Abstract
The future airport surface communication system, called AeroMACS, shall be based on the IEEE 802.16 standard, in particular on the "WiMAX Mobile System Profile Specification". In the course of the SANDRA project the IEEE standard and the WIMAX mobile profile have been investigated and different configuration options have been evaluated. This paper presents an overview of options related to data exchange and possibilities how to integrate an AeroMACS system into an IPS based communication network. Furthermore, selected results from a performance evaluation study are shown.

Introduction
The future Air Traffic Management (ATM) concept shall be based on network centric operations, consequently on information sharing. In order to support such a vision not only a versatile and capable ground based communication network is necessary but also a network which includes the air to ground sub-networks which shall have sufficient capacity and capability. One such air to ground sub-network shall be established for the airport surface intended to be used by departing and arriving aircraft as well as by surface vehicles. This communication system is currently (2011) emerging and shall be called Aeronautical Mobile Airport Communications System (AeroMACS). AeroMACS shall be based on the IEEE 802.16-2009 standard [1] and especially on the WiMAX Forum™ Mobile System Profile Specification rel1.0 v0.9 [2]. A draft profile has been developed and is being evaluated currently, e.g. in the EU research project SANDRA [3].

The IEEE 802.16-2009 standard [1] specifies the air interface of combined fixed and mobile point to multipoint broadband wireless access systems with the possibility to support different services. The standard specifies the Medium Access Control (MAC) and the Physical (PHY) layer, where the MAC is capable to support multiple PHY specifications applicable to a specific operational environment. The Service Specific Convergence Sub-layer (CS) accepts service data units (SDU) from higher layers via the CS service access point (SAP). Thereby, the CS classifies each SDU according to available policies and maps each SDU to a so called service flow identifier. The IEEE 802.16 standard provides multiple CS specifications in order to provide interfaces for a variety of higher layer protocols. The MAC Common Part Sub-layer (CPS) provides the core functionality for data exchange via the wireless medium. A separate security sub-layer is also available. Generally, the IEEE 802.16-2009 standard provides a large amount of options. Thereby, different options may fit better for certain use cases than others. Due to the large amount of options it is merely impossible to be interoperable among different vendors based on the sole standard. Additional documentation and specification is necessary. This task has been conducted by the WiMAX Forum™. This group specifies so called "WiMAX profiles" where a selected set of options from the IEEE 802.16 standard is qualified for such a profile.

The WiMAX Forum™ has been established in June 2001 and is an industry led not for profit organization. The purpose of the WiMAX forum™ is to certify compatibility and interoperability of broadband wireless products based on the IEEE 802.16 standard. In such a way rapid introduction of technology and market competition shall be enforced. The WiMAX Forum™ has many members comprising the majority of operators and equipment vendors.

The WiMAX Forum is organized into several working groups, one of them is the Technical Working Group (TWG), which develops technical product specifications and certification test suites for the air interface based on the OFDMA PHY. Such specifications are complementary to the IEEE 802.16 standards in order to achieve interoperability and certification of mobile stations and base stations conforming to the 802.16 standards. The TWG has produced a “Mobile System Profile Specification” which determines mandatory and optional functions.

for AeroMACS is being specified through standardization bodies such as EUROCAE and RTCA. This draft profile is further evaluated by members of the SESAR Joint Undertaking and by members of the SANDRA project. The tentative AeroMACS draft profile is further a subset of the WiMAX Forum™ Mobile System Profile Specification. Within this paper an overview of the core functionalities related to data exchange are given.

This paper discusses AeroMACS profile items related to data exchange mechanisms and the integration of such a sub-network into an IPS based aeronautical network (i.e. IPS/ATN). A chapter briefly discusses the expected data traffic which would be delivered via an AeroMACS system. Selected results from a performance evaluation campaign are presented and discussed at the final chapter. Eventually the paper finishes with concluding remarks.

AeroMACS Profile Overview

The WiMAX Forum™ Mobile System Profile Specification [2] represents a subset of the IEEE 802.16 standard [1]. Currently (2011) a draft profile for AeroMACS is being specified through standardization bodies such as EUROCAE and RTCA. This draft profile is further evaluated by members of the SESAR Joint Undertaking and by members of the SANDRA project [3]. The tentative AeroMACS draft profile is further a subset of the WiMAX Forum™ Mobile System Profile Specification.

Physical Layer

The Physical Layer (PHY) of the AeroMACS system shall be based on the OFDMA Physical Layer specification of the IEEE 802.16 standard with a channel bandwidth of 5 MHz. Thereby, the frame length shall be 5 ms. As the PHY will be based on the "Common part TDD profile" [4], the Downlink and Uplink portions can vary dependent on the system settings. The IEEE 802.16-2009 supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) modes. However, AeroMACS shall be based on the TDD mode of operation. Reasons therefore are the dynamic allocation of Downlink (i.e. from base station to mobile station) and Uplink (i.e. from mobile station to base station) resources in order to efficiently support asymmetric Downlink (DL)/Uplink (UL) traffic, only a single channel is required which alleviates spectrum issues, and the TDD options is less complex.

The DL subframe and the UL subframe consist of a number of OFDM symbols where a reasonable setting could be to have 29 OFDM symbols for the DL and 18 OFDM symbols for the UL (Table 1 and Table 2 show possible data rates with different coding and modulation schemes). However, the individual setting is dependent on the service provider. Valid values can be taken from the WiMAX Forum™ Mobile System Profile Specification TDD Specific Part [4].

### Table 1. Possible DL Data Rates

<table>
<thead>
<tr>
<th></th>
<th>QPSK</th>
<th>16 QAM</th>
<th>64 QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 1/2</td>
<td>2,016 Mbit</td>
<td>3,859 Mbit</td>
<td>6,048 Mbit</td>
</tr>
<tr>
<td>CC 2/3</td>
<td>2,572 Mbit</td>
<td>5,376 Mbit</td>
<td>8,064 Mbit</td>
</tr>
<tr>
<td>CC 3/4</td>
<td>3,024 Mbit</td>
<td>6,048 Mbit</td>
<td>9,072 Mbit</td>
</tr>
<tr>
<td>CC 5/6</td>
<td>3,360 Mbit</td>
<td>6,720 Mbit</td>
<td>10,08 Mbit</td>
</tr>
</tbody>
</table>

### Table 2. Possible UL Data Rates

<table>
<thead>
<tr>
<th></th>
<th>QPSK</th>
<th>16 QAM</th>
<th>64 QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 1/2</td>
<td>0,979 Mbit</td>
<td>1,958 Mbit</td>
<td>(2,9 Mbit)</td>
</tr>
<tr>
<td>CC 2/3</td>
<td>1,305 Mbit</td>
<td>2,611 Mbit</td>
<td>(3,9 Mbit)</td>
</tr>
<tr>
<td>CC 3/4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC 5/6</td>
<td>1,632 Mbit</td>
<td>3,264 Mbit</td>
<td>(4,9 Mbit)</td>
</tr>
</tbody>
</table>

The standard supports multiple schemes for dividing the time & frequency resources among users, this may also be called sub-channelization. AeroMACS shall be based on the pseudo-random permutation for frequency diversity (i.e. PUSC). The available spectrum has to be utilized by the resource scheduler through an integer number of DL and UL slots, respectively. A slot is a logical n x m rectangle where n is the number of sub-carriers and m is the number of contiguous OFDM symbols. All slots, no matter which sub-channelization scheme is being used, contain 48 data symbols. Thereby, a DL slot consists of 2 OFDM symbols and 28 subcarriers. As the total usable amount of subcarriers is 420 for the DL, this results in 210 usable DL slots per 5 ms.
frame in the downlink direction (considering 28 OFDM symbols plus 1 OFDM symbol used for the DL Prefix). In contrast a UL slot consists of 3 OFDM symbols and 24 subcarriers. For the uplink direction the total usable amount of subcarriers is 408, consequently there are 102 usable UL slots per 5 ms frame in the uplink direction (assuming 18 OFDM symbols).

Dependent on the coding and modulation scheme different throughput can be achieved. The modulation schemes are QPSK and 16 QAM for both directions as well as 64 QAM for the DL direction. 64 QAM is still an option for the UL direction. Dependent on the robustness of the coding scheme different theoretical throughput values can be achieved.

A broad range of combinations exists, however, most likely is a combination with robust coding (i.e. convolution code (CC) with rate 1/2) with modulation of QPSK or 16 QAM for the UL and 16 QAM or 64 QAM for the DL.

Each 5 ms AeroMACS frame starts with a DL Prefix which occupies one entire OFDM symbol. The Frame Control Header (FCH) follows immediately the DL Prefix and contains information about the following DL Map. The DL Map and the UL Map are important management elements which tell the Mobile Stations (MSs) how the upcoming frame is to be used to exchange either data or management information. The mentioned elements of DL Prefix, FCH, DL Map, and UL Map appear in each DL subframe. The UL direction needs to schedule ranging opportunities for Mobile Stations in order to keep synchronized with the Base Station and in order to request bandwidth if a MS needs to do so. The remaining bandwidth may be used to transmit user data.

Medium Access Control

The IEEE 802.16 standard specifies a point to point and connection oriented link, i.e. each Service Data Unit (SDU) received from an interfacing higher layer is mapped to a unique and unidirectional service flow with specific quality of service (QoS) parameters. Thereby, the interfacing higher layer can be one of several different types.

The MAC common part sub-layer operates in a point to multipoint environment. The Base Station is the only user of the Downlink (DL) resources, whereas the Mobile Stations have to share the Uplink (UL) resources. All Mobile Stations are able to receive DL transmissions. Based on the Connection Identifier (CID) carried within the generic MAC header of each MAC PDU a MS is able to determine whether a MAC PDU is destined to it or not.

A central concept of the IEEE 802.16 standard is the usage of transport connections which allows the utilization of Quality of Service (QoS) at MAC level. Each service flow has specific QoS parameters initialized at connection setup. Thereby, different data delivery strategies can be utilized (e.g. best effort, polling, etc.).

At system initialization two pairs of management connections, namely the basic connection and the primary management connection, have to be established between the MS and the BS. A third management connection, the secondary management connection, may be established, too. However, such a connection is only mandatory for managed "subscriber stations". In certain circumstances especially if remote airport equipment is being used such a secondary management connection would probably make sense. However, the basic management connection shall be used to transmit short and time urgent MAC management messages while the primary management connection shall be used to exchange longer and delay tolerant MAC management messages.

Automatic Repeat Request (ARQ)

Usually, Automatic Repeat Request (ARQ) protocols are used to synchronize data flows between sending and receiving entities. Thereby, the flow control procedure takes care that the data source is not overloading the data sink. Also erroneous data packets are indicated to the source (through negative acknowledgments).

The IEEE 802.16 standard offers four different types of ARQ, namely, go-back-n, selective-reject, and two combinations of go-back-n and selective-reject. Go-back-n may also be called as cumulative ARQ. An ARQ information element has at least a size of 4 byte and at most of 12 byte. The basic components of an ARQ information element are the connection identifier field and the block sequence number (BSN) field. The CID identifies the transport
connection and the BSN is differently used dependent on the ARQ type.

The ARQ protocol of the IEEE 802.16 standard is based on ARQ blocks, which all have a size of ARQ_BLOCK_SIZE in byte. An exception may only be for the last ARQ block of an SDU which may be smaller. Each incoming SDU from a higher layer is logically divided into a number of ARQ blocks. Thereby, each ARQ block gets a Block Sequence Number (BSN). Compare Figure 1 which is showing an example with ARQ_BLOCK_SIZE set to 32 byte and a sequence of three arriving SDU with a size of 90, 10, and 64 byte.

<table>
<thead>
<tr>
<th>SDU 1</th>
<th>SDU 2</th>
<th>SDU 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(90 byte)</td>
<td>(10 byte)</td>
<td>(64 byte)</td>
</tr>
<tr>
<td>block 1 (32 byte)</td>
<td>block 2 (32 byte)</td>
<td>block 3 (26 byte)</td>
</tr>
<tr>
<td>block 4 (10 byte)</td>
<td>block 5 (32 byte)</td>
<td>block 6 (32 byte)</td>
</tr>
</tbody>
</table>

Figure 1. Mapping of SDUs to ARQ Blocks

ARQ Acknowledgement Types

Acknowledgment type 0 (i.e. selective ACK entry) contains up to 4 fixed length acknowledgment maps. The length of such a map is 16 bits where each bit indicates whether a corresponding ARQ block has been received successfully (i.e. bit is set) or not (i.e. bit is not set). When using the selective ACK entry option the BSN corresponds to the first bit of the following acknowledgement map. It is important to realize that such an acknowledgement type is only applicable if more than or equal to 16 ARQ blocks have been received without prior sent acknowledgment. However, the BSN may be shifted backward in order to circumvent this issue (i.e. certain ARQ blocks will be acknowledged twice, which does not influence the protocol performance).

Acknowledgment type 1 (i.e. cumulative ACK entry) uses the BSN to cumulatively acknowledge all ARQ blocks received. This acknowledgement type has a fixed size of 4 byte.

Acknowledgment type 2 (i.e. cumulative with selective ACK entry) is a combination of acknowledgment type 0 and type 1. In this case the BSN is interpreted as cumulative acknowledgment and the first bit of the following map is set - the remaining bits of the map can be used as in type 0.

Acknowledgement type 3 (i.e. cumulative with block sequence ACK entry) is a combination of type 1 and a series of sequence ACK maps. The BSN acknowledges all correctly received ARQ blocks cumulatively. The sequence ACK map contains either two sequences with a length given in 6 bit or three sequences with a length given in 4 bit. Thereby, each sequence specifies a number of consecutive BSN entries, with the first sequence starting at the cumulative BSN plus one (which is always a negative acknowledgment; otherwise the cumulative BSN would be increased).

The WiMAX Forum™ Mobile System Specification requires ARQ acknowledgment types 1, type 2, and type 3 to be implemented. ARQ acknowledgment type 0 is optional. The AeroMACS profile intends to support the same set of acknowledgment options.

Each acknowledgment type has its advantages but is dependent on feedback intervals, error patterns, and computational complexity. The size of the ARQ block has an impact as well, if large ARQ blocks are used it is more unlikely to fill acknowledgment maps or acknowledgment sequence maps. The standard does not specify any strategy how and when ARQ acknowledgments shall be scheduled.

Quality of Service (QoS)

Quality of Service in IEEE 802.16 is supported through the concept of unicast transport connections. These transport connections are called service flows, where each service flow utilizes a particular set of QoS parameters. The standard provides several QoS parameters to be adjusted; for instance maximum sustained traffic rate, maximum traffic burst, minimum reserved traffic rate, maximum latency, etc. - in principle latency, jitter, and throughput assurance.

Service flows are either provisioned or dynamically added by the base station or optionally by the mobile station. How to provision service flows is out of the scope of the IEEE 802.16 standard, consequently it is also not specified in the AeroMACS draft profile. Certain service flows may be added dynamically for instance after the network entry procedure. The standard provides options to create, change, and delete a service flow dynamically. Such a procedures can be either initiated by the base station or by the mobile station. The WiMAX mobile profile makes these options
mandatory to be supported by the base station. The capability to dynamically create or change a service flow is optional for a mobile station, however, the deletion of a service flow is mandatory. The AeroMACS profile intends to support only the dynamic service flow creation, change, and deletion procedures to be initiated by the base station.

How these service flows are initiated and/or triggered is not specified by the AeroMACS profile. QoS parameters of ATC traffic flows shall probably be regulated while QoS parameters of AOC traffic flows may be provider dependent.

**Scheduling & Data Delivery Services**

There are different possibilities to provide bandwidth to a mobile station, realized through a scheduling service. Uplink request and grant scheduling is performed by the base station in order to provide each mobile station with bandwidth for uplink transmissions or opportunities to request bandwidth. By specifying a scheduling type and its associated QoS parameters, the base station scheduler can anticipate the throughput and latency needs for the uplink traffic and provide polls and/or grants at the appropriate times. The different scheduling services are:

- Unsolicited Grant Service (UGS)
- real-time Polling Service (rtPS)
- non-real-time Polling Service (nrtPS)
- Best Effort (BE)

The unsolicited grant service (UGS) is intended for real-time applications which generate fixed-rate data. Among others QoS parameters such as tolerated jitter, minimum reserved traffic rate, maximum latency, and the unsolicited grant interval are defined. This means that a service flow with a data delivery service of UGS gets periodically UL resources assigned without requesting them each time.

The real-time Polling service (rtPS) is intended for real-time applications with variable bit rates. Among others QoS parameters such as maximum latency, minimum reserved traffic rate, traffic priority, and the polling interval are defined. In this case the resource scheduler polls a mobile station regularly at fixed intervals. These polls may be used to request bandwidth.

The non-real-time Polling Service (nrtPS) is intended for applications which require guaranteed data rate but are insensitive to delays. QoS parameters such as minimum reserved traffic rate, maximum sustained traffic rate, and traffic priority are defined. In this case the unicast polls are issued at a variable interval length (dependent on the available resources). The polls may be used to request bandwidth.

The Best Effort (BE) service is intended for applications with no rate or delay requirements. In this case bandwidth request ranging opportunities are provided to transmit bandwidth request ranging codes. If a bandwidth request range code is successfully received by a base station it polls the associated mobile station.

For the downlink direction similar QoS classes can be utilized. However, these are called slightly different but have comparable QoS parameters. The scheduler does not need to consider any polls or ranging opportunities for the downlink, though. The different QoS classes or data delivery services are:

- Unsolicited Grant Service (UGS)
- Real-Time Variable Rate (RT-VR) service
- Non-Real-Time Variable Rate (NRT-VR) service
- Best Effort (BE) service

What kind of QoS class a specific application or set of applications will require is dependent on the requirements. How the different data delivery services and scheduling strategies are implemented is not specified by the standard. Thus, they are vendor dependent. In any case the communication service provider has to assure that safety related communication is preferred over non-safety related communication. It might be that a simple priority scheme with a best effort service is sufficient.

**Request Grant Mechanism**

A mobile station is required to support at least three different connections. That is, two management connections which are set up at network entry and one data bearer to transmit user data.

Every connection with a QoS service other than UGS needs to adapt its resource requirements. This is done through bandwidth requests. This is a mechanism where a mobile station indicates to the
base station that it requires uplink resources. Bandwidth requests are either sent as standalone Bandwidth Request (BR) headers or as a Piggy Back Request (i.e. included in the Grant Management Sub-header (GMSH)).

Bandwidth Requests may be either incremental or aggregated. When a BS receives an incremental BR, it shall add the quantity of bandwidth requested to its current perception of the bandwidth needs of the connection. When the BS receives an aggregate BR, it shall replace its perception of the bandwidth needs of the connection with the quantity of bandwidth requests. Piggybacked bandwidth requests are always incremental.

The base station issues resource grants towards a mobile station based on the basic CID (i.e. basic management connection). This means that a mobile station is able to utilize the concept of bandwidth stealing where a certain amount of requested bandwidth for a specific QoS class may be utilized differently. However, the resource requests are based on the transport connection which requires bandwidth. If a base station polls a mobile station it typically assigns enough resources to issue a bandwidth request.

**AeroMACS over IPv6**

The Network Working Group (NWG) of the WiMAX Forum™ has defined a network architecture for IEEE 802.16 sub-networks. Thereby, considering topics at layers above those defined by the 802 standards. The Internet Engineering Task Force (IETF) has worked out a Request For Comment (RFC) “Transmission of IPv6 via the IPv6 Convergence Sub-layer over IEEE 802.16 Networks” [5] which provides a full conformant IPv6 connectivity through an IP point to point link. This solution fits the general business use case where each subscriber resides in its own sub-network. However, the requirements of the sub-network in an aeronautical environment might be different than the one of an ordinary business use case. Running IPv6 over AeroMACS shall be fully compliant to the IP standard, thereby, IP multicast shall be supported preferably in an efficient manner. It might also be desirable to support multicast at link layer which is difficult with point to point links.

First of all it is important to identify the relevant concepts of IPv6 addressing. In IPv6, nodes are attached to an access network via an interface, which is given at least one IPv6 address (i.e. the link local unicast address). Within this context a node can be understood as a device which implements IPv6. This means that an interface gets one or more IPv6 addresses assigned and not the node itself, which is a fundamental concept of IP. In other words a node may host several network interfaces which have different addresses. Thereby, the same node may be reachable through different IPv6 addresses.

An IPv6 capable node must be able of configuring its IPv6 address autonomously. An IPv6 address is created through a valid interface identifier and a valid subnet prefix. The subnet prefix may be a constant link local prefix (i.e. FE80::0), an advertised prefix received by Router Advertisements, or a prefix by a DHCPv6 server. The prefix is only valid on the link on which it is received - the prefix shall not be used on different links. Link local addresses allow communications between devices on a local link; such addresses cannot be used to communicate outside a sub-network.

Native multicast capability can be described through the following general concepts of the IP addressing model - first through the concept of a link and secondly through the concept of a subnet. A link is a term used to refer to a topological area bounded by routers that decrement the IPv6 Hop Limit when forwarding a packet (c.f. [6]). The term subnet is generally used to refer to a topological area that uses the same address prefix, where that prefix is not further subdivided except into individual addresses (c.f. [6]). Thereby, it is important to recognize that IPv6 continues the IPv4 model that a subnet is associated with one link. Multiple subnets may be assigned to the same link (c.f. [7]). Ideally, the Data Link layer addressing mechanisms can be directly used for the Internet Protocol addressing method. Some of the Internet layer protocols (e.g. Address Auto-configuration [8], Neighbour Discovery [9], Dynamic Host Configuration Protocol [10], or more generally protocols used for service discovery or name resolution) require native multicast capability of the underlying link, that is data packets can be distributed to all interested nodes on the same link without a decrement of the IPv6 Hop Limit field. If such a native multicast capability is not given by a certain link technology, an IP link model has to be
presented towards the Internet layer which fulfills this requirement.

In principle, if a layer 2 link characteristic is problematic at the Internet layer, mechanisms have to be defined that the link model appears properly at the Internet layer. The Internet Architecture Board (IAB) recommends using one of the two following models: The multi-access link model or the point to point link model. These models, if implemented properly, have no problems regarding the IP addressing model and the native multicast capability.

**Convergence Sub-Layer**

The convergence sub-layer (CS) of the IEEE 802.16 standard specifies the interface towards higher layer protocols. The standard provides a variety of convergence sub-layer options in order to provide the possibility to interface with a versatile set of higher layer protocols. A main function of the convergence sub-layer is the acceptance and interpretation of service data units (SDU) received from higher layers. Based on a manageable policy, SDUs are mapped to specific service flows. Additionally, header compression techniques or any other appropriate processing may be conducted by the convergence sub-layer protocol.

The AeroMACS draft profile intends to support the IP CS (specifically IPv6), additionally the support of Ethernet is discussed. In principle the issue of the convergence sub-layer seems straightforward - either AeroMACS supports higher layer protocol A, higher layer protocol B, or even both. However, recalling the principle design issues of layered communication protocol architectures there may be problems. Considering the two options of the packet based convergence sub-layer, namely IP CS and Ethernet CS. The required service differs from the IP point of view and may cause problems when considering IP over AeroMACS. Using IP CS would require to manage each individual connection to a mobile station as a point to point link. In contrast an Ethernet CS would model a point to multi-point link. Consequently the service offered towards IP is different.

**Multicast**

Multicast is a cost-effective way to broadcast data from a single point to several receivers. However, there are known shortcomings like poor reliability (through packet loss), lack of standards, and lack of support by Internet Service Providers (ISPs). However, upcoming business areas like multimedia streaming may initiate further research and support by industry. Additionally, many wireless systems offer the possibility to adjust their power level for unicast transmissions based on link layer receiver feedback. In such a way throughput can be optimized for single point to point connections, however, this is not the case for point to multipoint connections. Only if several active multicast listeners are present at the same time multicast connections become more economic than replicating traffic many times. Due to the fact that aeronautical wireless links may serve a comparably large amount of users multicast may be still desirable, though.

Within the context of aviation multicast should be considered from a local perspective rather than from a global one (i.e. from a sub-network point of view). Multicast routing protocols do not have any impact on the data link itself; however, the way how IP multicast is implemented over a specific link technology does indeed. Considering multicast capability for the edge network, there are mainly two operational aspects. First, the kind of application data to be supported, and second the kind of operational service a sub-network shall be capable of.

Within this context the distinction between IP multicast (L3) and native multicast (L2) has to be made. IP multicast shall be always supported if the IP model is implemented properly. However, native multicast is not intrinsically supported by a link like AeroMACS. By native multicast a native mechanism at the link layer for sending packets to all or a subset of all neighbors is understood (c.f. [9]). Therefore, additional non standard mechanisms might be necessary to support native multicast.

Today, there are already applications which might make use of IP multicast; examples are notice to airmen, updates on weather reports, runway visual reports, etc. - ATC situational awareness (as given today by party-line voice communications) could probably be better supported by native multicast (i.e. layer 2). In any case the future ATM concept may benefit extraordinarily from the efficient realization of multicast.

Applications may make use of native multicast, however, mostly protocols which offer certain
configuration services use this capability. This allows a layer 2 network attached to a single router to auto-
configure and run additional services offered by the layer 2 network. This means a user does not need to
do anything manually (at least in theory). In contrast
IP multicast is based on layer 3 routing protocols and
is utilized solely by applications. IP multicast traffic
may be supported more efficiently by layer 2
networks which support native multicast. Especially
if multiple recipients are present and the multicast
traffic content is data intensive.

Considering the aforementioned IP link models
(i.e. point to point and point to multipoint) different
possibilities exist. The point to point link model
offers little room to exploit native multicast
capability. If a point to point link is employed,
theoretically each such link at the access gateway
needs to be virtually mapped to a device (i.e. a device
driver implemented in an operating system). From
the protocol stack point of view, each of these
interfaces needs to run a separate instance of MLDv2
(as it is a separate sub-network). In such an
environment the advantages of link scoped multicast
cannot be exploited as each link is dedicated to a
single mobile node. IP based multicast can be
supported at the edge router (which is most probably
also the gateway), however, if several multicast
listeners are present resources may be wasted.

A possible non standard solution could be to
employ single sub-networks for each mobile station
according to QoS and security requirements; and to
employ one domain based sub-network which is
specifically targeted for multicast traffic. Such a
solution requires additional specification at the access
gateway where the mapping of multicast data traffic
is handled according to the requirements of an IP
model. Additionally, it would be desirable to provide
a specific function at the mobile station which is
dedicated to the support of multicast applications. In
such a way the domain specific sub-network would
also support link scoped multicast capabilities.

A point to multipoint environment would
natively support layer 2 multicast. However, in such
an environment this would need to be supported
through additional non standard mechanisms. That is,
a bridging functionality would be necessary at the
access gateway. Similar to the solution discussed
before.

In an Ethernet based environment all point to
point connections from a mobile station to a base
station need to be put on a single port of a bridging
function, which enables the Ethernet environment.
Such a mapping of connections to Ethernet ports
would require additional specification work.
Furthermore, it would be beneficially to employ more
functionality at the bridging device (e.g. multicast
snooping, V-LAN (c.f. 802.2Q), etc.). Such a
solution would also be a non-standard, hence, the
benefit of such a possibility is limited in comparison
to the aforementioned as also additional work needs
to be done.

Expected Data Profile

The AeroMACS draft profile shall be evaluated
through simulations. In order to assess the
performance properly an assumption on the data
traffic load for airport surface communications was
necessary. The data traffic load model used as input
for the AeroMACS communication profile definition
has been described in detail in [11]. In the following
a brief summary of the activity.

In order to assess different deployment scenarios
for the future airport surface communication system
an airport scenario hypothesis was necessary.
Thereby, the aircraft traffic model, the ground vehicle
traffic model, and the applications model were taken
into account.

The aircraft traffic model considers different
zones for the airport area as described in COCRv2
[12]. The different zones are RAMP, GROUND, and
TOWER. The RAMP zone is the area where the
aircraft parks at the gate (or at a parking position)
before departure or after arrival; for departing aircraft
the GROUND zone denotes the area where an aircraft
is released from its parking position (e.g. push-back)
until it taxis to the runway; for arriving aircraft the
GROUND zone denotes the area where the aircraft is
taxiing back to the gate or parking position until it is
parked; and the TOWER zone denotes the area where
control is handed over from ground to tower and
vice-versa. Furthermore, an aircraft is either arriving
or departing. Dependent on that the time an aircraft is
connected to the AeroMACS communication system
is longer or shorter, respectively. Typical dwell times
for arriving and departing aircraft within the different
airport zones have been taken from COCRv2, too.
This distinction was necessary and important as
Aeronautical applications are triggered dependent whether aircraft are departing or arriving and in which position they currently are. The vehicular model was kept simple and modeled through an arrival process based on an exponential distribution. A further detail of the simulation campaign was the distinction between an overall airport and a single sector (i.e. part of a communication cell) evaluation.

The gained results showed that ATC applications require almost no bandwidth in comparison to AOC applications. Furthermore, some AOC applications would require significant resources. These applications are "Electronic Flight Folder Exchange", "Update of Electronic Libraries", and "E-Charts Update". These applications are all interesting for departing aircraft and would be initiated while in parking position. Furthermore, the post flight applications "Flight Journal Documentation" and "Flight Operational Quality Assurance" contribute significantly to the overall load on the system when aircraft are returning to their parking position. Today, these applications are uploaded manually and not via data link.

Some example results where 25 aircraft and 10 ground vehicles on average reside within the airport environment are shown in the Table 3.

Table 3. Example Results of the Load Analysis

<table>
<thead>
<tr>
<th></th>
<th>Average offered load ATC (Kbits/sec)</th>
<th>Average offered load AOC (Kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>arrival</td>
<td>Overall: 0.47</td>
<td>79.26</td>
</tr>
<tr>
<td></td>
<td>FL: 0.19</td>
<td>69.42</td>
</tr>
<tr>
<td></td>
<td>RL: 0.28</td>
<td>9.84</td>
</tr>
<tr>
<td>RAMP</td>
<td>Overall: 1.02</td>
<td>~2.3 MBit/sec</td>
</tr>
<tr>
<td>departure</td>
<td>FL: 0.41</td>
<td>1992.86</td>
</tr>
<tr>
<td></td>
<td>RL: 0.60</td>
<td>325.45</td>
</tr>
<tr>
<td>GROUND</td>
<td>Overall: 1.23</td>
<td>~12 MBit/sec</td>
</tr>
<tr>
<td>arrival</td>
<td>FL: 1.14</td>
<td>196.97</td>
</tr>
<tr>
<td></td>
<td>RL: 0.09</td>
<td>12066.22</td>
</tr>
<tr>
<td>GROUND</td>
<td>Overall: 1.05</td>
<td>~5.8 MBit/sec</td>
</tr>
<tr>
<td>departure</td>
<td>FL: 0.98</td>
<td>95.58</td>
</tr>
<tr>
<td></td>
<td>RL: 0.07</td>
<td>5737.92</td>
</tr>
<tr>
<td>TOWER</td>
<td>Overall: 0.58</td>
<td>141.97</td>
</tr>
<tr>
<td>arrival</td>
<td>FL: 0.57</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>RL: 0.02</td>
<td>141.97</td>
</tr>
<tr>
<td>TOWER</td>
<td>Overall: 0.44</td>
<td>287.38</td>
</tr>
<tr>
<td>departure</td>
<td>FL: 0.43</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>RL: 0.01</td>
<td>287.38</td>
</tr>
</tbody>
</table>

Performance Evaluation

In order to assess the characteristics of a data link design properly various general performance evaluations are conducted on the system. These evaluations examine:

- the link behavior with different channel conditions, i.e. a constant amount of users transmits a constant amount of data with error probabilities from low to high,
- the link behavior with various load conditions, i.e. a constant amount of users transmits a varying amount of data from low to high load, thereby assuming a stable channel condition (constant bit error probability), and
- the link behavior with diverse population conditions, i.e. the amount of users subscribed to the data link system is alternated from low to high, assuming a constant load per user and a stable channel condition.

Thereby, different aspects such as latency, throughput, or loss are investigated. Note, that in the simulation results we used a different terminology for data traffic - i.e. Forward Link (FL) is similar to Downlink (DL) and Reverse Link (RL) is similar to Uplink data traffic.

Parameter Settings

For the simulation the available bandwidth has been divided into 5 ms TDD frames. Where each frame contains 210 slots for Forward Link (FL) data transmissions and 102 slots for Reverse Link (RL) data transmissions. Thereby, the modulation and coding scheme has been chosen in such a way that each slot may carry 48 bits of data. This results in 2016 kbit/sec for the FL and 979 kbit/sec for the RL direction (compare Table 1 and Table 2, respectively).

Packing is enabled for management as and data connections, for unicast FL as well as RL traffic. ARQ is enabled on all data connections with a window size set to the maximum of 1024 blocks. Unless noted otherwise the block resend timeout for unacknowledged blocks is set to 500 ms and the block lifetime is set to 5000 ms. The used block size may vary and is mentioned for each presented result.
Application level data are generated with a random packet generator which specifies a packet size and the desired data bandwidth. Then packets are generated at a frequency matching this bandwidth. Each simulation is run 10 times with a random seed value in order to receive confidential intervals.

**Selected Results**

Considering the different aforementioned evaluations various simulation scenarios have been conducted in order to evaluate different parameter settings. Selected results are presented in the following.

**Different Bit-Error Rates**

Figure 2 and Figure 3 show the offered load curves for higher layer load (HiL) and data link layer load (DLL). The figures show a decreasing channel condition from left to right (i.e. the bit error rate increases). The simulation scenario used default parameter settings with 20 mobile routers logged into the system. Each mobile router produced 1500 byte application layer packets, where the average data rate for FL traffic was 60 kbit/sec and 30 kbit/sec for RL traffic per mobile router. In total the average offered higher layer load was 1200 kbit/sec for the FL and 600 kbit/sec for the RL direction. The ARQ block size has been set to 128 bytes and the maximum fragment size to 612 bytes.

**Figure 3. Offered Load RL - Various BER**

The required bandwidth for the data link layer rises with higher bit-error rates as more data need to be resent, until there is no more bandwidth available. The offered load decreases slightly for high error rates due to a simulation artifact where generated packets which have not been treated yet are considered to be canceled instead of lost at the end of the simulation.

A detailed break-down of the different items consuming the available bandwidth is listed in Table 4. This table lists the average bandwidth of all transmitted packets (with and without error) for one simulation run with a bit error rate set to $10^{-6}$ and $5\times10^{-5}$, respectively.

The figures in Table 4 are given in kilobits per second (kbit/s). The upper part breaks down the FL bandwidth utilization and the lower part breaks down the RL bandwidth utilization. The application load (FL and RL) is the offered load received by higher layers. The resent application data (FL and RL) indicates the amount of data which had to be resent due to bit errors within a given PDU. The row indicating acknowledgements (FL and RL) accounts for the bandwidth which was necessary to convey acknowledgments. Thereby, the headers where not accounted as acknowledgments may also be piggybacked. Similar the amount of bandwidth consumed for bandwidth requests (BR) and GSMH headers in the RL direction did not include header overhead. Headers (FL and RL) account for all MAC headers and additional sub-headers transferred via the wireless medium. Broadcast (FL) includes management items such as the DL Prefix, DCD, UCD, DL MAP and UL MAP messages. Ranging
(RL) lists the bandwidth reserved to stations for initial ranging and bandwidth request ranging.

<table>
<thead>
<tr>
<th>Table 4. Break-Down of Bandwidth Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER 10^-6</td>
</tr>
<tr>
<td>data</td>
</tr>
<tr>
<td>Application load FL</td>
</tr>
<tr>
<td>Resent appl. data FL</td>
</tr>
<tr>
<td>Acknowledgments FL</td>
</tr>
<tr>
<td>Headers FL</td>
</tr>
<tr>
<td>Broadcast FL</td>
</tr>
<tr>
<td>Sum FL</td>
</tr>
<tr>
<td>Application load RL</td>
</tr>
<tr>
<td>Resent appl. data RL</td>
</tr>
<tr>
<td>Acknowledgments RL</td>
</tr>
<tr>
<td>Bandwidth requests</td>
</tr>
<tr>
<td>Headers RL</td>
</tr>
<tr>
<td>Ranging</td>
</tr>
<tr>
<td>Sum RL</td>
</tr>
</tbody>
</table>

Figure 4 and Figure 5 show the corresponding goodput for FL and RL, respectively. The FL results show a controlled behavior until a BER of 10^-5. The higher layer data packets are still delivered at a BER of 5*10^-5, however the DLL goodput increases due to re-transmissions caused by ARQ timeouts. Further decreasing the quality of the channel (i.e. BER equals 10^-4) results in massive loss of higher layer data packets. Higher layer packets are dropped as soon as the ARQ block lifetime of a MAC SDU (i.e. the higher layer data packet) expires. Considering the RL (i.e. mobile station to base station) a controlled behavior is only available until a BER of 10^-5. After that a similar behavior than the one of the FL can be observed. Due to the nature of the scheduling strategy used for the RL (i.e. best effort), acquiring new resources may be more time demanding, therefore an ARQ block lifetime timeout is more likely with a similar error rate than in the FL.

Given the maximum fragment size of 612 bytes the expected number of fragments with at least one bit error would be 4.8% at a bit error rate of 10^-5 and 37.7% at a bit error rate of 10^-4. The ARQ implementation causes all lost ARQ blocks in such packets to be resent. If all ARQ blocks have been received correctly the high-level packet is re-assembled and accounted as delivered. At a bit error rate of 10^-4 and a higher layer packet size of 1500 bytes the system is not able to transmit the corresponding amount of data link layer packets within ARQ block lifetime correctly. As a result most of the higher layer data packets are lost. Therefore, the loss percentage of the higher layer packets grows faster than the one of the data link layer packets.

Figure 6 and Figure 7 show the average and 95%-percentile latency of the higher layer packets in FL and RL direction, respectively. It measures the time from creation of a 1500 byte packet to successful reception at the receiver. RL in general has
more latency because bandwidth must be requested before data can be sent.

---

**Figure 6. Latency FL - Various BER**

---

**Figure 7. Latency RL - Various BER**

---

**Different Loads**

Figure 8 and Figure 9 show goodput for different offered loads with a fixed bit-error rate of $10^{-6}$. The figures show an increasing higher layer load from left to right. Twenty aircraft are sending 1500 byte packets. The low bit error rate causes only very slight loss at the highest load. Table 5 lists the breakdown of the data link layer bandwidth consumption with low load and high load, respectively. The listed items are identical to those as explained for Table 4. The table shows that the broadcast bandwidth increases slightly due to an increased size of the UL_MAP message. Additionally, the amount of acknowledgments and bandwidth requests grows slightly.

---

**Table 5. Break-Down of Bandwidth Utilization**

<table>
<thead>
<tr>
<th>Data</th>
<th>360 kbit FL 180 kbit RL</th>
<th>1240 kbit FL 620 kbit RL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application load FL</td>
<td>361</td>
<td>1217</td>
</tr>
<tr>
<td>Resent appl. data FL</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments FL</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Headers FL</td>
<td>17</td>
<td>56</td>
</tr>
<tr>
<td>Broadcast FL</td>
<td>134</td>
<td>144</td>
</tr>
<tr>
<td><strong>Sum FL</strong></td>
<td><strong>516</strong></td>
<td><strong>1429</strong></td>
</tr>
<tr>
<td>Application load RL</td>
<td>176</td>
<td>604</td>
</tr>
<tr>
<td>Resent appl. data RL</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledgments RL</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bandwidth requests</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Headers RL</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>Ranging</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Sum RL</strong></td>
<td><strong>270</strong></td>
<td><strong>706</strong></td>
</tr>
</tbody>
</table>
Different Number of Aircraft

Figure 10 and Figure 11 show the offered load for an increasing number of aircraft from left to right. The packet generator for each aircraft has been set to produce on average 20 kbit/s for FL data and 10 kbit/s for RL data. Similar to the scenario where just the application load is increased, this scenario shows the same effects where load and overhead increase slightly. However, more bandwidth is required for the UL_MAP message if more aircraft are logged on to the same cell. Only when the data rate gets too high there is loss, as seen in Figure 12 and Figure 13. The explanation for the loss is that our bandwidth scheduling algorithm cannot distribute bandwidth to each airplane in time consequently ARQ blocks time out. A single timed out block means the complete high level packet is lost. Table 6 lists the breakdown of the data link layer bandwidth consumption with 10 and 60 aircraft, respectively. The listed items are identical to those as explained for Table 4.

Table 6. Break-Down of Bandwidth Utilization

<table>
<thead>
<tr>
<th>data</th>
<th>10 aircraft</th>
<th>60 aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application load FL</td>
<td>201</td>
<td>1176</td>
</tr>
<tr>
<td>Resent appl. data FL</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments FL</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Headers FL</td>
<td>9</td>
<td>55</td>
</tr>
<tr>
<td>Broadcast FL</td>
<td>132</td>
<td>147</td>
</tr>
<tr>
<td><strong>Sum FL</strong></td>
<td><strong>344</strong></td>
<td><strong>1390</strong></td>
</tr>
<tr>
<td>Application load RL</td>
<td>99</td>
<td>573</td>
</tr>
<tr>
<td>Resent appl. data RL</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledgments RL</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bandwidth requests</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Headers RL</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Ranging</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Sum RL</strong></td>
<td><strong>156</strong></td>
<td><strong>679</strong></td>
</tr>
</tbody>
</table>

Figure 10. Offered Load FL - Various Aircraft

Figure 11. Offered Load RL - Various Aircraft

Figure 12. Packet Loss FL - Various Aircraft

Figure 13. Packet Loss RL - Various Aircraft
Acknowledgment Message Types

This simulation scenario examines the type of acknowledgment message the implementation takes. The scenario contained 20 aircraft where each generates a data rate of 50 kbit/s for FL traffic and 20 kbit/s for RL traffic, respectively. The following figures show the different behavior when decreasing the channel quality (from left to right). Figure 14 shows a setting where all acknowledgment types were enabled. At low bit error rates the most common acknowledgment type is type 1 (i.e. cumulative acknowledgment). This is reasonable as a cumulative acknowledgment is most efficient if no ARQ blocks are missing considering the last received BSN number. In case packets are re-ordered type 0 acknowledgments (i.e. selective acknowledgments) become more efficient. If the channel quality decreases cumulative acknowledgments become ineffective and type 3 acknowledgements (i.e. cumulative with block sequence ACK entry) are utilized in addition to type 0 acknowledgments. At high bit error rates type 3 acknowledgements are used more often than type 0 acknowledgments as this type requires less bandwidth if the gaps between consecutive correctly received BSNs increases.

Figure 15 shows the results of a run with the same settings, however, type 0 acknowledgments are not allowed. In this case type 2 (i.e. cumulative with selective ACK entry) messages are used instead, with the cumulative BSN set to a number which can be cumulatively acknowledged. Otherwise the behavior is quite similar to the one shown in Figure 14.

Figure 16 shows the results of a run with the same settings, but only acknowledgment type 1 and acknowledgment type 2 are allowed.

Figure 17 shows the results of a run with the same settings, but only acknowledgment type 1 and acknowledgment type 3 are allowed.
In general acknowledgement type 1 shall be always supported. Additionally, either type 2 or type 3 should be supplemented. At high bit error rates throughput is slightly better if acknowledgment type 1 and 3 (cumulative with block sequence ACK entry) are supported compared to acknowledgment type 1 and 2 (cumulative with selective ACK entry).

Conclusion

The demand to integrate the aircraft into the network centric concepts requires capable air ground data-links. AeroMACS shall provide this functionality at the airport surface. Infrastructure and equipage used for aeronautical procedures is evolving very slowly due to several reasons. Cost, interoperability, and safety issues are some among many reasons. Any new system integrated into the aeronautical environment will last for decades until it might eventually be replaced through a new system. Therefore, it is of importance to design new systems carefully and with mature concepts in order to remain prepared for changing requirements in the future.

Integrating the AeroMACS sub-network into an IPv6 based aeronautical telecommunication network (ATN) is generally a problem which needs to be resolved from the application's point of view and from the operator point of view. It is also important to keep flexibility in order to be capable to adapt to any future changes of requirements. Especially if products have such long life cycles as in the aeronautical world it is almost impossible to assess the proper requirements.

Multicast applications may be very attractive to the future ATM concept, however, most of these applications are not realized yet (i.e. they exist only in theory). With a wrong sub-net configuration the introduction of application layer concepts based on multicast may be quite difficult and/or expensive.

During the course of the SANDRA project a data traffic load analysis has been conducted which showed that applications with significant load requirements would justify the introduction of a broadband wireless communication system for airport surface communications. Furthermore, MAC performance simulations have shown performance figures to be expected by a future AeroMACS system.

The implementation of the MAC layer in our simulation provided performance results for throughput and latency with standard settings. One additional showed experiment consisted of simulation runs with only some of the different acknowledgment types available, which show similar performance as long as cumulative as well as selective acknowledgments are possible. More detailed results will be published in the corresponding SANDRA deliverable.

The current status of the AeroMACS profile is a draft. This means that further assessments on the maturity and performance of the technology shall clarify the suitability of AeroMACS for supporting the needs of future ATM concepts. Although currently prototypes are being implemented it is not believed that AeroMACS would be introduced before 2020. A realistic target for the deployment of an AeroMACS system is rather 2025 and beyond.

References


Acknowledgements

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