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Spectral Requirements of ANLE Networks for the Airport Surface

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July 2008

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Sponsor: Federal Aviation Administration

Dept. No.: F085

Contract No.: DTFA01-01-C-00001

Project No.: 0208FB02-AR

PBWP: 2-1.A-1 Spectral Requirements of ANLE Networks for the Airport Surface

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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-data-rate airport-surface wireless network, with terminals on the ground and on taxiing aircraft. In this analysis, The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has updated the potential classes of sensors and other fixed and mobile applications that may participate in such networks. We have also determined approximate upper bounds on the aggregate data rates for these potential applications for two implementation phases: Phase 1 (2020) and Phase 2 (beyond 2020). We have also estimated approximate upper bounds on spectral requirements needed to support these 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.

Acknowledgments

The author would like to thank Frank Box, Dr. Yan-Shek Hoh and Dr. Lisandro del Cid for their critical review of the manuscript and valuable comments.

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1 Introduction

Data transmissions that require broadband capabilities are increasing in the airport area. Running new cable or fiber, especially under runways, carries high installation costs. Airports also need to provide broadband connectivity to mobile users on the airport surface. Wireless broadband networks could be used to address these emerging needs, by supporting high-data-rate aeronautical applications on the airport surface. These wireless networks have been denoted as Airport Network and Location Equipment (ANLE) networks, as discussed in [1], [2]. The Federal Aviation Administration (FAA) is considering the use of the 5091-5150 megahertz (MHz) band for the future potential implementation of such ANLE networks.

Figure 1-1 shows an airport environment for a potential ANLE network. It illustrates how ANLE could provide the means of transporting data for fixed and mobile users such as sensors, taxiing aircraft, surface vehicles, and other users on the airport surface.

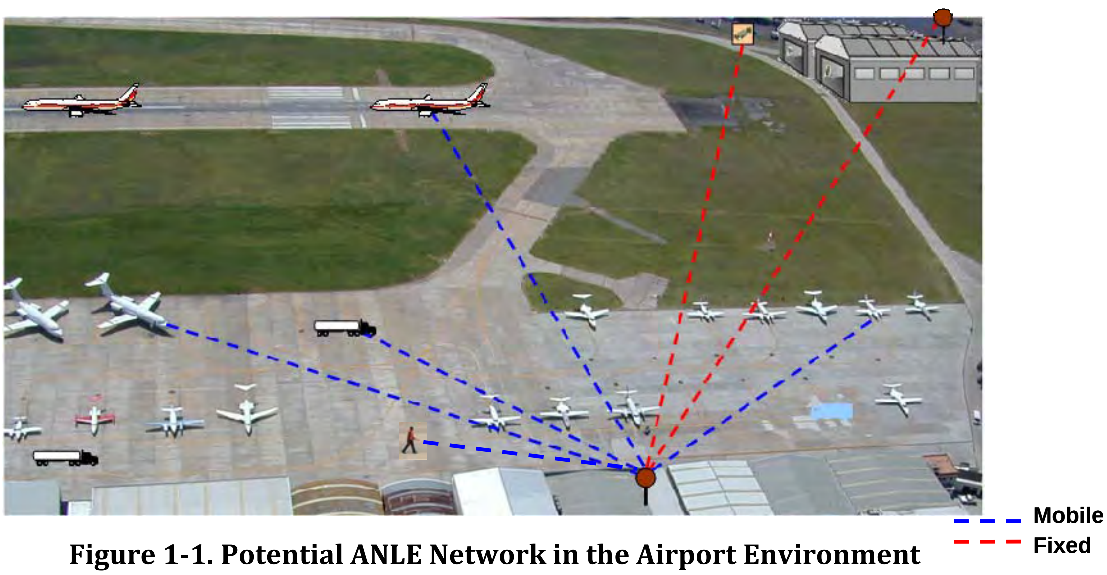

Figure 1-1. Potential ANLE Network in the Airport Environment

The FAA's office of Air Traffic Control (ATC) Spectrum Engineering Services has requested the MITRE Corporation's Center for Advanced Aviation System Development (CAASD) to estimate spectral bandwidth requirements for such ANLE networks. This is an update to earlier preliminary work performed by CAASD in this area [1]. The updated analysis takes into account recently identified potential applications, the impact of aircraft transmissions on the overall spectral occupancy of such networks, and new developments that have arisen since the previous study.

2 OFDMA Characteristics in the IEEE 802.16e Standard

The Institute of Electrical and Electronics Engineers (IEEE) 802.16-2004 [3] and IEEE 802.16e-2005 [4] standards have been investigated for the potential implementation of ANLE networks [1], [2], [5]. 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. It discusses the medium access control (MAC) layer and multiple physical layer specifications. The standard [3] can be implemented in licensed and license-exempt frequency bands below 10 gigahertz (GHz); therefore it is applicable to the 5091-5150 MHz band being considered for ANLE networks [1].

IEEE 802.16e-2005 standard expands IEEE 802.16-2004 to allow for mobile subscriber stations moving at vehicular speeds, by providing handover mechanisms for the mobile stations [4]. The Orthogonal Frequency Division Multiple Access (OFDMA) physical layer specification is scalable so that various channelizations from 1.25 MHz to 20 MHz can be used in the implementation [4], [5].

The OFDMA implementation of IEEE 802.16e-2005 is used in the analysis performed in this report to evaluate spectral requirements of ANLE networks.

This section discusses the main characteristics of this implementation, as well as the assumptions and parameters that will be used in the spectral requirements estimation analysis discussed in Section 4.

2.1 Physical Layer Characteristics and Parameters

This subsection describes the main parameters and characteristics of the OFDMA physical layer implementation as presented in IEEE 802.16e-2005 [4]. This subsection starts with a short description of the orthogonal frequency division multiplexing (OFDM) waveform as it applies to the OFDMA implementation. Then, the OFDMA channelization parameters and the frame structure are presented.

The OFDM waveform is obtained through an inverse fast Fourier transformation, as discussed in detail in [1]. In the time domain, the symbol structure [1], [3] is shown in Figure 2-1, 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

$T_s = T_b + T_g$

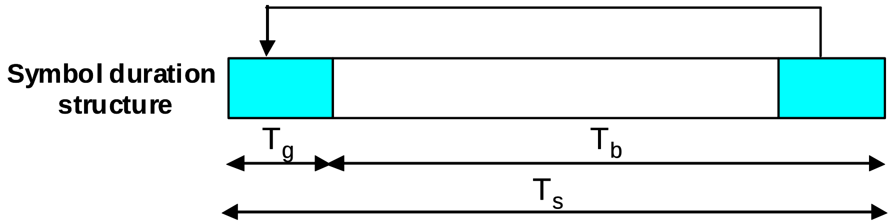

Figure 2-1. Symbol Time Structure

In the frequency domain, an OFDM symbol contains a number of subcarriers equal to the size of the fast Fourier transform (FFT) [1], [3]. The types of subcarriers are data subcarriers used for data transmission, pilot subcarriers used for estimation purposes, and null (inactive) subcarriers used for guard band and the DC subcarrier.

In OFDMA, the data subcarriers are divided into subsets, each of which is identified as a subchannel [1], [3], [4]. This allows for simultaneous transmissions by multiple users to a given base station (BS) on the reverse link (RL); each user might be allocated one or more subchannels. This can be seen in Figure 2-2 [1], which shows an example with data subcarriers divided in three subchannels.

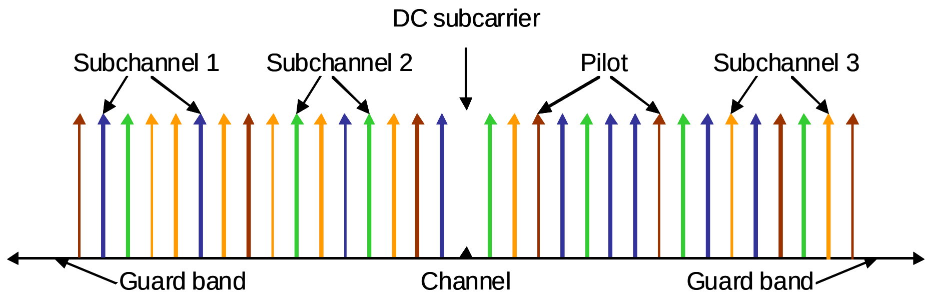

Figure 2-2. Example OFDMA Structure With 3 Subchannels

As noted earlier, the OFDMA implementation in IEEE 802.16e-2005 is scalable. Table 2-1 shows OFDMA channelization parameters for different channel bandwidths. It can be observed that, for scalable OFDMA, the subcarrier spacing remains constant. This is obtained by using different FFT size values as the channel bandwidth changes. This allows for constant symbol duration across the various channel bandwidths, and therefore the impact on the higher layer protocols is minimized for the scalable OFDMA implementation [6], [7].

Table 2-1. Scalable OFDMA Channelization Parameters

Parameters	Values			
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			

Further calculations in this document are performed for channel bandwidth values of 20 MHz [1] and 10 MHz [5].

Figure 2-3 [4] shows an illustration of the OFDMA frame structure for a time division duplex (TDD) implementation. The frame starts with the preamble that 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, respectively. The transmit/receive transition gap (TTG) and receive/transmit transition gap (RTG) are also shown in the figure.

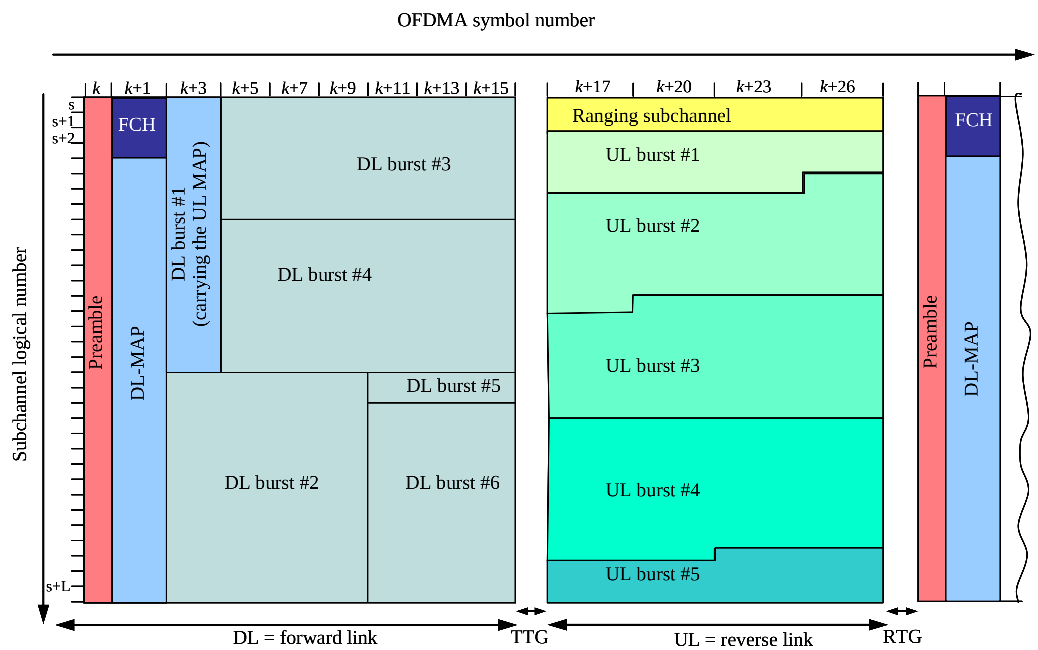

Figure 2-3. OFDMA TDD Frame Structure

2.2 Physical Layer Data Rates

Maximum physical layer bit rates and maximum physical layer data rates for the OFDMA implementation are evaluated in this subsection. The following assumptions are used in the analysis:

- The framing structure is TDD.
- Two different channel bandwidths, 20 MHz and 10 MHz, are considered.
- The subchannel allocation with partial usage of subchannels (PUSC) is used, which is mandatory in the OFDMA frame structure.
- No repetition coding is assumed for these calculations.

These physical layer rates are evaluated for the various modulation types and coding rates identified in the standard [4]. Adaptive modulation and coding allows a network to adjust the signal modulation scheme on the basis of the received signal to noise ratio (SNR). Higher-order modulation schemes are used for subscriber stations close to the base station (i.e., higher SNR). A higher order modulation allows for higher data rates as shown by the analysis presented in this subsection.

The OFDMA physical layer parameters used in this analysis are presented in Table 2-2 for both the forward link (FL) and reverse link. The term “forward link” describes the link from the base station to the subscriber station, and it can be used interchangeably with the term “downlink” (used in the standard). The term “reverse link” describes the link from the subscriber station to the base station, and it can be used interchangeably with the term “uplink” (used in the standard). A subscriber station can be fixed, portable, or mobile.

Table 2-2. Physical Layer Parameters

Parameters	OFDMA PUSC Implementation			
	Forward Link	**Reverse Link**	**Forward Link**	**Reverse Link**
Channel Bandwidth (BW) (MHz)	20		10	
FFT Size (N_{FFT})	2048		1024	
Sampling Factor (n)	1.12		1.12	
Sampling Frequency (F_s) (MHz)	22.4		11.2	
Subcarrier Spacing (Δf) (kHz)	10.94		10.94	
Cyclic Prefix Ratio ($G=T_g/T_b$)	1/8		1/8	
OFDM Symbol Duration (T_s) (μs)	102.9		102.9	
Frame Duration T_{FR}(ms)	5		5	
Number of OFDM Symbols/Frame (N_{OFDM})	48		48	
Number of Transmitted OFDM Symbols/Frame (N'_{OFDM})	47		47	
Number of Data Subcarriers (N_{data})	1440	1120	720	560

The following equations are used in the analysis:

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

where

$$T_s = T_b + T_g = (1/\Delta f)(1+G)$$

The parameter N'_{OFDM} takes into consideration the effects of the TTG and RTG transition gaps, as seen in the frame structure shown in Figure 2-3. As discussed in [8], [9], one symbol duration is used for TTG/RTG in the OFDMA frame structure, so 47 symbols are used for the transmission of data and control information in each OFDMA frame.

The maximum physical layer bit rates $R_b^{(FL)}$ and $R_b^{(RL)}$ for the various modulation and coding schemes are obtained using the following equations, and are presented in Tables 2-3 and 2-4.

$$R_b^{(FL)} = b_m c_r N'_{OFDM} N_{data}^{(FL)} / T_{FR}$$

and

$$R_b^{(RL)} = b_m c_r N'_{OFDM} N_{data}^{(RL)} / T_{FR}$$

where:

b_m = number of bits per modulation symbol

c_r = coding rate

The equations presented above show that the maximum physical layer (PHY) bit rates $R_b^{(FL)}$ and $R_b^{(RL)}$ include all the overhead associated with the frame structure (such as preamble, frame control header, downlink maps, uplink maps, etc). The corresponding maximum data rates $R_d^{(FL)}$ and $R_d^{(RL)}$ are also shown in the same tables (as the last two columns), without the frame overhead [8], [9]. These various data rates are expressed in megabits per second (Mbps).

Tables 2-3 and 2-4 also show the modulation and coding pairs as discussed in the standard, from Quadrature Phase-Shift Keying (QPSK) with a coding rate of ½, to 64-Quadrature Amplitude Modulation (64-QAM) with a coding rate of ¾. The corresponding required SNR values for the various modulation and coding schemes are also presented in these tables [4] and are expressed in decibels (dB).

Table 2-3. Maximum Physical Layer Rates for BW=20 MHz

Modulation	Coding Rate	Rx. SNR (dB)	Max OFDMA PHY Bit Rate (Mbps)		Max OFDMA PHY Data Rate (Mbps)	
			BW = 20 MHz		BW = 20 MHz	
			Forward Link	Reverse Link	Forward Link	Reverse Link
QPSK	1/2	5	13.54	10.53	12.67	9.41
	3/4	8	20.30	15.79	19.01	14.11
16-QAM	1/2	10.5	27.07	21.06	25.34	18.82
	3/4	14	40.61	31.58	38.02	28.22
64-QAM	1/2	16	40.61	31.58 (1)	38.02	28.22 (1)
	2/3	18	54.14	42.11 (1)	50.69	37.63 (1)
	3/4	20	60.91	47.38 (1)	57.02	42.34 (1)

NOTE: (1) Implementation of 64-QAM is optional for the reverse link as discussed in [6].

Table 2-4. Maximum Physical Layer Rates for BW=10 MHz

Modulation	Coding Rate	Rx. SNR (dB)	Max OFDMA PHY Bit Rate (Mbps)		Max OFDMA PHY Data Rate (Mbps)	
			BW = 10 MHz		BW = 10 MHz	
			Forward Link	Reverse Link	Forward Link	Reverse Link
QPSK	1/2	5	6.77	5.26	6.34	4.70
	3/4	8	10.15	7.90	9.50	7.06
16-QAM	1/2	10.5	13.54	10.53	12.67	9.41
	3/4	14	20.30	15.79	19.01	14.11
64-QAM	1/2	16	20.30	15.79 (1)	19.01	14.11 (1)
	2/3	18	27.07	21.06 (1)	25.34	18.82 (1)
	3/4	20	30.46	23.69 (1)	28.51	21.17 (1)

NOTE: (1) Implementation of 64-QAM is optional for the reverse link as discussed in [6].

The following observations can be made regarding the results in Tables 2-3 and 2-4:

- The data rates shown in these tables assume that the entire transmission is *either* on the forward link *or* on the reverse link. This means that, in a TDD frame with a FL:RL ratio of 1:1, the maximum physical layer data rate on the FL would be *half* the value shown in the table for the given bandwidth, for the FL, at a given modulation and coding. Similarly the maximum physical layer data rate on the RL would be *half* the value in the table for the RL at the same given modulation and coding.
- More advanced options such as smart antenna technologies could further increase the bit rates, but have not been used in this analysis.

3 Potential Applications for the Airport Surface

Airport-surface wireless networks could provide the means of transporting data for fixed and mobile users in the airport environment. With terminals located on the ground, on taxiing aircraft, and on other vehicles on the airport surface, ANLE networks are envisioned to support short-range, high-data-rate applications. A preliminary set of potential applications that could be supported by an ANLE network was discussed in [1]. Additional applications have been presented in [5], and one new potential application is identified in this section. The list of potential applications is then updated. Data rate requirements have also been updated using information from [4], [6], [8], [10]. They are calculated for the two phases identified in the Communications Operating Concept and Requirements (COCR) document [10], which are Phase 1 (2020) and Phase 2 (beyond 2020). The following potential applications have been identified, and their requirements are included in the bandwidth requirements analysis described in Section 4 of this report:

- Mobile application classes
    - Airport surface data for situational awareness
    - Video streaming
    - Voice over internet protocol (VoIP) over wireless
    - Aeronautical Operational Control (AOC) data, including Electronic Flight Bag (EFB) data
    - Radio frequency identification (RFID) data
- Fixed application classes
    - Surveillance data
        - Airport Surface Detection Equipment Mode X (ASDE-X) data from remote units (RU) to the multi-processor
        - Airport Surveillance Radar (ASR) data
    - Sensor data
        - Video surveillance
        - Navigational Aids (NAVAIDS) to Terminal Radar Approach Control (TRACON)
    - 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, and TDWR data for Integrated Terminal Weather System (ITWS)

- Other data
    - ATC voice (diversity path to Remote Transmitters/Receivers (RTR))
- TRACON – (non-collocated) Air Traffic Control Tower (ATCT) data
    - Digital Bright Radar Indicator Tower Equipment (DBRITE) data
    - ITWS display data
    - Enhanced Traffic Management System (ETMS) data
    - Center-TRACON Automation System (CTAS) data
    - ATC voice (diversity path between TRACON and ATCT)
    - ASDE-X display data

Figure 3-1 shows these potential application classes at a large airport with a TRACON facility and a non-collocated ATCT.

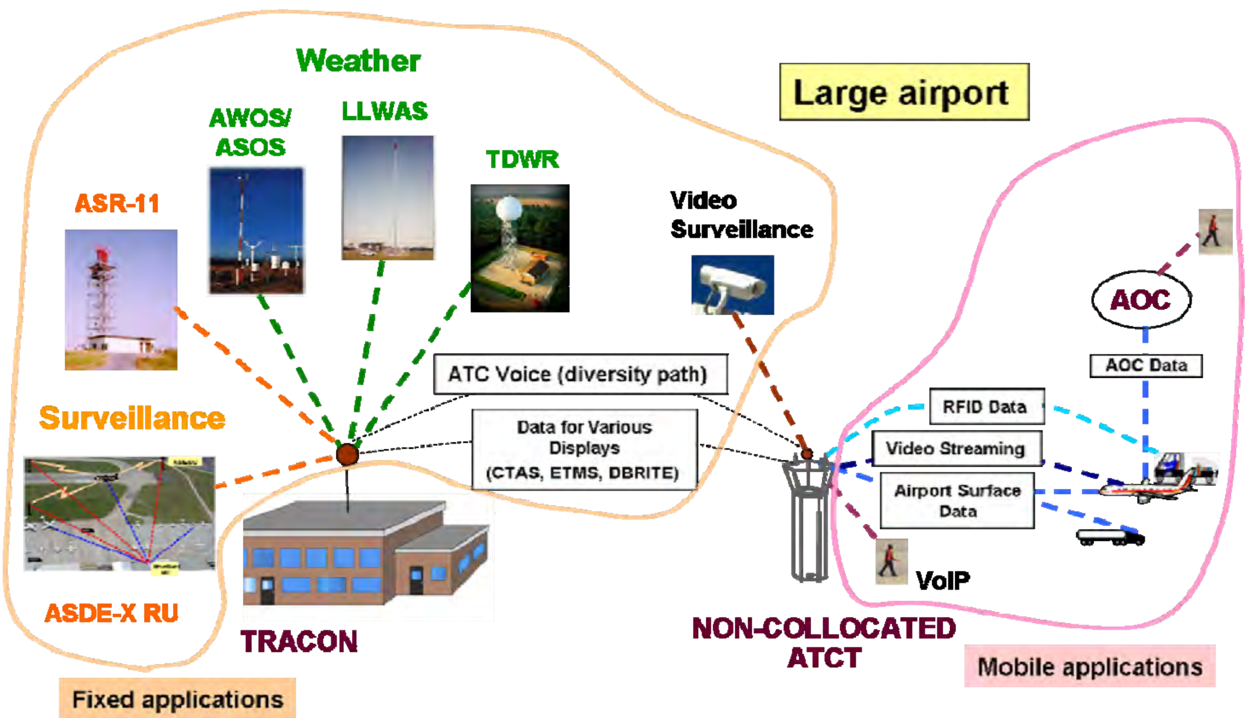

Figure 3-1. Potential Application Classes for ANLE Networks

3.1 Mobile Application Classes

The mobile application classes discussed in this section are airport surface data for situational awareness, video streaming, VoIP over wireless, AOC data (including EFB data), and RFID data. The RFID data transmission application has not been analyzed in our previous efforts. The other mobile application classes will be reviewed in this document, and updated as needed. These applications have been studied in detail in [5].

Data from [10] was used to identify the maximum number of aircraft that could be supported by mobile applications in Phases 1 and 2. Aircraft counts from a high-density (HD) airport (APT) are used in the analysis, and are shown in Table 3-1.

Table 3-1. Aircraft Counts

APT Position	Phase 1		Phase 2	
	HD	**LD**	**HD**	**LD**
Clearance/Ramp	134	4	194	7
Ground	48	3	70	4
Tower	18	5	26	8
Total	200	12	290	19

3.1.1 Airport Surface Data for Situational Awareness

The ASDE-X system provides air traffic controllers with aircraft and vehicle location on the airport surface. The ASDE-X system was discussed in detail in [1], [11], [12].

A potential application for an ANLE network is to also transmit the ASDE-X data to moving aircraft and to other vehicles on the airport surface, for improved situational awareness.

For this analysis it is assumed that the ANLE network would use the broadcast/multicast features of the IEEE 802.16e standard. The data rate requirement depends on the airport configuration. Five simultaneous transmissions are considered, with the assumption that the base stations use omnidirectional antennas. The impact of using sectoral antennas is also discussed at the end of the next section. Each transmission has a data rate requirement of 593 kilobits per second (kbps) [11]. This data rate requirement does not include any network overhead.

3.1.2 Video Streaming

The COCR document [10] states that new security services that monitor and control the physical security of aircraft are being considered; the provision of real-time video transmission from the cockpit is mentioned as one such service.

The ANLE network could provide the means of implementing this potential application. Video streaming was discussed in detail in [5], and it will be briefly discussed in this section, since it is a potential application studied after our initial work in [1].

The standard used for this potential application is described in the recommendation ITU-T H.264 [13]. The standard supports various applications such as videoconferencing, digital storage media, television broadcasting, and video streaming, by defining various profiles and levels. Characteristics for some of the levels allowed within the baseline profile of the standard, which is the recommended profile for mobile wireless applications, are shown in Table 3-2 [13], and discussed in more detail in [5]. The term macroblock used in the table, identifies a 16x16 block of pixels that are encoded/decoded in accordance with the methodology specified in the standard.

Table 3-2. Characteristics of H.264 for Video Streaming

Level					**1**	**1b**	**1.1**	**1.2**
Max frame size (Macroblocks)					99	99	396	396
Max macroblock processing rate (Macroblock/s)					1485	1485	3000	6000
Max video data rate (kbps)					64	128	192	**384**
Video Format	**Picture width (pixels)**	**Picture height (pixels)**	**Picture size (Macroblocks)**	**Picture size (samples)**	**Frames/second**			
SQCIF	128	96	48	12288	30.9	30.9	62.5	125.0
QCIF	176	144	99	25344	15.0	15.0	30.3	60.6
QVGA	320	240	300	76800	-	-	10.0	20.0
525 SIF	352	240	330	84480	-	-	9.1	18.2
CIF	352	288	396	101376	-	-	7.6	**15.2**

Level 1.2 of the baseline profile is used (shown in blue in the table) in the analysis. This means that the maximum application data rate for video streaming is 384 kbps (no overhead is included in this value). For the common intermediate format (CIF), the maximum frame rate is 15.2 frames per second, for a resolution of 352x288 pixels. This resolution is supported by currently available EFB equipment.

For this study, five simultaneous video streaming transmissions are assumed for Phase 1, and seven are assumed for Phase 2.

3.1.3 VoIP over Wireless

ANLE could support VoIP transmissions, which could be used by airport personnel to communicate on the airport surface.

This application is denoted as VoIP over wireless, to emphasize the wireless aspect of the transmission. VoIP over wireless was analyzed in detail in [5]; it will be only briefly discussed in this section, since it is a potential application studied after our initial work in [1].

The G.723.1 [14] vocoder with a data rate of 6.3 kbps (no network overhead included in this value) is widely used for VoIP-type applications in terrestrial wireless networks, and it is used in this analysis. Voice activity detection is also considered, and it is assumed that the VoIP traffic is modeled as an interrupted deterministic process with two states, ON and OFF, as discussed in detail in [5].

In this study 45 simultaneous VoIP transmissions are assumed [15].

3.1.4 AOC Data

The main AOC applications discussed in our preliminary study [1] were related to the transfer of EFB-type data that require large data transfers such as:

- Software uploading for non-safety related aircraft systems while the aircraft is at the gate
- Electronic library update to the EFB data
- Graphic weather data to the aircraft for display in the cockpit

AOC data transfer may contain information regarding aircraft status, maintenance logs, flight logs, as well as EFB-type data. All these various types of AOC data have been updated in [10], and these updated requirements are used in this study. In addition, both Phase 1 and Phase 2 data are used.

Reference [10] also identifies message sizes, duration of aircraft position at the gate, and number of aircrafts located at gates in a high-density airport. Aircraft counts for high-density and low-density (LD) airports have been presented in Table 3-1.

The data rate requirements for AOC operations are shown in Table 3-3 [10]. As previously discussed, on the forward link data is transmitted to the aircraft, and on the reverse link data is transmitted from the aircraft.

Table 3-3. AOC Data Rates (kbps) – Single Aircraft

Description		**APT Dep**	**APT Arr**
AOC - Phase 1	**FL**	8	0.3
	RL	1	1
	FL & RL	8	1
AOC - Phase 2	**FL**	40	0.3
	RL	1	1
	FL & RL	40	1

For the AOC applications modeled in this study, 200 aircraft are considered on the airport surface for Phase 1, and 290 aircraft are considered for Phase 2, for a high-density airport. The assumed data rate requirements for each aircraft for Phase 1 are: 8 kbps on the FL, and 1 kbps on the RL. Similarly, the assumed data rate requirements for each aircraft for Phase 2 are: 40 kbps on the FL, and 1 kbps on the RL. This means that the largest AOC data rate requirements from the previous table are being used in the analysis.

3.1.5 RFID Data

A potential future ANLE application is the transmission of RFID data from tag readers to a central location on the airport surface. The use of RFID tags for luggage tracking in currently being investigated [16], for increased security and efficiency at airports. In order to read such tags, hand-held readers, ramp-loader readers, as well as sortation system readers would be needed. ANLE could provide the means of transporting RFID data from hand-held readers, mobile ramp-loader readers, and universal loading devices on the airport surface.

For this analysis, it is assumed that RFID tags would contain 256 bits of information per tag for Phase 1, and 2048 bits per tag for Phase 2 [17]. Data storage capacity of up to 64 kbits per tag could be available in the time frame identified by Phase 2 (beyond 2020) [17]. For this analysis, 1500 tags per aircraft are assumed for both phases.

Other possible future applications of RFID technology that are not considered in this study are ticket matching to luggage tags [16] and maintenance applications at airports [18], [19].

3.2 Fixed Application Classes

Data rate requirements for the various fixed applications have been obtained primarily from references [11], [20] and [21]. Reference [11] analyzed various types of applications at Dallas/Forth Worth (DFW) and identified the numbers of subscriber 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 [11] as an approximate upper bound on the expected number of fixed stations that might be served by a wireless broadband network at a single airport. These applications and data rate requirements have been discussed in detail in [1].

The video surveillance application was identified and studied in detail in [5], therefore after our initial work. It will be briefly discussed in this section.

3.2.1 Video Surveillance

Video surveillance is a potential fixed application that could be supported by an ANLE network; it could be used to improve airport security. It was discussed in detail in [5].

The Motion JPEG 2000, also known as MJPEG2000 is a standard described in ITU-T recommendation T.802 [22]. A MJPEG2000-based video surveillance camera using image sizes of 640x480 pixels are assumed, and a frame rate of 8 frames per second, would require an application data rate of 1.97 Mbps [5]. This data rate does not include any network overhead.

The H.264 standard was also described in detail in [5], and characteristics of the various levels within the baseline profile are shown in Table 3-4 [13].

Table 3-4. Characteristics of H.264 for Video Surveillance

Level					**1.3**	**2**	**2.1**	**2.2**
Max frame size (Macroblocks)					396	396	792	1620
Max macroblock processing rate (Macroblocks/s)					11880	11880	19800	20250
Max video data rate (kbps)					768	2000	4000	**4000**
Video Format	**Picture width (pixels)**	**Picture height (pixels)**	**Picture size (Macroblocks)**	**Picture size (samples)**	**Frames/second**			
CIF	352	288	396	101376	30.0	30.0	50	51.1
525 HHR	352	480	660	168960	-	-	30	30.7
625 HHR	352	576	792	202752	-	-	25	25.6
VGA	640	480	1200	307200	-	-	-	**16.9**

As can be seen in Table 3-4, for a video surveillance application using level 2.2 (highlighted in blue), and for the video graphics array (VGA) format, the maximum frame rate is 16.9 frames per second, and the maximum data rate is 4 Mbps (without any network overhead). The VGA video format is characterized by a picture resolution of 640x480 pixels. However, a frame rate of 8.45 frames per second is assumed for this analysis, such that the required application data rate is 2 Mbps. This value is very similar to the data rate requirement obtained for the MJPEG2000 example, so the 2 Mbps data rate is used for video surveillance applications. No network overhead is included in this value.

It is assumed that up to 10 simultaneous video surveillance transmissions could occur on the airport surface at a large airport [5].

3.3 Summary of Potential Applications

Table 3-5 shows a summary of the potential application classes and their data rate requirements for the Phase 1 implementation, which is expected to be complete around 2020. Table 3-6 shows a summary of the potential application classes and their data rate requirements for Phase 2 (beyond 2020) implementation.

The differences between the tables describing Phase 1 and Phase 2 implementations are observed for the mobile applications, due to the increase in aircraft counts identified in [10] and also due to increases in data rate requirements for the AOC and RFID applications. The data rate requirements and number of sensors for the fixed applications are assumed to be the same in Phases 1 and 2.

Table 3-5. Summary of Potential Applications for Phase 1

Application Class Description	Estimated Data Rate (kbps) [1]	Estimated Maximum Number Per Airport	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)
Mobile Applications					
Airport Surface Data to Mobile Users	619.1	5 [2]	3095.5	3095.5	
Video Streaming	449.4	5	2247		2247
VoIP	23.4	45	1053	526.5	526.5
AOC Data (includes EFB)	9.0	200	1800	1600	200
RFID Data	0.5	134	67		67
Fixed Applications					
Surveillance Data					
ASR-11	352.5	2	705		705
ASDE-X RU to ASDE-X processor	78.1	10	781		781
Sensor Data					
Video Surveillance	2044	10	20440		20440
NAVAIDS to TRACON	839.4	4	3357.6		3357.6
Weather Data					
LLWAS	11.7	32	374.4		374.4
AWOS/ASOS	23.4	1	23.4		23.4
TDWR	182.7	1	182.7		182.7
TDWR Data for ITWS	1578	1	1578		1578
Other Data					
ATC Voice (Diversity) (RTR tx)	1578	4	6312	3156	3156
TRACON – ATCT Data					
DBRITE video to ATCT	1578	4	6312	6312	
ITWS Display	267.3	2	534.6	534.6	
CTAS to ATCT	534.5	6	3207	3207	
ETMS to ATCT	267.3	2	534.6	534.6	
ATC Voice (Diversity)	1578	4	6312	3156	3156
ASDE-X Display	619.1	3	1857.3	1857.3	
Total Estimated Data Rates (kbps)			**60774.1**	**23979.5**	**36794.6**

Notes:
(1) Network overhead is considered.
(2) Value is implementation dependent; it is assumed for omnidirectional antennas at a large airport (DFW).

Table 3-6. Summary of Potential Applications for Phase 2

Application Class Description	Estimated Data Rate (kbps) [1]	Estimated Maximum Number Per Airport	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)
Mobile Applications					
Airport Surface Data to Mobile Users	619.1	5 [2]	3095.5	3095.5	
Video Streaming	449.4	7	3145.8		3145.8
VoIP	23.4	45	1053	526.5	526.5
AOC Data (includes EFB)	41.0	290	11890	11600	290
RFID Data	2.2	194	426.8		426.8
Fixed Applications					
Surveillance Data					
ASR-11	352.5	2	705		705
ASDE-X RU to ASDE-X processor	78.1	10	781		781
Sensor Data					
Video Surveillance	2044	10	20440		20440
NAVAIDS to TRACON	839.4	4	3357.6		3357.6
Weather Data					
LLWAS	11.7	32	374.4		374.4
AWOS/ASOS	23.4	1	23.4		23.4
TDWR	182.7	1	182.7		182.7
TDWR Data for ITWS	1578	1	1578		1578
Other Data					
ATC Voice (Diversity) (RTR tx)	1578	4	6312	3156	3156
TRACON – ATCT Data					
DBRITE video to ATCT	1578	4	6312	6312	
ITWS Display	267.3	2	534.6	534.6	
CTAS to ATCT	534.5	6	3207	3207	
ETMS to ATCT	267.3	2	534.6	534.6	
ATC Voice (Diversity)	1578	4	6312	3156	3156
ASDE-X Display	619.1	3	1857.3	1857.3	
Total Estimated Data Rates (kbps)			**72122.7**	**33979.5**	**38143.2**

Notes:
(1) Network overhead is considered.
(2) Value is implementation dependent; it is assumed for omnidirectional antennas at a large airport (DFW).

Only the main data traffic direction is shown in Tables 3-5 and 3-6 (and assumed in the analysis presented in Section 4). For example, sensor information is considered as reverse link traffic only; the forward link traffic for network control purposes is not considered. Similarly, for display-type data, transfers are considered forward link only, although there will also be some reverse link traffic (for example, to support channel estimation). A more detailed analysis is needed to refine the traffic distribution between the forward and reverse links.

The data rates shown in these tables also take into account the network overhead, including the MAC layer overhead. No header compression is assumed in these calculations; therefore the data rate requirements are conservative estimates. These data rates do not include the physical layer overhead (i.e., the overhead inside the frame structure), which will be studied as part of the bandwidth requirements analysis presented in the next section.

The total aggregate estimated data rate needed to support the identified potential applications is about 60.8 Mbps for Phase 1 implementation, and about 72.1 Mbps for Phase 2 implementations, as can be seen in Tables 3-5 and 3-6.

4 Spectral Requirements Estimation

The methodology of estimating the spectral requirements of an ANLE network is presented in this section. This methodology is then applied to the set of possible applications identified in Section 3, with their data rate requirements evaluated for Phases 1 and 2. The following assumptions are used in developing the methodology:

- The IEEE 802.16e OFDMA implementation is used
  - PUSC is used, since it is mandatory in the OFDMA frame.
- The physical layer parameters are as defined in Section 2.
- All subscriber stations (fixed and mobile) are uniformly distributed around the airport area.
- The propagation path loss exponent is 2.3 [23].
- No repetition coding is assumed.

4.1 Average Physical Layer Data Rates

In order to evaluate average physical layer data rates, the effects of adaptive modulation need to be taken into account. Adaptive modulation and coding allow a network to adjust the signal modulation scheme on the basis of the received SNR. This means that a higher-order modulation is assumed for subscriber stations close to the base station (i.e., higher SNR). A higher order modulation allows for higher data rates as shown by the analysis presented in Section 2, and the results summarized in Tables 2-3 and 2-4.

The IEEE 802.16e standard discusses seven modulation and coding pairs, from QPSK with a coding rate ½, to 64-QAM with a coding rate ¾, as shown in Tables 2-3 and 2-4. The associated SNR value is also shown in the tables for each modulation and coding pair. An illustration of the adaptive modulation concept is shown in Figure 4-1.

For this analysis, it is assumed that at the edge of the coverage area (shown notionally as a circle of radius d_1), the minimum SNR is met for decoding QPSK ½. This minimum SNR is denoted as SNR_1. At distance d_i, the SNR value is SNR_i. If noise power is assumed constant throughout the coverage area, the following equation holds:

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

where:

d_1 = distance to the edge of the coverage area

$\Delta SNR(i) = SNR_i - SNR_1$

n = path loss exponent (assumed to be 2.3)

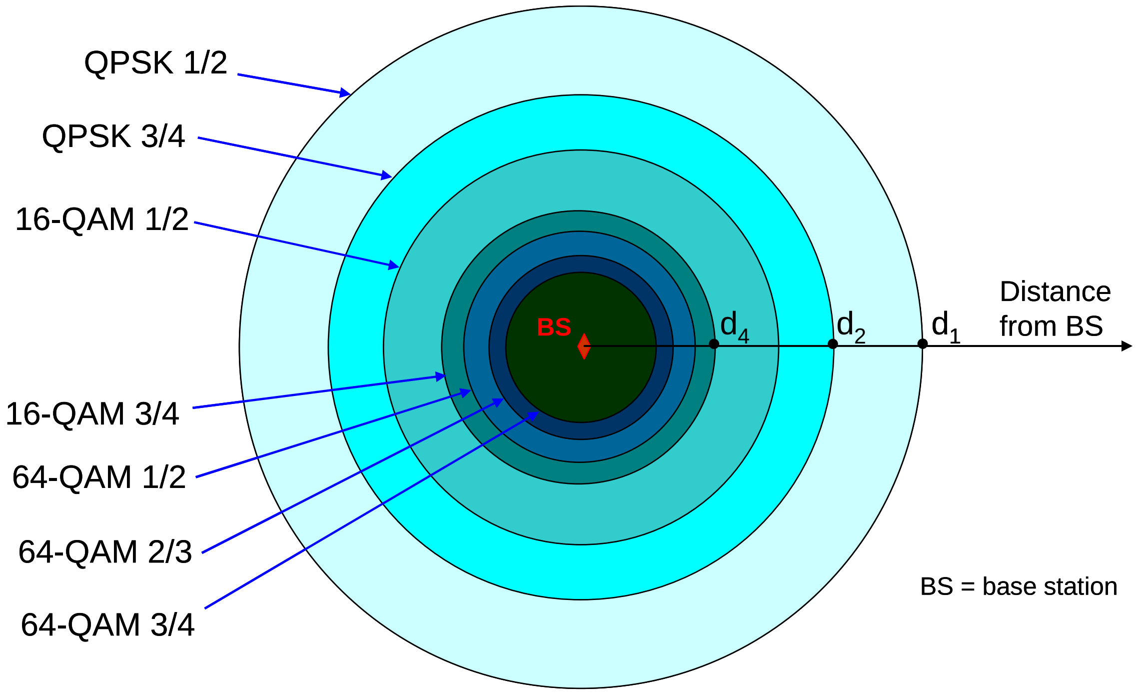

Figure 4-1. Adaptive Modulation Illustration

Assuming that the subscriber stations are uniformly distributed in the coverage area, the probability that a subscriber station is using modulation type *i* is:

$$P_i = 10^{\frac{-2\Delta SNR(i)}{10n}} - 10^{\frac{-2\Delta SNR(i+1)}{10n}} \qquad \text{for i=1...6}$$

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

Table 4-1 shows the probabilities calculated for the seven modulation types, and for a path loss exponent *n* of 2.3.

Table 4-1. 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	0.05
64-QAM	1/2	5	0.33	0.04
	2/3	6	0.27	0.02
	3/4	7	0.22	0.05

To further estimate the impact of simultaneous transmissions, the average data rate takes into account the number of subchannels for each modulation type (*i*) on both the forward and reverse links. On the reverse link, these simultaneous transmissions can occur from aircraft and/or other sensors on the airport surface. This is due to the fact that the total number of subchannels can be divided among various aircraft transmitting at the same time (i.e, during the same OFDMA symbol duration). This can be seen in the OFDMA frame structure shown in Figure 2-3, as well as the description of the OFDMA subcarrier allocations [4]. Similarly, on the forward link, data on different subchannels can be sent simultaneously from the base station to various groups of users, as needed, and it also can be seen in the OFDMA frame structure shown in Figure 2-3.

$$R_{davg}^{(FL)} = \sum_{i=1}^{7} R_{di}^{(FL)} N_{sch}^{(i)(FL)} / N_{Tsch}^{(FL)}$$

where:

$$N_{sch}^{(i)(FL)} = \begin{cases} N_{Tsch}^{(FL)} - \sum_{i=2}^{7} N_{sch}^{(i)(FL)} & \text{for } i = 1 \\ round(P_i N_{Tsch}^{(FL)}) & \text{for } i = 2 \ldots 7 \end{cases}$$

and:

$N_{Tsch}^{(FL)}$ = total number of subchannels on the FL

$R_{di}^{(FL)}$ = physical layer data rate on the FL for modulation type (*i*)

Similarly:

$$R_{davg}^{(RL)} = \sum_{i=1}^{7} R_{di}^{(RL)} N_{sch}^{(i)(RL)} / N_{Tsch}^{(RL)}$$

where:

$$N_{sch}^{(i)(RL)} = \begin{cases} N_{Tsch}^{(RL)} - \sum_{i=2}^{7} N_{sch}^{(i)(RL)} & \text{for } i = 1 \\ round(P_i N_{Tsch}^{(RL)}) & \text{for } i = 2 \ldots 7 \end{cases}$$

and:

$N_{Tsch}^{(RL)}$ = total number of subchannels on the RL

$R_{di}^{(RL)}$ = physical layer data rate on the RL for modulation type (i)

Using the results shown in Table 2-3 for the physical layer data rates, and the methodology described above, the following average physical layer data rates are obtained for an ANLE network with a channel bandwidth of 20 MHz:

$$R_{davg}^{(FL)} = 21.12\ Mbps$$

$$R_{davg}^{(RL)} = 16.13\ Mbps$$

Similarly, using the results shown in Table 2-4 for the physical layer data rates, and the methodology described above, the following average physical layer data rates are obtained for an ANLE network with a channel bandwidth of 10 MHz:

$$R_{davg}^{(FL)} = 10.67\ Mbps$$

$$R_{davg}^{(RL)} = 8.20\ Mbps$$

4.2 Spectral Requirements Estimation Methodology

The following additional assumptions are used in developing the spectral requirements estimation methodology:

- The IEEE 802.16e broadcast/multicast features of the standard will be used to transmit the airport surface data to mobile users on the airport surface.
- This broadcast application is transmitted at the lowest modulation (i.e, QPSK ½), and therefore its data rate requirement is separated from the rest of the FL data.

The spectral efficiencies for the data transmissions on the FL and RL are calculated using the average physical layer data rates obtained in the previous subsection. The spectral efficiency for the broadcast transmission is also evaluated, using the corresponding data rate for the transmission (i.e., the FL data rate for the QPSK ½ modulation).

$$S_{EFFd}^{(FL)} = \frac{R_{davg}^{(FL)}}{BW}$$

$$S_{EFFd}^{(RL)} = \frac{R_{davg}^{(RL)}}{BW}$$

$$S_{EFFd}^{(FL)(bc)} = \frac{R_{d}^{(FL)(bc)}}{BW}$$

$$BW_{Tavg}^{(req)} = ceil\left(\left(\frac{R_{dreq}^{(FL)(bc)}}{n_s S_{EFFd}^{(FL)(bc)}} + \frac{R_{dreq}^{(FL)} - R_{dreq}^{(FL)(bc)}}{S_{EFFd}^{(FL)}} + \frac{R_{dreq}^{(RL)}}{S_{EFFd}^{(RL)}}\right) / \left(\rho_{ch} BW\right)\right) BW$$

where:

$S_{EFFd}^{(FL)}$ = spectral efficiency of data transmission on the forward link

$S_{EFFd}^{(RL)}$ = spectral efficiency of data transmission on the reverse link

$S_{EFFd}^{(FL)(bc)}$ = spectral efficiency of data broadcast on the forward link

$R_{dreq}^{(FL)}$ = data rate requirement on the forward link to support the identified applications

$R_{dreq}^{(RL)}$ = data rate requirement on the reverse link to support the identified applications

$R_{dreq}^{(FL)(bc)}$ = data rate requirement on the forward link to support the broadcast application (i.e., airport surface data transmission to mobile users)

$R_{davg}^{(FL)}$ = average physical layer data rate on the forward link

$R_{davg}^{(RL)}$ = average physical layer data rate on the reverse link

$R_{d}^{(FL)(bc)}$ = physical layer data rate used for broadcast on the forward link (i.e., QPSK ½ for our analysis)

BW = channel bandwidth (for each carrier frequency)

n_s = number of sectors/cell

ρ_{ch} = channel loading factor

The parameter ρ_{ch} models the effect of channel loading (also denoted as channel utilization) on the bandwidth requirements. A theoretical value of 1 would represent a fully loaded case. However, due to stochastic fluctuations in traffic, lower loading values are assumed in analyses [24], [25]. Values no higher than 0.7-0.8 have been considered in order to keep packet response times at acceptable levels [25].

For the calculations performed in this section, a value of 0.75 is assumed as an example. However, further modeling and simulation efforts, as well as measurements, are needed to determine the applicable range for this parameter for aeronautical applications.

Table 4-2 shows the estimated spectral requirements for an ANLE network $BW_{Tavg}^{(req)}$ at a large airport (DFW) that would support the set of applications presented in Section 3. Two different channel bandwidths are used: 20 MHz and 10 MHz. As previously mentioned, the airport surface data transmission is envisioned to be implemented by using the broadcast/multicast features of the standard. For the 20-MHz bandwidth case, it is assumed that the base stations would have omnidirectional antennas. For the 10-MHz bandwidth case, it is assumed that the base stations would be sectorized (with 3 sectors for each base station) [5]. At a large airport (DFW) five base stations are assumed. For the sectorized base stations, the airport surface data is transmitted in each sector. Therefore, higher data rate requirements are obtained for the 10-MHz bandwidth case with sectorized base stations (for both Phase 1 and Phase 2).

Table 4-2. Spectral Requirements Estimates

COCR Implementation Phase	**Channel BW = 20 MHz**		**Channel BW = 10 MHz**	
	Maximum Estimated Data Rate (Mbps) for a Large Airport (1)	Estimated Spectral Requirements (MHz)	Maximum Estimated Data Rate (Mbps) for a Large Airport (2)	Estimated Spectral Requirements (MHz)
Phase 1 (2020)	60.8	100	67.0	100
Phase 2 (beyond 2020)	72.1	120	78.3	110

NOTES:
(1) Value is implementation-dependent; it is assumed for omnidirectional antennas at a large airport (DFW).
(2) Value is implementation-dependent; it is assumed for sectoral antennas at a large airport (DFW).

Estimated spectral requirements of at least 100 MHz have been obtained for ANLE networks at large airports that would support the set of applications described in Section 3. Higher values are needed for Phase 2 (beyond 2020), as can be seen in the table above. These values exceed the amount of spectrum currently available for such networks in the 5091-5150 MHz band.

4.3 Observations

- The spectral requirements derived above are considered conservative estimates, since all subscriber stations were assumed uniformly distributed on the airport surface. This assumption was used in calculating the average data rates on the forward and reverse links. Higher data rates could be obtained for fixed subscribers, so the spectral efficiency of the network could improve. Also the advanced features of the IEEE 802.16e standard, such as smart antenna technologies, were not used in the analysis. Their use is also expected to improve the spectral efficiency of the network.
- The broadcast/multicast features in the IEEE 802.16e standard may have an impact on the frame structure and overhead, which should be analyzed in detail in future work.
- The parameters used to determine the physical layer data rates are based on the assumptions used in [8] by the Worldwide Interoperability for Microwave Access (WiMAX) forum. Modeling and simulations are needed to validate these assumptions for ANLE networks supporting aeronautical applications.
- ANLE spectral requirements are scenario-specific. The methodology used in this report to evaluate spectral requirements at DFW should be applied to other application scenarios as well.

- Detailed analyses are needed to determine data traffic at airports. As an initial step, the methodology developed in [5] should be used at a large airport for two scenarios. One would use base stations with omnidirectional antennas; the other would use base stations with sectoral antennas, and all other parameters would remain fixed across these scenarios. The impact of the antenna types on the traffic analysis results could then be analyzed in detail. The next step would be the development of more refined traffic models for the aeronautical environment.
- The impact of the channel loading factor should be analyzed in detail, through modeling and simulation, by using traffic models for the aeronautical applications.
- Additional applications could be identified in the future, such as additional RFID applications, other sensor applications, or future unmanned aircraft systems' transmissions on the airport surface. The list of potential applications would need to be updated, but the same methodology could be used to evaluate the spectral requirements.

5 Concluding Remarks

5.1 Findings

The OFDMA implementation of the IEEE 802.16e-2005 standard has been used in this study to evaluate the spectral requirements of an ANLE network at a large airport (DFW). The main physical layer parameters of the OFDMA implementation are discussed in Section 2, where the maximum physical layer data rates have been evaluated for two channel bandwidths: 20 MHz and 10 MHz.

A set of potential applications for ANLE networks is discussed in Section 3, where data rate requirements for these applications have been evaluated for two potential implementation phases: Phase 1 (2020) and Phase 2 (beyond 2020).

Average physical layer data rates have been evaluated using adaptive modulation considerations in Section 4. This evaluation also took into account the impact of aircraft transmissions by considering the number of subchannels for each modulation type identified in the standard. Estimated spectral requirements of at least 100 MHz were obtained for an ANLE network at DFW, as described in Section 4.

5.2 Recommended Future Work

Recommended areas of further study regarding the potential implementation of ANLE networks using the IEEE 802.16e standard are as follows:

- The advanced features of the IEEE 802.16e standard, such as the support of smart antenna technologies, have not been used in this analysis. These features should be used in future simulation and modeling efforts. Their use is expected to improve the spectral efficiency of the network.
- The characteristics of broadcast/multicast features in the IEEE 802.16e standard need to be further studied. Their impact on the frame structure and overhead need to be analyzed in detail.
- ANLE spectral requirements are scenario-specific. The methodology used in this report to evaluate spectral requirements at DFW should be applied to other application scenarios as well.
- Detailed analyses are needed to evaluate data traffic at airports. As an initial step, the methodology developed in [5] should be used to evaluate traffic loading using the list of potential applications discussed in this report. The next step would be the development of more refined traffic models for the aeronautical environment.

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Appendix A Glossary

ANLE	Airport Network and Location Equipment
AOC	Aeronautical Operational Control
APT	Airport
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
BW	bandwidth
BWA	broadband wireless access
CAASD	Center for Advanced Aviation System Development
CIF	common intermediate format
COCR	Communications Operating Concept and Requirements
CTAS	Center-TRACON Automation System
dB	decibel
DBRITE	Digital Bright Radar Indicator Tower Equipment
DFW	Dallas Fort Worth
DL	downlink
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
FL	forward link
GHz	gigahertz
HD	high-density
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITWS	Integrated Terminal Weather System
kbps	kilobits per second
LD	low-density
LLWAS	Low Level Wind Shear Alert System
MAC	medium access control
Mbps	megabytes per second
MHz	megahertz
MJPEG2000	Motion Joint Photographic Experts Group 2000, or Motion JPEG 2000
NAVAIDS	Navigational Aids
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PHY	physical layer
PUSC	partial usage of subchannels

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RF	radio frequency
RFID	RF identification
RL	reverse link
RTG	receive/transmit transition gap
RTR	Remote Transmitters/Receivers
RU	remote unit
SNR	signal to noise ratio
TDD	time division duplex
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control facility
TTG	transmit/receive transition gap
UL	uplink
UL-MAP	uplink map
VGA	video graphics array
VoIP	Voice over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access