading	see Table 2.1		3.6 - 22
Electronic Library Update	see Table 2.1		6.6 - 85.4
Graphic Weather	see Table 2.1		10.7 – 93.1
Airport Surface Data to Mobile Users	593	3 - 9	1779 - 5337

3 Impact of IEEE 802.16 Standards Evolution

The Institute of Electrical and Electronics Engineers (IEEE) 802.16-2004 [19] and IEEE 802.16e-2005 [20] standards are used in this analysis for the potential implementation of the ANLE network. Both standards allow for the implementation of high-speed broadband wireless networks.

The IEEE 802.16-2004 standard specifies the air interface for fixed broadband wireless access (BWA) systems. The standard includes the medium access control (MAC) layer and multiple physical layer specifications. The standard can be implemented in frequency bands below 10 gigahertz (GHz) (licensed and license-exempt); therefore it is applicable to the 5091-5150 MHz band being considered for the ANLE network.

IEEE 802.16e-2005 standard expands IEEE 802.16-2004 to allow for mobile subscriber stations moving at vehicular speeds. It provides for handover mechanisms for the mobile station (MS). Handover occurs when the MS leaves the coverage area of a BS and enters the coverage area of a different BS. The Orthogonal Frequency Division Multiple Access (OFDMA) physical layer specification is scalable such that various channelizations from 1.25 MHz to 20 MHz can be used in the implementation.

3.1 OFDM and OFDMA Characteristics

OFDM (orthogonal frequency division multiplexing) and OFDMA are specifications for the physical layer implementations in the IEEE 802.16 standards.

The OFDM waveform is obtained through an inverse Fast Fourier transformation. In time domain, the symbol structure [19] is shown in Figure 3-1, where:

T_b = time duration used to create the OFDM symbol (useful symbol time)

T_g = guard time used to combat multipath effects

T_s = total symbol time

$$T_s = T_b + T_g$$

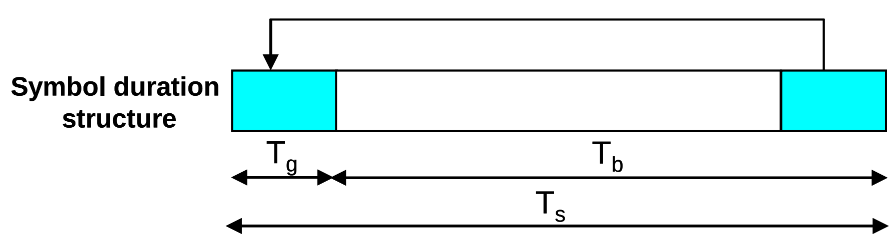

Figure 3-1. Symbol Time Structure

In the frequency domain, an OFDM symbol contains a number of subcarriers equal to the size of the Fast Fourier transform (FFT). Figure 3-2 shows the types of subcarriers as follows:

- data subcarriers used for data transmission
- pilot subcarriers used for estimation purposes
- null subcarriers used for guard band and the DC subcarrier (non-active)

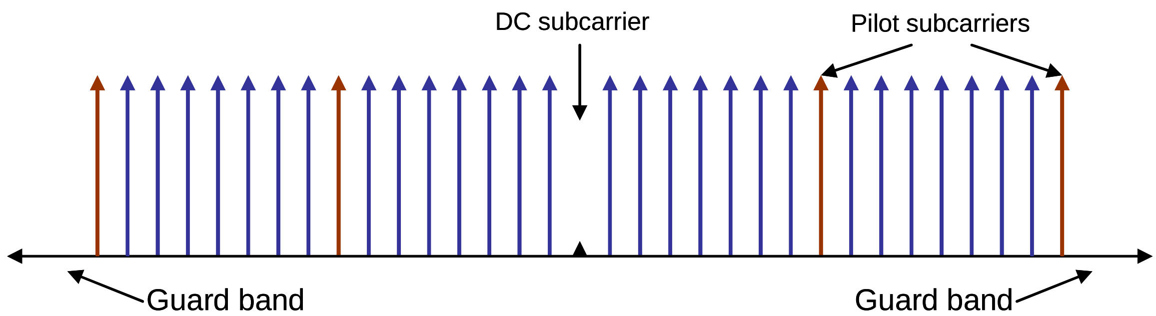

Figure 3-2. OFDM Frequency Structure

In OFDMA, the active subcarriers are divided into subsets of subcarriers, each subset is known as a subchannel. In the forward link (FL) (i.e., BS to MS), subchannels might be intended for different receivers. In the reverse link (RL) (i.e., MS to BS), a transmitter might be allocated multiple subchannels and multiple transmitters can transmit simultaneously [19]. This is shown in Figure 3-3.

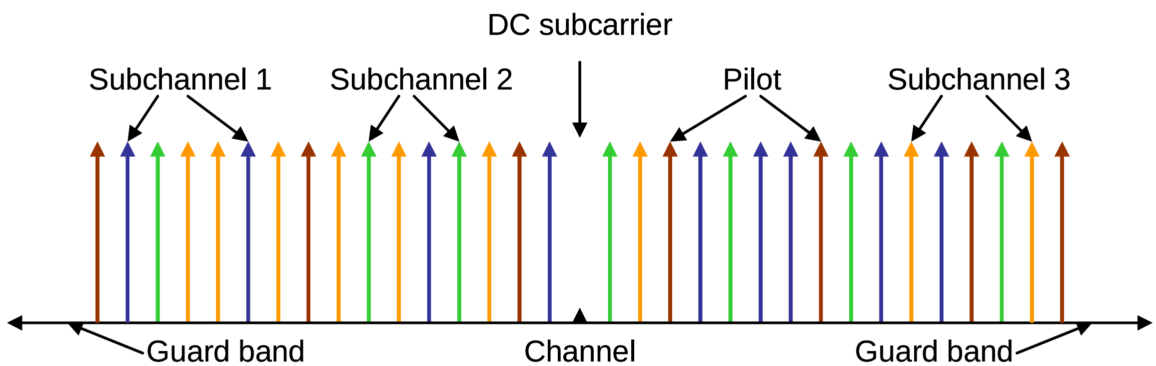

Figure 3-3. Example OFDMA Structure with 3 Subchannels

Figure 3-4 shows an example of resource allocations in OFDM and OFDMA on the reverse link using three subscriber stations [21]. In OFDM all subcarriers are allocated to the same user at a given time. In OFDMA multiple users can each be allocated some of the subcarriers, therefore they can transmit simultaneously. Therefore OFDMA allows for increased flexibility in resource allocation.

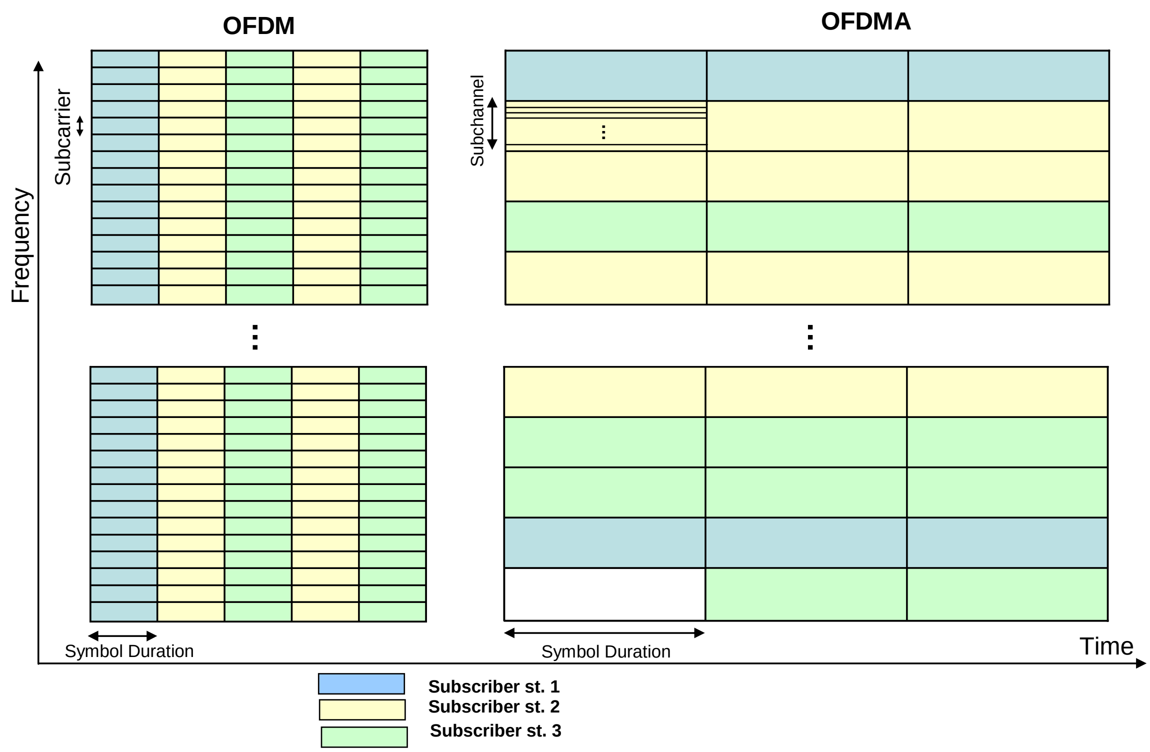

Figure 3-4. Reverse Link OFDM and OFDMA Resource Allocation Example

In IEEE 802.16e-2005 the scalable OFDMA is used for the OFDMA implementation. Scalable OFDMA uses the same subcarrier frequency spacing for various system bandwidths, as shown in Table 3-1. Further calculations in this document assume that the system bandwidth for a potential ANLE network is 20 MHz.

Table 3-1. Scalable OFDMA Example

Parameters	Values			
System Channel Bandwidth (BW) (MHz)	1.25	5	10	20
Sampling Frequency (F_s) (MHz)	1.4	5.6	11.2	22.4
FFT Size (N_{FFT})	128	512	1024	2048
Subcarrier Frequency Spacing Δf (kHz)	10.94			
Useful Symbol Time (T_b) (μs)	91.4			
Guard Time (T_g=1/8*T_b) (μs)	11.4			
OFDMA Symbol Duration (T_s) (μs)	102.9			

Figure 3-5 [20] shows an illustration of the OFDMA frame structure for time division duplex (TDD), which is the option being considered for a potential ANLE network. The frame starts with the preamble which is used for synchronization, followed by the frame control header (FCH), and the downlink map (DL-MAP) and the uplink map (UL-MAP). The DL-MAP and UL-MAP define the structure of the forward and reverse link portions of the frame. The transmit/receive transition gap (TTG) and receive/transmit transition gap (RTG) are also shown in the figure.

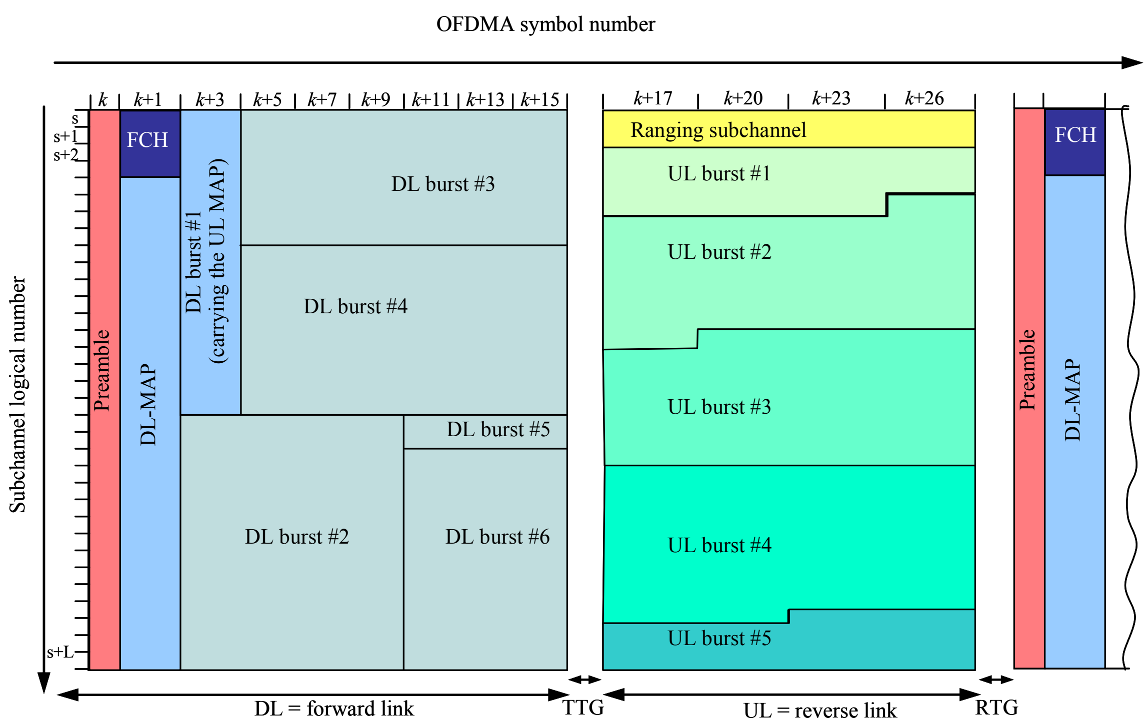

Figure 3-5. Example of OFDMA TDD Frame Structure

3.2 Physical Layer Bit Rate Analysis

This analysis uses both the OFDM and OFDMA implementations. For OFDMA, the subchannel allocation with partial usage of subchannels (PUSC) is used, which is mandatory in the OFDMA frame structure. The maximum achievable physical layer (PHY) raw bit rates are evaluated for each modulation type on the forward and reverse links. Then, using adaptive modulation considerations, an average physical layer raw bit rate is calculated for the forward and reverse links.

3.2.1 Maximum Achievable Physical Layer Raw Bit Rate

The following parameters, based on [19], [20], and [22], are used in the analysis to determine the maximum achievable physical layer raw bit rates for the various modulation types.

Table 3-2. Physical Layer Parameters for the Analysis

Parameter	OFDM	OFDMA PUSC	
		Forward Link	**Reverse Link**
System Bandwidth (BW) (MHz)	20	20	20
FFT Size (N_{FFT})	256	2048	2048
Sampling factor (n)	1.152	1.12	1.12
Sampling frequency (F_s) (MHz)	23.04	22.4	22.4
Subcarrier spacing Δf (kHz)	90.00	10.94	10.94
Cyclic prefix ratio (G=T_g/T_b)	1/8	1/8	1/8
Symbol period T_s (μs)	12.5	102.9	102.9
Frame duration T_{FR}(ms)	5	5	5
Number of OFDM symbols/frame (N_{OFDM})	400	48	48
Number of data subcarriers (N_{data})	192	1440	1120

The following equations are used in the analysis:

$$T_b = \frac{1}{\Delta f} \tag{3-1}$$

$$T_s = T_b + T_g = T_b(1+G) \tag{3-2}$$

$$N_{OFDM} = \mathrm{int}(T_{FR} / T_s) \tag{3-3}$$

The maximum achievable bit rates $R_b^{(ach)}$ for the various modulation and coding schemes are obtained using the following equation, and are presented in Table 3-3.

$$R_b^{(ach)} = b_m c_r N_{OFDM} N_{data} / T_{FR} \tag{3-4}$$

where

b_m=number of bits per modulation symbol

c_r = coding rate

Table 3-3. Maximum Achievable PHY Raw Bit Rates

Modulation	Coding Rate	PHY Raw Bit Rate (Mbps) [1]		
		OFDM	OFDMA PUSC	
			Forward Link	Reverse Link
QPSK	1/2	15.36	13.82	10.75
	3/4	23.04	20.74	16.13
16-QAM	1/2	30.72	27.65	21.50
	3/4	46.08	41.47	32.26
64-QAM	2/3	61.44	55.30	43.01 [2]
	3/4	69.12	62.21	48.38 [2]

NOTES:

(1) The maximum raw PHY bit rates include the OFDM/OFDMA frame overhead

(2) Implementation of 64-Quadrature Amplitude Modulation (QAM) is optional for the reverse link [22]

The following observations can be made regarding the results in Table 3-3:

- The high data rates for the 16-QAM and 64-QAM modulations are achievable only for mobile stations close to the base station. The impact of adaptive modulation is discussed in detail in the following subsection.
- More advanced options such as smart antenna technologies will further increase the bit rates, but have not been used in this analysis.
- No repetition coding was assumed.

3.2.2 Average Physical Layer Raw Bit Rates

Adaptive modulation considerations are used in this analysis to evaluate average physical layer raw bit rates for the forward and reverse links. Adaptive modulation allows an IEEE 802.16e-based system to adjust the signal modulation scheme on the basis of the received signal to noise ratio (SNR) at the subscriber station. If the radio link quality is good (high SNR), then a higher-order modulation is used, which allows for high data rates. As the radio link quality deteriorates (low SNR), modulations that allow lower data rates are used.

Assume that at the edge of the cell the modulation is Quadrature Phase-Shift Keying (QPSK) with a coding rate of ½. Closer to the base station, more-efficient modulations can be achieved using the adaptive modulation feature of the standard. Table 3-4 shows SNR values for various modulation and coding pairs according to [20]. The modulation number shown in the last column was defined only for the purpose of this derivation.

Table 3-4. Receiver SNR Assumptions

Modulation	Coding Rate	Receiver SNR (dB)	Modulation type (i)
QPSK	1/2	5	1
	3/4	8	2
16-QAM	1/2	10.5	3
	3/4	14	4
64-QAM	2/3	18	5
	3/4	20	6

Consider that at the edge of the coverage area represented notionally as a circle of radius d_1, a subscriber station meets the minimum SNR required for demodulating the QPSK ½ modulation (type 1). This minimum SNR value is denoted as SNR_1. At distance d_i the SNR value is denoted as SNR_i, and the following equation is obtained:

$$d_i = d_1 10^{\frac{-\Delta SNR(i)}{10n}} \tag{3-5}$$

where:

d_1 = distance from the base station to the edge of the coverage area

$$\Delta SNR(i) = SNR_i - SNR_1 \tag{3-6}$$

n = path loss exponent

Figure 3-6 shows the areas in which signals with various modulation and coding schemes can be received [23].

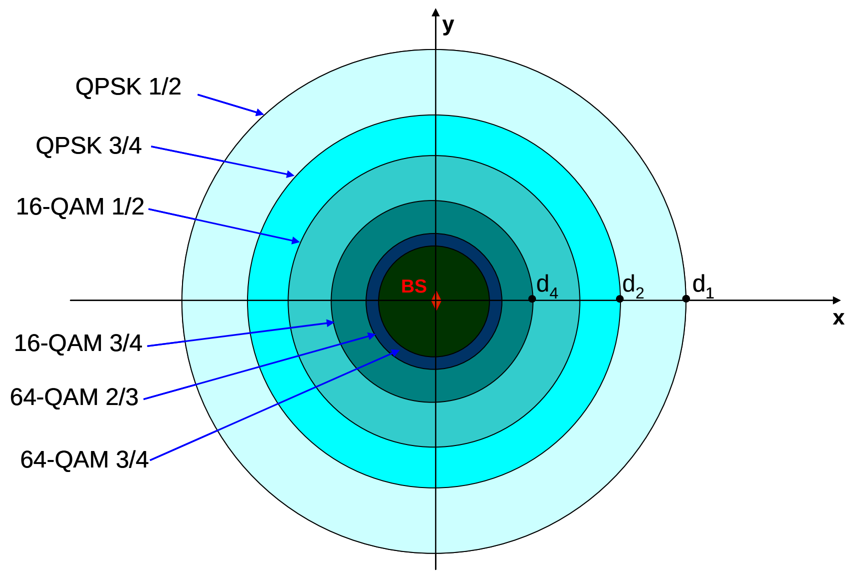

Figure 3-6. Adaptive Modulation Illustration

Assume that the subscriber stations are uniformly distributed in the coverage area. The probability that a radio link to a subscriber station is using modulation type *i* (as defined in Table 3-4) is

$$P_i = 10^{\frac{-2\Delta SNR(i)}{10n}} - 10^{\frac{-2\Delta SNR(i+1)}{10n}} \quad \text{for } i = 1\ldots5 \qquad (3\text{-}7)$$

$$P_i = 10^{\frac{-2\Delta SNR(i)}{10n}} \quad \text{for i} = 6 \qquad (3\text{-}8)$$

Table 3-5 shows the probabilities calculated for the various modulation types, using a path loss exponent *n* of 2.3 based on measurements that will be discussed in Section 4.

Table 3-5. Adaptive Modulation Results

Modulation	Coding Rate	Modulation type (i)	Calculated distance ratio d_i/d_1	Calculated Probability P_i
QPSK	1/2	1	1	0.45
	3/4	2	0.74	0.22
16-QAM	1/2	3	0.58	0.17
	3/4	4	0.41	0.09
64-QAM	2/3	5	0.27	0.02
	3/4	6	0.22	0.05

The average physical layer bit rates, using adaptive modulation considerations, for the forward and reverse links for all subscriber stations (assuming that they are uniformly distributed) are:

$$R_{bavg}^{(ad)(FL)} = \sum_{i=1}^{6} P_i R_{bi}^{(ach)(FL)} \tag{3-9}$$

$$R_{bavg}^{(ad)(RL)} = \sum_{i=1}^{6} P_i R_{bi}^{(ach)(RL)} \tag{3-10}$$

where:

$R_{bi}^{(ach)(FL)}$ is the achievable forward link data rate for the i^{th} modulation type (see Table 3-3)

$R_{bi}^{(ach)(RL)}$ is the achievable reverse link data rate for the i^{th} modulation type (see Table 3-3)

P_i is the probability that a subscriber station uses the i^{th} modulation (see Table 3-5)

Using the results shown in Tables 3-3 and 3-5, the following average physical layer raw bit rates are obtained:

$$R_{bavg}^{(ad)(FL)} = 23.43 \quad \text{(Mbps)} \tag{3-11}$$

$$R_{bavg}^{(ad)(RL)} = 18.22 \quad \text{(Mbps)} \tag{3-12}$$

3.3 Preliminary Estimate of ANLE Bandwidth Requirements

The following assumptions are used in the analysis:

1. ANLE network implementation would be based on the IEEE 802.16e standard using the OFDMA physical layer implementation.
2. The MAC protocol data unit (MPDU) size that is received by the MAC layer of the IEEE 802.16e standard is assumed as 1500 bytes [20], [24].
3. OFDMA PUSC with the FFT size of 2048 implementation is considered.
4. OFDMA frame overhead is assumed 11 OFDM symbols [22]. This is considered a conservative value in [22]. The forward link overhead is 7 OFDM symbols, the reverse link overhead is 3 OFDM symbols and 1 OFDM symbol is used for the transmit/receive transition gap [22]. The frame overhead value and its distribution among the forward and reverse link components must be validated by future detailed modeling and simulations. The values used in this analysis are given as an example to illustrate the methodology developed in this report to estimate bandwidth requirements.
5. The frame size is 5 ms. This is a typical value for mobile applications [24], and here it is also assumed for fixed applications.
6. 48 OFDM symbols are transmitted in a frame.

7. Only the main data traffic direction is assumed in the analysis. For example sensor information is considered as reverse link traffic only, the forward link traffic for network control purposes is not considered. Similarly, EFB type data transfers are considered forward link only, although there will also be some reverse link traffic (for example to support channel estimation) on the reverse link. A more detailed analysis is needed to refine the traffic distribution between the forward and reverse links.
8. For the ATC Voice Diversity application a 1:1 ratio is assumed between the forward and reverse links (symmetric traffic).
9. The airport surface data application is assumed to use the broadcast/multicast features of the standard. A more detailed analysis of these features, and their potential use to support this application, is needed.

The ANLE potential applications used in this analysis are shown in Table 3-6.

As can be seen in the table, this analysis does *not* include the WSP display and the ASR-9 data. The WSP display is not included due to the fact that ITWS display is assumed available at the airport (i.e., the WSP display could be used at smaller airports where ITWS or TDWR was not available). The ASR-9 is not included because the airport is assumed equipped with ASR-11.

Table 3-6. Potential ANLE Applications Data Rates for the Analysis

Application Class Description	Maximum Estimated Aggregate Data Rate per Airport (kbps)	Maximum Estimated Aggregate FL Data Rate per Airport (kbps)	Maximum Estimated Aggregate RL Data Rate per Airport (kbps)
ASR-11	675.2		675.2
ASDE-X RU to ASDE-X processor	640		640
ASDE-X Display	1779	1779	
LLWAS	307.2		307.2
AWOS/ASOS	19.2		19.2
TDWR	175		175
TDWR Data for ITWS	1544		1544
ITWS Display	512	512	
NAVAIDS to TRACON	3216		3216
TRACON Totals	*8867.6*	*2291*	*6576.6*
DBRITE video to ATCT	6176		6176
RTR	6176	3088	3088
ATCT - TRACON (ATC Voice)	6176	3088	3088
CTAS to ATCT	3072		3072
ETMS to ATCT	512		512
Software Loading	22	22	
Electronic Library Update	85.4	85.4	
Graphic Weather	93.1	93.1	
Airport Surface Data to Mobile Users	5337	5337	
ATCT Totals	*27649.5*	*11713.5*	*15936*
Total Aggregate Estimated Data Rates (kbps)	**36517.1**	**14004.5**	**22512.6**

Table 3.6 shows that the total aggregate estimated data rates required to support the potential ANLE network applications listed in the table is about 36.6 Mbps.

Assume a scenario in which the ANLE network is divided into two subnetworks. Aggregate data rates have also been calculated for the two subnetworks (in italics in the table). It is expected that at least one frequency carrier would be required to support each subnetwork, for an ANLE network in which the ATCT is non-collocated with the TRACON.

The following equations are used to estimate the aggregate bandwidth requirements to support the ANLE potential applications shown in Table 3-6 at a large airport. The *k* superscript denotes the subnetwork.

$$R_d^{(T)(k)} = R_d^{(FL)(k)} + R_d^{(RL)(k)} \quad (3\text{-}13)$$

$$r_d^{(FL)(k)} = \frac{R_d^{(FL)(k)}}{R_d^{(T)(k)}} \quad (3\text{-}14)$$

$$r_d^{(RL)(k)} = \frac{R_d^{(RL)(k)}}{R_d^{(T)(k)}} = 1 - r_d^{(FL)(k)} \quad (3\text{-}15)$$

where:

k = subnetwork index = 1…2 for this analysis

$R_d^{(FL)(k)}$ = estimated aggregate data rate per airport on the forward link, k^th subnetwork

$R_d^{(RL)(k)}$ = estimated aggregate data rate per airport on the reverse link, k^th subnetwork

$R_d^{(T)(k)}$ = estimated total aggregate data rate per airport, k^th subnetwork

$r_d^{(FL)(k)}$ = ratio of forward link data rate to total data rate, k^th subnetwork

$r_d^{(RL)(k)}$ = ratio of reverse link data rate to total data rate, k^th subnetwork

$$N_{OFDM}^{(data)} = N_{OFDM} - N_{OVH} \quad (3\text{-}16)$$

$$N_{OFDM}^{(FL)(k)} = ceil(r_d^{(FL)(k)} N_{OFDM}^{(data)}) + N_{OVH}^{(FL)} \quad (3\text{-}17)$$

$$N_{OFDM}^{(RL)(k)} = N_{OFDM} - N_{OFDM}^{(FL)(k)} - N_{OVH}^{(TTG)} \quad (3\text{-}18)$$

where:

N_{OFDM} = number of OFDM symbols per frame

N_{OVH} = number of overhead OFDM symbols per frame

$N_{OFDM}^{(data)}$ = number of OFDM data symbols per frame

$N_{OVH}^{(FL)}$ = number of overhead forward link OFDM symbols per frame

$N_{OVH}^{(TTG)}$ = number of overhead OFDM symbols per frame for transmit/receive transition gap

$N_{OFDM}^{(FL)(k)}$ = number of OFDM forward link symbols (data and overhead) per frame, k^th subnetwork

$N_{OFDM}^{(RL)(k)}$ = number of OFDM reverse link symbols (data and overhead) per frame, k^th subnetwork

$$R_b^{(FL)(k)} = R_d^{(T)(k)} \frac{N_{OFDM}^{(FL)(k)}}{N_{OFDM}} F_{OVH} \tag{3-19}$$

$$R_b^{(RL)(k)} = R_d^{(T)(k)} \frac{N_{OFDM}^{(RL)(k)}}{N_{OFDM}} F_{OVH} \tag{3-20}$$

where:

$R_b^{(FL)(k)}$ = bit rate on the forward link, kth subnetwork

$R_b^{(RL)(k)}$ = bit rate on the reverse link, kth subnetwork

F_{OVH} = overhead factor that includes the MAC and frame overhead. The value used in the analysis is 1.32 based on [20], [22], [24].

The average spectral efficiency on the forward and reverse links is calculated using the average physical layer raw bit rates calculated in Section 3.2.2. These bit rates considered the effects of adaptive modulation and were evaluated with the assumption that all subscriber stations (both fixed and mobiles) are uniformly distributed in the airport area.

$$S_{EFF\,avg}^{(FL)} = \frac{R_{bavg}^{(ad)(FL)}}{BW_S} \tag{3-21}$$

$$S_{EFF\,avg}^{(RL)} = \frac{R_{bavg}^{(ad)(RL)}}{BW_S} \tag{3-22}$$

$$BW_{avg}^{(req)(k)} = ceil\left(\left(\frac{R_b^{(FL)(k)}}{S_{EFF\,avg}^{(FL)}} + \frac{R_b^{(RL)(k)}}{S_{EFF\,avg}^{(RL)}}\right)\frac{1}{N_c^{(k)} BW_S}\right) BW_S \tag{3-23}$$

where:

$S_{EFF\,avg}^{(FL)}$ = average spectral efficiency on the forward link

$S_{EFF\,avg}^{(RL)}$ = average spectral efficiency on the reverse link

$R_{bavg}^{(ad)(FL)}$ = average physical layer raw bit rate on the forward link

$R_{bavg}^{(ad)(RL)}$ = average physical layer raw bit rate on the reverse link

BW_S = system bandwidth (for each carrier frequency) = 20 MHz for this analysis

$N_c^{(k)}$ = number of cells for the kth subnetwork

$BW_{avg}^{(req)(k)}$ = average aggregate bandwidth requirement, kth subnetwork

The values for the input parameters used in the bandwidth estimation analysis are shown in Table 3-7.

Table 3-7. Input Parameters for Preliminary Bandwidth Estimation

Parameter	Value
Number of OFDM symbols per frame N_{OFDM}	48
Number of overhead OFDM symbols per frame N_{OVH}	11
Number of overhead OFDM symbols per frame on the forward link $N_{OVH}^{(FL)}$	7
Number of overhead OFDM symbols per frame on the reverse link $N_{OVH}^{(RL)}$	3
Overhead factor F_{OVH}	1.32
Average physical layer bit rate on the forward link $R_{bavg}^{(ad)(FL)}$ (Mbps)	23.43
Average physical layer bit rate on the reverse link $R_{bavg}^{(ad)(RL)}$ (Mbps)	18.22
System Channel Bandwidth BW_S (MHz)	20

Using the input parameters presented in Table 3-7, the methodology discussed above, and assuming a scenario in which:

$$N_c^{(k)} = 1 \qquad \text{for } k=1 \text{ and } k=2 \tag{3-24}$$

the following results are obtained:

$$S_{EFF\,avg}^{(FL)} = 1.17 \text{ bps/Hz} \tag{3-25}$$

$$S_{EFF\,avg}^{(RL)} = 0.91 \text{ bps/Hz} \tag{3-26}$$

$$BW_{avg}^{(req)(1)} = 20 \text{ MHz} \tag{3-27}$$

$$BW_{avg}^{(req)(2)} = 40 \text{ MHz} \tag{3-28}$$

$$BW_{avg}^{(req)(T)} = 60 \text{ MHz} = \text{the total aggregate required bandwidth} \tag{3-29}$$

Therefore, the total bandwidth requirement for this scenario is 60 MHz, which is the entire available spectrum for ANLE. This is considered a conservative estimate because the number of overhead symbols is identified as conservative in [22]. Also, the analysis does not take into account multi-cell scenarios which could increase spectral efficiency.

3.3.1 Observations

The following observations can be made regarding the preliminary bandwidth requirements analysis:

- Advanced features of the IEEE 802.16e standard, such as smart antenna technologies, have not been taken into account. These features should be studied in detail, and their effects on the bandwidth requirements should be included in future analyses. Higher data rates and bandwidth efficiencies would be expected.

- The MPDU size used in the analysis is 1500 bytes. This is a typical value, but other MPDU sizes should also be considered in a future analysis. Their effects on the bit rate calculations on the forward and reverse links should be analyzed.
- The number of overhead OFDM symbols and their partition between the forward and reverse links need to be determined based on detailed modeling and simulation efforts. The values in this report [22] are used as an example to illustrate the developed methodology.
- Bandwidth requirements for each type of application should also be calculated on the basis of further simulation and modeling; the values presented here are average aggregate values.
- The analysis assumes that all subscriber stations are uniformly distributed around the airport area, for both fixed and mobile users. This assumption is used to calculate the average data rates in Section 3.2.2. It is possible that a better link quality can be assumed for the fixed applications, which would increase their supported data rates and spectral efficiencies.
- The channel bandwidth was assumed to be 20 MHz throughout this report. As previously mentioned, the scalable OFDMA feature of the standard allows for the use of various system bandwidths. Smaller system bandwidths should also be considered. Higher spectral efficiencies could potentially be achieved for scenarios with less-conservative traffic-loading assumptions.
- The division of the ANLE network into subnetworks needs to be further studied both multi-frequency and multi-cell implementations. The example shown in the report is only to illustrate the methodology. Multi-cell implementations could be more spectrally efficient, but such scenarios need to be analyzed in greater detail.
- The characteristics of the broadcast/multicast services in IEEE 802.16e should be studied in further detail. Modeling and simulations are needed to assess their impact on the frame structure and overhead.
- Load balancing between the subnetworks (and between the required carrier frequencies) should be performed as needed to ensure that the ANLE network would not interfere with low Earth orbit (LEO-D and LEO-F) satellites.
- The ANLE bandwidth system requirements are scenario-specific. A methodology was developed in this report to evaluate ANLE aggregate bandwidth system requirements, and an example scenario was provided to illustrate the methodology. In this example scenario the entire 60-MHz bandwidth would be used. Other scenarios, particularly those involving less-conservative traffic-loading assumptions, would yield considerably different results.

4 Impact of Recent 5-GHz Test Results

MITRE performed an interference analysis of potential band-sharing between ANLE and mobile satellite service (MSS) feeder links in 2005 [25]. Our analysis used certain assumed values for ANLE transmitter power. Those values were chosen to ensure adequate ANLE performance over a 3-km path, using a postulated 11-dB fade margin (L_m) and a path-loss exponent (n) of 2.2. The National Aeronautics and Space Administration (NASA) subsequently funded Ohio University to perform field tests on Microwave Landing System (MLS) band channel characterization for mobile and fixed airport surface communications. The test results included an estimation of the parameter n. Since our ANLE-to-MSS interference predictions are sensitive to n, as part of the present effort, we revisited our interference predictions in light of the new measurement results, which were provided to us in 2006 [26]. This subsection determines the impacts of the recent NASA/Ohio University test results on the MITRE 2005 ANLE link and interference analysis.

With the other system parameters held fixed, the ANLE-to-MSS interference is determined by the path loss of the signals. The path loss is a function of the path distance d in meters. For an ANLE system the propagation path loss is evaluated on the airport surface where the path loss characteristics could be different from the free-space path loss. The path loss in decibels is given by:

$$L_{path}(d) = L_{free}(d_0) + 10n\log_{10}(d/d_0) \quad (4\text{-}1)$$

where:

L_{free} = free-space path loss in decibels,

d_0 = distance (in meters) up to which path loss can be modeled using the free-space equation,

n = path loss exponent,

and

$$L_{free}(d_0) = 32.44 + 20\log_{10}(f_{MHz}) + 20\log_{10}\left(\frac{d_0}{1000}\right) \quad (4\text{-}2)$$

with:

f_{MHz} = operating frequency (in MHz)

Table 4-1 lists the values of n and d_0 used in our 2005 analysis. Also included are the NASA/Ohio University recent estimations obtained from a curve fitting of the measured data with a standard deviation of 9 dB [26].

Table 4-1. Values of n and d_0

Parameter	Values Assumed in 2005 MITRE Study	Values Obtained from 2006 Measurement Results
Path loss exponent n	2.2	2.3
Distance d_0 (m)	5	462

At the mid-band frequency of 5120 MHz, the path losses, $L(d)$ and $K(d)$, can be computed using (4-1) where:

$L(d)$ = path loss obtained using 2005 MITRE assumptions

$K(d)$ = path loss obtained using 2006 measurement results

The quantity, $L(d) - K(d)$, being the difference between these two versions of path loss, as a function of d, is shown in Figure 4-1.

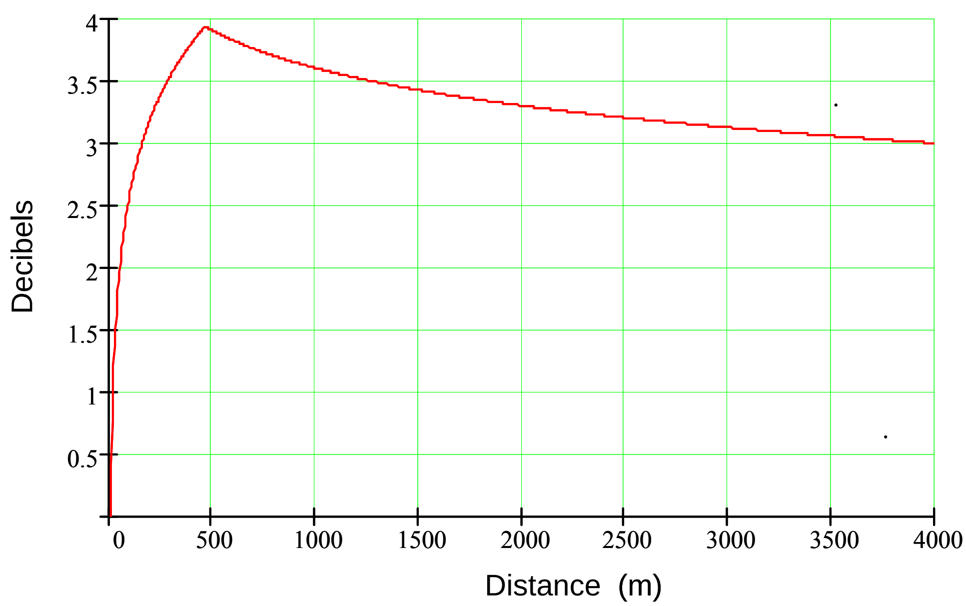

Figure 4-1. Difference Between 2005 and 2006 Path-Loss Predictions

From the above figure, it is seen that the path loss used in MITRE's 2005 study of ANLE/MSS feeder link band-sharing is larger (thus more conservative) than the path loss obtained using the new measurement results. The difference between the calculated path losses is less than 4 dB. Nevertheless, the recent new measurement results of n and d_0 were obtained from a curve fitting with a 9 dB standard deviation, which is much larger than the present calculated path loss difference of 4 dB. Given these results, we conclude that no changes to the MITRE 2005 calculations are necessitated by the current information regarding the new measurement results.

However, it is recommended that future ANLE analyses use the path-loss parameters based on the new measurement results. Accordingly, the analysis performed in Section 3.2.2 of this report uses the new path loss exponent parameter based on the 2006 measurement results.

5 Concluding Remarks

5.1 Findings

Various potential ANLE application classes have been presented in Section 2. Data rate requirements have been identified for each potential ANLE application class.

The impact of the IEEE 802.16e standards evolution for a potential implementation of the ANLE network using these standards has been analyzed in Section 3. Both the OFDM and the scalable OFDMA physical layer implementations have been discussed, and maximum achievable physical layer raw bit rates have been obtained. Average physical layer bit rates were calculated based on adaptive modulation considerations. For this calculation it was assumed a uniform distribution of ANLE users throughout the ANLE coverage area on the airport surface. A methodology was developed to estimate ANLE aggregate bandwidth requirements, and a preliminary ANLE bandwidth requirements estimation was performed for a given scenario at a large airport. For the given scenario a conservative estimate of the ANLE bandwidth requirements is 60 MHz using a system channel bandwidth of 20 MHz.

Section 4 of the report discusses the impact of NASA/Ohio University 5-GHz test results on the interference analysis of potential band-sharing between ANLE and MSS feeder links performed by MITRE in 2005. It is shown that the recent measurements tend to support the findings of our 2005 band-sharing analysis.

5.2 Future Work

Areas of further study regarding the potential implementation of an ANLE network using the IEEE 802.16e standards are identified as follows:

- Advanced features of the IEEE 802.16e standard such as the support for smart antenna technologies have not been taken into account. These features should be used in further modeling and simulation efforts. It is expected that these features would yield higher data rates and bandwidth efficiencies.
- The analysis assumes that all subscriber stations are uniformly distributed around the airport area, for both fixed and mobile users. This assumption is used to calculate the average data rates in Section 3.2.2. It is possible that a better link quality can be assumed for the fixed applications, which would increase their supported data rates and spectral efficiencies.
- The channel bandwidth was assumed to be 20 MHz throughout this report. As previously mentioned, the scalable OFDMA feature of the standard allows for the use of various system bandwidths. Smaller system bandwidths should also be considered. Higher spectral efficiencies could potentially be achieved for scenarios with less-conservative traffic-loading assumptions.

- The division of the ANLE network into subnetworks needs to be further studied both for multi-frequency and multi-cell implementations. Multi-cell implementations could be more spectrally efficient, but such scenarios need to be analyzed in greater detail.
- The characteristics of the broadcast/multicast services in IEEE 802.16e should be further analyzed. Modeling and simulations are needed to assess their impact on the frame structure and overhead.
- The list of potential applications for the ANLE network should be further refined and prioritized. A smaller list of likely candidates and a set of scenarios should be generated for a detailed analysis.

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Glossary

ADS-B	Automatic Dependent Surveillance – Broadcast
ANLE	Airport Network and Location Equipment
AOC	Aeronautical Operational Control
ARNS	aeronautical radionavigation service
ARTCC	Air Route Traffic Control Center
ASDE-X	Airport Surface Detection Equipment Mode X
ASOS	Automated Surface Observing System
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
AWOS	Automated Weather Observing System
BS	base station
BWA	broadband wireless access
CAASD	Center for Advanced Aviation System Development
CTAS	Center-TRACON Automation System
dB	decibel
DBRITE	Digital Bright Radar Indicator Tower Equipment
DFW	Dallas Fort Worth
DL-MAP	downlink map
EFB	Electronic Flight Bag
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FCH	frame control header
FFT	Fast Fourier transform
GHz	gigahertz
IEEE	Institute of Electrical and Electronics Engineers
ILS	Instrument Landing System
ITWS	Integrated Terminal Weather System
kbps	kilobits per second
LCU	link control unit

LDRCL	Low Density Radio Communications Link
LEO	low Earth orbit
LLWAS	Low Level Wind Shear Alert System
MAC	medium access control
Mbps	megabits per second
MHz	megahertz
MLS	Microwave Landing System
MPDU	MAC protocol data unit
MS	mobile station
MSS	mobile satellite service
NASA	National Aeronautics and Space Administration
NAVAIDS	Navigational Aids
nmi	nautical miles
OFDM	orthogonal frequency division multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPI	Precision Approach Path Indicator
PHY	Physical Layer
PUSC	partial usage of subchannels
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RCSU	remote control and status unit
RTG	receive/transmit transition gap
RTR	Remote Transmitters/Receivers
RU	remote units
RVR	Runway Visual Range
SNR	signal to noise ratio
TDD	time division duplex
TDWR	Terminal Doppler Weather Radar
TMA	Traffic Management Advisor
TRACON	Terminal Radar Approach Control
TTG	transmit/receive transition gap
UL-MAP	uplink map

WAN	wireless local area network
WSP	Weather Systems Processor