A Realization of Integrated Satellite-Terrestrial Communication Networks for Aeronautical Services via Joint Radio Resource Management

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Abstract. Despite air travel has not grown as predicted, air travel is still expected to rise to just less than doubling the current figure by 2030. This creates an urging need to develop more efficient Air Traffic Management (ATM) solutions. Around the globe, research and development initiatives have been launched to modernize the air traffic control infrastructures. These modernized infrastructures will be built around continuous information gathering, sharing and transferring of data between aircraft and air navigation service providers and airports ground infrastructure, which will be difficult for current aeronautical communications systems to handle. As a result, new communication infrastructures are required to manage future aeronautical communication traffic demand. This paper proposes an integrated aeronautical communication architecture consisting of four radio access technologies for communications between aircrafts and ground Aeronautical Telecommunication Network (ATN). The design and implementation of a Joint Radio Resource Management (JRRM) framework to manage these radio resources are discussed. The design is verified by a proof-of-concept JRRM prototype which is developed for the management of radio resource between the Inmarsat Broadband Global Area Network (BGAN) and the Aeronautical Mobile Airport Communication System (AeroMACS).

Keywords: Aeronautical Communication, Satellite-Terrestrial Communication, JRRM, Integrated Modular Radio.

1 Introduction

The continuous growth in air travel has resulted in an increasingly congested airspace. According to the EUROCONTROL forecast [1], the Instrument Flight Rules (IFR) flights in Europe will increase to 22 million in 2030, which is equivalent to 18 to 33 thousand more flights in the European network in one day than it is now. Despite air traffic has not grown as predicted since 2010 due to the economic recession, the impact of this short-term traffic downturn on the long term air traffic forecast is expected to be marginally down by 6% [2]. This prompts an urging need to develop more efficient Air Traffic Management (ATM) solutions around the globe. Research and development initiatives such as the EU

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Single European Sky ATM Research (SESAR) project and the US Next Generation Air Transportation System (NextGen) have been launched to modernise the air traffic control infrastructure. It is envisaged that advanced ATM techniques and operations, automated airspace concept and intelligent decision support tools will be deployed in different stages between the next few years and the year 2020 and beyond. These advanced methods and tools will be built around continuous information gathering, sharing and transferring of data between aircraft and air navigation service providers and airports ground infrastructure.

However current aeronautical communications systems will be insufficient to handle the vast amount of information transfer created by these advanced ATM systems. As a result, new communication infrastructures are required to manage future aeronautic communication traffic demand and to provide an always-connected infrastructure for air-ground communication. According to the technology investigations carried out under the Action Plan 17 (AP17) of the EUROCONTROL-FAA Memorandum of Cooperation, the following three datalink systems are proposed as the air-ground communications [3] infrastructures:

1. A ground-based, high-capacity, airport surface datalink system, referred to as the Aeronautical Mobile Airport Communications System (AeroMACS);
2. A ground-based datalink system for continental airspace in general, referred to as the L-band Digital Aeronautical Communications System (LDACS);
3. A satellite-based datalink system for the oceanic, remote (deserted) and continental environment (in the latter case complementing the terrestrial systems).

While AeroMACS will be based on the IEEE802.16 WiMAX mobile communications standard in order to benefit from commercial general telecom developments and minimise the required development resources, further investigations have yet to be carried out to select and standardise the other two proposed systems.

To complement the study carried out by AP17, the EU FP7 project SANDRA (Seamless Aeronautical Networking through integration of Data links Radios and Antennas) [4] started in 2009 aims to design, specify and develop an integrated aircraft communication system that consists of VDL2, AeroMACS and two candidate satellite technologies, namely, Inmarsat BGAN and DVB-S2. The goal is to demonstrate the communication technologies and the flexibility, scalability, modularity and reconfigurability offered by the SANDRA system.

As a ‘system of systems’, SANDRA examines four integration levels, including:

1. Service integration of aeronautical communication service provision through the development of a middleware layer;
2. Network integration using the Internet Protocol (IP) as a unification technology;
3. Radio integration using software defined radio (SDR) technology to realise the physical and data link layers radio;
4. Antenna integration for the realisation of a dual L-Band and Ku-Band antenna.

From the communication architectural point of view, SANDRA spans across three segments, namely, the Ground Segment, the Transport Segment and the Aircraft Segment as shown in Figure 1.

The Aircraft segment consists of three main physical components: the Integrated Router (IR), the Integrated Modular Radio (IMR) and the Antennas. These three components form the SANDRA terminal.

In the Transport Segment, four different radio transport technologies are considered: VDL mode 2 [5] in VHF band, BGAN [6] in L-band, DVB-S2 [7] in Ku-band and AeroMACS[8].

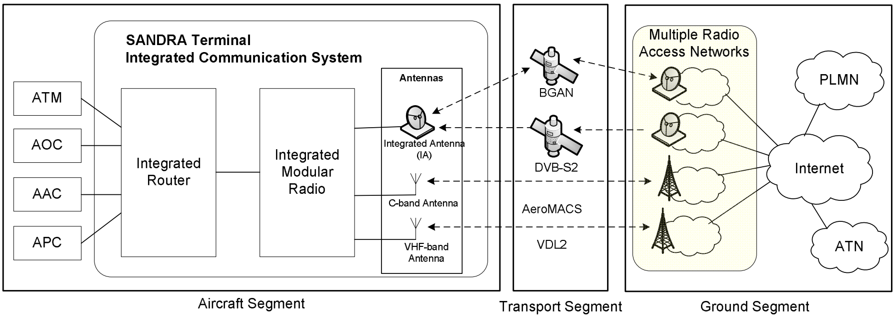

Fig. 1. SANDRA Communication Network Architecture

The Ground Segment consists of multiple Radio Access Networks (RANs) and their corresponding core networks of the radio transport technologies, the Aeronautical Telecommunication Network (ATN), the Internet and possibly the Public Land Mobile Network (PLMN), for passenger communications. The RANs can also be connected directly to the ATN and the PLMN on the ground. In order to provide mobility service and security services for aeronautical communications, functional components such as the mobility server, security and authentication server are required in the ground segment to provide corresponding mobility information services as well as security services. These components will be provided by the ATS, AOC, AAC and APC service providers of the ATN on ground.

The SANDRA scope focuses on the aircraft segments while making use of the existing transport and ground segments facilities. Authorities, such as the FAA, specify a minimum level of redundancy of equipment that must be operational before an aircraft is allowed to take off. The design should avoid single point of failure to meet the minimum level of the aeronautical aircraft equipment requirements; the size, complexity and cost in aircraft avionics equipments are highly constraint; the system should be able to manage radio resources whose availabilities will depend on different flight phases, i.e. AeroMACS will only be available when the airplane is on ground and taxing speed is less than a certain amount, e.g. 50 knot; the BGAN system will have the always available coverage but limited bandwidths.

To enable interoperability and to manage radio resources among heterogeneous radio links, this paper proposed a realization of joint radio resource management (JRRM) framework to allocate radio resources of the heterogeneous radio transport networks to different applications taking into consideration QoS and routing related parameters and in conjunction with the real-time link conditions and characteristics. A unified cluster of interface primitives[9] between different link layer technologies and the JRRM are defined by extending the MIH framework[9, 10]. Hence, the JRRM monitors and manages the resources available in the different radio links via the unified interface to ensure that the application QoS/SLA requirements are met during connection establishment and the handover process. Sitting on top of the data link layer, the JRRM framework also provides the interface between the IP based network layer and lower layer protocol stacks.

In addition, the proposed JRRM is designed to have Master-Slave (1+1) redundancy capability which meets the minimum level of the aeronautical aircraft equipment requirements.

The primary focus of this paper is to report on the functional design, and software realization of the JRRM. A prototype implementation of the JRRM interfacing with AeroMACS and Inmarsat BGAN lower layer stacks and higher layer stacks is described and results obtained from the prototype are analysed.

The rest of the paper is organised as follows: Section two recalls the system architecture design from our previous work; Section three is the detailed design of the proof-of-concept test bed; experiment results and analysis are discussed in Section four. Our conclusion is given in section five.

2 JRRM System Architecture Design

Figure 2 shows the architecture of the JRRM described in [11, 12]. The JRRM, with its provision of adaptation functions and together with the link management functions, forms an Adaptation Layer between the higher network layer and the lower link layer. This Adaptation Layer is primarily required for RRM purposes. It hides the underlying complexities due to multiple radio protocol stacks from the network layer and provides a uniform interface to control the multiple radios.

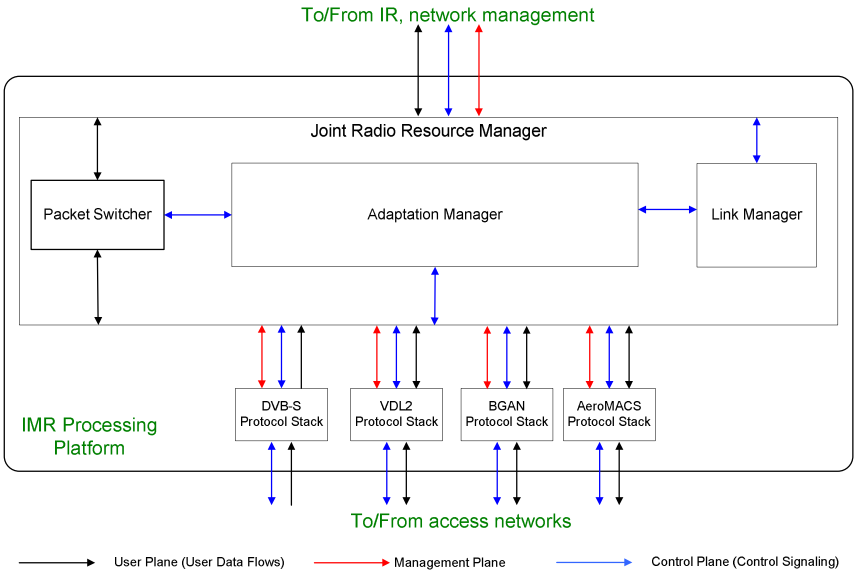

Fig. 2. JRRM Functional Architecture

The JRRM functional entities are further described below from the protocol stack perspective:

- *Link Manager (LM):* the Link Manager is a cross-layer entity performs network layer and link layer connection management, QoS management and mobility management in relation to admission control, packet scheduling and handover functions together with the Resource Manager (RM) in the IR.
- *Adaptation Manager (AM)*: The adaptation manager is primarily responsible for providing the various adaptation functions required for proper interfacing between the IR and the radio stacks.
- *Packet Switcher (PS):* The PS is responsible for switching data packets received from the IR in the user plane to the destined radio modules according to a packet switching table generated and passed by the address resolver in the AM during connection establishment. Sessions established between the higher layer IR and the Link layers are identified by Queue Identifiers (QIDs) which are mapped onto Link IDs and the link's specific connection IDs. And the mapping is synchronized and stored in PS. As a result, each data packet can be switched directly to the radio modules without passing through the AM in the user plane.

3 Proof of Concept Testbed Software Design

3.1 Software Architecture Design

Figure 3 depicts the proposed software architecture of the SANDRA terminal down to the Radio Stacks which makes use of the JRRM to integrate different radio technologies. Hardware nodes are represented by the grey boxes. As shown in the miniature figure of the SANDRA terminal, the IMR is built up by two identical IMR processing platforms. The JRRMs on the two platforms work in a Master-Slave configuration, whereby a hot swap can take place if the current master JRRM fails due to any hardware or software failure. These provide the reliability and redundancy feature that is critical for the aeronautical communication systems. The Master JRRM controls and manages the various radio links and control which radio link is loaded onto the processing platform. It can then establish connection over the links according to the various QoS requirements. Handover of connections from one link to another can then be performed if a radio link is lost.

The JRRM software consist several modules: the JRRM Manager module, the Link Manager module, the Packet Switcher module, the Adaptation Manager module, the JRRM health checker module, the Waveform Status Servo module and the Flight Status Detector module. The ***JRRM Manager Module*** reads and sets system settings of the radio technologies which can be used, handover strategies and policies etc.; Information fusion, radio link control, synchronizations between JRRMs and decisions making are carried out in the ***Link Manager Module***; the ***Packet Switcher Module*** is responsible for switching data packets between the radio technologies and the IR via tunnels created by the Virtual tunnel Manager application; the ***Adaptation Manager Module*** is primarily responsible for providing the various adaptation functions required for proper interfacing between the IR and different radio technologies; the ***Health Checker Module*** responses and monitors keep alive messages of the system to prevent itself being killed by the Supervisor application

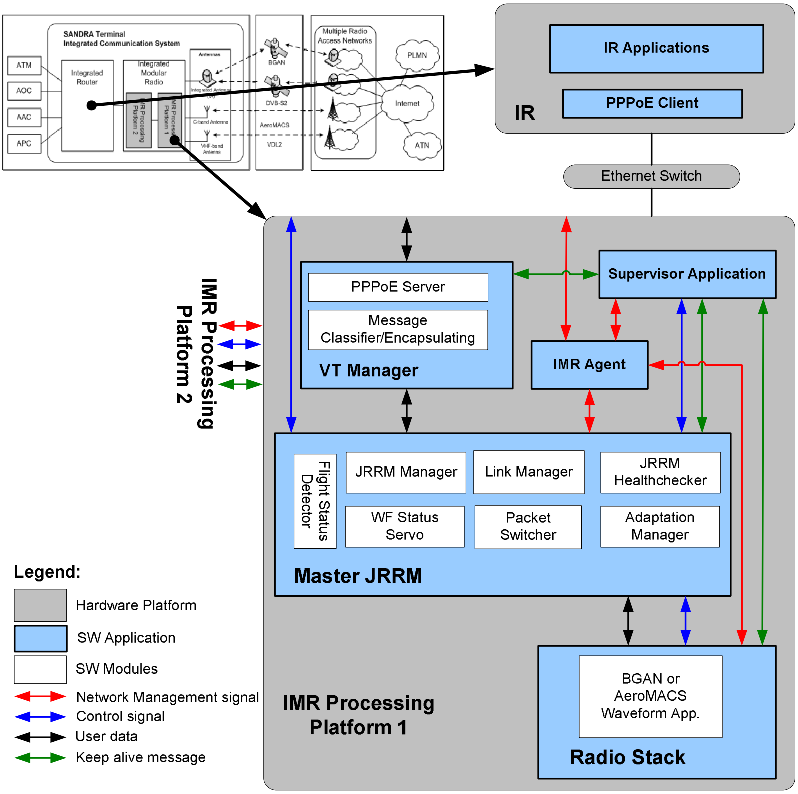

Fig. 3. Testbed Software Architecture

and decide whether a Master-Slave swap should be triggered; the ***WFStatus Servo Module*** is dedicated for managing the various waveform related processes such as loading or unloading of a waveform upon different flight status detected by the ***Flight Status Detector Module***.

In addition to the JRRM application, there are four other applications running on each IMR process platform to supporting the integration of the radio technologies:

- The Supervisor Application: This is responsible for launching the JRRM and the various waveforms. The JRRM can then tell the Supervisor Application which application to launch. If a waveform application goes down, the supervisor will inform the JRRM.
- The Virtual Tunnel (VT) Manager: This is a user plane entity responsible for carrying user traffic between the IR and the IMR. The IMR works as PPPoE server and the IR behaviour as PPPoE client. On one hand, the VT Manager receives and opens the user plane PPPoE packets sent by the IR and encapsulates the extracted IP packets in the SANDRA specific SAP messages and passes to the JRRM PS; on the other hand, the VT Manager processes the SANDRA messages and packets them as PPPoE session data to the IR.
- The Waveform application: In this paper, it can be either the BGAN or the AeroMACS radio protocol stacks.

- The IMR agent: This is a network management application which is responsible for collecting network management related information. It consists of three main parts: a management interface, a Management Information Base (MIB), and the core agent logic.

3.2 Detailed Design of JRRM Modules

To process multiple requests in parallel, the Link Manager is designed with multiple sub-link managers which are separate working threads, dedicated to process individual sessions. One session is identified by a queue identifier (QID). In case for the waveforms which do not support parallel requests, a mutex mechanism is designed. One type of radio has one mutex lock to keep all sub-link managers synchronized when processing link specific messages. Each sub link manager has a state machine as shown in Figure 4.

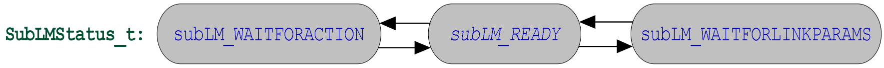

Fig. 4. Sub link manager state machine

When the sub-link manager is in the READY state, it can start processing new requests. When the sub link manager starts processing a request, it will enter the ACTION state and wait for confirmation messages. Either a timeout event or a confirmation can drive the sub link back to the READY state.

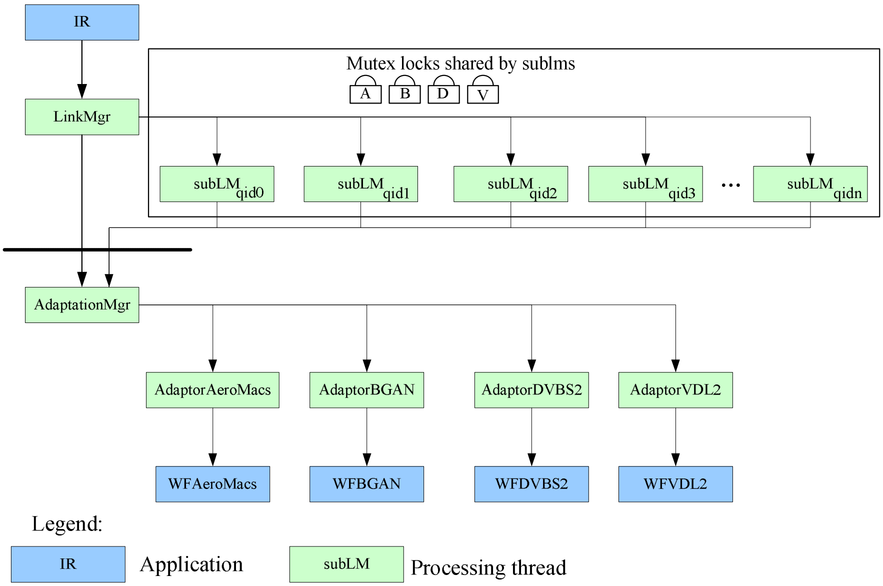

Fig. 5. JRRM return signal handling design

As shown in Figure 5, when the general Link Manager receives messages from the higher layer entity, the IR, it will forward all requests to the related sub-link managers. The sub-link manager will first try to get the locks of its links and perform the requests accordingly. As an exception, the sub-link manager 0 is not related to any connections. It is reserved for the Link Manager to process non-connection specific messages. For example if the Link Manager receives a Close request from the IR but the QID does not exist, then QID 0 will handle this message and sends an Error code to the IR.

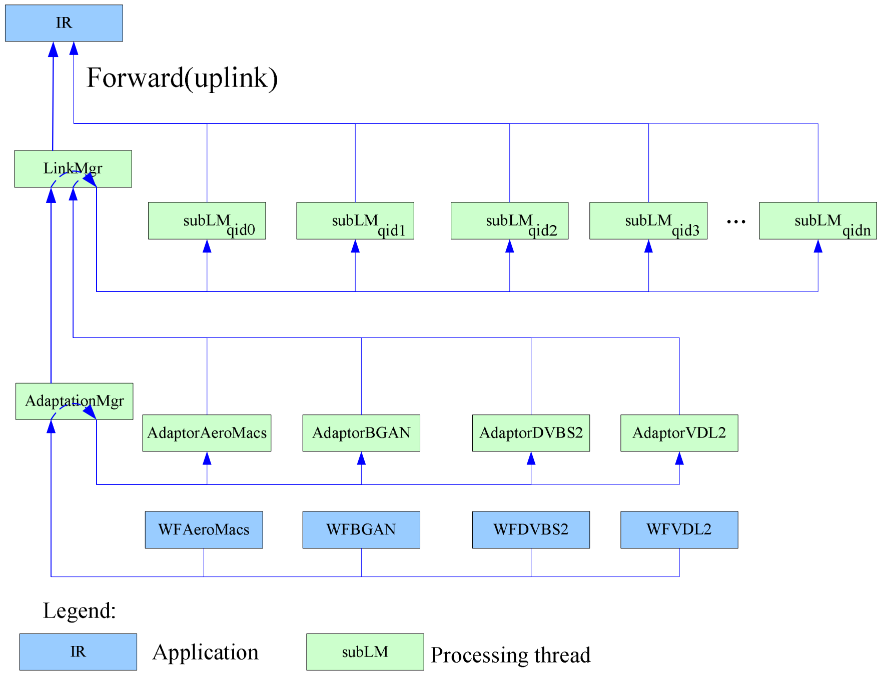

Fig. 6. JRRM forward signal handling design

Figure 6 shows the forward signal handling design of the JRRM. There are different waveform adaptors controlled by the Adaptation Manager, where each of them is dedicated for one kind of link. When the adaptors received messages from the waveforms, the messages will be processed and translated by the adaptors and then sent to the Link Manager for further processing. If the messages are related to connections, then sub-link managers will process them, otherwise the Link Manager will handle the messages directly (e.g. link up events).

4 Experiments Results

4.1 Testbed Configurations

The testbed is consisted of four Dell Vostro 430, Interl® Core™ i5 CPU, 2x2.67GHz, 2.00GB Memory PCs, with one performing as the IR, two working as IMR processing platforms and one working as a application workstation. In supporting the JRRM core software, one AeroMACS Emulator and one BGAN Emulator software from Future Ubiquitous Network (FUN) Lab, University of Bradford are deployed. Testing software includes iperf [13] and Wireshark [14] are used to collect results.

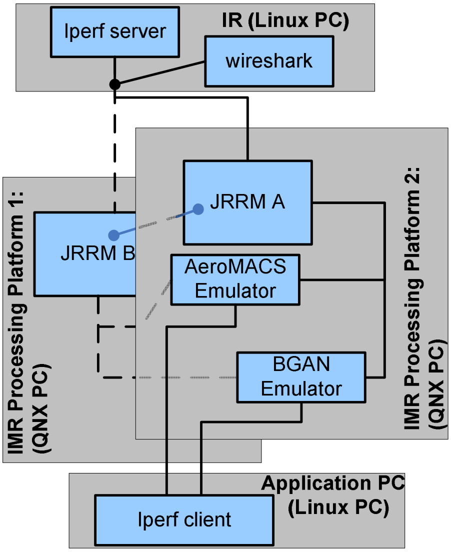

Fig. 7. Settings of the experimental environment

As shown in Figure 7, iperf server and client are running on two Linux PCs to stream TCP packets. The JRRM software runs on each QNX PC as 1+1 redundancy. One JRRM is active as the Master to process all the traffic whilst the other JRRM is inactive as the Slave but keeps synchronization with the Master. Connections will be established by the Master JRRM to carry data between the applications on the two Linux PCs.

Two sets of experiments are collected from the testbed:

1. Master-Slave JRRM hot swap during data transmission via the established AeroMACS connections.
2. Sessions handover from AeroMACS to BGAN.

4.2 Master-Slave Swap

The parameters used in iperf server and client are listed as below:

server	-s –P 0 –i 1 –p 5001 –f k
client	-c server_ip_addr –P 1 –i 1 –p 5001 –f k –t 100 –T 1

Upon receipt of a connection request from the IR, a Sub Link Manager is created by the Link manager. The Adaptation Manager translates the request from the Sub Link Manager to AeroMACS waveform to start the session. User TCP packets sent from the iperf server to the client is collected by wireshark network protocol analyzer. The JRRM process is terminated by a shell script on each QNX PC every 30 seconds during data transmission. From Figure 8, we can see the connection established successfully hence the TCP data can pass through the JRRM. Because the connection information are synchronized between the two JRRMs, one is killed, another JRRM takes over the tasks immediately (300ms delay due to the keep alive health check interval). When the JRRM and the AeroMACS are on the same processing platform, the average throughputs are, as can be observed in Figure 8, 9500000B/s * 8/1024/1024 = 72.4Mbps. If the JRRM and the AeroMACS emulator are running on different processing platforms; the average data rate is 1000000B/s * 8/1024/1024 = 7.6Mbps. The data rate is limited by the QNX Neutrino Inter-Process Communication across platform POSIX messages.

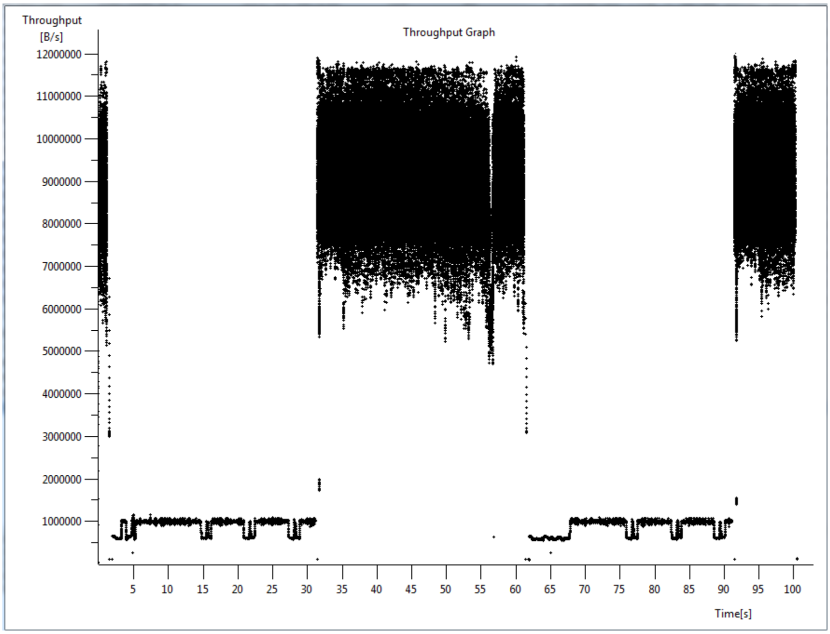

Fig. 8. Master-Slave swap throughput graph

Another observation from Figure 8 is when the Master-Slave switchover happens from JRRM/waveform co-located platform to across platforms, the instantaneous throughput varies between 1000000B/s and 950000MBps, for example, at time 5, 15, 22, 28 etc.. This is caused by the processing congestions when TCP retransmissions occurred.

From the experiment, the hot swap feature of the JRRM has avoided single point of failure successfully and maintained the continuity of service in the case of Master JRRM being terminated.

4.3 Handover

A twenty seconds transmission of data is sent from the iperf client, on the user application PC, to the iperf server running on the IR. This is shown in Figure 9. During the first ten seconds, data were sent via the AeroMACS link. The average data rate is 73Mbps. On 10th second, AeroMACS stack is torn down due to flight phase changes [15]. The connections then switch to the available BGAN link. There is around three seconds' interruption of data transmission due to the link establishment of BGAN. The data transmission resumed at 13th second, and the average data rate is now about 300kpbs (the maximum date rate is set to 320kbps for BGAN Emulator) and the waveform loading delay causes the connections handed over to available BGAN link.

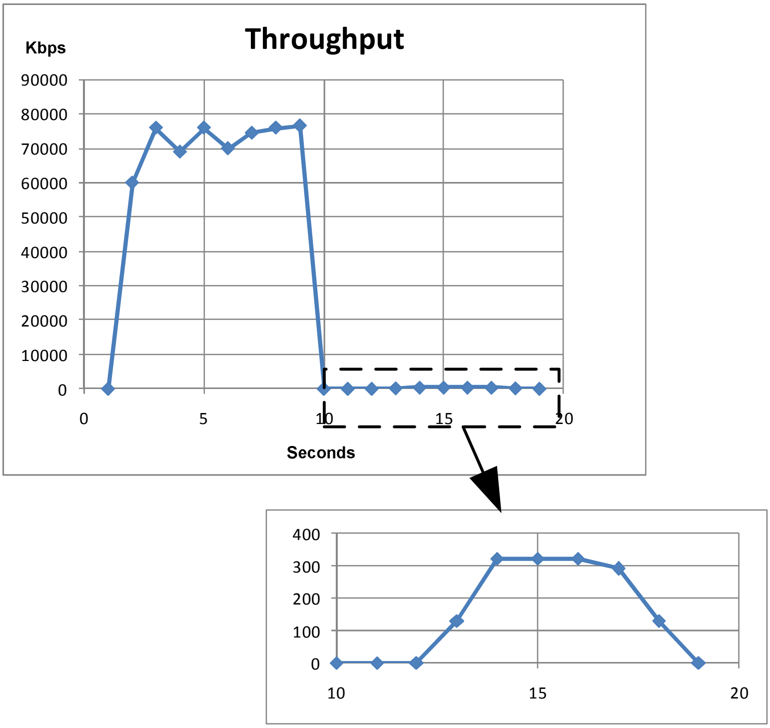

Fig. 9. Handover from AeroMACS to BGAN

The JRRM approach implemented in the testbed has demonstrated the benefit of integrating AeroMACS and BGAN links, namely, the high availability of BGAN link with the high bandwidth of the AeroMACS link and the successful inter-technology handover from one link to another.

5 Conclusion

This paper presents a realization of the integrated satellite-terrestrial communication networks for aeronautical services via JRRM approach. Details of the software design are described. The integrated modular radio shares a common radio resource management which minimized the level of the size, complexity and cost of aeronautical on board communication system as well as increased the availability of links by introducing multiple radio technologies. The results collected from the proof-of-concept JRRM prototype verified the validity of the design.

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