

International Telecommunication Union

ITU-R
Radiocommunication Sector of ITU

Report ITU-R M.2197
(11/2010)

Technical characteristics and operational objectives for wireless avionics intra-communications (WAIC)

M Series
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Electronic Publication
Geneva, 2011

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REPORT ITU-R M.2197

**Technical characteristics and operational objectives for wireless avionics
intra-communications (WAIC)**

(Question ITU-R 249/5)

(2010)

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Objective

This Report provides technical characteristics and operational objectives of WAIC systems for a single aircraft. This Report does not give an indication of selected frequency bands. The content presented in this Report hence represents the current state of information on WAIC applications anticipated by the international commercial aviation industry.

This Report analyses a representative WAIC system for a single aircraft and derives the maximum required transmission power for low and high, inside and outside application classes as a function of a theoretical carrier frequency and bandwidth. The results presented in Figs 11 to 17 provide insight into potential trade-offs between the technical characteristics; transmission power, bandwidth and carrier frequency.

It is assumed that WAIC systems will require a maximum transmit power of approximately 10 dBm between 1 GHz and 10 GHz given the needs of energy-limited sensor nodes. It is also assumed that WAIC systems may require a maximum transmit power of up to 30 dBm between 10-66 GHz.

1 Introduction

The commercial aviation industry is developing the next generation of aircraft to provide airlines and the flying public more cost-efficient, safer, and more reliable aircraft. One important way of doing this is to reduce aircraft weight. It is believed that wireless technologies can reduce the weight of systems on an aircraft thereby providing significant cost savings. Reducing the amount of fuel required to fly can also reduce costs and benefit the environment.

Installed wireless avionics intra-communications (WAIC) systems are one way to derive these benefits. WAIC systems consist of radiocommunications between two or more points on a single aircraft. Points of communication may include integrated wireless components and/or installed components of the system. In all cases communication is assumed to be part of a closed, exclusive network required for operation of the aircraft. WAIC systems do not provide air-to-ground or air-to-air communications. It is anticipated that WAIC systems will only be used for safety-related aircraft applications. Also, WAIC systems transmissions may not be limited to the interior of the aircraft structure, depending on the type of aircraft. For example, sensors mounted on the wings or engines could communicate with systems within the airplane. WAIC systems may be used on regional, business, wide-body, and two-deck aircraft, as well as helicopters. These different aircraft types may place different requirements on the WAIC systems and may also impact the type of propagation path between the WAIC transmitter and receiver.

As the reliance on wireless technology continues to expand, the use of WAIC systems to transmit information important to the safe and efficient operation of an aircraft may provide significant advantages over current wired systems.

This Report focuses on technical characteristics and operational objectives of potential WAIC systems on a single aircraft and does not include bandwidth requirements. The discussion on candidate frequency bands is also not addressed in this Report. This Report does not cover the impact of using wireless technologies for this purpose.

2 Discussion

WAIC systems are envisioned to provide communications over short distances between points on a single aircraft. WAIC systems are not intended to provide communications, in any direction, between points on an aircraft and another aircraft, terrestrial systems or satellites. WAIC systems are intended to support data, voice and video (to monitor different areas on the aircraft) communications between systems on an aircraft including communications systems used by the

crew. It is also envisioned that wireless sensors located at various points on the aircraft will be used to wirelessly monitor the health of the aircraft structure and all of its critical systems, and communicate information within the aircraft to those who can make the best use of such information.

Points of communication may include integrated wireless components and/or installed components of the system. In all cases communication between two points on a single aircraft is assumed to be part of a closed, exclusive network required for operation of the aircraft. WAIC systems are not intended to provide air-to-ground communications or communications between two or more aircraft. They are also not intended to include communications with consumer devices, such as radio local area network (RLAN) devices that are brought on board the aircraft by passengers or for in-flight entertainment applications.

WAIC systems are envisioned to offer aircraft designers and operators many opportunities to improve flight safety and operational efficiency while reducing costs to the aviation industry and the flying public.

Because WAIC systems are installed on aircraft, they are as transient as the aircraft itself and will cross national boundaries. Therefore, the ITU-R, national and international organizations involved in radiocommunications and air travel should work together in addressing this issue. The scope of WAIC applications is limited to applications that relate to the safe, reliable and efficient operation of the aircraft as specified by the International Civil Aviation Organization (ICAO). It is intended that WAIC systems will only be used for safety-related aircraft applications.

WAIC systems are envisioned to provide significant benefits to all who use the sky to travel. Some of the potential benefits of WAIC systems are described below.

2.1 Substitution of wiring

Cabling and wiring present a significant cost to the aircraft manufacturer, operator, and ultimately the flying public. Costs include the wiring harness designs, labour-intensive cable fabrication, reliability and replacement costs of connectors, as well as the associated operating costs of flying copper and connectors that represent 2-5% of an aircraft's weight.

Wiring harness design is one of the critical factors that determine the time required to design a new aircraft, requiring the designers to specify and determine the routes for miles of wire onboard the aircraft. This includes providing separate routing paths for redundant wiring, so that a single point failure does not affect redundant circuits, and enables safety critical systems to be properly isolated from other system wiring. Wireless products offer solutions that can reduce the time and costs associated with wiring harness design, harness installation design, aircraft manufacturing time, and aircraft lifecycle costs.

Wiring also constitutes over 50% of the instances of electromagnetic interference on board aircraft. Wiring can act as antennas and collect unwanted energy that may impact interconnected system immunity. Wiring can also radiate energy with the risk of inducing electro-magnetic interference on surrounding systems. Providing wireless links, in lieu of wiring can provide connectivity without the need for redundant wiring harnesses that are specific to a specific aircraft type, resulting in economies of scale for small, medium and large aircraft.

As an airframe is utilized during its lifetime, it may be necessary to install new sensors to monitor portions of the aircraft structure or aircraft systems either as a result of incident or accident awareness or as a result of the availability of new types of sensing technology. On current aircraft, adding a new sensor is very expensive due to the requirements to install wiring, connections to the central processing system, and modifications to software. WAIC networks could allow new sensors to be mounted with much less difficulty and expense, and enable easier modification of systems and structural monitoring throughout the life of the aircraft, which typically exceeds 25 years.

2.2 Enhance reliability

Wiring is a significant source of field failures and maintenance costs. It is extremely difficult to troubleshoot and repair such failures in aircraft system wiring which occur primarily at interface points where connectors, pins, and sockets come together. The large number of parts and human error also contribute to failure at these interface points. A wireless system may significantly reduce electrical interfaces and thus significantly increase system reliability.

Wireless technologies are intended to offer the means to implement systems that enhance reliability. By having fewer wires on an aircraft, the need for wire maintenance to remediate chafing conditions, aging wiring and associated fire hazards is reduced, thereby improving the safety and reliability of the aircraft. Adding new sensors on an aircraft to monitor functions such as equipment cooling status that measure the temperature around components to provide a more accurate status of equipment cooling, has the potential to improve the reliability of aircraft. The introduction of these additional sensors has been limited due to wiring weight and cost impact, but they might be implemented using wireless technology. Aircraft data networks could also take advantage of redundant communication paths offered through mesh networks, which are not cost effective in hard-wired form.

Critical aircraft functions must be fault-tolerant, which leads aircraft designers to include redundant components and redundant wiring harnesses. However, the use of identical technology (in this case duplicate wiring harnesses) to provide fault tolerance can make a design susceptible to “common mode failures” such as fire or lightning strike. The use of a wireless link as a backup to a wiring harness introduces *redundancy through dissimilar means* that can in fact enhance reliability in some critical situations, and can provide connectivity without the need for redundant wiring harnesses specific to a particular aircraft type.

2.3 Additional functions

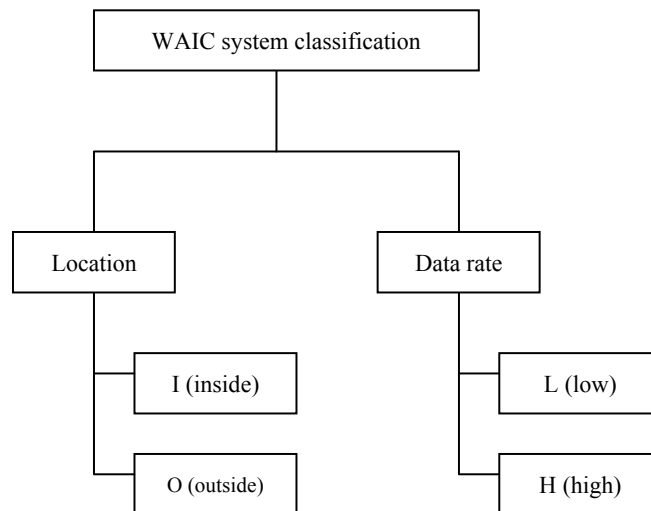
Wireless technologies are also envisioned to provide new functionalities to aircraft manufacturers and operators. Manufacturers are provided additional installation options for previously wired systems, while operators are afforded more opportunities to monitor aircraft systems. Currently, there are few dedicated sensors for monitoring the health of aircraft systems and structure as the aircraft ages. Wireless technologies could provide additional opportunities to monitor more systems without increasing the aircraft’s weight. Some additional functions that could be incorporated on an aircraft with wireless technology that cannot be performed with wires include engine rotator bearing monitoring and lightning damage sensors. Reliably routing wiring harnesses to engine rotator bearings is impractical due to the movement of parts. Utilizing a special temperature sensor and transmitting this sensor information wirelessly could provide significant benefits by furnishing sensor data while the aircraft is in-flight. Another example includes on-board sensing of lightning or other environmental damage that occurs while the aircraft is in flight.

Another application is wireless voice, video and data crew communications. It is envisioned that flight deck crew voice and video services could provide enhanced aircraft safety by enabling the monitoring of cabin, luggage compartments and other areas in and around the aircraft. In addition, wireless technology could provide more adaptive cabin configurations and potentially more customized subsystems.

3 WAIC system classification

In discussing the requirements and performance of future wireless aircraft systems, it is useful to simplify the discussion by classifying these systems according to two characteristics: data rate, and internal versus external aircraft location. By classifying aircraft wireless applications accordingly, the discussions can focus on a small number of classes, instead of trying to deal with the myriad of sensors and applications.

FIGURE 1
WAIC system classification



3.1 Classification process description

Each of the potential WAIC systems was studied to determine their operational requirements for net data transmission rates per communication link, and possible location (within or outside the aircraft). It is believed that most applications will be internal to the aircraft structure, but some applications will be outside at least some of the time. Landing gear sensors, for example, will be external when the gear is extended. Some structural health monitoring sensors may be installed outside.

3.1.1 System data rate classification

Potential wireless applications can be broken down into two broad classes corresponding to application data rate requirements. Low (L) data rate applications have data rates less than 10 kbit/s, and high (H) data rate applications have data rates above 10 kbit/s. These classifications will be signified by “L” and “H” respectively.

3.1.2 System location classification

Applications that are enclosed by the airplane structure (e.g. fuselage, wings) are classified as inside (I). Those applications that are not enclosed are classified as outside (O). Some applications may be classified differently depending upon a specific operational scenario. For sharing study purposes, the “worst-case” scenario will be utilized.

3.1.3 Class definition

WAIC applications can be classified by XY following the previous definitions. The parameter X represents the data rate (H, L), and the parameter Y represents the location (I, O). For example, a typical class is LI, representing an application with low data rate requirements, and located internal to the aircraft structure. Detailed descriptions of the applications in each class will be given in the following sections.

3.2 Detailed description of applications by class

In this section each potential application is described under the classification for that application.

3.2.1 Classification LI

General: The class of LI applications is characterized by the following main attributes:

- data rate: low (< 10 kbit/s);
- installation domain: inside metallic or conductive composite enclosures.

Most of the LI RF transceiver nodes will be active during all flight phases and on the ground, including during taxiing. Estimates predict the number of LI nodes installed in an aircraft will be around 3 500.

3.2.1.1 LI class member applications

The LI class includes applications from the domain of low data rate wireless sensing and control signals, e.g. cabin pressure control, smoke sensors, as well as door position sensors. Detection of objects that can be removed from the aircraft, like life vests and fire extinguishers, using wireless technology is seen as a member application of this class. Table 1 lists the anticipated applications of the LI class including further attributes associated with each individual application.

TABLE 1
LI class member applications

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Cabin pressure	Wire reduction	0.8	11	Ground, takeoff, cruise, landing	Existing
Engine sensors	Wire reduction, maintenance enhancement	0.8	140	Ground, takeoff, cruise, landing	Existing
Smoke sensors (unoccupied areas)	Wire reduction, maintenance enhancement, safety enhancements	0.1	30	Ground, takeoff, cruise, landing, taxi	Existing
Smoke sensors (occupied areas)	Wire reduction, flexibility enhancement safety enhancements	0.1	130	Ground, takeoff, cruise, landing	Existing
Fuel tank/line sensors	Wire reduction, safety enhancements, flexibility enhancements, maintenance enhancement	0.2	80	Ground, takeoff, cruise, landing, taxi	Existing

TABLE 1 (end)

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Proximity sensors, passenger and cargo doors, panels	Wire reduction, safety enhancements, operational enhancements	0.2	60	Ground, takeoff, cruise, landing, taxi	Existing
Sensors for valves and other mechanical moving parts	Wire reduction, operational enhancements	0.2	100	Ground, takeoff, cruise, landing, taxi	Existing
ECS sensors	Wire reduction, operational enhancements	0.5	250	Ground, takeoff, cruise, landing	Existing
EMI detection sensors	Safety enhancements	1.0	30	Ground	New
Emergency lighting control	Wire reduction, flexibility enhancement	0.5	130	Ground, takeoff, cruise, landing	Existing
General lighting control	Wire reduction, flexibility enhancement	0.5	1 000	Ground, takeoff, cruise, landing	Existing
Cabin removables inventory	Operational improvement	0.1	1 000	Ground	New
Cabin control	Wire reduction, flexibility enhancement	0.5	500	Ground, takeoff, cruise, landing	Existing

3.2.1.2 Expected data rates per application

Per-link data rates are expected to be relatively low, i.e. below 10 kbit/s, because anticipated applications of the LI class are mainly identified for monitoring or controlling slow physical processes, such as temperature variation at sampling rates of, for example, 1 sample per second or less. Furthermore, transmission delay constraints are not considered an issue for this class. Both of the above aspects allow transmission of data at per-link data rates at or below 10 kbit/s. However, it is noted here that these low per-link data rates do not allow any conclusion on overall aggregate data rates without a reasonable estimate of the number and density of concurrently active radio links associated with LI applications, as well as their traffic statistics. For example:

– Cabin pressure WAIC applications should require the following net per-link data rates:

- 64 bit/s for navigation and air data interfaces;
- 320 bit/s for each controlled valve;
- 800 bit/s for display information.

As 11 nodes are estimated then the aggregate data rate would be 8.8 kbit/s worst-case.

– Engine sensor WAIC application should require the following net per-link data rates:

- 0.8 kbit/s worst-case for each engine sensor (temperature, fuel flow, oil pressure, fire detection, etc.), giving a total of 28 sensors per engine.

– Fuel tank line sensors should require the following net per-link data rates:

- 240 bit/s for refuel/defuel commands (fuel management and quantity gauging sensors);
- 32 bit/s for fuel temperature data in the main and collector tanks.

– Passenger door sensors utilize one sensor for each door position. The expected net per-link data rate is 0.2 kbit/s.

- Cargo or baggage door sensors utilize one sensor for each door position. Each position is managed by 1 sensor. The expected net per link data rates for this application will be 0.2 kbit/s.
- Emergency door sensors utilize one sensor for the *door locked* position. This will need a 0.2 kbit/s link.

3.2.1.3 Installation domain

All applications of the LI class are anticipated to operate within the aircraft structure. WAIC transceivers installed in different compartments may, in some cases, be able to operate on the same communications channel and benefit from the ability to reuse frequencies.

3.2.1.4 Additional class attributes

Different LI applications will have different channel access, duty cycle and activity time characteristics. Some of the LI class applications will be constantly active, while other applications will only be active for limited periods of time.

The expected required communication range will vary between several centimetres to several tens of metres, depending on the installation locations of the RF transceivers and network topology. Propagation conditions are expected to be dominated by non-line-of-sight (NLoS) paths, because most of the RF transceivers associated with applications of the LI class are likely to be mounted in hidden locations.

Engine sensors are considered “Inside” only when the nacelle is made of metallic material or some other material that provides EMI attenuation similar to metal.

3.2.2 Classification LO

General: The LO class of applications is characterized by the following main attributes:

- data rate: low (< 10 kbit/s);
- installation domain: outside aircraft structure.

Most of the LO RF transceiver nodes will be active during all flight phases and on the ground, while some applications will only be active during certain flight phases. The anticipated number of nodes belonging to this class is estimated to be as many as 900 (for a large airliner).

3.2.2.1 LO class member applications

The LO class includes applications from the domain of low data rate wireless sensors such as temperature, pressure, humidity, corrosion detection sensors, structural sensors, and proximity sensors. Also included are cargo compartment sensors. Wheel speed for anti-skid control, wheel position for steering control, engine parameters for engine control and flight surface parameters for flight control are included within this class.

Table 2 lists the anticipated applications of the LO class including further attributes associated with each application.

TABLE 2
LO class member applications

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Ice detection	Operational and safety enhancement	0.5	20	Ground, takeoff, cruise, landing	Existing and new
Landing gear (proximity) sensors	Wire reduction, flexibility enhancement	0.2	30	Ground, takeoff, cruise, landing	Existing
Landing gear sensors, tyre pressure, tyre and brake temperature and hard landing detection	Wire reduction, flexibility and operational enhancement	1.0	100	Ground, takeoff, landing	Existing
Landing gear sensors, wheel speed for anti-skid control and position feedback for steering	Wire reduction, flexibility and operational enhancement	5.5	40	Ground, takeoff, landing	Existing
Flight control system sensors, position feedback and control parameters	Wire reduction, flexibility enhancement	8.0	60	Ground, takeoff, cruise, landing	Existing
Additional proximity sensors, aircraft doors	Wiring reduction, flexibility enhancement	0.2	50	Ground, takeoff, cruise, landing	Existing
Engine sensors	Engine performance, wire reduction, flexibility enhancement	0.8	140	Ground, takeoff, cruise, landing	Existing and new
Cargo compartment data	Wire reduction, operational enhancements	0.5	25	Ground, takeoff, cruise, landing, taxi	Existing
Structural sensors	Wire reduction, flexibility enhancement, safety enhancements	0.5	260	Ground, takeoff, cruise, landing, taxi	New
Temp./humidity and corrosion detection	Wire reduction, safety enhancements, operational enhancements	1.0	260	Ground, takeoff, cruise, landing, taxi	Existing and new

3.2.2.2 Expected data rates per application

Per-link data rates are expected to be below 10 kbit/s because some of the anticipated applications will be utilized for monitoring status (e.g. door position) which requires a low sampling rate, while other applications are anticipated to use low amounts of data for relatively fast control loops (e.g. wheel speed for anti-skid control at 2.5 ms).

Although transmission of data will be at low per-link data rates, there may be a large number of these transmissions in a small area. Therefore, these low per-link data rates do not allow any conclusion on overall aggregate data rates without a reasonable estimate of the number and density of concurrently active radio links associated with LO applications as well as their traffic statistics.

3.2.2.3 Installation domain

All applications of the LO class are assumed to operate outside the aircraft structure. Therefore, they are not considered to receive the benefits of fuselage attenuation. A significant number of the LO class applications are anticipated to be mounted on the landing gear and in the landing gear bay. The landing gear bay is considered a harsh environment, so there is a strong desire to remove wiring to improve aircraft maintenance tasks. It is anticipated that a significant number of wireless transmission devices will be outside the aircraft when the landing gear is down.

Other LO applications may be mounted on exposed areas of the wing where data may be transmitted to and from flight control sensors and actuation devices. These types of devices are typically mounted on the leading and trailing edges of the wings and are exposed when the slats, flaps, spoilers or ailerons are moved.

Engine transceivers may also be included as an LO application depending upon the materials utilized for the nacelle. Therefore, depending on the nacelle construction, engine sensors are included in both application classes (LI or LO).

3.2.2.4 Additional class attributes

Different LO WAIC applications will have different characteristics in terms of channel access, duty cycle and activity time. Some devices will be constantly active while other devices will only be active for a limited period of time.

The transmissions range will vary between several metres to several tens of metres, depending on the installation locations of the RF transceivers and the network topology. It is envisioned that some applications will transmit while the aircraft is in close proximity to other aircraft also transmitting. Furthermore, propagation conditions for some applications will be NLoS paths.

3.2.3 Classification HI

General: The class of HI applications is characterized by the following main attributes:

- data rate: high (> 10 kbit/s burst rate per node);
- installation domain: inside aircraft structure.

Most HI RF-transceiver nodes will be active during all flight phases and on the ground. However, the nature of the data source traffic for the transmitters is a mix of regular periodic updates for sensor reporting for the entire duration of the flight, interlaced with irregular message bursts on an on-demand basis (voice, video) that do not reflect any periodic or sustained average loading. The maximum number of nodes which belong to this class is anticipated to be 100 per aircraft.

Note that some of these voice/video/imagery source nodes (cameras and microphones) are dual purpose in that they may be utilized by either the flight deck or cabin crew, depending on the situation (emergency or alert vs. routine) and level of service. While, they are shown as separate rows in Table 3, they are actually the same application.

3.2.3.1 HI class member applications

The HI WAIC application class includes flight deck and cabin crew communications throughout the aircraft. These communications are primarily (digitized) voice, but include frame imagery and video, as well as Electronic Flight Operations (EFO) data and other data file transfers. It also includes special higher rate engine (and other) sensor applications for condition based maintenance.

The flight deck crew voice and video/image communications allow expeditious coordination with cabin flight attendants, as well the ability to monitor the conditions of the aircraft cabin, luggage compartments, and other areas only accessible by camera. HI WAIC applications also include engine prognostic sensors, used for in-flight monitoring of various engine parameters for post-flight

analysis and preventative condition based maintenance. The prognostic engine monitors are mainly for ground based maintenance, and would not be intended for flight control purposes. They may, however, be used to supplement other sensors in order to optimize fuel efficiency, structural wear down, or passenger comfort (noise reduction), etc., during a flight.

Table 3 lists the anticipated applications of the HI-class, including further attributes associated with each individual application. Note that virtually all voice, video/imagery, and data sources are identical for the flight deck crew and cabin crew applications, although the Quality of Service (QoS) may differ – voice quality, video resolution, update/transfer rates, etc. The difference between application categories is only the intended destination – flight deck headsets or monitors, vs. flight attendant headsets and monitors, as well as possibly cabin PA speakers and screens.

TABLE 3
HI class member applications

Application	Type of benefit	Net peak data rate per data-link (kbit/s)	Node quantity	Activity period	New or existing application
Air data sensors	Wire reduction, maintenance enhancement	100	8	Ground, takeoff, cruise, landing	Existing
FADEC aircraft interface	Wire reduction, maintenance enhancement	12.5	10	Ground, takeoff, cruise, landing, taxi	Existing
Engine prognostic sensors	Wire reduction, operational enhancements	4 800 peak 80 average per sensor	30	Ground, takeoff, cruise, landing, taxi	New
Flight deck and cabin crew voice	Wire reduction, untethered operation, operational enhancements	64 raw 16 CVSD 2.4 MELP	10	Ground, takeoff, cruise, landing, taxi	Existing and new
Flight deck crew fixed imagery	Wire reduction, flexibility enhancement safety enhancements	2 000 File sizes to > 1 Mbyte 2.5 s update each	50	Ground, takeoff, cruise, landing, taxi	New
Cabin crew fixed imagery	Wire reduction, flexibility enhancement safety enhancements	1 000 File sizes to > 1 Mbyte 5 s update each	20 (included in above)	Ground, cruise, taxi	New
Flight deck crew motion video	Safety enhancements	64 or 256	50 (same as above)	Ground, takeoff, cruise, landing, taxi	Existing and new
Cabin crew motion video	Safety enhancements	64 or 256	20 (same as above)	Ground, takeoff, cruise, landing, taxi	Existing and new

TABLE 3 (*end*)

Application	Type of benefit	Net peak data rate per data-link (kbit/s)	Node quantity	Activity period	New or existing application
Flight deck crew digital data (EFO...)	Wire reduction, flexibility enhancement	< 1 000 (1 250 kb, > 10 s transfer time)	10	Ground, takeoff, cruise, landing, taxi	New
Cabin crew digital data	Wire reduction, flexibility enhancement	< 100 (125 kb, > 10 s transfer time)	5 (included in above)	Ground, cruise, taxi	New

3.2.3.2 Expected data rates per application

Per-link data rates are expected to be above 10 kbit/s per source node. The highest peak data rate is anticipated to be 4.8 Mbit/s from each engine vibration sensor, due to high sample rates and large sample precision (up to 24 bits); however, these sensors are operated at low duty cycle (< 2%), so the average data rate is approximately 80 kbit/s each. Sampled data can be stored at the sensor, and forwarded in the gaps between imagery and voice, to smooth out the average channel traffic loading. (Alternatively, the sensor network itself can be interlaced so that the sensors report in sequence, instead of simultaneously, if this affords adequate smoothing and rate reduction). Then for a network of 24 sensors, 6 on each of 4 engines, the aggregate data rate could be 1.92 Mbit/s, or roughly 2 Mbit/s average. Note that this rate is worst-case, and if bandwidth limitations demand it, on-board signal processing at each sensor can be added to reduce the data content per (approximately 2 minute) frame by a factor of 10 or more. However, this does create a larger, more power-consuming, and more costly sensor, and will be avoided if traffic capacity supports the raw data flows.

The available rates for the crew voice/video/imagery communications is anticipated to be in the tens of kbit/s for voice and data, in the hundreds of kbit/s for video, and up to 1-2 Mbit/s for precision imagery. However, data rates can be traded off against quality of service in order to support numerous simultaneous messages, as usage conditions vary. Quality of service could be automatically controlled by a network monitor that regulates the offered traffic vs. quality of service. In general, cabin applications will tend to have lower priority and thus QoS than flight deck crew communications, and thus draw lower operational data rates to ease the total network traffic load.

Adaptable data rates are beneficial for HI WAIC applications because such actions cannot be achieved by adjusting low data rate traffic, since it could mean dropping essential sensor information. Furthermore, it is anticipated these HI applications will require reasonably low latency (< 0.5 s), as well as a low delay jitter of less than 50 ms, to maintain quality. Therefore, many HI applications readily lend themselves to data rate adaptation.

3.2.3.3 Installation domain

HI WAIC class applications are assumed to operate within the aircraft structure. Transmitters within engine nacelles are considered as belonging to this class. Other fixed transmitter devices will be installed in different compartments, such as the flight deck, cabin, luggage bays, equipment bays, interior surfaces (interior cameras), etc.

3.2.3.4 Additional class attributes

Different HI WAIC applications have different channel access, duty cycle and activity time characteristics. For example, motion video and fixed frame imagery have different purposes; frame imagery may be used for periodic status updates, or to provide a precision view of an equipment failure while motion video could be used to scan/survey an area or to monitor continuously changing conditions, perhaps on a control surface.

The expected required communications range will vary between several centimetres to several tens of metres for WAIC HI class applications. Propagation conditions are expected to be dominated by line-of-sight (LoS) paths in the cabin environment, and non-LoS for other areas of the aircraft.

3.2.4 Classification HO

General: The class of HO applications is characterized by the following main attributes:

- Data rate: high (> 10 kbit/s);
- Installation domain: outside aircraft structure.

It is anticipated that WAIC HO RF transceiver nodes will be active during all flight phases and on the ground. It is anticipated that the number of nodes belonging to this class will be approximately 300 per aircraft.

3.2.4.1 HO class member applications

The HO application class includes applications from the domain of high data rate sensing and control signals, such as structural health monitoring, and active vibration control. It also includes applications from the domain of voice and video data transfer for flight deck crew communications and for external imaging. Flight deck voice systems may be classified as external for example in rotorcraft applications due to the specific physical layout of the vehicle. Similarly, some avionics data bus applications may be placed without an attenuating enclosure, communicating data from outside sensors, which justifies their inclusion in the HO class. Structural health monitoring applications are also included.

Table 4 lists the anticipated applications of the HO class including further attributes associated with each individual application.

TABLE 4
HO class member applications

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
Avionics communications bus	Wire reduction, flexibility enhancement, safety enhancements	100	30	Ground, takeoff, cruise, landing, taxi	Existing
Audio communications system	Wire reduction, flexibility enhancement, safety enhancements	20	10	Ground	Existing
Structural sensors	Wire reduction, flexibility enhancement, safety enhancements	45	250	Ground, takeoff, cruise, landing, taxi	New

TABLE 4 (*end*)

Application	Type of benefit	Net peak data rate per data-link/ (kbit/s)	Node quantity	Activity period	New or existing application
External imaging sensors (cameras, etc.)	Wire reduction, flexibility enhancement, safety enhancements	1 000	5	Ground; rotorcraft operations/hover in confined areas	Existing
Active vibration control	Wire reduction, operational enhancements	50	25	Helicopter cruise	Existing

3.2.4.2 Expected data rates per application

Per-link data rates are expected to be above 10 kbit/s. However, not all applications from this class will operate continually and simultaneously at their respective peak rates, which will afford lowering the average data rate through appropriate load control. Data latency and availability requirements of monitoring systems may not be as stringent as those involved in control loops, which may allow further lowering instantaneous data rates by delaying sensor information that is not time-critical. Furthermore, quality of service parameters of voice and video communications may be adaptively adjusted during the peak demand period. The resulting average per-system data rates will be carefully evaluated in the subsequent phases of this study taking into account the overall wireless system architecture. Currently, only the worst-case peak data rates are addressed here.

- For avionics data bus applications, the peak data rate is assumed to be ARINC¹ 429 high rate of 100 kbit/s. With up to 30 nodes predicted per aircraft, the total data rate may be 3 Mbit/s.
- For audio communications, as explained above, the per-link data rate depends on the coding scheme chosen and on quality of service trade-offs. The average expected per link data rate is predicted to be 20 kbit/s. With up to 10 nodes predicted per aircraft, the total data rate may be 200 kbit/s. The maximum range considered for an audio communication system is anticipated to be 30 m under unobstructed radio propagation conditions.
- For external imaging, the per-link data rate may be as high as 1 Mbit/s. With up to 5 nodes per aircraft, the total data rate may be as high as 5 Mbit/s.
- For active vibration control, the per-link data rate may be as high as 50 kbit/s. With up to 25 nodes per aircraft, the total data rate may be 1.25 Mbit/s.

3.2.4.3 Installation domain

Applications of the HO class are assumed to operate outside the aircraft structure. Devices installed at different locations outside the aircraft could cause mutual interference. The possibilities of reusing one or more of the same RF channels for various simultaneous HO radio links will be studied in order to ensure maximum spectrum efficiency.

¹ ARINC – An acronym for Aeronautical Radio Inc., a corporation that provides communication support for air traffic control (ATC) and aeronautical operational control (AOC) and establishes consensus on avionics technical standards known as ARINC Standards.

3.2.4.4 Additional class attributes

Some HO applications are also listed as members of the previously discussed classes. This overlap occurs mostly for systems installed on rotorcraft. Many systems that fall into the “inside” classification for fixed-wing aircraft may be characterized as “outside” on a helicopter due to the physical layout of the vehicle. For example, a helicopter flight deck is typically much more open to increase the pilot’s visual field of view. In addition, the nature of helicopter propulsion and flight controls dictates significant external control and sensing. Another reason for the category overlap is the impact of sensor data processing. Data rate requirements are implementation-dependent to an extent. For example, Health and Usage Monitoring Systems (HUMS) accelerometer data may fall into the “High” category if it is digitized and “streamed” to an access point in real time, but it could be “Low” rate if the sensor node analyses the data and sends summary statistics.

4 Typical wireless system characteristics

4.1 Reference architecture concept

This section defines the reference physical network architecture for each application class providing the basis for the spectrum requirements analysis for each class of WAIC systems. This specific reference architecture definition allows for a simplification of the overall WAIC system analysis. Only one system architecture is considered for a class of applications, and this model is assumed to apply to all aircraft designs, thus avoiding the need to analyse each aircraft design individually.

The reference physical network architecture comprises the following aspects:

- network nodes² connecting two or more communication paths in a WAIC network; a network node in the given context is always equipped with a transceiver utilizing radio spectrum, when active;
- physical network topology, i.e. the physical arrangement of network nodes;
- number of network nodes including transceivers and repeaters;
- geometrical distances between network nodes and associated required minimum radio range of a network node;
- an estimate of the expected node densities in various regions of the aircraft.

The network architecture described herein is based on the analysis of a typical passenger aircraft layout with 150 to 220 seats. The aviation industry considers this layout as the most likely candidate aircraft type for the introduction of WAIC systems. It is considered to be sufficiently representative for other commercial passenger aircraft types as well.

4.2 Physical architecture

The physical architecture will utilize the following components:

- Gateway node: a network node having an interface connected to an existing communication network onboard the aircraft, such as an avionics data bus and a WAIC radio interface providing wireless access for WAIC network nodes to that on-board communication network.
- End node: a network node, with an interface on one side to one or more end devices, such as sensors, actuators, displays, etc. and a WAIC radio interface on the other side.

² The term “node” is known from network theory, it is a generic term for a network device that connects two or more communication paths in a network.

- Relay node: a network node enabling multi-hop connectivity between end nodes and a gateway node. A relay node may also interface directly to one or more end devices.
- Wireless node: any of the above.

It is anticipated that radio coverage is provided via wireless sub-networks comprised of a gateway, one or more end nodes, and/or one or more relay nodes to account for multi-hop transmission within a sub-network. Multi-hop transmission may be used to overcome severe radio propagation issues, for example to bypass obstacles in the propagation path.

4.2.1 Applications within aircraft structure

4.2.1.1 Aircraft compartments (LI and HI)

In identifying a network architecture for LI and HI class systems, one way is to consider the aircraft structure as an ensemble of different compartments. A typical passenger aircraft is partitioned into the following major compartments:

- flight deck;
- cabin compartment;
- auxiliary power unit (APU) compartment;
- avionics compartment;
- forward cargo compartment;
- aft cargo compartment;
- bilge;
- nacelles;
- centre tank;
- wing fuel tanks;
- vertical and horizontal stabilizers;
- main landing gear bays;
- nose landing gear bay;
- slats and flaps stowage bays.

Figure 2 depicts an exploded view of a typical passenger aircraft, including its compartment locations.

4.2.1.2 Compartment dimensions

The approximate maximum dimensions of the compartments identified in § 4.2.1.1 above are listed in Table 5. These dimensions determine the required radio range of WAIC network nodes installed in interior compartments, considering topology choices made per compartment.

FIGURE 2

Major components of a typical passenger aircraft and location of compartments

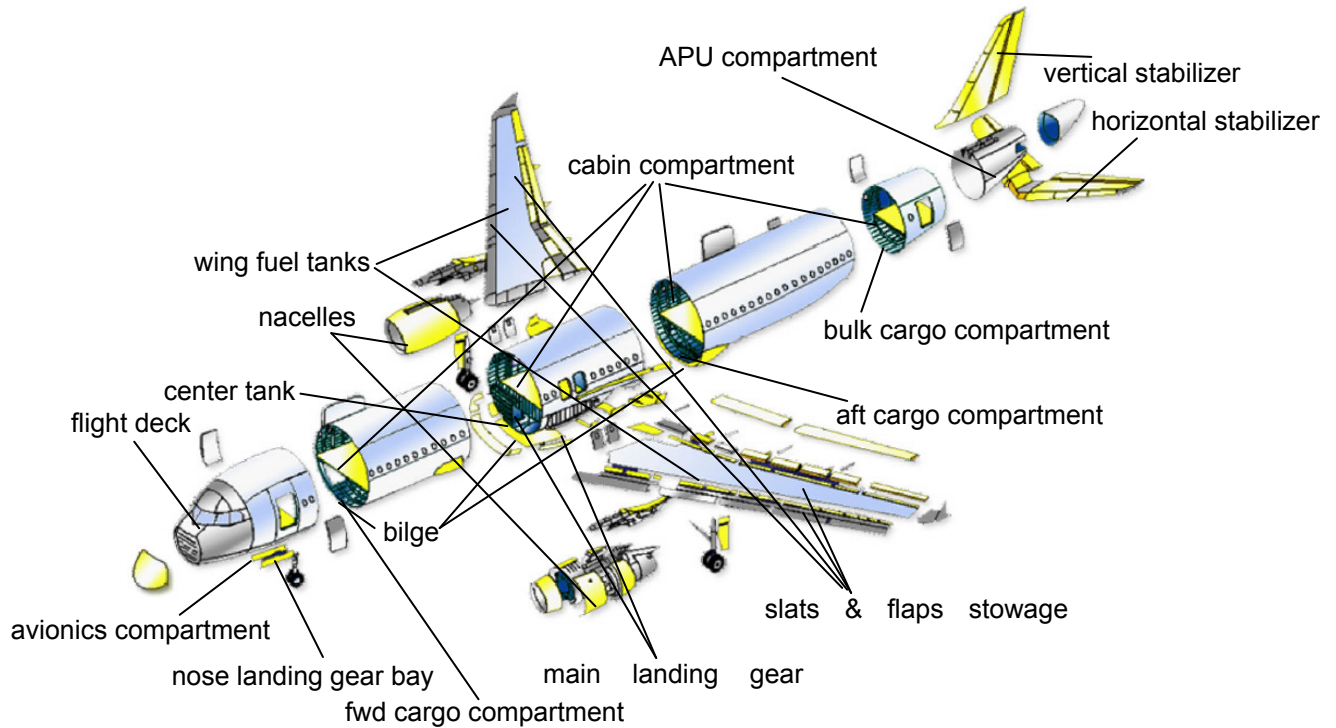


TABLE 5

Approximate maximum compartment dimensions

Compartment	maximum length (m)	maximum width (m)	maximum height (m)	maximum volume (m ³)
Flight deck	3.2	3.7	2.4	28.4
Cabin compartment	28.0	3.7	2.4	248.6
APU compartment	6.5	3.7	2.4	57.7
Avionics compartment	2.8	2.6	1.5	10.9
Fwd cargo compartment	8.3	2.6	1.2	25.9
Aft cargo compartment	11.4	2.6	1.2	35.6
Bulk cargo compartment	4.8	2.6	1.2	15.0
Bilge	22	1.8	0.2	7.9
Nacelles	3.2	1.8	2.1	12.1
Centre tank	2.8	3.9	0.7	7.6
Wing fuel tanks	15.0	3.8	0.7	39.9
Horizontal stabilizers	12.5	1.8	0.3	6.75
Vertical stabilizers	5.4	3.3	0.3	5.3
Main landing gear bays	2.8	1.6	1.9	8.5
Nose landing gear bay	2.7	1.0	1.0	2.7
Slats stowage bays	15.8	0.5	0.3	2.37
Flaps stowage bays	6.3	0.5	0.3	0.9

4.2.1.3 Network topology for WAIC nodes in closed inboard compartments (LI and HI)

It is anticipated that radio coverage is provided to compartments via wireless sub-networks. A sub-network comprises a gateway node having an interface (wired or wireless) connected to an on-board communication network such as an avionics data bus, and a WAIC radio interface. WAIC relay or end nodes attach to the gateway node via the WAIC radio interface. It might be reasonable to account for multi-hop transmissions within a sub-network for some of the compartments to overcome severe radio propagation issues (e.g. to bypass obstacles in the propagation path). In these cases specific relay nodes are required, which forward incoming data packets to the next relay node on the route or to the final destination depending on the position in the routing path. These relay nodes can, in addition to the relaying functionality, also host features such as sensor capabilities.

As long as the isolation between different compartments is sufficient, several of these sub-networks could coexist within the same “radio resource”³, including frequency, time, space and/or signal domain. If reuse of the same spectrum is not possible, radio-frequency management techniques may be utilized.

Depending on the size of the compartment and the maximum transmit power, the physical network topology may consist of one or more radio cells. A radio cell is the coverage area of a single gateway node, or the area covered by the gateway node plus the area covered by all relay nodes belonging to a multi-hop connection associated with that gateway node. A single radio cell will be sufficient for small compartments like the flight deck or the APU compartment. Medium to large size compartments like the cargo compartment or the passenger cabin may require multiple radio cells to provide sufficient coverage.

Figure 3 depicts a typical WAIC network topology anticipated for closed compartments. For small compartments like the flight deck, and avionics compartment, a star topology with the gateway node being the coordinator is considered to be most suitable. For the largest compartment, the cabin, a multi-star topology was chosen, because it provides a better compromise between link reliability and data rate. Star topologies extended by multi-hop line topologies are considered to be most suitable for avionics and cargo compartments, due to the expected severe radio propagation conditions caused by many metallic obstacles in the propagation path.

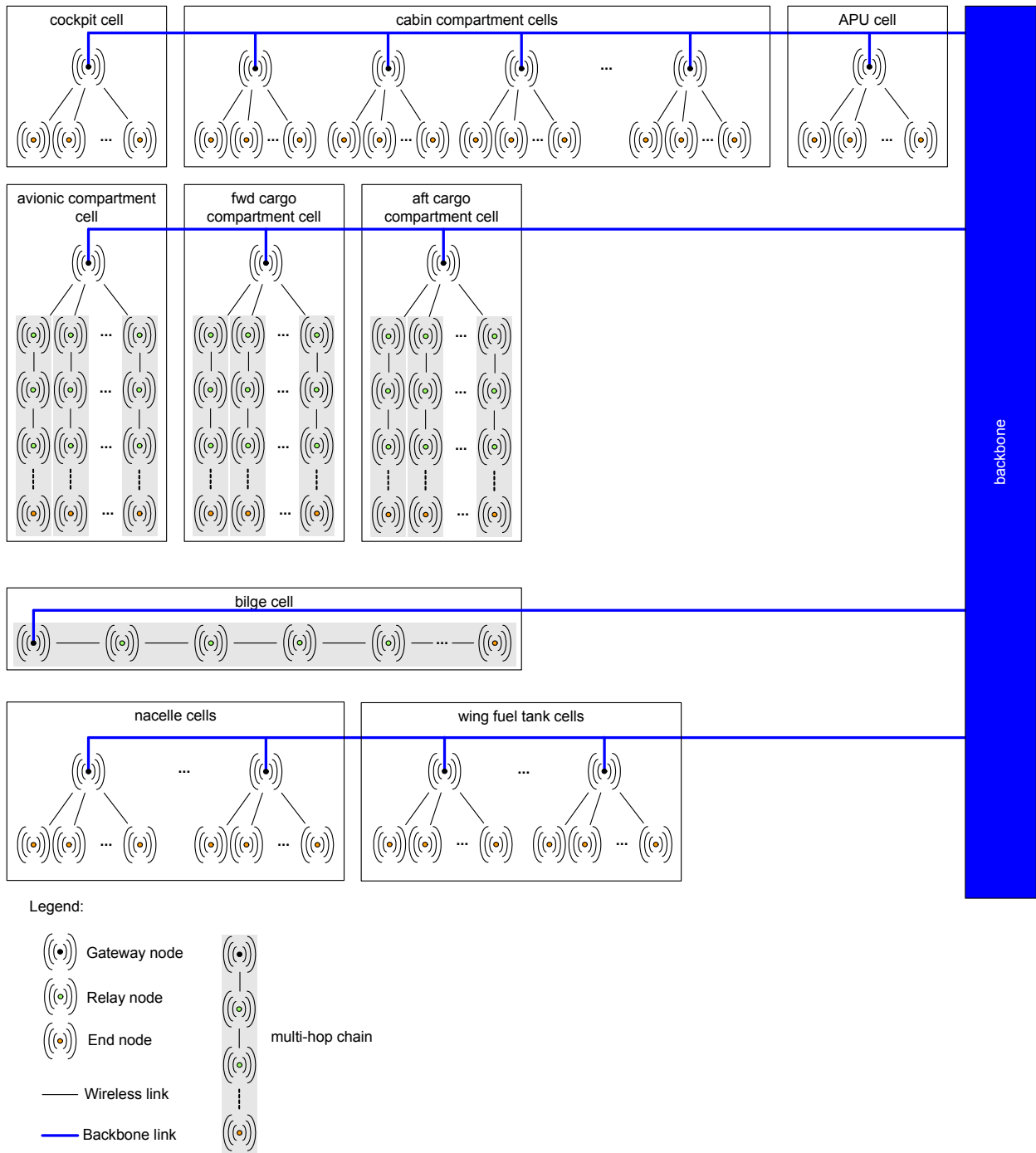
4.2.1.4 Radio range for WAIC systems in closed inboard compartments (LI and HI)

The required radio range for usage inside the aircraft structure would typically be correlated with the dimensions of the respective compartment. An exception may be the passenger cabin, which is the largest compartment for a typical commercial passenger aircraft. It may not be necessary to cover the entire passenger cabin with a single WAIC gateway node. Medium and small compartments should only require a single gateway node. In general a maximum radio range around 20 m for LI and HI applications seems to be sufficient.

³ The term “radio resource” is generic and used as such. The aerospace industry has not yet designed the WAIC radio interface, whether it uses a TDMA, FDMA, CDMA or SDMA component or combinations thereof. Therefore, a radio resource is not the same as a specific radio frequency. For this text, a radio resource will be defined in the multidimensional space made up of the frequency, time, space and signal domains.

FIGURE 3

Network topology of WAIC system installed in compartments inside the aircraft structure



4.2.1.5 Node quantity and density estimation (LI and HI)

The number of nodes served by a single gateway node is determined by the gateway node density, the estimated amount of WAIC transceiver nodes and their spatial distribution. In general the node density not the node quantity is a measure for the expected traffic in a certain area of the aircraft.

In order to estimate node densities a model of a typical aircraft, as depicted in Fig. 4, allows keeping the estimation of node densities generic for most passenger aircraft, while maintaining a sufficient level of detail for deriving meaningful node density estimates. The following areas hereafter referred to as aircraft regions, have been defined:

- F1U: upper nose section of the aircraft fuselage containing the flight deck;
- F1L: lower nose section of the aircraft fuselage containing the avionics compartment and the nose landing gear bay;
- F2U: upper mid section of the aircraft fuselage containing 4/5 of the cabin compartment;
- F2L: lower mid section of the aircraft fuselage containing fwd and aft cargo compartments, centre tank, main landing gear bays and bilge;
- F3U: upper aft section of the aircraft fuselage containing 1/5 of the cabin compartment;
- F3L: lower aft section of the aircraft fuselage containing bulk cargo compartment;
- W1: inner wing including wing tanks;
- W2: outer wing including wing tanks;
- HS: horizontal stabilizer including trim tank;
- VS: vertical stabilizer;
- N: nacelle, including engines and pylon.

To determine an estimate of node density per region, the number of nodes in a region is divided by the enclosing volume of that region. It is assumed that the densities are symmetric about the longitudinal axis of the aircraft.

FIGURE 4
Region definition for a generic aircraft

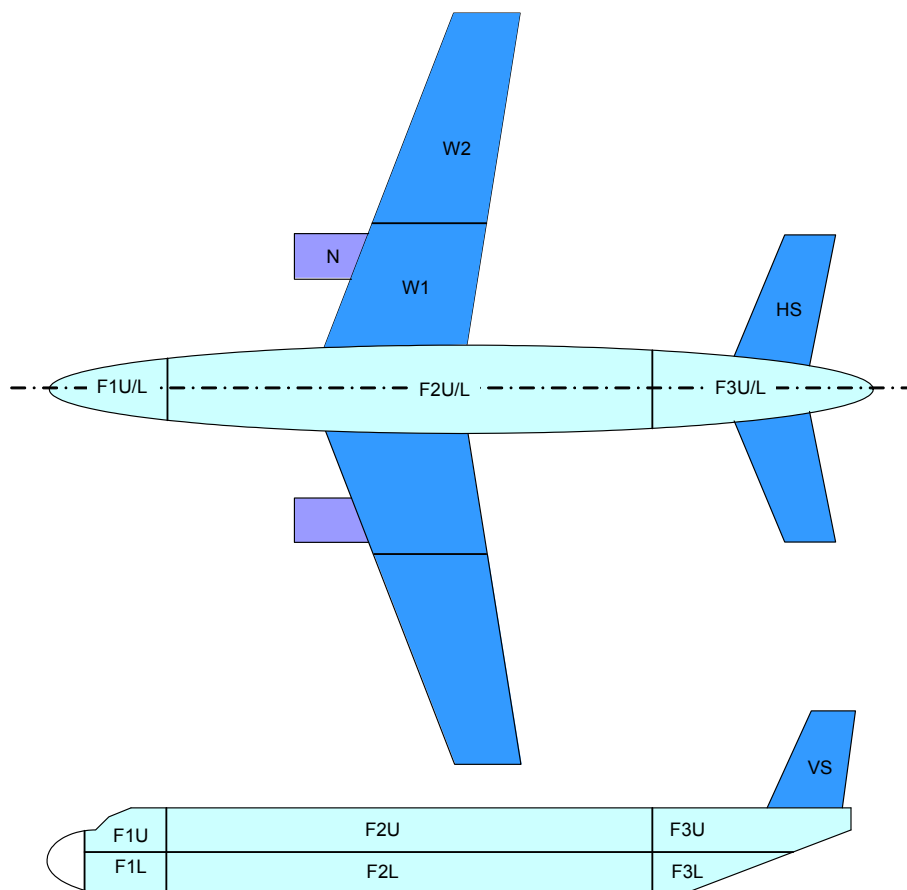


Table 6 and Table 7 provide node density estimates for the various regions of the aircraft for LI and HI class applications, respectively.

TABLE 6
Node density estimation for LI class applications per aircraft region

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
F1L (avionics compartment)	Smoke sensors (unoccupied areas)	40	10	10.9	1.83	1.5
	Proximity sensors, passenger and cargo doors, panels	60	5			
	EMI detection sensors	30	5			
F1U (flight deck)	Smoke sensors (occupied areas)	30	5	28.4	0.88	1
	Proximity sensors, passenger & cargo doors, panels	60	15			
	EMI detection sensors	30	5			
F2L (fwd and aft cargo compartment, centre tank, LG bays, bilge)	Smoke sensors (unoccupied areas)	40	20	94	2.18	3
	Proximity sensors, passenger and cargo doors, panels	60	10			
	ECS sensors	250	60			
	EMI detection sensors	30	5			
	General lighting control	1 000	75			
	Sensors for valves and other mechanical moving parts	100	15			
	Fuel tank/line sensors	80	20			

TABLE 6 (continued)

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
F2U (4/5 of cabin compartment)	Smoke sensors (occupied areas)	130	10	198.9	10.6	1
	Proximity sensors, passenger and cargo doors, panels	60	15			
	ECS sensors	250	120			
	EMI detection sensors	30	5			
	Emergency lighting control	130	100			
	General lighting control	1 000	700			
	Cabin removables inventory	1 000	800			
	Cabin control	500	350			
F3L (bulk cargo compartment)	Smoke sensors (unoccupied areas)	40	10	15.0	6.0	1
	Proximity sensors, passenger and cargo doors, panels	60	5			
	ECS sensors	250	20			
	EMI detection sensors	30	5			
	General lighting control	1 000	25			
	Sensors for valves and other mechanical moving parts	100	15			
	Fuel tank/line sensors	80	10			
F3U (1/5 of cabin compartment)	Cabin pressure	11	11	49.7	13.4	1
	Smoke sensors (occupied areas)	130	10			
	Proximity sensors, passenger and cargo doors, panels	60	10			
	ECS sensors	250	50			
	EMI detection sensors	30	5			
	Emergency lighting control	130	30			
	General lighting control	1 000	200			
	Cabin removables inventory	1 000	200			
	Cabin control	500	150			

TABLE 6 (end)

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
W1 (wing fuel tank)	Fuel tank/line sensors	80	20	39.9	1.4	1
	Sensors for valves and other mechanical moving parts	100	35			
W2 (wing fuel tank)	Fuel tank/line sensors	80	20	39.9	1.4	1
	Sensors for valves and other mechanical moving parts	100	35			
HS (horizontal stabilizer)	Fuel tank/line sensors	80	10	6.75	1.5	1
N (nacelle)	Engine sensors	140	140	24.2	5.8	2

TABLE 7

Node density estimation for HI class applications per aircraft region

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
F1L (avionics compartment)	Air data sensors	14	7	10.9	1.00	1.5
	Flight deck crew fixed imagery and cockpit crew motion video	30	4			
F1U (flight deck)	Flight deck and cabin crew voice	10	4	28.4	0.32	1
	Flight deck crew fixed imagery and flight deck crew motion video	30	4			
	Flight deck crew digital data (EFO...)	5	5			
F2L (fwd and aft cargo compartment, centre tank, LG bays, bilge)	Air data sensors	14	7	94	0.16	3
	Flight deck crew fixed imagery and flight deck crew motion video	30	8			

TABLE 7 (end)

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
F2U (4/5 of cabin compartment)	Flight deck and cabin crew voice	10	4	198.9	0.18	1
	Flight deck crew fixed imagery and flight deck crew motion video	30	11			
	Cabin crew fixed imagery and cabin crew motion video	20	16			
	Cabin crew digital data	5	4			
F3U (1/5 of cabin compartment)	Flight deck and cabin crew voice	10	2	49.7	0.20	1
	Flight deck crew fixed imagery and flight deck crew motion video	30	3			
	Cabin crew fixed imagery and cabin crew motion video	20	4			
	Cabin crew digital data	5	1			
N (nacelle)	FADEC aircraft interface	10	10	24.2	1.65	2
	Engine prognostic sensors	30	30			

4.2.2 Applications outside aircraft structure (LO and HO)

4.2.2.1 Network topology for WAIC nodes outside the aircraft structure (LO and HO)

In this section, a WAIC network topology for low-bandwidth, outside aircraft structure (LO) and high bandwidth, outside aircraft structure (HO) applications is proposed. Figure 5 depicts areas of the aircraft in which WAIC nodes for these application classes might be installed. Based on these potential installation areas the following seven main regions have been defined, which constitute particular radio cells:

- fuselage;
- wings;
- stabilizers;
- nacelles;
- nose landing gear;
- main landing gear;
- cabin and cargo door areas.

Figure 6 depicts the location and provides an estimate of the dimensions of each of these radio cells. It further gives the approximate volume per radio cell required for node density estimation carried out in § 4.2.2.3.

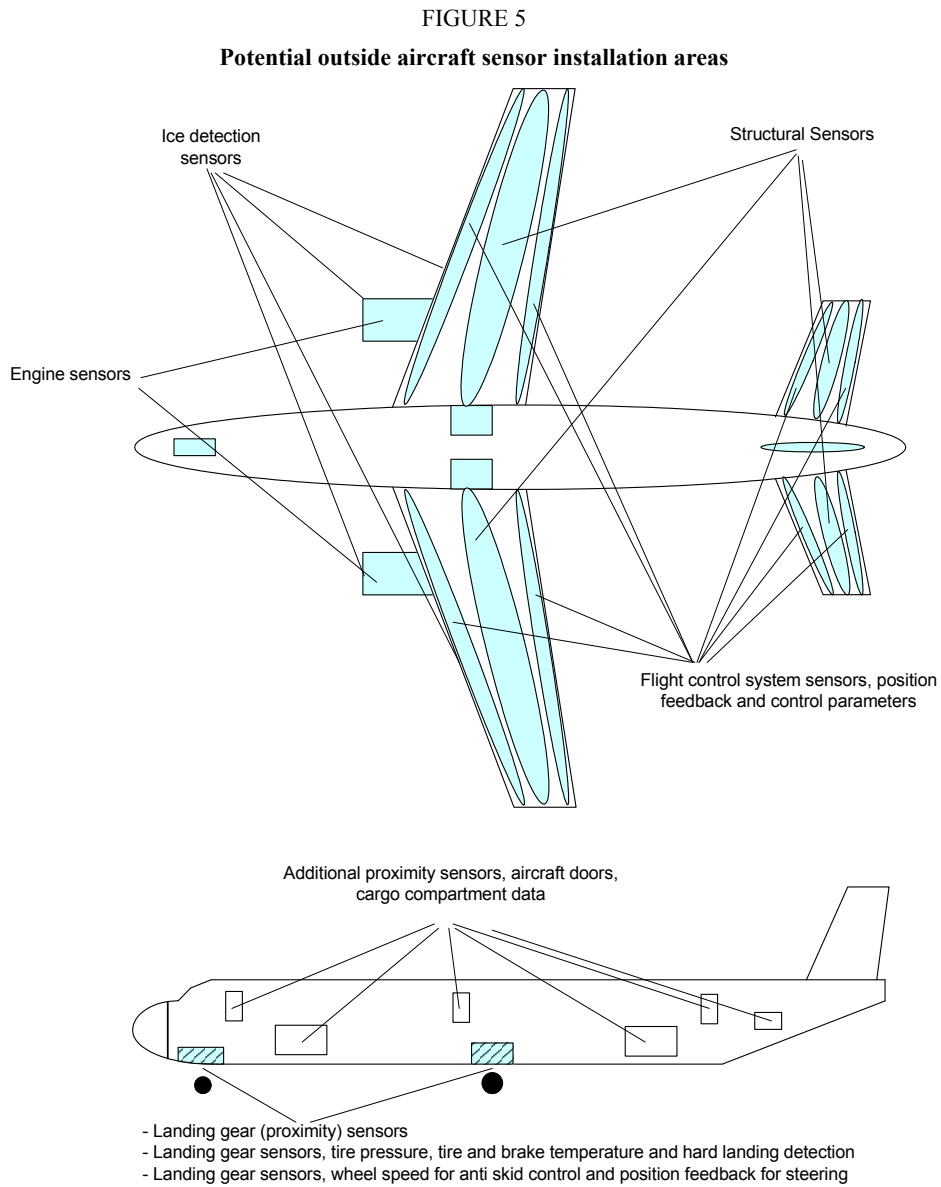


FIGURE 6
Aircraft main regions for LO and HO applications

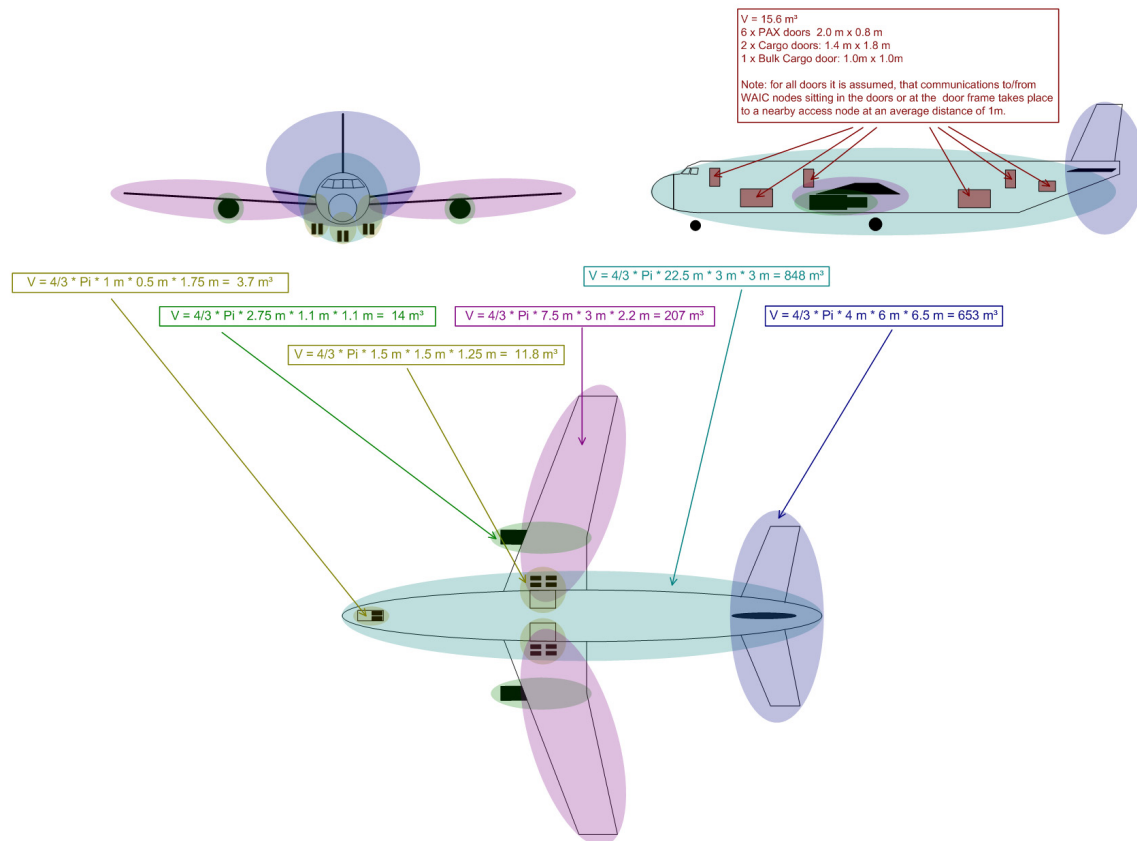


Figure 7 shows the proposed WAIC network topology for the LO and HO application classes. The fuselage, wings and stabilizer radio cells constitute star or multi-star topologies with multi-hop extension. The main purposes of multi-hop communications in these aircraft areas is to have the option to extend the range of a radio cell without increasing the gateway and/or end node's transmit power levels in cases of severe propagation conditions. Nacelle, nose landing gear, main landing gear and cabin and cargo door areas cells employ pure star or multi-star topologies. Multi-hop extensions are not necessary in these areas due to the relatively short and line-of-sight distances. The gateway nodes are connected to the aircraft's on-board communication data network using either wired or, if possible, even wireless connections.

For the fuselage cell it is assumed the entire vicinity of the aircraft fuselage is covered by a single gateway node. This gateway node's antennas are assumed to be located on top and underneath the aircraft's fuselage.

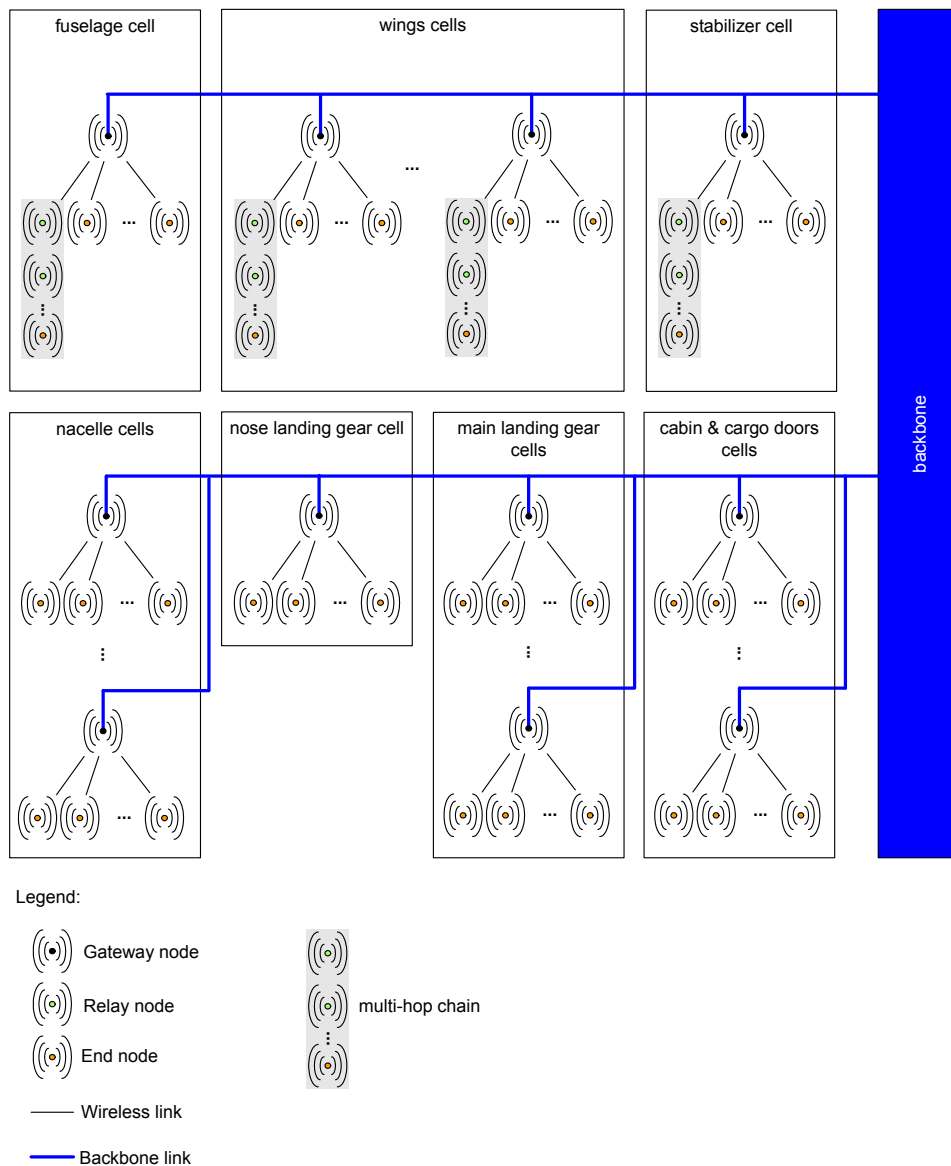
Similarly, each wing and the stabilizers are covered by separate gateway nodes.

The nacelle cell is already handled in § 4.2.1. It is however treated here as well, since a subset of the engine sensors transmit outside the aircraft.

For landing gear sensors a dedicated gateway node situated within each landing gear bay is appropriate. Although communications between a WAIC sensor node located near the wheel axle and a gateway node located outside the aircraft structure might be possible when the landing gear is lowered, communications will suffer from large path loss when the gear is retracted and the doors are closed. Therefore, a separate gateway node per each landing gear bay is desired.

FIGURE 7

Network topology of WAIC system installed outside aircraft structure



The “cabin and cargo doors” cells provide radio coverage for WAIC applications used in these respective areas, such as data related to cabin and cargo door positions and aircraft load management applications assisted by wireless sensors (see application “cargo compartment data”). This information is assumed to be transmitted only when corresponding doors are opened through separate gateway nodes located in range of the corresponding end nodes, near the doors within the cabin and cargo compartments.

It may be desirable to include directional antenna designs at certain wireless nodes to enhance performance and minimize power. Sensor mesh topologies may be utilized for sensor nodes measuring structural health. These nodes may be located along the wings or stabilizers.

4.2.2.2 Required radio range

For WAIC usage scenarios outside the aircraft structure, the maximum required radio range is given by the aircraft dimensions. A typical commercial passenger aircraft has a wingspan of approx. 34 m and an overall length between 31.5 and 44.5 m. Assuming the largest possible separation between WAIC transmitter and receiver, the required radio range will be in the order of 50 m for this aircraft class.

Assuming a maximum required 50 m radio range and evenly spaced multi-hop nodes between a gateway and the farthest transceiver node, we can estimate an average radio range for this aircraft class as given in Table 8.

TABLE 8
Transmitter-receiver separation for LO class WAIC applications
and a typical commercial aircraft

LO application	Max distance (distance between furthest end node to gateway node in multi-hop chain) (m)	Average number of hops	Average distance between nodes (m)
Nacelle	10	1	10
Wing and stabilizers	50	1.5	33
Landing gear	10	1	10
Cabin and cargo doors	10	1	10

4.2.2.3 Node quantity and density estimation (LO and HO)

The number of WAIC transceiver nodes to be served by a single gateway node is determined by the gateway node density, the estimated amount of WAIC transceiver nodes and their spatial distribution throughout the aircraft. In general the node quantity per unit volume, i.e. the node density is a measure for the amount of traffic, which can be expected for a certain region of the aircraft, which in turn allows deriving spectrum requirement estimates. Tables 9 and 10 provide node density estimates for the various regions of the aircraft for LO and HO class applications, respectively.

TABLE 9
Node density estimation for LO class applications per aircraft region

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
Wing (leading wing edges)	Ice detection	20	5	414	0.555	3
	Flight control system sensors, position feedback and control parameters	60	20			
Wing (trailing wing edges)	Ice detection	20	5			
	Flight control system sensors, position feedback and control parameters	60	20			
Wing (main wing structures)	Structural sensors	260	180			

TABLE 9 (end)

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
Stabilizers (leading and trailing edges and main structure)	Ice detection	20	6	653	0.162	2
	Flight control system sensors, position feedback and control parameters	60	20			
	Structural sensors	260	80			
Landing gear and landing gear bays	Landing gear (proximity) sensors	30	30	27	6.30	1
	Landing gear sensors, tyre pressure, tyre and brake temperature and hard landing detection	100	100			
	Landing gear sensors, wheel speed for anti-skid control and position feedback for steering	40	40			
Passenger and cargo doors	Additional proximity sensors, aircraft doors	50	50	16	20.9	1
	Cargo compartment data	25	25			
	Temperature/humidity and corrosion detection	260	260			
Nacelles	Ice detection	20	4	28	5.14	1
	Engine sensors	140	140			

TABLE 10

Node density estimation for HO class applications per aircraft region

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
Fuselage	Avionics communication bus	30	10	848	0.017	3
	External imaging sensors (cameras, etc.)	10	4			
Wings (leading wing edges)	Structural sensors	250	20	414	0.304	3
	External imaging sensors (cameras, etc.)	10	2			

TABLE 10 (*end*)

Region	Associated applications	Total No. of nodes	No. of nodes per region	Maximum region volume (m ³)	Node density (nodes/m ³)	Average number of hops
Wings (trailing wing edges)	Structural sensors	250	20			
Wings (main wing structures)	Avionics communication bus	30	4			
	Structural sensors	250	80	653	0.075	2
Stabilizers (leading and trailing edges and main structure)	Avionics communication bus	30	6			
	Structural sensors	250	40			
Landing gear and landing gear bays	External imaging sensors (cameras, etc.)	10	3	27	1	1
	Avionics communication bus	30	6			
	Audio communication system	20	20			
Passenger and cargo doors	External imaging sensors (cameras, etc.)	10	1	16	3.75	1
	Structural sensors	250	60			
Nacelles	Avionics communication bus	30	4	28	1.21	1
	Structural sensors	250	30			

4.3 Data transfer requirements

This section describes the data transfer requirements for LI, LO, HI, and HO aircraft applications. The subsections that follow describe the factors influencing data transfer needs, quantitative bounding definitions, and the data transfer requirements for each of the different application types. This section provides the maximum data rates and average data rates per aircraft application.

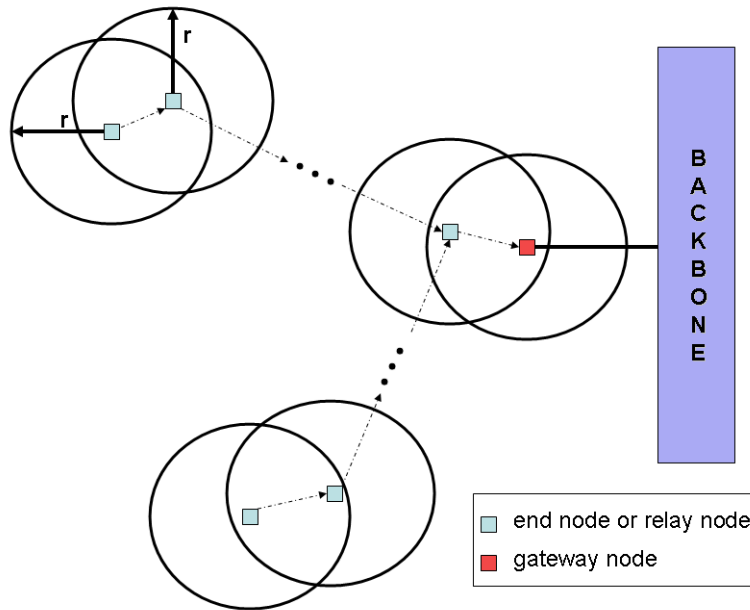
4.3.1 Factors influencing data transfer requirements

This section describes how wireless node data transfer needs are influenced by:

- aircraft interior environment and wireless architecture;
- application nodes;
- wireless protocol.

Figure 8 shows an arrangement of a generic wireless architecture for a sub-network, including a gateway node and a number of end and relay nodes. The circles with radius, r , around each wireless node represent their respective maximum transmission range.

FIGURE 8
Generic 2-D omnidirectional wireless network architecture



It is assumed for this analysis that all wireless nodes have omnidirectional and equal transmission range or (r). A higher range reduces the number of “hops” required for a message to reach a gateway node. The above assumptions only affect the number of “hops” which is related to data rate.

4.3.1.1 Aircraft interior environmental and wireless architecture effects

In contrast to inside applications, outside applications experience less obstructed propagation paths since the devices are not in separate compartments, and environmental obstacles remain relatively stationary. However, these WAIC nodes can experience interference from external sources more readily and the distances traversed are longer. The environment can affect data transmission by these means:

1. Multi-hop communications are required to route communications around interfering obstacles that drive signal-to-noise (S/N) levels below acceptable levels. This delays the signal propagation to gateway nodes. Additionally, data may accumulate along a multi-hop chain, so wireless nodes in the latter part of the chain must be capable of transmitting higher data-rate loads.
2. Communication protocols increase data overhead to overcome aircraft interior signal interference levels, to enable communication decoding, etc. This includes message retransmission, error correction coding, compression, etc.
3. Redundant nodes for fault/interference tolerance could distribute data transfer loads under no-fault conditions. However, when a node fails, the remaining nodes (that are capable) should be able to handle the higher data-rate loads with a prescribed message error rate. Redundant nodes will not be considered in the analysis.

On a typical aircraft, it will be assumed that data from each application is transmitted via a multi-hop chain that has no more than H_{max} number of hops before reaching the wired communications network. For aircraft applications, it is assumed that $H_{max} \leq 3$.

4.3.1.2 Application nodes

Application nodes are considered as data generator nodes. Examples of application nodes are data concentrator or sensor nodes, user interface nodes, etc., each of which may have several different types of data to be transmitted. Each sensor node can receive and transmit wireless signals from other nodes allowing for multi-hop capability. Each application node has a maximum specified peak data rate at which data must be transmitted. This is the primary driver of the requirements.

4.3.1.3 Wireless protocol

Typically, communication protocols are defined as different layers. For example, the open system interconnection (OSI) model defines seven different layers from physical (layer 1) to application (layer 7). The different layers determine how messages are packaged/divided for transmission and reassembled when received; if and how data is encrypted/decrypted and compressed/decompressed; the definition of the network topology; if error coding is applied, etc. Each layer of a communication protocol encapsulates payload data with additional protocol level data that must be applied to a message when transmitting and removed when received. Thus, a protocol produces overhead in data transmission rates due to the message encapsulation and encapsulation removal operations induced by the layers.

The magnitude of the effect that a protocol has on data rate can depend on many factors. By applying these layer wrappers on a message, the required overall data to transmit increases, which makes the effective data rate lower than the physical data rate. However, if error correction coding is included, the data rate may improve by reducing retransmission requests. In addition, compression techniques can reduce the amount of data to be transmitted, thus effectively increasing the data rate.

4.3.2 Methodology for quantifying data transfer requirements

This subsection describes the data transfer quantitative bounds for aircraft applications.

4.3.2.1 Protocol overhead parameters (α : percentage change)

In order to simplify our analysis of the effect of protocols on data rates, we assume that a protocol provides a percentage increase in peak data rates required. Thus, equation (1) relates the physical peak data rate (p_{phy}) required with the effective data rate (p_{eff}) utilizing the parameter, $\alpha > 0$. The α parameter incorporates both data rate overhead from the communication protocol(s) and data aggregation from different applications within a region of the aircraft using multi-hop relay nodes.

$$p_{phy} = \alpha p_{eff} \quad \alpha > 0 \quad (1)$$

Equation (1) provides an estimate of the data rate required to physically transmit messages at the required effective data rate specified by an application.

4.3.3 WAIC data transfer requirements for application class LI

Table 11 shows some estimated physical peak and average LI application data rates. The α parameter for this class is assumed to have a value of 5.

TABLE 11

Estimated physical peak and average LI application data rates

Application	Maximum average application data rate p_{eff}, kbit/s	Transmitted average data rate, per node, kbit/s
Cabin pressure	0.8	4
Engine sensors	0.8	4
Smoke sensors (unoccupied areas)	0.1	0.5
Smoke sensors (occupied areas)	0.1	0.5
Fuel tank/line sensors	0.2	1
Proximity sensors, passenger and cargo doors, panels	0.2	1
Sensors for valves and other mechanical moving parts	0.2	1
ECS sensors	0.5	2.5
EMI detection sensors	1.0	5
Emergency lighting control	0.5	2.5
General lighting control	0.5	2.5
Cabin removables inventory	0.1	0.5
Cabin control	0.5	2.5

4.3.4 WAIC data transfer requirements for application class LO

Table 12 shows some estimated physical peak and average LO application data rates. The α parameter for this class is also assumed to have a value of 5.0.

TABLE 12

Estimated physical peak and average LO application data rates

Application	Maximum average application data rate p_{eff}, kbit/s	Transmitted average data rate, per node, kbit/s
Ice detection	0.5	2.5
Landing gear (proximity) sensors	0.2	1
Landing gear sensors, tyre pressure, tyre and brake temperature and hard landing detection	1.0	5
Landing gear sensors, wheel speed for anti-skid control and position feedback for steering	5.5	27.5
Flight control system sensors, position feedback and control parameters	8.0	40

TABLE 12 (*end*)

Application	Maximum average application data rate p_{eff} , kbit/s	Transmitted average data rate, per node, kbit/s
Additional proximity sensors, aircraft doors	0.2	1
Engine sensors	0.8	4
Cargo compartment data	0.5	2.5
Structural sensors	0.5	2.5
Temperature/humidity and corrosion detection	1.0	5

4.3.5 WAIC data transfer requirements for application class HI

Table 13 shows some estimated physical peak and average HI application data rates. The α parameter for this class is assumed to have a value of 2.

TABLE 13

Estimated physical peak and average HI application data rates

Application	Maximum average application data rate p_{eff} , kbit/s	Transmitted average data rate, per node, kbit/s
Air data sensors	100	200
FADEC aircraft interface	12.5	25
Engine prognostic sensors	80	160
Flight deck and cabin crew voice	64 raw 16 CVSD 2.4 MELP	128 raw 32 CVSD 4.8 MELP
Flight deck crew fixed imagery	2 000 File sizes to > 1 Mbyte 2.5 s update each	4 000
Cabin crew fixed imagery	1 000 File sizes to > 1 Mbyte 5 s update each	2 000
Flight deck crew motion video	64 or 256	128 or 512
Cabin crew motion video	64 or 256	128 or 512
Flight deck crew digital data (EFO...)	< 1 000 (1 250 kb, > 10 s transfer time)	< 2 000 (2 500 kb, > 10 s transfer time)
Cabin crew digital data	< 100 (125 kb, > 10 s transfer time)	< 200 (250 kb, > 10 s transfer time)

4.3.6 WAIC data transfer requirements for application class HO

Table 14 shows some estimated physical peak and average HI application data rates. The α parameter for this class is also assumed to have a value of 2.0.

TABLE 14

Estimated physical peak and average HO application data rates

Application	Maximum average application data rate p_{eff} kbit/s	Transmitted average data rate, per node, kbit/s
Avionics communication bus	100	200
Audio communication system	20	40
Structural sensors	45	90
External imaging sensors (cameras etc.)	1 000	2 000
Active vibration control	50	100

4.4 WAIC propagation characteristics**4.4.1 Path-loss inside aircraft**

The aircraft compartments described in § 4.2.1.1 present complex and variable RF propagation paths. Metal and carbon-fibre composite materials reflect, refract, and diffract electromagnetic signals, resulting in significant multipath. Additionally, electromagnetic signals can be substantially attenuated (through absorption and/or shadowing) in compartments crowded with interior structures (seats, galleys, lavatories, beverage/food carts, etc.), passengers, baggage and/or cargo.

For the purposes of calculating expected path loss in support of determining required transmit power level, signal fading resulting from shadowing and absorption (slow-fading) is modelled through adjustments to the path-loss exponent. Signal fading resulting from multipath (fast-fading) will be modelled through use of a Rayleigh fading model, and accounted for through the addition of a fading margin. Figure 9 illustrates the relationship of path-loss exponent, slow-fading, and fast-fading.

4.4.1.1 Aircraft propagation testing

Testing has been conducted on a number of “wide-body” aircraft (an aircraft with two aisles). The data presented here are representative of propagation within a wide-body cabin. A network analyser was used to measure path loss (S21) for multiple transmit and receive locations under both occupied (by passengers) and not occupied conditions, and in locations with varying degrees of obstructions. Frequency was swept around 2.4 GHz and 5 GHz to assess fast-fading and multipath.

4.4.1.2 Calculation of path loss exponent

Path loss exponents (PLEs) for each condition were calculated by combining measurements at various locations and antenna orientations. Table 15, summarizes the mean, standard deviation, minimum and maximum PLE for each condition.

FIGURE 9
Airplane path loss data

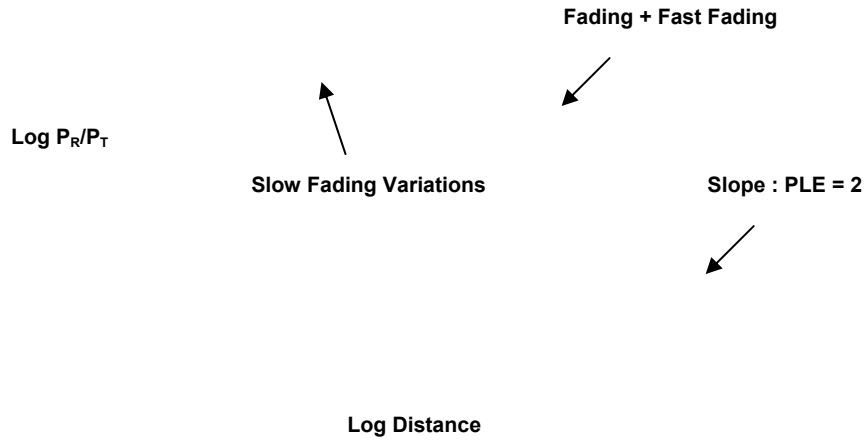


TABLE 15
Airplane path loss exponents

Condition			Path loss exponent		
Absorbers present	LoS/NLoS	Frequency	Mean	Maximum	Std dev
				Minimum	
Occupied	More LOS	2.4 GHz	2.37	2.84	0.29
				2.05	
	5 GHz	2.57	2.84	0.25	
					2.09
More NLOS	2.4 GHz	3.27	3.77	0.29	
					2.86
	5 GHz	3.33	3.60	0.14	
					3.09
Non-occupied	More LOS	2.4 GHz	1.70	1.89	0.18
				1.41	
	5 GHz	2.02	2.23	0.18	
					1.76
	More NLOS	2.4 GHz	1.87	2.16	0.14
5 GHz		2.20	2.49	0.16	
					1.95

The mean PLE for a non-occupied cabin in all cases is substantially less than for an occupied cabin. For the non-occupied conditions, the calculated PLE is sometimes less than that expected for free space (PLE = 2), indicating that the cabin is acting as a resonant cavity. However, when the cabin is fully loaded with passengers, the PLE is substantially greater than 2, indicative of a NLoS path.

4.4.1.3 Applying calculated path loss exponents to WAIC

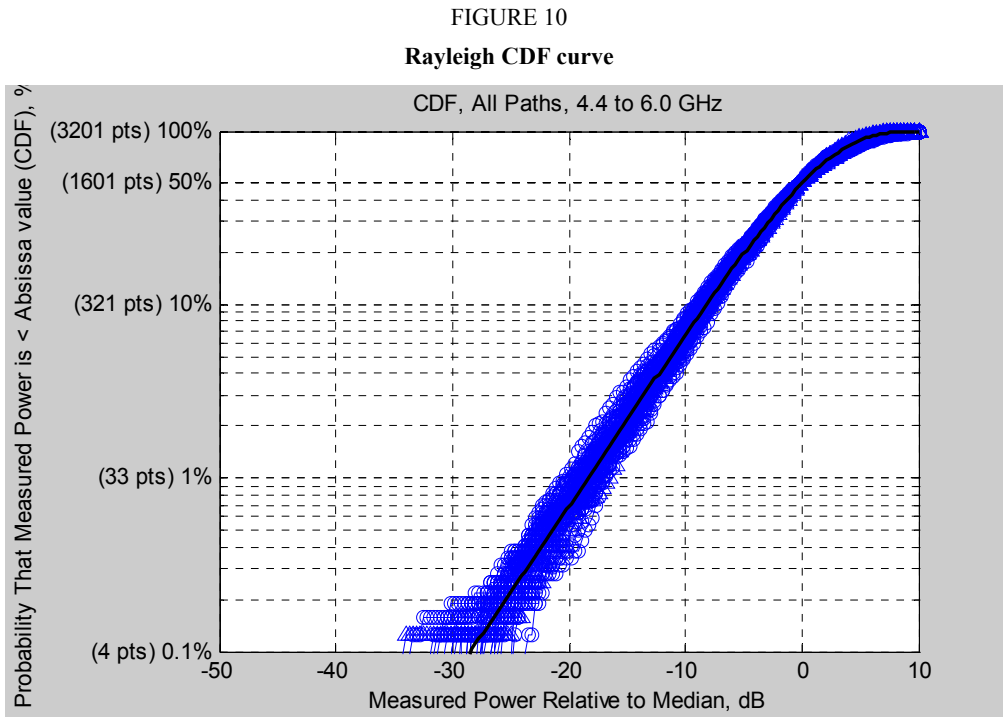
The cabin PLE results can be extrapolated to other aircraft compartments by selecting the condition that is most similar to the particular compartment. This classification is based on the “occupied” or “non-occupied” status, i.e. on presence of absorbers, and on the distinction between LoS and NLoS conditions. Based on this, the proposed PLE values for each compartment are calculated and assumed to be valid within the 1 GHz to 10 GHz frequency range. For frequencies above 10 GHz, experimental data relevant to aircraft environment is not available. However, the published data on propagation in office, home and commercial environments suggests that the PLE values for high frequencies are similar. Therefore, the values derived for lower frequencies will be used, until experimental data becomes available. The PLE values are given in Table 16.

TABLE 16
Proposed path loss exponent values

Compartment	Absorbers present	LoS/NLoS	Proposed PLE values for WAIC
APU compartment	Not occupied	More LoS	2.0
Avionics compartment	Not occupied	More LoS	2.0
Bilge	Not occupied	More LoS	2.0
Stabilizers (inside of structure)	Not occupied	More LoS	2.0
Main landing gear bays	Not occupied	More LoS	2.0
Nose landing gear bay	Not occupied	More LoS	2.0
Slats and flaps stowage bays (slats and flaps extended)	Not occupied	More LoS	2.0
Slats and flaps stowage bays (slats and flaps retracted)	Not occupied	More NLoS	2.0
Nacelles	Not occupied	More NLoS	2.0
Flight deck	Occupied (crew)	More LoS	2.5
Centre tank	Occupied (fuel)	More LoS	2.5
Wing fuel tanks (intra-tank propagation only)	Occupied (fuel)	More LoS	2.5
Cabin compartment	Occupied (pax)	More NLoS	3.0
Fwd cargo compartment	Occupied (cargo)	More NLoS	3.0
Aft cargo compartment	Occupied (cargo)	More NLoS	3.0

4.4.1.4 Fading margin

Modifications to the PLE account only for effects of shadowing and absorption. Additional fading may occur due to destructive interference from multipath effects. Data from the testing described above confirms that fading in the aircraft cabin can be accurately modelled through use of a Rayleigh distribution. Figure 10 illustrates test data (normalized for distance using average PLE) plotted against a theoretical Rayleigh distribution with $\sigma = 1$.



The Rayleigh CDF curve plots the amplitude of the fade against probability that it will occur. Fast fading can occur over very small intervals of time or distance. For example, in the cabin environment where propagation path losses change because of passengers and carts moving, even the cabin structure flexing. These changes alter the propagation paths such that standing wave nulls and peaks move around. For the purposes of WAIC systems, where reliable communications are required to support higher-criticality airplane functions, a large fading margin must be selected that will ensure low probability or low frequency of a deep fade resulting in loss of communications. A fading margin on the order of 20 dB is proposed, which should be seen less than 0.7% of the time. Methods to overcome deep fading, such as frequency spreading will be employed in the design of the radio and coding mechanisms.

4.4.2 Propagation outside aircraft

For outside environments, the path loss exponent is assumed to be 2.0, representing free-space propagation.

4.5 RF characteristics

This section provides a broad overview of the potential types and potential technical characteristics of WAIC RF transmitters and receivers which will then be used to generate the spectrum requirements for WAIC systems. The RF characterization will be broken down into three parts:

antenna, transmitter, and receiver systems. Following the discussion of the characteristics for these systems, an analysis of the system power and bandwidth requirements will be provided.

4.5.1 Antenna system characteristics

WAIC systems will utilize antennas as transducers, both transmitting and receiving the RF signal. Characteristics of the antenna which include gain, side-lobe levels, directivity, and useable bandwidth impact the total power transmitted by WAIC systems.

4.5.1.1 Antenna gain and size

The peak gain (in the main lobe) of an antenna is described by the following equation:

$$G = \frac{4\pi f^2}{c^2} A_{eff} \eta_l \quad (2)$$

where:

- f : the frequency
- c : the speed of light
- A_{eff} : the effective area of the antenna
- η_l : the antenna ohmic efficiency.

Antenna gain is measured relative to an isotropic source in units of dBi. Antenna gain directly impacts the required power of WAIC systems; systems which employ higher gain require less total power. Systems employing higher antenna gain may also interfere less with other systems, decrease their own susceptibility to outside interference, and allow for greater spectrum reuse aboard the aircraft.

Because of various practical constraints on individual systems within or on an aircraft, it is expected that a range of antenna gains will be required for WAIC systems. Physical size is one such constraint. Antenna gain is largely a function of the antenna's size, A_{eff} , and frequency. As gain increases, either antenna size or frequency must increase, for a fixed efficiency. For WAIC systems that must be placed in small enclosed areas, physical size becomes a constraint on increasing gain. On the other hand, for higher frequencies there may be physical limits which make the manufacture of low-gain antennas difficult.

Gain is directly proportional to the directional focusing of power, namely directivity. Increased directivity results in narrower beamwidths, and as a result increased sensitivity to pointing errors. In many applications for WAIC systems, there may be considerable uncertainty in the placement and pointing of antennas. Moreover, obstructing objects may make the optimal pointing direction for WAIC systems unclear to designers and installers. This limits the practical amount of gain achievable for WAIC systems. Directivity and beamwidth are further discussed in § 4.5.1.2.

While WAIC system designers will likely use higher gain antennas when possible, engineers must balance between the beamwidth of the antenna, the antenna gain, as well as the frequency band utilized in order to achieve desired results. It is predicted that WAIC systems will use one of three broad classes of antennas based on gain: "high gain" (> 12 dBi); "moderate gain" (5-12 dBi); and "low gain" (< 5 dBi).

Table 17 shows a list of all applications, whether the system has fixed, ad hoc, or mobile wireless nodes, and the anticipated gain for antennas used by such systems.

TABLE 17
Antenna classification by application

Application	Application class	System type	Minimum likely antenna gain class (end or relay node/gateway node)
Cabin pressure	LI	Fixed	Mod/Mod
Engine sensors	LI	Fixed	Mod/Mod
Smoke sensors (unoccupied areas)	LI	Fixed	Mod/Mod
Smoke sensors (occupied areas)	LI	Fixed	Mod/Mod
Fuel tank line sensors	LI	Fixed	Mod/Mod
Proximity sensors passenger and cargo doors, panels	LI	Fixed	Mod/Mod
Sensors for valves and other mechanical moving parts	LI	Fixed	Mod/Mod
ECS sensors	LI	Fixed	Mod/Mod
EMI detection sensors	LI	Fixed	Mod/Mod
Emergency lighting control	LI	Fixed	Mod/Mod
General lighting control	LI	Fixed	Mod/Mod
Cabin removables inventory	LI	Mobile/ad hoc	Low/Mod
Cabin control	LI	Fixed	Mod/Mod
Additional proximity sensors, aircraft doors	LO	Fixed	Mod/High
Cargo compartment data	LO	Mobile/ad hoc	Low/Mod
Engine sensors	LO	Fixed	Mod/Mod
Flight control system sensors, position feedback and control parameters	LO	Fixed	High/High
Ice detection	LO	Fixed	Mod/High
Landing gear (proximity) sensors	LO	Fixed	Mod/High
Landing gear sensors, tyre pressure, tyre and brake temperature and hard landing detection	LO	Fixed	Mod/High
Landing gear sensors, wheel speed for anti-skid control and position feedback for steering	LO	Fixed	High/High
Structural sensors	LO	Fixed	Mod/High
Temp./humidity and corrosion detection	LO	Fixed	Mod/High
Air data sensors	HI	Fixed	Mod/Mod
Flight deck crew fixed imagery and motion video	HI	Fixed	High/High
Flight deck crew digital data (EFO...)	HI	Fixed	High/High
FADEC aircraft interface	HI	Fixed	Mod/Mod
Engine prognostic sensors	HI	Fixed	Mod/Mod

TABLE 17 (*end*)

Application	Application class	System type	Minimum likely antenna gain class (end or relay node/gateway node)
Avionics communication bus	HO	Fixed	High/High
External imaging sensors	HO	Fixed	High/High
Structural sensors	HO	Fixed	Mod/High
Flight control system sensors, position feedback and control parameters	HO	Fixed	High/High
Audio communication system	HO	Mobile/ad-hoc	Low/Mod

4.5.1.2 Beamwidth

The beamwidth of an antenna with moderate to high gain is closely approximated by equation (3):

$$\beta_{1/2} \approx \sqrt{\frac{4\pi\eta_l}{G}} \quad (3)$$

where:

- $\beta_{1/2}$: the half-power beamwidth in radians
- G : the peak gain (see equation (2))
- η_l : the antenna's ohmic efficiency.

High-gain antennas, as defined previously in § 4.5.1.1, are expected to have less than 50° beamwidths, moderate gain antennas to have between 50° and 180° beamwidths, and low-gain antennas to have beamwidths greater than 180°. The sensitivity of an antenna's gain due to pointing errors is inversely related to the beamwidth of the antenna. Less sensitivity results in larger beamwidths and greater sensitivity in smaller beamwidths.

Systems employing higher gain antennas are generally more efficient than the equivalent system with lower gain antennas, as long as the antennas can remain pointed in the proper direction. For potential fixed WAIC systems, overcoming gain variations due to minor pointing errors is not considered a problem. In an aircraft environment the impacts of blocking or multipath occur frequently and results in limitations to the useful amount of antenna gain achievable. However in multipath or blocking situations, other aspects of performance may be improved with higher gain antennas such as a reduction in delay spread and/or amplification of the primary transmission path.

4.5.1.3 Side-lobe levels

The amount of power received or transmitted from directions other than the main beam of the antenna is generally referred to the side-lobe level. Larger side lobes can increase interference to other systems and increase susceptibility to interference from other systems. It is desirable to reduce as much as possible the side lobes of WAIC transmissions. Therefore, WAIC antenna's aperture efficiency will be decreased as much as practicable, given size and gain constraints.

4.5.1.4 Antenna bandwidth

The antenna bandwidth is also an important consideration. The antenna must be able to effectively transmit over the entire band required by the transceiver. For antenna design, the fractional bandwidth, the bandwidth as a percentage of the centre frequency, is limited by the physics of the antenna size and configuration. For low frequencies the design of an antenna with a given bandwidth is more difficult (or impossible) than for a similar bandwidth at higher frequencies.

4.5.2 Shared transmitter/receiver characteristics

This section discusses the characteristics that are shared between WAIC transmitters, receivers, and transceivers. WAIC systems will use transmitters and receivers to transfer data from one or more locations on a single aircraft. Aircraft designers will have to consider several technical issues in designing WAIC systems. For example, how WAIC systems will communicate, how frequently they will communicate, how one or more frequency bands will be shared, and how WAIC systems will operate effectively.

4.5.2.1 Bandwidth

Each WAIC system requires an amount of frequency bandwidth to communicate the necessary data. The amount of bandwidth each system uses, and the amount of frequency reuse that can be achieved depends on many factors, such as the number of nodes in a given area and the modulation and coding techniques employed.

4.5.2.1.1 Multiple access

As described above, there will be many different types of WAIC applications. Because different classifications of WAIC systems will share spectrum with each other and potentially other users, common frequency sharing techniques must be used. Frequency sharing techniques being considered by WAIC designers are listed below:

- frequency division;
- time division;
- code division;
- spatial division.

It is likely that WAIC systems will use a combination of one or more of the techniques above. The exact mix of techniques depends on several factors not limited to; the number of nodes, isolation between nodes, density of nodes, availability/reliability requirements, latency requirements, peak-to-average data rates, determinability, resistance to interference, and spectral reuse and efficiency.

Determinism is an important aspect of aircraft systems including WAIC systems. Frequency and time division based multiple access are inherently deterministic, while code division and spatial division are not. However, these multiple access techniques can be implemented in a deterministic way. Moreover the benefits of code division and spatial division – increased spectral efficiency and reuse, resistance to interference, and improved security – may improve the reliability and availability which is highly desirable for WAIC systems.

4.5.2.1.2 Signal modulation

WAIC systems will also utilize modulation, the means of altering an RF signal to carry information. Modulation ultimately affects the channel capacity (the amount of data that can be transferred over a fixed bandwidth in a given amount of time). Channel capacity is ultimately limited by the Shannon-Hartley theorem which states,

$$C = B \log_2 \left(1 + \frac{S}{N} \right) \quad (4)$$

where:

C : the channel capacity in bits per second

B : the bandwidth

S/N : the ratio of the signal (or carrier) power to the noise power (SNR).

Thus increasing the capacity linearly requires an exponential increase in power, or a linear increase in bandwidth. The amount of power available usually dictates the general modulation technique; however, it is possible to increase the realized capacity through the use of error correction coding.

Generally, the maximum channel capacity outlined by equation (4) is not realized. To achieve a practical channel capacity, some margin of power above the minimum specified in equation (4) must be utilized. It is anticipated that a high reliability will be required for WAIC systems, and that many WAIC systems will have to be computationally simple and low-power; therefore, a margin of 14 dB may be required, and will be assumed in subsequent analysis. This is the margin that is required to achieve 1×10^{-6} unencoded bit error rate for binary phase shift keying (BPSK) modulation.

4.5.2.1.3 Spectral density

Spectral spreading techniques may also be used for WAIC systems in order to decrease the spectral density. To accomplish spectral spreading, the modulated WAIC signal is modulated again to spread the power across a wider bandwidth. This spreading modulation can be accomplished in a number of ways; direct modulation (DSSS), frequency hopping (FH), time hopping (TH) or any combination of the above. Though there are tradeoffs to each type, the end result is that a WAIC system using spread spectrum techniques can reduce its signal level as seen by other users.

Low data-rate systems are expected to employ some spectral spreading; however, high data-rate WAIC systems may not be able to use spectral spreading.

4.5.2.2 Interference resistance

Resistance to interference is an important aspect of WAIC systems because WAIC systems will be used to impact the safety and regularity of an aircraft's flight. Due to the high reliability/availability requirements, it must be assumed that WAIC systems must be able to mitigate various forms of potential interference without failure.

There are many ways to mitigate interference that will be used by WAIC applications. A few of these methods have been discussed above. Additional methods are antenna control and transmit power control.

4.5.2.3 Available energy

The amount of transmit power is ultimately limited by the amount of energy available to a node. Many WAIC systems are not expected to have access to the aircraft's line power, and thus must be powered by other means. Typically, these self-contained systems will be strictly limited in the amount of available energy – thus these systems will generally be forced to use low transmit and receive power levels to conserve energy.

4.5.3 Receiver characteristics

The receiver system is an important part of any wireless communication system. There are many aspects that are shared with the transmitter as discussed in the previous section, but there are several aspects that are unique to the receiver.

4.5.3.1 Sensitivity levels

A very significant component in determining WAIC spectrum requirements is a WAIC receiver's sensitivity level. There are two ways the receiver's sensitivity can be limited: noise limited, and interference limited.

Most commonly a receiver will be noise limited. Noise is a natural product of the random motion of charges due to thermal effects according the Rayleigh-Jeans Law.

$$P_n = kTB \quad (5)$$

where:

- P_n : the noise power
- k : Boltzmann constant
- B : the receiver bandwidth.

In addition to the thermal noise in the antenna and receiver input, imperfections in the receiver circuitry amplify this thermal noise more readily than the desired signal. Thus, one way to measure the effective sensitivity of a receiver is by describing the apparent temperature of the receiver, T_{sys} . For example, a low-power semiconductor receiver may have a T_{sys} of several 1 000 K. As the amount of power to the receiver is increased, or the receiver is physically cooled, the apparent temperature of the receiver can drop to values below 290 K. However for WAIC systems, especially self-contained/self-powered WAIC systems, it is expected that 2 000 K is a reasonable T_{sys} . This depends on the frequency band because low noise temperatures are more difficult to achieve for a given amount of power as the frequency is increased.

Interference limited receivers are more difficult to characterize due to the variables in interference levels. Nonetheless, receivers should be designed to maximize performance in the presence of potential interferers.

4.5.4 Transmitter characteristics

There are also several transmitter characteristics that WAIC systems must utilize in order to safely and efficiently utilize spectrum.

4.5.4.1 Maximum RF power output

The amount of available transmit power depends on many variables.

All WAIC systems are envisioned to be relatively low power and depending on the frequency band utilized may require power amplifiers (PA). Low-to-moderate PAs that may be considered typically range from 0 to 30 dBm (decibels relative to 1 mW). PAs in higher frequencies generally have lower available power and are less energy efficient. It is likely that most WAIC systems will require less than 20 dBm total transmit power.

4.5.4.2 Transmit power control

It is expected that while most WAIC systems will use similar transmit PAs for cost and reasons of simplicity, many of these may not need the same amount of power. In order to maximize efficiency, it may be beneficial to enable the transmitter to adjust its transmit power to levels necessary to maintain the link. Thus, by allowing the WAIC system to adjust as needed, it can reduce its transmit power and effectively improve the aircraft's energy budget. These power adjustments may permit greater channel reuse within the aircraft. Since the effectiveness of power control is difficult to predict, and the complexity of power control may not be warranted for some WAIC applications, no power control will be assumed in the analysis and technical characteristics described below.

4.5.5 Spectrum usage and potential channelization plans

This section provides a reference plan that can be used to assist in determining spectrum requirements. This reference plan uses an example protocol because WAIC systems are still under development and spectrum requirements have not yet been determined. However, this example protocol could provide a useful estimate of the power spectral requirements of WAIC systems.

4.5.5.1 Channel reuse factor

Section 4.2.1.2 describes the aircraft compartments used for this study. These compartments are combined into regions in § 4.2.1.5. It is anticipated that power transmitted in one aircraft region may cause interference in another. The amount of interference depends on numerous factors, some of which are described in previous sections. Because determining the effects of intra-aircraft RF interference is highly complex and involves many variables, a simplified analytical analysis will be provided in this Report.

In order to determine the potential harmful interference experienced by one aircraft region from another, an estimate of the RF isolation is needed. For simplicity, the region-to-region interference is estimated by assuming the following equation:

$$L_{iso} = \min(L_{start}, L_{end}) + \min_i (L_{i1} + L_{i2} + \dots + L_{iN_i} + (N_i + 1)L_{bulkhead}) + L_m \quad (6)$$

where:

- L_{iso} : the isolation path-loss
- L_{start} : the source regions maximum path-loss
- L_{end} : the destination region's maximum path-loss
- L_{ik} : the maximum path-loss of the i -th possible signal route and k -th step of N_i intermediate regions along that route
- $L_{bulkhead}$: the loss associated with transition between regions which is assumed to be 10 dB
- L_m : the frequency dependent loss that occurs in the first metre:

$$L_m = \left[\left(\frac{4\pi}{\lambda} \right)^2 \right]_{\text{dB}} \quad (7)$$

Each region's maximum path-loss is defined as:

$$L_{region} = \left[\left(\frac{R_{max}}{M_{hop}} \right)^{PLE} \right]_{\text{dB}} \quad (8)$$

where:

- R_{max} : the largest regional dimension
- M_{hop} : the average number of hops for the region
- PLE: the region's path-loss exponent.

This is only a rough estimate of the path loss, but should provide an adequate estimate for the purpose of channel reuse estimation which is not very sensitive to path-loss errors.

Once region-to-region path loss is determined, the amount of interference that one region presents to another region can be determined. The amount of interference from one aircraft region is compared to the noise power level for receivers in each region. Regions whose transmitters would present power levels greater than 6 dB below the noise floor to receivers in each region are labelled as interfering. This level of interference would increase the noise floor by 1 dB. Non-interfering regions present opportunity for channel reuse. Once all the interference/non-interference interactions between regions are determined, an optimization analysis can be performed to determine how much channel reuse is possible and whether that region's needs require an increase in the effective channel utilization. An optimum is reached when the effective channel utilization is minimized whilst maintaining the required signal-to-interference ratio. This optimization analysis consists of:

1. An estimate of the reusable rate or effective channel utilization (in terms of bits/sec).
2. A determination of the channel use requirements. This consists of determining the reusable rate or effective channel rate (from Step 1) minus the data rate seen from interfering regions. If the reusable rate is greater than zero, then some of the data created in that aircraft region can reuse spectrum.
3. The non-reusable contributions are summed to give an estimate for the effective utilization based on the previous estimate. If this ending estimate is not the same as the starting estimate, the average is taken of the two and used as the starting estimate for the next iteration. Iterations continue until the starting and ending estimates are the same.

Although aircraft models have different shapes and sizes, and reuse depends on the frequency and bandwidth utilized, it is anticipated that for low rate systems the channel reuse factor could be between 1 and 1.8 based on simulation across a wide variation of frequency and bandwidth. A reuse factor of 1 implies that for some band allocations no reuse may be possible within a single aircraft; however, where possible, frequency reuse will be applied.

4.5.5.2 Example: multiple access protocol

Another example of sharing spectrum by WAIC systems is discussed below. In this example, a time-division based protocol is analysed. In this type of multiple access protocol, all users that share a channel are given discrete time-slots in which to transmit and receive information. This protocol is deterministic, which is important for critical aircraft systems. Low-rate systems (LI and LO) will be considered separately from HI and HO systems, because they differ greatly in the data bandwidth and latency requirements.

For low-rate systems, it is anticipated that WAIC systems on an aircraft will require a total of approximately 2.6 Mbit/s. Combined with encapsulation, security, reliability, and other higher level protocol overhead, the amount of data needed to be transmitted could be as great as 17.3 Mbit/s. For this data to be transmitted on the shared frequency channel within or on a single aircraft, some multiple access schemes must be employed. All multiple access techniques add additional overhead, so an estimate of this overhead is needed. For this example we assume a time-slot based scheme. However, any combination of deterministic multiple access techniques are likely to result in similar levels of efficiency: time division has dead time between slots, frequency division has unusable separating guard bands, etc. The following example, which outlines this methodology for estimating the overhead is done for LI and LO systems only; however, the methodology is easily extended to HI and HO systems using the appropriate parameters.

To simplify the analysis we assume that all low-rate systems have similar latency requirements, and use a single repeating time-slot allocation loop 100 ms long. A round consists of a single pass through the allocation loop. Each end node serviced will have an opportunity to transmit data every round. There is projected to be up to 4 341 low-rate end nodes to service on a single aircraft. Not all nodes share the same channel due to reuse of time slots on different sections of the aircraft.

A model for channel reuse is described in § 4.5.5.1. For this example, a channel reuse factor of 1.15 will be used, which is typical for many band allocations according to simulated results. After factoring in reuse, it is expected that up to 3 786 of the total 4 341 nodes will have to share a common channel.

For time-slot divided channels, a certain amount of time must be given between time slots to insure that conflicts do not arise between adjacent slot users as well as to allow receivers to synchronize with the next transmitter. We assume that between 2 and 10 μ s may be enough time between time slots. Given current technology, this time is limited by the settling time of typical phase locked loops (PLL). For the purpose of this document, 5 μ s will be used as the time between slots. In this example, in order to maximize channel efficiency each time slot should consist of 42 bytes of data, determined by a simple linear search; however, efficiencies are similar over a broad range of slot data lengths. End nodes that require more than 42 bytes per round (3.36 kbit/s) use two time slots per round, end nodes that require more than 84 bytes per round (6.72 kbit/s) use three slots per round, and so forth. A certain number of time slots are given to gateway nodes for bidirectional communication. Thus for 3 786 nodes, up to 6 966 time slots are needed, and as a result 34.83 ms is used in each round as time for PLL settling and hence dead time. The length of a single time slot is therefore 9.355 μ s long not including dead time, and requires that each node communicate at an uncoded modulation rate of 35.9 Mbit/s; or in other words, this multiple access scheme is 48% efficient.

4.5.5.3 Link budget calculations

Each node in the aircraft has a unique set of operating conditions that affects the amount of power it requires. Frequency band, distance to receiver, type of antenna, receiver sensitivity, bandwidth, path-loss exponent and fade margin all determine the amount of power required. For simplicity, receiver sensitivity, fade margin, and frequency will be considered the same across all applications. Since we are using a single frequency channel with time division multiple access, each node will also share the signal bandwidth in common. This leaves only the distance, antennas, and path-loss exponent as parameters for a given link.

For noise limited receivers, the required power transmitted P_t is:

$$[P_t]_{dBm} = \frac{E_b}{N_0} + k + T_{sys} + R_b + L_m + L_{region} - G_t - G_r + M_{fading} \quad (9)$$

where:

E_b/N_0 : the SNR in terms of bit energy per noise density

k : Boltzmann's constant

T_{sys} : the receiver equivalent temperature

R_b : the data rate

L_m : the frequency dependant path-loss described in equation (7)

L_{region} : the region's maximum path-loss described in equation (8)

M_{fading} : the margin for fading and attenuation, with all parameters specified in dB.

E_b/N_0 is a function of the channel capacity,

$$\left[\frac{E_b}{N_0} \right]_{dB} = \left[2^{\frac{R_b}{B}} - 1 \right]_{dB} + M_{SNR} \quad (10)$$

where:

B : the channel bandwidth

M_{SNR} : the modulation margin described in § 4.5.2.1.2.

The antenna gains for each application are selected according to Table 17, using 5 dBi for low-gain, 9 dBi for moderate-gain and 12 dBi for high-gain antennas for band allocations where antennas are gain limited and effective areas of 20 cm², 50 cm², and 100 cm² for low-, moderate- and high-gain antennas for frequencies when the antennas are aperture-limited.

Using equations (7), (8), and (10) in equation (9) gives a straightforward relationship between the channel allocation and the power required. The only parameter that is not calculated in straightforward manner is the required data rate, R_b , which includes the channel reuse factor. Calculation of the reuse factor is not straightforward, as it depends on the frequency and bandwidth.

4.6 Relationship between frequency, bandwidth, and transmit power level for WAIC systems

Any graphs depicted frequency ranges are not intended to suggest or promote the use of any particular band.

The transmit power level requirements for WAIC systems will vary depending on the frequency and bandwidth. To assist in describing the power-level requirements across a broad range of frequency bands, several charts are given. The methodology reached in establishing these requirements is described in §§ 4.1-4.5 and summarized here for convenience. This approach uses frequency and bandwidth as parameters and derives the transmit power level. While one could approach this problem using frequency and power as parameters to determine bandwidth, it is felt that this approach lends better to examining sharing in specific bands.

The steps for determining the transmit power level are as follows:

1. Define the applications classes and systems in those classes (§ 3).
2. Define the physical operating environment conditions (§ 4.2).
3. Determine the required data rate to satisfy the system's requirements (§ 4.3).
4. Define a centre frequency and bandwidth.
5. Determine and define the RF propagation environment (§ 4.4).
6. For each frequency and bandwidth determine transmit power level by:
 - a) Determine the maximum path loss for each region (§§ 4.4 and 4.5.5.3).
 - b) Determine the inter-region path loss (§ 4.5.5.1).
 - c) Determine antenna gain for the three antenna classes (§ 4.5.1).
 - d) Apply channel reuse factor (on first iteration use reuse factor of 1, see § 4.5.5.1) determine required transmit data rate for TDMA based protocol (§ 4.5.5.2).
 - e) Use transmitted data rate to calculate required SNR and link budget (§ 4.5.5.3) to determine transmit power levels.
 - f) Estimate channel reuse factor (§ 4.5.5.1).
 - g) Repeat Steps 5d) through 5f) with improved channel reuse factor estimate until convergence is met.

4.6.1 Power levels for LI and LO systems

Figure 11 shows the expected maximum transmitted power levels for LI systems. LO systems require 4 dB lower power levels than those shown in Fig. 11. Figure 12 shows the spectral density vs. centre frequency and bandwidth for LO systems, which are potentially unshielded to outside users. LI systems are expected to experience some signal attenuation due to shielding from the aircraft body. Because LO systems' transmit power level is only 4 dB lower than that of LI systems, and it is assumed that LI systems will experience aircraft body attenuation at least in the same order of magnitude, the LO spectral density is considered the worst case for low-rate WAIC systems.

Figure 13 shows the transmit e.i.r.p. levels for the LI systems; LO systems have e.i.r.p. approximately 1 dB lower than LI systems. The trend of the curves with frequency for Figs 11, 12 and 13 are largely due to the effect of antenna gain. A transition occurs in the figures around 3.5 GHz. Below this frequency, WAIC antennas are likely to be limited by their physical size, which in turn limits gain. Below this frequency the antennas are aperture-limited, and so gain varies with the square of the frequency. Above approximately 3.5 GHz antenna's gain may be limited by pointing and other restrictions. The maximum antenna gain for LI and LO systems are 9 dBi and 12 dBi, respectively, at frequencies above approximately 3.5 GHz.

For reasons described in § 4.5, WAIC system's transmit power levels must be kept low. For low-rate LI and LO systems ideally the transmit power levels should be limited to no greater than 10 dBm. This limits the minimum bandwidth of LI and LO systems. Complexity will ultimately limit the maximum bandwidth.

Figure 14 shows the reuse factors used for each of the frequencies and bandwidths. Wider bandwidths generally decrease the interference and increase the reuse. Note that for frequencies above 3.5 GHz, when gain is limited by pointing sensitivity, the reuse factor is a function of bandwidth only.

FIGURE 11

Graph of requisite total transmit power vs. centre frequency at several bandwidths for LI and LO systems operating in the same band

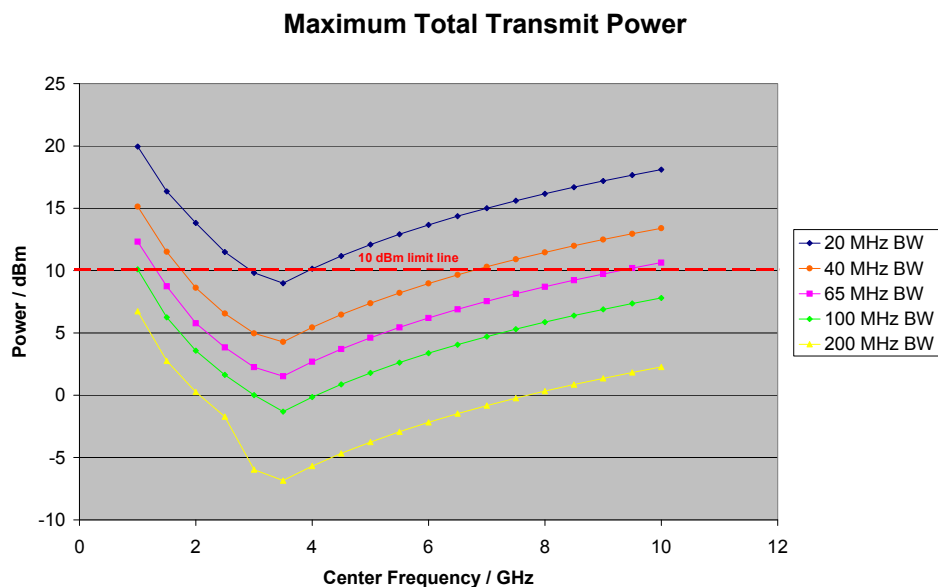


FIGURE 12

Graph of power spectral density vs. centre frequency at several bandwidths for LI and LO systems operating in the same band

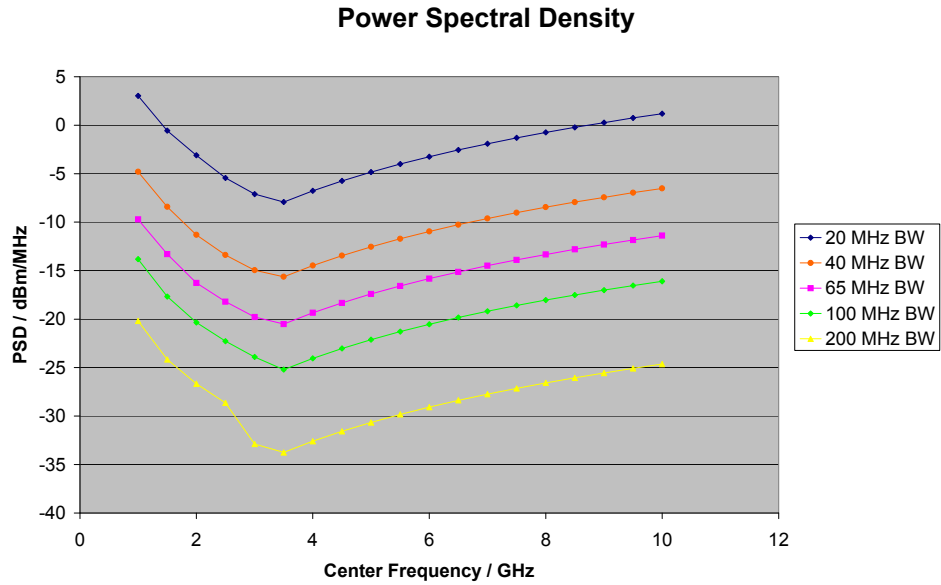


FIGURE 13

Graph of e.i.r.p. vs. centre frequency at several bandwidths for LI and LO systems operating in the same band

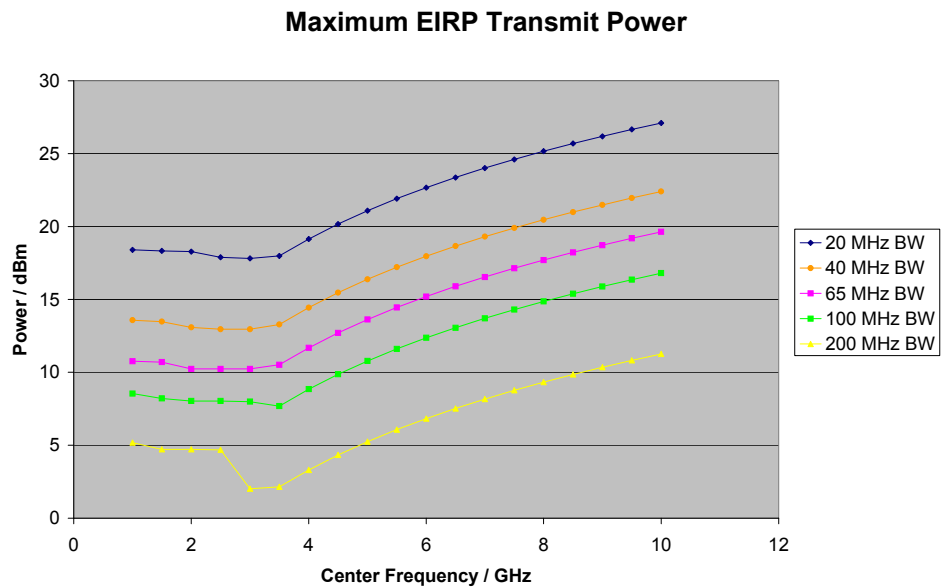
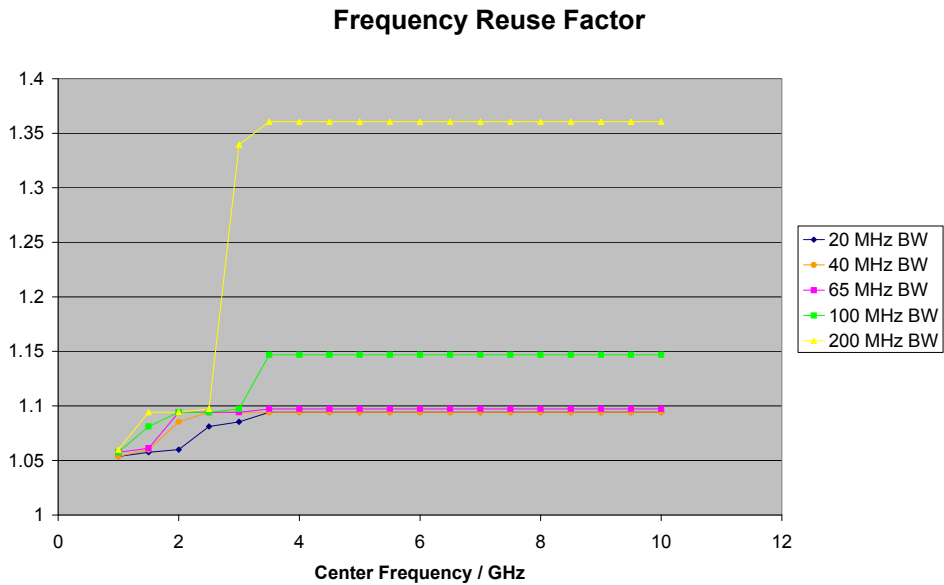


FIGURE 14

Frequency reuse factor vs. centre frequency at several bandwidths for LI and LO systems operating in the same band



4.6.2 Power levels for HI and HO systems

Figure 15 shows the expected maximum transmitted power levels for HI systems. HO systems require 8.5 dB lower power levels than those shown in Fig. 15. Figure 16 shows the spectral density vs. centre frequency and bandwidth for HO systems, which are potentially unshielded to outside users. Like LI systems, HI systems are expected to experience some signal attenuation due to shielding from the aircraft body. While HO system's transmit power level is down 8.5 dB lower than that of HI systems, rather than 4 dB as was the case for the low-rate systems, it is still reasonable that HI systems will experience aircraft body attenuation at least in the same order of magnitude as this difference. Therefore, we present the HO spectral density as being the worst case for low-rate WAIC systems. Figure 17 shows the transmit e.i.r.p. levels for HI systems. As was the case for transmit power, e.i.r.p. power levels are 8.5 dB lower for HO systems. Because the antennas are gain-limited for all frequencies shown in Figs 15, 16, and 17, power increases with frequency due to increased path losses. The reuse factor used in Figs 15, 16 and 17 was estimated to be 1.18 for all centre frequencies with 200 MHz bandwidth, and 1.22 for all centre frequencies for both the 650 MHz and 2 000 MHz bandwidth.

For reasons described in section 4.5, WAIC system's transmit power levels must be kept low. For low rate HI and HO systems ideally the transmit power levels should be limited to no greater than 30 dBm.

FIGURE 15

Graph of requisite total transmit power vs. centre frequency at several bandwidths for HI and HO systems operating in the same band

Maximum Total Transmit Power

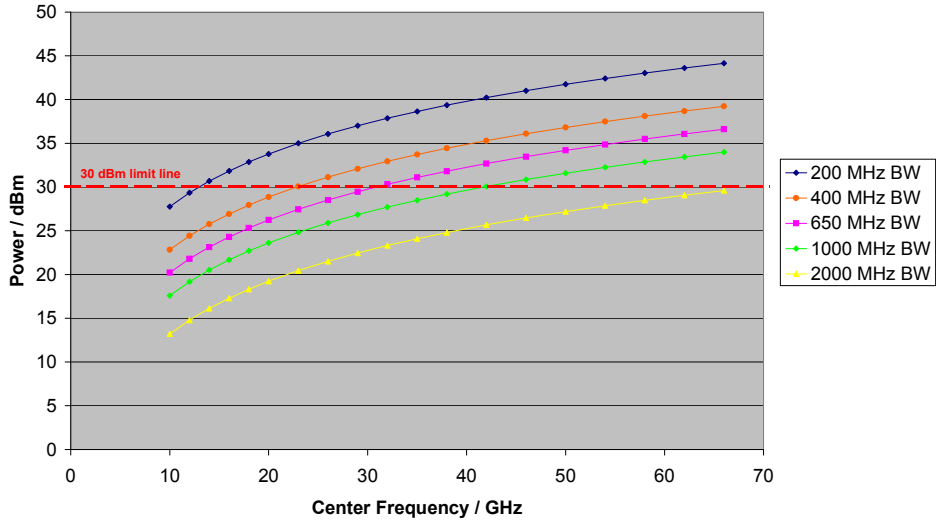


FIGURE 16

Graph power spectral density vs. centre frequency at several bandwidths for HI and HO systems operating in the same band

Power Spectral Density

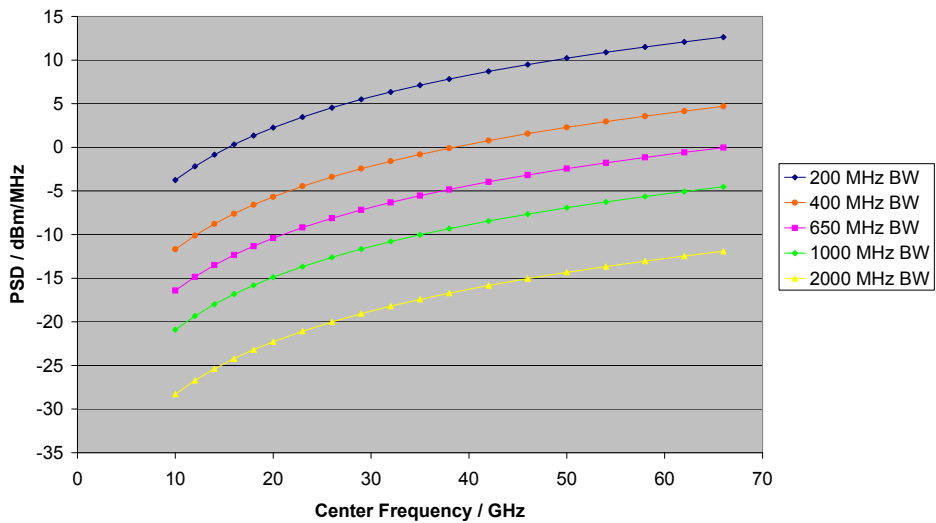
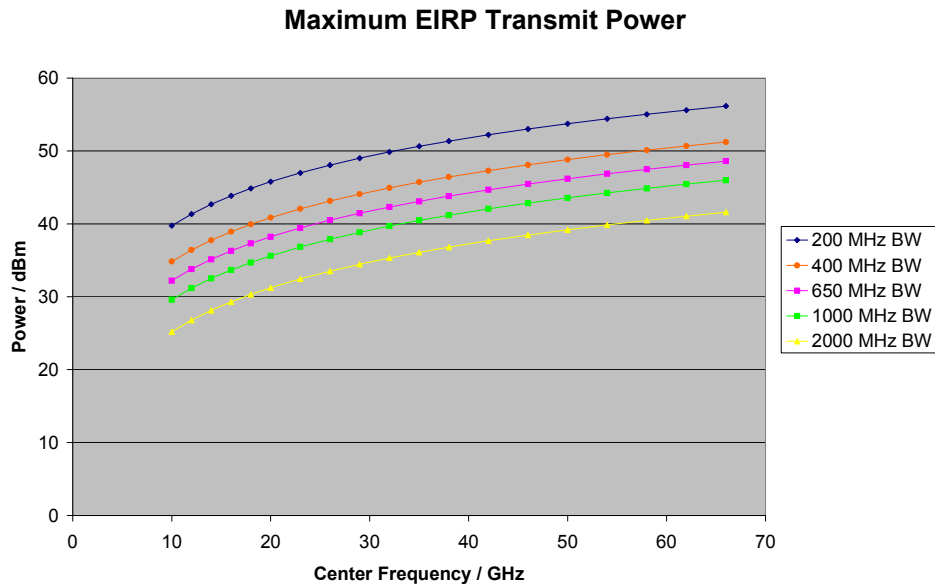


FIGURE 17

Graph of e.i.r.p. vs. centre frequency at several bandwidths for HI and HO systems operating in the same band



5 Summary

This Report, specifically Chapter 4, discusses a representative WAIC system for a single aircraft and derives the maximum required transmission power for application classes LI, LO, HI and HO as a function of a theoretical carrier frequency and bandwidth. The results presented in Figs 11 to 17 illustrate potential trade-offs between the technical characteristics; “transmission power”, “bandwidth” and “carrier frequency”.

5.1 Technical considerations for LI and LO class systems

As shown in Fig. 11, the total maximum transmit power jointly required for LI and LO systems varies by approximately 11 dB between 1 GHz to 10 GHz for 20 MHz of theoretically available bandwidth; and 13.5 dB for 200 MHz of theoretically available bandwidth. Absolute requisite power levels are between approximately -7 dBm and 20 dBm depending on the frequency and assumed theoretically available bandwidth. WAIC systems will require a maximum transmit power of approximately 10 dBm between 1 GHz and 10 GHz given energy-limited sensor node requirements.

5.2 Technical considerations for HI and HO class systems

As shown in Fig. 15, the total maximum transmit power jointly required for HI and HO systems varies by approximately 16.4 dB between 10 GHz to 66 GHz for all assumed bandwidths. Absolute requisite power levels are between approximately 13 dBm and 44 dBm depending on the frequency and assumed available bandwidth. WAIC systems will require a maximum transmit power of up to 30 dBm between 10 GHz to 66 GHz.

6 Conclusion

The commercial aviation industry is developing the next generation of aircraft to provide airlines and the flying public more cost-efficient, safer, and more reliable aircraft. Wireless technologies can reduce the overall weight of systems, reducing the amount of fuel required to fly and thus benefiting the environment. The ability to use WAIC communication systems globally is extremely important to the commercial aviation industry, but presents a significant challenge given the international nature of air travel. The aviation industry is striving to utilize wireless systems for both system upgrades on current aircraft, and in new aircraft design that will be as safe as current wired systems, while reducing costs.

This Report provides technical characteristics and operational objectives of WAIC systems for a single aircraft. This information can be utilized to partially respond to Question ITU-R 249/5. The content presented in this Report hence represents the current state of information on WAIC applications anticipated by the international commercial aviation industry.

This Report focuses on technical characteristics and operational objectives of potential WAIC systems on a single aircraft and does not include bandwidth requirements. The discussion on candidate frequency bands is also not addressed in this Report. This Report does not cover the impact of using wireless technologies for this purpose.

Annex 1

Glossary

ARINC 429 – Aeronautical Radio Inc. ARINC 429 is an application-specific standard for a wired data bus used for communications between aircraft avionics components. It uses a full duplex data bus (transmission and reception are on separate ports) known as the Mark 33 Digital Information Transfer System (DITS).

ATC – Air traffic control – A service operated by an appropriate authority to promote the safe, orderly and expeditious flow of air traffic.

AVSI – Aerospace Vehicle Systems Institute is a cooperative of aerospace companies and US government agencies working together to improve the integration of complex subsystems in aircraft.

ECS – Environmental control system – The environmental control system of an airliner provides air supply, thermal control and pressurization for the passengers and crew. Avionics cooling, and fire suppression are also commonly considered part of the environmental control system.

EMI – Electromagnetic interference.

FADEC – Full authority digital engine control – It is a system consisting of a digital computer (called EEC – electronic engine controller or ECU – electronic control unit) and its related accessories which control all aspects of aircraft engine performance.

HUMS – Aircraft health and usage monitoring system.

IFE – In-flight entertainment – refers to the entertainment available to aircraft passengers during a flight.

MELP – The MELPe or enhanced-MELP (mixed excitation linear prediction) is a speech coding standard used mainly in military applications and satellite communications, secure voice, and secure radio devices.
