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Abstract : Air traffic control operators guide aircraft within their sectors using broadcast radio communication. In general, an aircraft trajectory crosses several sectors. When an aircraft changes sector, responsibility is transferred from one controller to another. This transfer of responsibility requires a complex radio communication procedure as it is performed via a third party, namely the aircrew. About 60% of today's air-ground radio communication is wholly or partly related to sector change procedures. Communication represents a major bottleneck for further growth in air traffic control capacity. In the long term, digital end-to-end communication (which is similar to mobile phone technology) will replace today's broadcast radio communication. The end-to-end communication concept brings major benefit for aircrew and controllers. Among other things, end-to-end communication makes the internal air traffic control structure transparent for the aircrew. The aircrew does not need to know the internal air traffic control structure for flight operation purposes, as the end-to-end communication system automatically links the aircraft calls to the controller responsible. This paper discusses the problems and benefits of the end-to-end communication concept for air traffic control and shows how the broadcast radio communication standard currently in use might be adapted to provide a pseudo end-to-end air-ground voice communication system.						

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1. INTRODUCTION

In the current operational air traffic control (ATC) concept, the voice radio communication is the main tool enabling controllers to give flight instructions and clearances to aircrews. A controller is responsible for the safe separation of traffic within a defined airspace volume called a sector. Air-ground voice communications in a sector are broadcast on a single radio channel. This is usually called a "party line" and is used on a time-share basis by one air traffic control operator and all aircraft in the corresponding flight sector. Each sector has a different designated channel frequency. The ground-based radio transceivers of all sectors in a large area (area control centre - ACC) are mainly grouped at a common location. The transmission power of the radios (20 to 50-W carrier) allows safe radio communication over a few hundred nautical miles, given that in almost all situations there is a direct line of sight between transceiver ground station and aircraft. The reuse of the same channel frequency requires a large geographical separation (around 1000 nm), which severely limits the set of radio channels available.

For civil continental air-ground communication, the carrier frequency is within a range from 118 MHz to 137 MHz, on the 'very-high frequency' (VHF) band, with a channel spacing of 25 kHz (around 700 VHF voice channels). Owing to the shortage of VHF channels in Europe, some European areas have since 1999 been operating with a reduced channel spacing of 8.33 kHz. EUROCONTROL predicts a shortage of VHF frequencies within the current VHF communication system by 2015 [1].

The standardised technology has a very small speech frequency bandwidth (300 Hz to 3.4 kHz) and is known for its poor transmission quality. For 8.33-kHz channel spacing, the speech frequency bandwidth was reduced to 350 Hz to 2.5 kHz. Poor transmission quality and the narrow speech bandwidth decrease the intelligibility of the speech transmitted.

In order to establish meaningful party-line communication, all pilots have to start their messages with the verbal call sign to identify themselves to the controller. Likewise, controllers have to start all messages with the call sign of the aircraft addressed. The call sign plays an essential role in the party-line communication.

Mishearing, misunderstanding and confusion of call signs are a major problem for ATC safety. A EUROCONTROL study [2] showed that

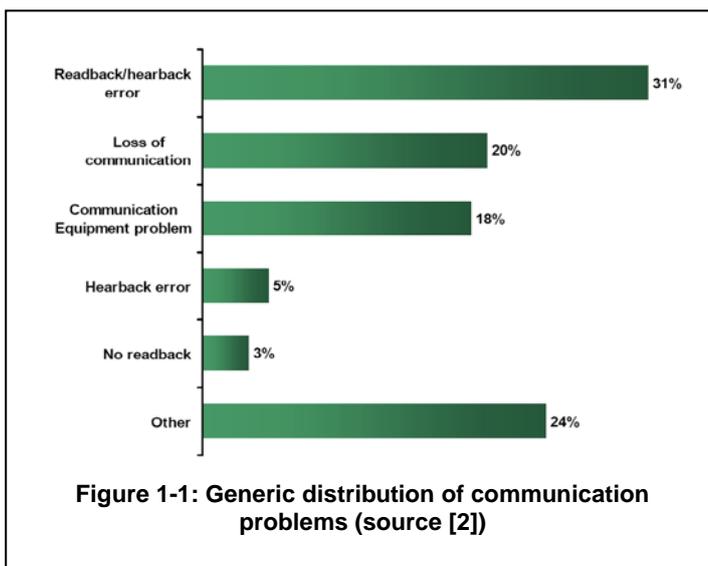


Figure 1-1: Generic distribution of communication problems (source [2])

“incidents involving air-ground communication problems between controllers and pilots are rare and encompass about 1% of all reported occurrences and 23% of ATC-related occurrences”.

Figure 1-1 shows the generic distribution of the reported communication problems.

The two major contribution factors – ‘readback/hearback error’ and ‘loss of communication’ are directly linked to the current communication concept and standard. Readback/hearback errors are amongst other things closely correlated with the intelligibility of the speech transmitted. More than a third of reported readback/hearback errors are directly related to the call sign. Non-identified voice messages in party-line communication are meaningless, may require supplementary communication, and reduce safety.

Each sector change involves a risk of loss of the air-ground communication link, as the channel frequency has to be changed by the aircraft. Several factors, such as human imperfection in speaking and understanding, low VHF transmission quality, pilot delay in the execution of the frequency change, or other human error can result in failure to change the frequency or selection of the wrong frequency. In such cases, an aircraft could enter a sector without radio contact being made with the controller responsible. Such incidents at the very least create supplementary workload for the pilot and the sector controller, but may also cause hazardous situations.

This paper presents the idea of applying the end-to-end communication concept to the ATC domain. The end-to-end concept has already been implemented for public mobile telephony and ATC data-link communication. The end-to-end concept does not depend on the lower transport layers for communication. In addition, the paper demonstrates a way in which the current analogue broadcast communication layer can be adapted to support a pseudo end-to-end communication concept.

2. THE CURRENT AIR-GROUND COMMUNICATION CONCEPT

The broadcast radio channels for air-ground communication are overloaded with pilot and controller voice communication. The French VOCALISE study [3] reports an average channel occupation of 24 minutes per hour (40%). The channel occupation can rise to 90% during 5-minute peak periods. The study further reports that about 60% of voice communications are wholly or partly related to sector change procedures. An earlier EUROCONTROL study [4] confirms the voice communication statistics for sector changes.

When an aircraft changes sector, responsibility is transferred from one controller to another. This transfer of responsibility requires a complex radio communication procedure, which is performed via a third party, namely the aircrew. For the aircrew, sector changes may interfere with important onboard tasks and in any case involves a risk of loss of the communication link to the aircraft. Figure 2-1 shows the five steps required for the transfer of responsibility for an aircraft.

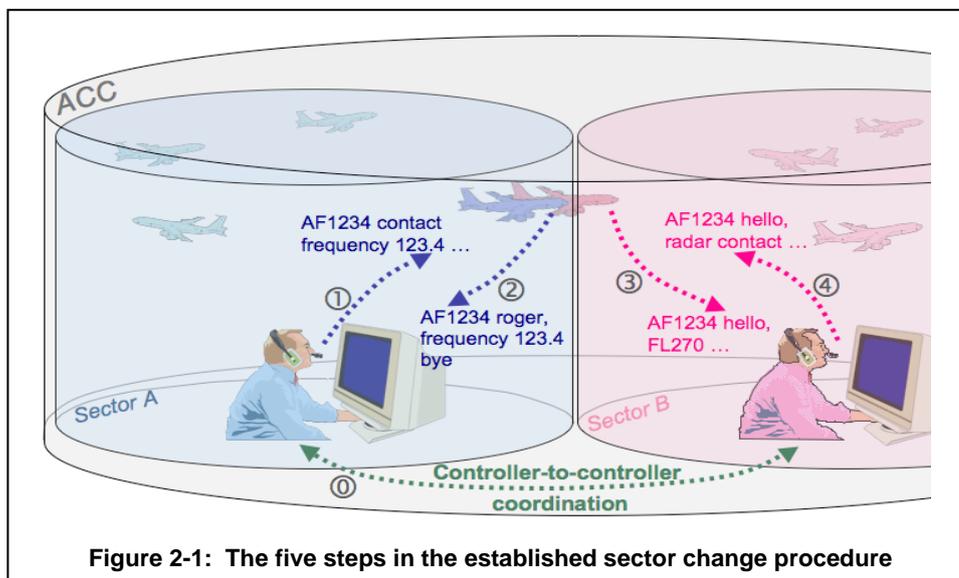


Figure 2-1: The five steps in the established sector change procedure

The initial step 'zero' – controller-to-controller coordination – may be performed explicitly and verbally or implicitly without verbal communication on the basis of defined rules specified in so-called 'letters of agreements'. In the first step, the transferring controller instructs the aircrew to change the communication channel to the frequency of the sector taking over. The aircrew confirms the controller's instruction by reading back the frequency of the sector taking over (step 2). On board, the aircrew selects on the radio the frequency of the sector taking over, and calls the new sector controller (step 3). The controller taking over confirms the call (step 4), which terminates the procedure for the transfer of responsibility. Air-ground radio communication for the transfer of responsibility between controllers (steps 1 to 4) creates work for the aircrew that is not actually required for flight operation purposes.

2.1. DATA-LINK COMMUNICATION

Data-link communication (DLC) was developed in order to relieve the voice communication bottleneck. DLC is non-verbal communication between controller and aircrew using digital data exchange. Controller-pilot data-link communication (CPDLC) represents a standardised communication protocol, which can be used on different transport layers such as designated VHF channels, ACAS (airborne collision-avoidance system), ADS (automatic dependent surveillance), satellites, etc. CPDLC is an addressed communication generally between two partners only. DLC in Europe is in an early stage of deployment.

Among other things, CPDLC provides services for the sector change procedure. Consequently, the transferring sector controller initiates a specific CPDLC message, which provides the aircraft with the information required to contact the next sector. The CPDLC message format is specified as 'UM117' (uplink message 117) with the content 'CONTACT [sector name] [frequency]'. The aircrew has to answer with a CPDLC message 'WILCO', 'UNABLE', 'STANDBY', etc. For safety reasons, the aircrew has to contact the next sector, which is taking over on the specified voice frequency. Figure 2-2 shows the five steps required for the transfer of responsibility for an aircraft via CPDLC and voice.

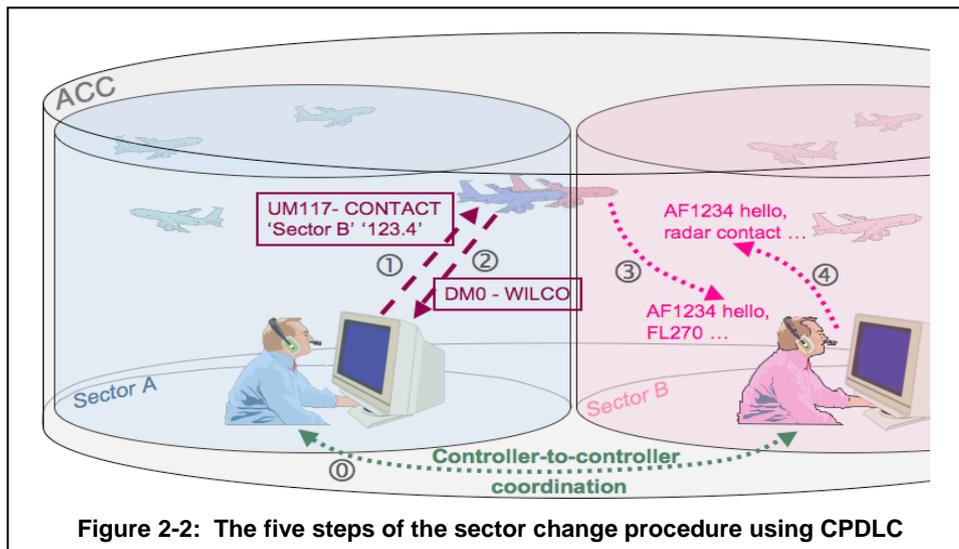


Figure 2-2: The five steps of the sector change procedure using CPDLC

The use of CPDLC for the initialisation of the sector change will reduce voice channel occupation. CPDLC replaces the voice communication channel with a digital communication channel. The human underlying mental tasks involved in initiating/sending a transfer message and watching for acceptance seem to be similar for the controller. A EUROCONTROL study 'Task load generated by frequent sector changes for aircrews and controllers – state-of-the-art literature study' [6] showed advantages but also major drawbacks for CPDLC. CPDLC shows clear advantages as regards the 'understandability' of the message.

2.2. HF ASPECTS OF THE CURRENT VOICE COMMUNICATION CONCEPT

Some kind of communication between controllers and pilots remains a vital element of air traffic control operations. However, communication problems are involved in 70% of aviation accidents and incidents (Corradini & Cacciari, 2002 [5]).

“Little has been done about the workload induced by the amount of communication and frequency congestion leading to human errors in the current ATC systems. Likewise, no study has focused on ways to reduce communications (voice and data) between pilots and controllers, in order to reduce workload and errors” [6].

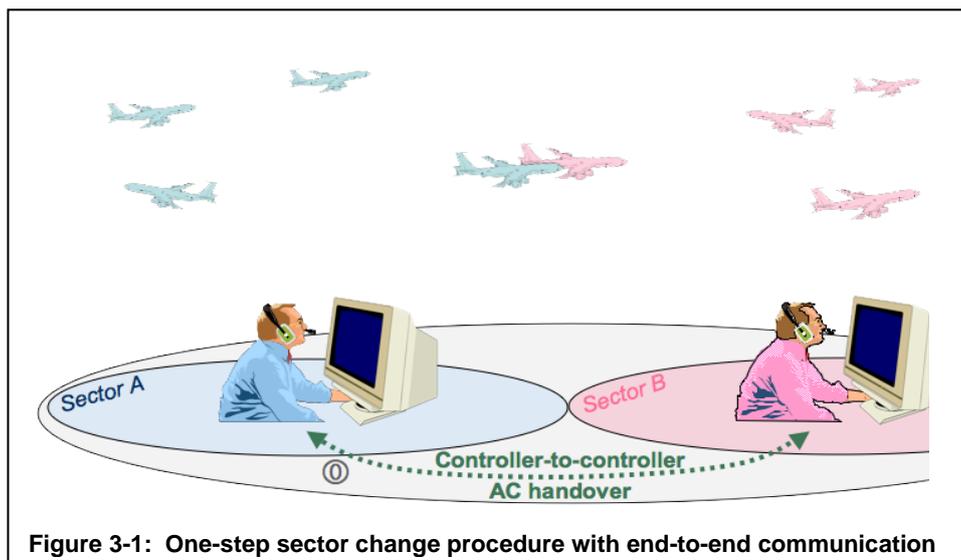
This aspect seems to be of particular interest, as it is known that about 60% of conventional voice communication is related to communication for channel management purposes resulting from internal ATC organisational requirements. The internal ATC organisation is of no interest whatsoever to the users of the ATC services (aircrew). In the current communication concept, the users are obliged to play an active role in the transfer of responsibility between controllers. This active role represents a major communication bottleneck, limiting future capacity increases and at the same time threatening air traffic safety.

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3. THE END-TO-END COMMUNICATION CONCEPT

Imagine you are travelling by high-speed train from Paris to Amsterdam. Let us further assume that you have a mobile phone with a pre-programmed shortcut key for your office. Whenever you press the key, you are connected to your office. You do not notice that your handset was connected via numerous different network cells along your trajectory, nor that the telephone service provider changed at the border. An operator will never ask you to change the frequency of your phone in order to stay in contact, because the telephone network automatically guarantees the seamless connection to your office. In mobile telephone language this is called end-to-end connection. This means that a mobile handset at one end is connected to a handset at the other end. One or both handsets may be mobile; the supporting network will automatically provide a permanent, seamless link between the two ends, which is transparent for the users.

The requirements for ATC air-ground voice communications are very similar. An aircrew needs a permanently available end-to-end voice connection to the controller responsible. In our current operational concept, the airspace volume (sector) defines the responsibility of a specific controller. Hence, on the basis of the position of an aircraft in the airspace, the end-to-end communication system knows which controller is responsible. To use mobile phone jargon, an aircrew will press the 'shortcut key' (push-to-talk – PTT) and gets an end-to-end voice link to the controller responsible, automatically provided by the supporting network. The network makes the ATC organisational structure transparent for the aircrew. Figure 3-1 shows the one-step sector change procedure in such an end-to-end communication concept. A controller so to speak hands over communication with an aircraft to the controller of the adjacent sector in order to transfer responsibility. The aircrew is not involved in the procedure at all.



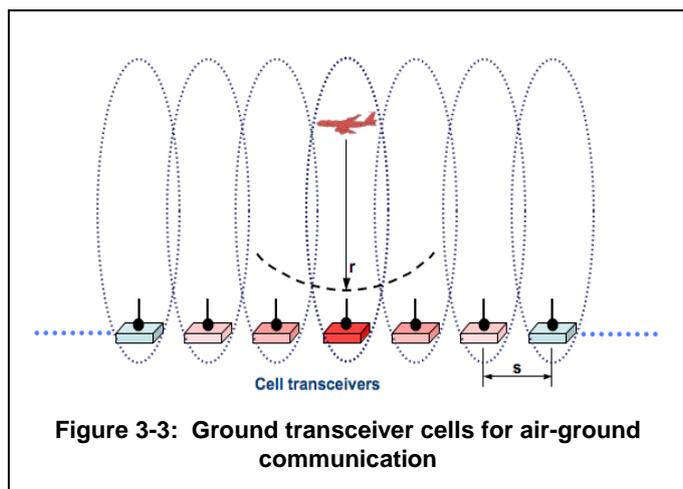
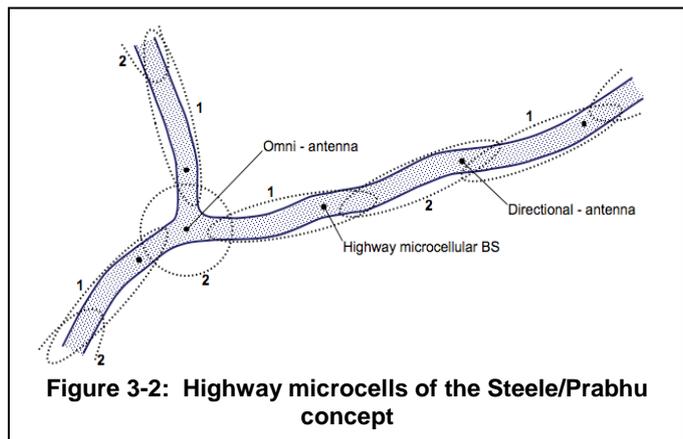
The end-to-end communication concept is not linked to a specific communication transport layer. Various established transport layers can be used for the concept such as mobile telephony (GSM), voice over IP (Internet Protocol), digital radio, and so on. The controller pilot data link communication (CPDLC) is an end-to-end communication, but its concept does not allow the transmission of digitalised voice. Future ATC planning [13] foresees digital communication for voice, too. This requires new aircraft and ground communication equipments. The next chapter describes how the current ATC air-ground communication standard can be adapted to provide a pseudo end-to-end communication concept. The stated advantages and disadvantages of end-to-end communication are independent of the transport layer.

3.1. END-TO-END CONCEPT BASED ON THE CURRENT RADIO COMMUNICATION SYSTEM

In 1985, Steele and Prabhu [7] presented a concept of highway microcells for mobile telephony. The concept was a cell-based structure with directional antennas along the highway. Figure 3-2 shows the principle of their highway microcell concept.

A similar principle could be employed for ATC airways. Directional antennas with a horizontal response pattern for 2D ground traffic have to be rotated through 90 degrees to create a vertical 3D pattern for aircraft communication.

The end-to-end communication system consists of the mobile air part and a fixed ground-based part. The air part mainly uses unchanged conventional aircraft transceivers (see next chapter). The ground part consists of a large number of transceivers all operating on the same frequency. Each transceiver represents an air-ground communication cell for a specific volume of airspace (Figure 3-3). All cells are connected to a communication network management unit, which provides the ground link between the geographically distributed cells and the associated controller working positions responsible for them.



3.1.1. Cellular System and Transmission Power

In a cellular system for air-ground communication, there is always a direct line of sight between transmitter and receiver. Only meteorological phenomena such as clouds may obscure the line of sight. The nearest cell to an aircraft will be straight below it. This cell will relay the air-ground end-to-end communication between aircrew and sector controller. The geographical position of the cell determines which sector is responsible. As an aircraft will not always be directly above the centre of the cell, triangulation techniques applied by the network management unit designate which cell is to relay aircraft communication. Aircraft signals received from surrounding cells may be inhibited for cells at the sector boundary.

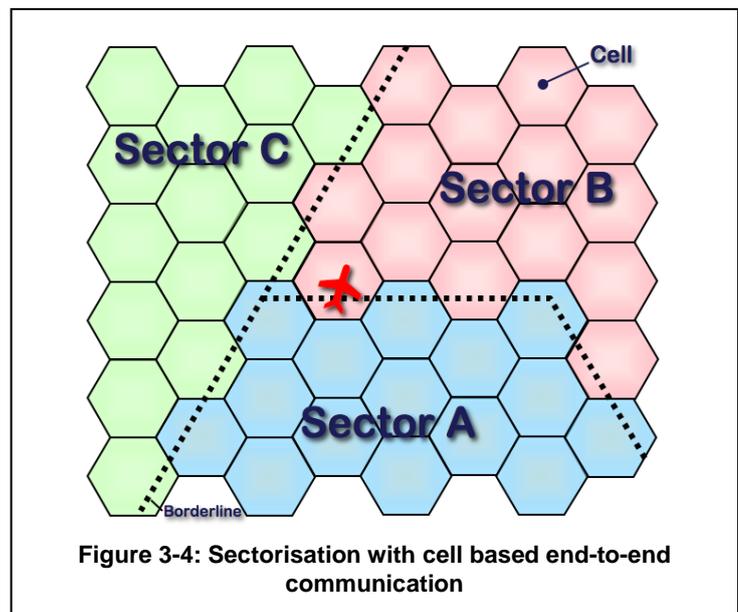
Consequently, the maximum distance ‘r’ (Figure 3-3) that a transmission has to cover is between five and ten nautical miles (FL300 approx. an altitude of 5 nm). The transmission power of the aircraft and the ground transmitter has to be reduced accordingly in order to safely cover this range using an estimated power of a few hundred milliwatts.

If an aircraft reduces its transmitting power, only other aircraft in proximity can hear it. This allows distant aircraft in the same sector to call the controller at the same time. In such cases, the network management unit links the first call to the controller and queues the other call(s), listing these for the controller. The problems seem less significant for the following reasons:

- ATC communication consists of a chronological sequence of voice messages in general initiated by the controller and confirmed by the aircrew reply;
- Each voice message is very short (on average 4 to 5 seconds) and is followed by an almost instant reply;
- Initial aircrew requests are rare and have low operational priority;
- The system represents a reduction of more than 50% in voice channel occupation (since no sector change involving communication) involving mainly all initial aircrew calls.

3.1.2. Air-to-ground Transmission

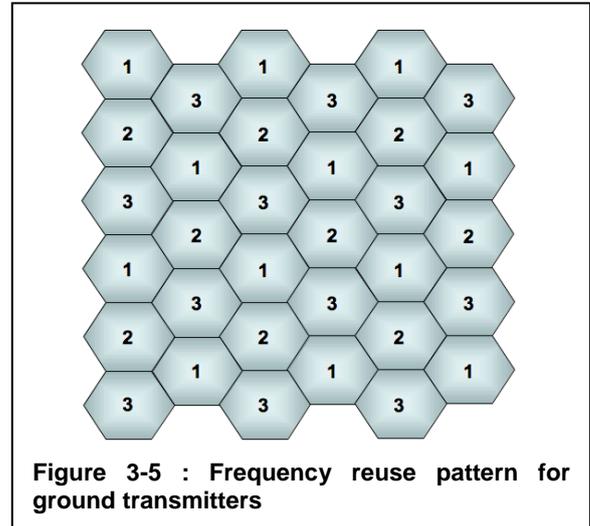
The geographical position of the aircraft determines which cell is to relay air-to-ground communication for this aircraft. The geographical position of the aircraft also determines the associated control sector. It is the task of the network management unit to link the received voice signal to the corresponding controller working position (Figure 3-4).



3.1.3. Ground-to-air transmission

In general, the controller-to-aircraft communication is transmitted by one cell only. The network management unit assigns that cell, just below the aircraft, by exploring known aircraft position data (radar plots). The controller has to indicate to the network management unit which aircraft is being addressed. This is discussed in more detail in a separate section.

Where an aircraft is close to the limit of the cell coverage, the network can use two or a maximum of three cells for transmission. To avoid interference between the transmitting cells, they have different frequencies distributed by a frequency reuse pattern. The frequencies differ by a few kHz within the limits of the receiver bandwidth. Figure 3-5 shows a possible frequency reuse pattern for the cell network. The same cell numbers indicate the same cell frequency.



3.1.4. Cell Size

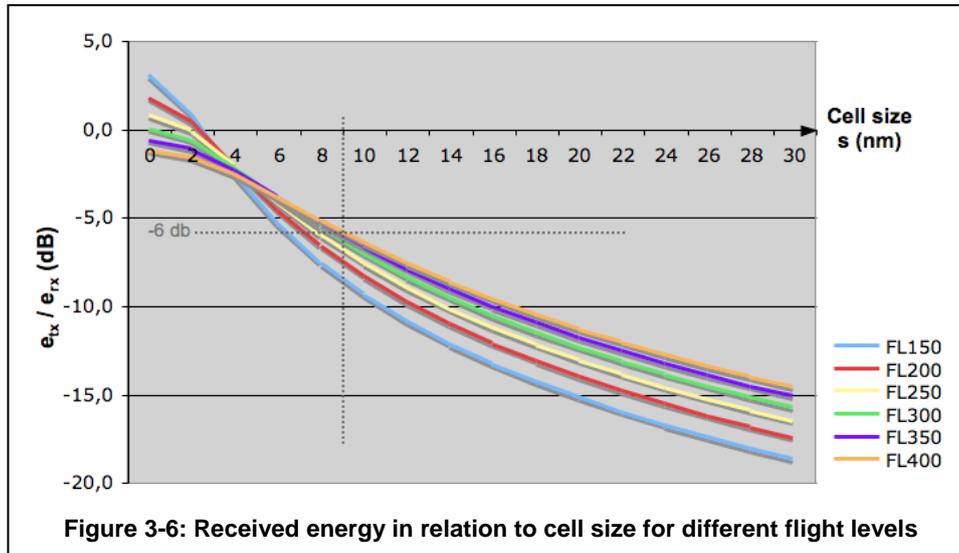
The received energy e_{rx} of an omnidirectional ideal transmitter is a function of the distance 'r' (Figure 3-3) to the transmitter:

$$e_{rx} = e_{tx} / r^2.$$

Working from this, the attenuation in the received energy for neighbouring ground receivers as a function of their distance 's' (Figure 3-3) can be estimated. The different curves in Figure 3-6 show the attenuation for aircraft flying at different flight levels (e_{tx} is constant). With a cell size of 10 nm, a significant attenuation in the received signal energy of at least 6 db can be predicted.

A reasonable cell size is between ten and fifteen nautical miles. This means that the cell will be crossed by a flight in one to two minutes, and horizontally separate aircraft will seldom be in communication via the same cell.

Vertical stacking of sectors cannot be supported by such a pseudo end-to-end communication concept based on the proposed modification of the current communication concept.



3.2. ADDRESSING OF END-TO-END COMMUNICATION

Currently, in order to transmit a voice message on the radio, the speaker has to press and hold down a so-called PTT (push-to-talk) switch. The PTT switch is a push-button that is physically integrated in the headset cable or at a specific position in the speaker's working environment. Pressing the PTT switch activates radio transmission. The radio transmits the voice signal from the microphone as long as the PTT switch is depressed. Otherwise the radio transmitter is in stand-by mode (reception). This is the well-established working procedure for current broadcast air-ground voice communications between pilots and controllers.

In contrast to broadcast radio communication, end-to-end radio communication generally involves only two partners. The underlying end-to-end system therefore requires information about the identity of the communicating partners. A future digital ATC communication system will be based on findings regarding our current telecommunication systems. Such systems split the digitalised speech into data packages, adding the addresses of the originator, the destinations and possibly some additional useful information. At the destination, the data packets are reassembled and transformed into analogue speech for the listener.

In the current broadcast system, the addressing of voice messages takes place at two separate levels:

- Implicit addressing – use of the specific communication channel frequency;
- Explicit addressing – verbal identification of the originator or destination of every voice message.

The hardware of our current broadcast communication ground system links the transceiver station of an area control centre (ACC) directly to the controller working positions (CWPs) of the centre.

In the case of end-to-end communication, the ground network system would cover the areas of several ACCs. The network management system would therefore be responsible for routing the messages between the cell relaying the communication to the aircraft and the CWP responsible. For routing purposes, the network management system requires at least the originator and destination addresses.

For air-to-ground communication, there is a single destination address - the CWP responsible. The CWP responsible is defined in our current control concept by the airspace volume occupied by an aircraft at any given time.

For the ground-to-air communication, it is more complicated, because the controller (assuming that there are more than one aircraft under control) has to indicate for each voice message the designated aircraft address to the communication system. This will interact with the current controller working procedures. The following chapter makes reference to earlier research, which proposed and evaluated a new controller working procedure.

3.2.1. New Controller Working Procedures for End-to-end Communication

The end-to-end communication system requires the destination address for each voice message. Conceivably, this is possible automatically by means of voice recognition technology applied to the controller voice message, but the state of the art for voice recognition is not sufficiently reliable and would in any case result in delays of at least two to three seconds (the time taken to read a call sign) before the spoken call sign (address) was recognised. Consequently, the addressed aircraft must be actively indicated at the start of the controller's voice communication. Clearly, this process has to be as simple as possible for the controller. Moreover, major modifications to the established communication procedures need to be avoided.

The method described in 'Towards Selective Addressing of Aircraft with Voice Radio Watermarks' [8] could be applied for the addressing of ground-to-air transmissions using an end-to-end system. The paper proposes that aircraft are selectively addressed using the mouse pointer on the radar display. At the same time as pressing the PTT switch, the controller must indicate the addressed aircraft using the mouse pointer on his radar display. The mouse pointer must therefore be hovered over part of the addressed aircraft representation (symbol, label, etc.) on the radar display. For usability testing, the study reports an overall mean of 2.49 on a scale from one (strongly agree) to seven (strongly disagree).

The study described a method of selecting the destination call sign of a voice message in order to embed the call sign as a digital watermark in the analogue speech [9,10]. The described method could also be used for end-to-end communication addressing.

3.3. ADVANTAGES AND DISADVANTAGES OF THE END-TO-END COMMUNICATION CONCEPT

In comparison with current broadcast radio communication and its well-established procedure, an end-to-end communication concept would bring major advantages for air-ground voice communication, but also a few disadvantages:

- Aircrew's situation awareness based on party-line communication would be lost, but this could be compensated for by technical equipment such as TCAS;
- Controllers could receive simultaneous aircraft calls; technical call polling would be required;
- For controllers, there would be a slight change of procedure for calling aircraft, as they would need to indicate the aircraft address;
- A new controller-to-controller handover procedure would need to be established.

End-to-end air-ground communication has the following advantages:

- Aircrews would no longer be involved in the transfer of responsibility between controllers, which would make the ATM structure and sectors transparent to pilots;
- It would avoid a shortage of communication channels;
- It would eliminate the task for aircrew of changing frequency at sector boundaries;
- It would prevent the risk of loss of communications in connection with frequency changes;
- It would reduce controller workload related to sector change procedures;
- It would eliminate aircrew party-line monitoring tasks.

In addition to the above advantages, end-to-end communication could be an enabler for new operational concepts. We reference here to operational concepts which cannot be implemented with broadcast communication such as for example a team of controllers jointly handling a sector proposed in 'Operational Concepts for SuperSector' [11], or a controller having responsibility for one or more flights from departure to arrival, etc. Future ATC concepts may deviate from the geographical responsibility concept and opt for a concept where the originator address of the aircraft determines which controller is responsible. The ground system would then use a routing table and apply it to the originator address available with the message. In both cases, however, the ground system could automatically derive from the aircraft position the destination address of the CWP.

3.3.1. End-to-end Communication based on the Current Communication System

This paper points out that the current broadcast communication standard could potentially be adapted for pseudo end-to-end communication. Reserving one frequency for pseudo end-to-end communication could do this. Such a pseudo end-to-end communication system would have certain additional advantages and disadvantages as described in the previous chapter.

Additional disadvantages would be as follows:

- Aircraft transceiver equipment would have to attenuate the transmission power for the end-to-end communication channel;
- New ground infrastructure would have to be deployed for the end-to-end communication network;
- Vertical sectorisation could not be supported.

The advantages of the adapted end-to-end communication system are as follows:

- It would not depend on the future standardization and deployment of a digital communication system;
- It could be deployed earlier as a new digital communication system;
- It could coexist with current broadcast radio communication;
- Regional deployment would be possible;
- Little change would need to be made to current certificated aircraft communication equipment (only a reduction in transmission power);
- There would be cost efficiency in view of anticipated future communication charges.

EUROCONTROL research has demonstrated the possibility of robust embedding of digital watermarks in analogue speech. For the ATC narrowband speech, "Speech Watermarking and Air Traffic Control" [12] reports a watermark bit rate of the order of magnitude of 500 bits. Applying digital watermark features to analogue speech in conjunction with the end-to-end concept would facilitate further automation of the analogue communication with features of digital communication.

4. CONCLUSION

Progressing from broadcast radio communication towards an end-to-end communication concept promises great benefits for ATC capacity. One of the current ATC capacity bottlenecks is human mental capacity, which limits the number of aircraft a human can control simultaneously. Communicating with the aircraft is an essential part of the human control task. Under high workload conditions, channel occupancy can raise to 90% [3] during 5-minutes peak periods. Over 50% [3], [4] air-ground voice communications are devoted to the transfer of responsibility between controllers (sector changes). This transfer of responsibility is an internal ATC organisation matter that is of no operational significance to aircrews. End-to-end communication between aircrews and the controllers responsible would make internal ATC organisation transparent for aircrews. This would make air-ground communication in connection with the transfer of responsibility between controllers obsolete, thus considerably reducing the number of communications (voice and data). This would free up human mental capacity, which is beneficial for overall ATC capacity.

For aircrews, end-to-end communication would also bring major advantages. For the pilot responsible for communication with ATC, picking out from the stream of voice communications those addressed to his/her flight is by no means an easy task ([3] stated that there are an average of 324 voice communications per hour, i.e. more than five a minute). There is no operational need to involve the aircrew in the transfer of responsibility between controllers, but there is a major risk of loss of the communication link with the ATC services.

Our current broadcast voice communication standard has been in place for more than 60 years. The FAA-EUROCONTROL roadmap for future mobile communication (Figure 4-1) starts with the planning for a future VHF link in 2022. Digital voice communication is mentioned beyond 2025.

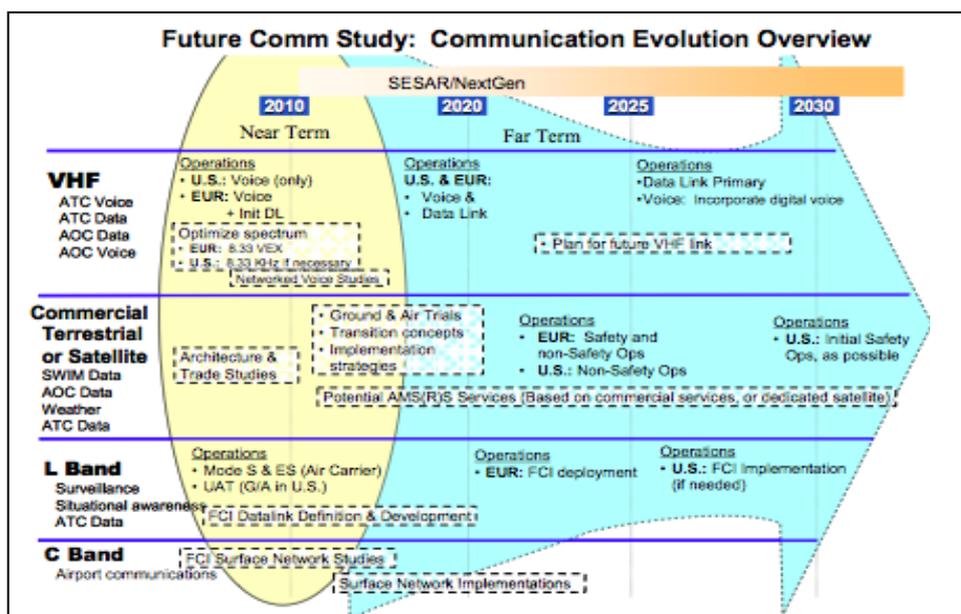


Figure 4-1: Overview of trends in aeronautical mobile communication (source [13])

Digital communication, however, is end-to-end communication. One dedicated broadcast radio channel could be adapted for pseudo end-to-end communication without disturbing the current broadcast communication. The pseudo end-to-end communication concept proposed in this paper could be implemented earlier than the digital system. If digital watermarks are added to the analogue speech, pseudo end-to-end communication will have nearly all the features of real digital end-to-end communication techniques. The ground-based communication network for the pseudo end-to-end communication system could be put in place realised in conjunction with national mobile telephony service providers and their existing widespread infrastructure.

In general, throughout an aircraft's trajectory, its position in airspace determines which control sector is responsible for its guidance. On the basis of the aircraft's position, an end-to-end communication system can automatically establish a voice link to the controller responsible. The aircrew is no longer involved in the transfer of responsibility between controllers. Air-ground end-to-end communications make the ATM structure transparent for aircrews and open up the way for new operational concepts.

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