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Performance Evaluation of Network Mobility Handover over Future Aeronautical Data Link

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***Abstract*—The aviation community is currently working on the standardization of data communication systems for the future air traffic management. In this context, the ICAO and EUROCONTROL are working on the standardization of IP-based aeronautical telecommunications network and future radio access technologies, respectively. With this work, for the first time, we integrate L-DACS 1, which is one candidate for future radio access technologies, with realistic IP-based network layer functionality and analyze the handover delay performance. We first investigate the effect of link layer retransmissions on handover delay performance. We realized that for regions with low signal-to-noise ratio (BER of 10^{-3}), link layer retransmissions improve the total handover delay (layer 2 and 3) by about 80 %. Considering regions with high signal-to-noise ratio (BER of 10^{-5}), the benefit of link layer retransmissions becomes negligible due to the reduced number of packet losses. During our analysis, we notice frequent transmissions of router advertisement messages causing significant overhead on L-DACS 1 and propose two approaches in order to decrease the overhead to an acceptable range. In the last section, we tackle the increase in handover delay due to a limited number of return link resource request opportunities in congested cells.**

I. Introduction

In the aeronautical domain, there are two main communication services, namely Air Traffic Services (ATS) and Airline Operations Services (AOS) [1]. ATS corresponding nodes are used to provide navigation, control, and situational awareness services to the aircraft, whereas AOS corresponding nodes are mainly used for business operations of airline companies. Using today's communication technologies, these services are generally performed by using analogue voice communications. However, it is already known that digital data communication utilizes the bandwidth more efficiently and overall is much less error-prone than analogue voice communication.

For this reason, two main activities are running in parallel in order to build a future aeronautical communications network. On the one side, the ICAO is working on the standardization of the next generation IPv6-based Aeronautical Telecommunications Network (ATN/IPS) [2] and, on the other side, the European EUROCONTROL and the U.S. FAA are working on the standardization of future radio access technologies for aeronautics.

In this work, we analyze the handover performance of the L-Band Digital Aeronautical Communications System Option 1 (L-DACS 1) integrated with the IPv6 network layer functionality including Network Mobility (NEMO) support [3].

A. Related Work

Mobile IPv6 (MIPv6) and its extensions are very well studied protocols by the research community. Previous studies mainly considered link technologies from the domain of consumer electronics. For example, a simulation study of MIPv6 on IEEE 802.11b provides a performance evaluation of different smart handover extensions including link layer triggers for MIPv6 [4]. Another work presents testbed experiments related to the use of MIPv6 with IEEE 802.11g technology [5]. Similar results have been presented in [6]. Here, MIPv6 has been studied in an experimental testbed using WiMAX and Wi-Fi as underlying link layer technologies. In [7], NEMO is used as a base protocol in a testbed where two different 802.11 interface cards are used in order to perform make-before-break handovers. Although having multiple interfaces from the same technology provides better handover delay, it is not realistic in aeronautical domain due to cost, space and weight.

In the aeronautical domain another set of link technologies are considered, which mainly differ due to their data rate and cell size. Currently deployed link technologies provide data rates in the range of 3–30 $\mathrm{kbit\,s^{-1}}$ per cell. However, future radio access technologies like L-DACS 1, which this paper also focuses on, provide data rates in the range of 291–1318 $\mathrm{kbit\,s^{-1}}$ in the Forward Link (FL) and 270–1267 $\mathrm{kbit\,s^{-1}}$ in the Return Link (RL) per cell depending on selected modulation and coding scheme. Although L-DACS 1 increases the data rate beyond that provided by current aeronautical links, the link capacity is still far behind that of consumer electronics. Another difference is the cell size, with radii in the range of 100–200 km and each cell providing services for up to around 500 aircraft (abbreviated as "a/c" in the rest of this paper). This means that with the lowest modulation and coding scheme each a/c uses less than 1 $\mathrm{kbit\,s^{-1}}$ on average. It is thus vital to decrease the network layer signaling overhead on the wireless link without degrading the handover delay performance.

In our previous work, we presented an initial step towards investigations of MIPv6 handover delay in an aeronautical environment [8]. However, only generic link layers with certain bandwidth and delay values were considered, whereas we now assume a realistic link layer, i.e. L-DACS 1, including an Automatic Repeat Request (ARQ) component.

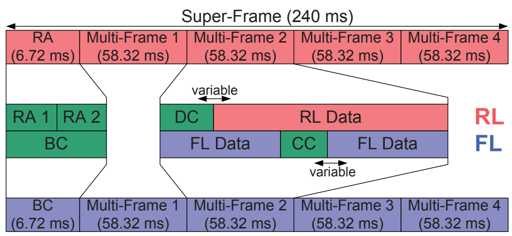

Fig. 1. L-DACS 1 frame structure

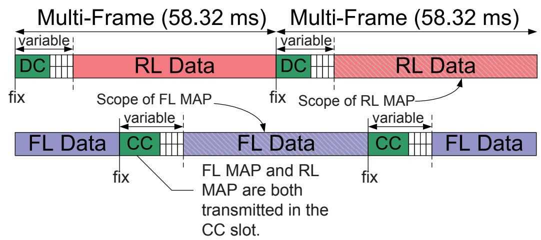

Fig. 2. L-DACS 1 resource allocation structure

B. Contribution

The contribution of this paper is threefold. First, after introducing L-DACS 1 (Section II), we analyze the handover performance in an integrated L-DACS 1 access network with realistic IPv6 network layer functionality (Section III). To the best of our knowledge, this integration has not yet been analyzed in detail, even though it is one of the most promising candidates for future aeronautical radio access technologies.

Secondly, as during our analysis, we noticed frequent transmissions of router advertisement messages, which cause significant overhead on L-DACS 1, we propose two approaches to solve this problem (Sections IV-A and IV-B). We show that these can decrease the overhead to an acceptable range without degrading handover delay performance.

Finally, we examine the handover delay increase when an a/c enters a congested cell. This is due to the limited number of sub-slots in the RL control channel. We propose a method to reduce the handover delay in such a case, only changing the control channel allocation strategy (Section V).

II. L-Band Digital Aeronautical Communications System Option 1

EUROCONTROL and the FAA are currently considering two candidate radio access technologies for the future provision of ATS and AOS services in the L-band.[1] These technologies are referred to as L-DACS 1 and 2. Initial specifications for both technologies have been published by EUROCONTROL, and it is planned that one of these two systems will become operational around 2020. L-DACS 1 has been designed for the transmission of both digital voice and data. In L-DACS 1, RL and FL are separated by means of Frequency Division Duplex (FDD). In the RL, a combination of Orthogonal Frequency Division Multiple Access (OFDMA) and Time Division Multiple Access (TDMA) is used, whereas in the FL, Orthogonal Frequency Division Multiplexing (OFDM) is applied. The TDMA component in the RL is selected in order to minimize the possibility of interference with legacy systems which are operating in the L-band (e.g. distance measuring equipment). This is important since an L-DACS 1 transmitter operates close to other receivers on board, so it should only be active for a short time, reducing these receivers' exposure to interference.

[1] see http://www.eurocontrol.int/communications/

A. Frame Structure and Resource Allocation

The frame structure is shown in Figure 1. Time is divided into superframes with a duration of $240\,\mathrm{ms}$. At the beginning of each superframe, a/c have the opportunity to log onto the network using a Random Access Channel (RACH), whereas the Base Station (BS) transmits general cell information in the Broadcast Channel (BCCH). The rest of the superframe consists of four multiframes, each with a duration of $58.32\,\mathrm{ms}$ and consisting of both data and control frames. In the FL, the BS transmits control information, such as resource allocation, i.e. FL mapping and RL mapping, and acknowledgments on the Common Control Channel (CCCH). In the RL, each a/c is assigned one slot per multiframe within the Dedicated Control Channel (DCCH) for the transmission of control data. At most, 52 a/c can be accommodated within the DCCH. If more a/c are registered with a single BS, a/c will not receive a DCCH slot in every multiframe. Both the CCCH and DCCH are of variable length to allow efficient use of the wireless resources.

Before any transmission can take place, either in the RL or the FL, resources must be requested from the BS. At the beginning of a CCCH slot, the BS considers all received resource requests (sent via an RSRC_RQST message) since the last CCCH slot. It allocates resources, i.e. TDMA slots and OFDMA subchannels, for the a/c, and informs the a/c via an RSRC_RESP message. The exact scheduling algorithm to be used by the BS is left open by the L-DACS 1 specification. In our implementation, we have adopted static priority queuing, i.e. requests with the highest priority are fulfilled first. The allocation of resources is broadcast to all a/c in the CCCH slot, specifying which a/c is allowed to transmit when and on which subchannels. The scope of this resource allocation is shown in Figure 2.

B. Automatic Repeat Request Mechanism

L-DACS 1 supports both unacknowledged and acknowledged data transfer modes. Due to the rigid frame structure of the L-DACS 1 protocol, a sender knows when it should expect an acknowledgment for data that it has transmitted. After one missed acknowledgment opportunity, a packet is retransmitted. After a certain number of subsequent retransmissions (in our scenarios, we considered one retransmission), the entire transmission is aborted and the packet is discarded at the transmitter. Note that the entire process of resource request and allocation must again be performed before the lost packet can be retransmitted.

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C. Handover Types

Two different types of handover are foreseen by the L-DACS 1 specification. In both handover types, the BS polls the a/c to provide power reports of their received signal strength. Polling of neighboring cells' received signal strength is requested by transmitting neighboring cell frequencies in the Broadcast Control Information (BCI) message. In the upcoming BCI slot, the a/c switches to the next BS frequency and measures the received power by listening to a BCI message from this BS. It then sends a POW_REP power report message to the current BS. If the adjacent cell's received power level is higher than that of the current cell, the current BS triggers a HO_COM handover message to this cell.

In the case of a type 1 handover, the a/c simply confirms the handover, sends a CELL_EXIT message to the current BS, and switches to the channel of the next BS, where it registers via the new station's RACH by sending a CELL_RQST message. If no collision has occurred on the RACH, the BS will respond with a CELL_RESP on the CCCH and assign a subscriber access code and a DCCH slot to the a/c. In the case of a collision on the RACH, the aircraft does not receive this response and will perform an exponential backoff, attempting to access the RACH again later.[2] In this paper, we only consider type 1 handover since it does not require any signaling between BSs and is more suitable for inter-access network handovers. The details of type 2 handover can be found in L-DACS 1 specification.

D. Handling of Control Message Losses

In this section, we will summarize how the system reacts if one of the control messages is lost during the transmission (the names of message types in small caps are taken from the L-DACS 1 specification).

An a/c sends a KEEP_ALIVE in order to inform the BS that it is still connected. After a certain amount of KEEP_ALIVE messages (in our simulations we used 20) is not received by the BS, it de-registers the a/c from its connected a/c list. If a POW_REP is lost, the BS continues to use the last measured value if it is available. If no information is available (which is the case during the first scanning request of the neighboring cell), the BS should wait for the next POW_REP message in order to decide whether a handover is needed. If a HO_COM is lost, the BS sends another one in the upcoming CCCH slot.

If a CELL_RQST is lost, the a/c sends another CELL_RQST in the upcoming random access slot, which is at the beginning of the next superframe (i.e., at $240\,\text{ms}$). If a CELL_RESP is lost, the a/c again sends another CELL_RQST and thus causes another CELL_RESP to be sent from the BS. If a CELL_EXIT is lost, the BS will consequently not receive any more KEEP_ALIVE messages from that a/c, so eventually the system will react as outlined there.

If an RSRC_RQST is lost, the a/c sends another request in the upcoming DCCH slot. If an RSRC_RESP is lost, the allocated slot information is not known by the a/c and the associated packets are not received by the a/c. If a BCI carrying a scanning request of the next BS is lost, the a/c will not start scanning of the next BS. In addition, if an a/c does not receive any BCI within a certain time (in our simulations we used $4\,\text{s}$), it will assume the connection was lost and switch to a scanning state. Finally, if a SLOT_DESC is lost, the a/c cannot identify the beginning of the FL data part. Moreover, no RL resource requests can be made for the upcoming multiframe. In general, the a/c needs to wait for the next SLOT_DESC in order to receive and send data.

[2]We did not investigate this effect due to its low probability of occurrence

TABLE I
LAYER 3 PARAMETERS RELATED TO HANDOVER

Parameter	Value
MIN_RTR_ADV_INTERVAL	0.03 s
MAX_RTR_ADV_INTERVAL	0.07 s
IPv6_DEFAULT_DUPADDRDETECTTRANSMITS	1
IPv6_DEFAULT_RETRANS_TIMER	1 s
IPv6_MAX_RTR_SOLICITATION_DELAY	1 s
MIPv6_INITIAL_BINDACK_TIMEOUT	1 s
MIPv6_INITIAL_BINDACK_TIMEOUT_FIRST	1.5 s
MIPv6_MAX_BINDACK_TIMEOUT	32 s

III. Performance Assessment

The aeronautical communications panel of the ICAO has recently recommended IPv6-based ATN/IPS [2]. In this specification, MIPv6 [9] is considered as a basic mobility management protocol and NEMO [3] is mentioned as an optional protocol extension of MIPv6. It is already known that since MIPv6 supports only host mobility, its mobility signaling overhead becomes problematic if we assume a/c with multiple mobile nodes on board. For this reason, we consider NEMO as a mobility management protocol in this paper.

In order to assess the performance of L-DACS 1 integrated with main network layer functionality, we modeled the protocols within the OMNeT++ simulator [10]. As mentioned we implemented L-DACS 1 offering type 1 handovers and integrate it with the NEMO protocol at the network layer in order to provide seamless mobility to the a/c. Table I shows the parameters used at the network layer. The first five parameters are related to the neighbor discovery protocol where the first two values define the Router Advertisement (RA) interval sent by the Access Router (AR) [9], [11] and the next three parameters are related to the Duplicate Address Detection (DAD) and Multicast Listener Discovery (MLD) procedures. The last three parameters are specific to the MIPv6/NEMO protocols and related to home registration.

In our simulations, when the a/c receives a new RA message with different prefix information, it assumes the RA is coming from a different access network – however, in reality different prefixes can be advertised by the same access network. As future work, we plan to use advanced movement detection methods as described in [12]–[14].

In addition, we also assume a certain Bit Error Rate (BER) in our simulations (BER $= 10^{-3}$ and BER $= 10^{-5}$) in order to reflect packet loss due to channel errors.

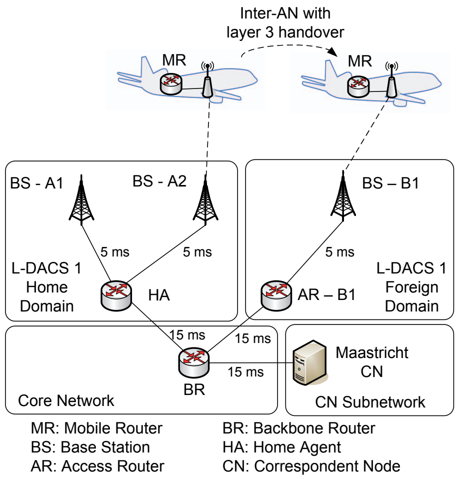

Fig. 3. Example topology for the European scenario

A. Considered topology

The main topological considerations for the ATN/IPS are provided in [15]. In our analysis, the European scenario shown in Figure 3 is considered, where the a/c are communicating with an ATS controller located in Maastricht. An a/c starts communication when it is located in the home domain, performs handover during communication, and moves to the foreign domain. This is a kind of inter-access network handover so that the aircraft should complete layer 2 and layer 3 handover procedures in order to continue communication. Within the ground network, the fixed delay values shown in the figure were used. In the aeronautical domain, the cell radius is generally between $100\,\mathrm{km}$ and $200\,\mathrm{km}$ and the cell overlapping regions are quite large so that the handover performance does not degrade due to high speed of an a/c.

B. Handover Performance with ARQ Mechanism

In this section, we analyze the benefit of the ARQ mechanism for handover delay performance under different channel conditions.

1) High BER Scenario: In this first scenario, we assume a BER of 10^{-3}. We calculate the corresponding packet error rate as $\mathrm{PER} = 1 - (1 - \mathrm{BER})^n$, with n denoting the packet length. Table II shows the average delay values for an a/c performing layer 2 and layer 3 handovers. These values are taken from 25 simulation runs where each run simulates 20 a/c handover instances. In particular, Table II shows the delay values of each step contributing to the total handover delay. As can be seen the main difference between both scenarios is the delay incurred by home registration, i.e. the Binding Update (BU)–Binding Acknowledgment (BA) exchange. In the case where ARQ is not used, due to more frequent loss of either BU or BA messages the handover takes much longer. Use of ARQ with single retransmission can thus improve the total handover delay performance by around $80\,\%$. Detailed plots of the delay distribution can be seen in Figs. 4(a) and 4(b).

TABLE II
AVERAGE HANDOVER DELAY VALUES FOR LAYERS 2 AND 3

	no ARQ	one re-tx
L2 Handover Completion Time in s	0.09	0.09
RA Reception Time in s	0.03	0.027
MLD-DAD Completion Time in s	1.5	1.5
Home Registration Time in s	33.17	5.68
Total Time in s	34.8	7.3

2) Low BER Scenario: In the second scenario, the same simulation settings have been used for BER $= 10^{-5}$. Due to the low BER, the system experiences less packet loss and the benefit of ARQ becomes negligible. Again, detailed plots of the delay distribution can be seen in Figs. 4(c) and 4(d). The average delay stays around 2.85–$2.9\,\mathrm{s}$ in both cases.

IV. Reducing Router Advertisement Overhead

MIPv6 specifies RA transmission intervals of 30–$70\,\mathrm{ms}$ in order to minimize the handover delay. If a RA message of around $100\,\mathrm{B}$ is sent at the MIN_RTR_ADV_INTERVAL, i.e. every $30\,\mathrm{ms}$, the overhead corresponds to around $9\,\%$ of the L-DACS 1 FL capacity with lowest modulation and coding scheme. This could be problematic in high density cells where there could be around 500 a/c. For this reason, we propose two methods in order to decrease the unsolicited RA overhead without degrading the handover delay performance. In this section, we used the same simulation settings of low BER scenario without considering ARQ mechanism.

A. Proposal 1

In our first proposal, we utilize the Link Down and Link Up event services of IEEE 802.21 [16] to improve handover performance. When the a/c sends a CELL_EXIT message to the current BS, L-DACS 1 in the a/c triggers a Link Down event. When the new link becomes available after the layer 2 handover is completed, a Link Up event is triggered by L-DACS 1. Upon reception of the Link Up event, the network layer transmits a Router Solicitation (RS) and waits for the RA message. According to [11], a host should transmit up to MAX_RTR_SOLICITATIONS RS messages, at intervals of at least RTR_SOLICITATION_INTERVAL seconds. In our case, when the network layer receives a Link Up event, it sends an RS immediately, ignoring this delay, in order to faster perform the handover. However, if the first RS or the respective solicited RA message is lost due to channel errors, the a/c delays the second RS according to the standard.

Fig. 5 shows the resulting performance compared with the regular case where only unsolicited RA messages are transmitted. Here, different unsolicited RA intervals between $0.07\,\mathrm{s}$ and $10\,\mathrm{s}$ are considered. As can be seen, the handover delay performance becomes independent of the unsolicited RA transmission interval when the mobile sends the RS message. If we consider unsolicited RAs with $10\,\mathrm{s}$ intervals, the overhead decreases significantly to a level of few hundred $\mathrm{bit\,s^{-1}}$.

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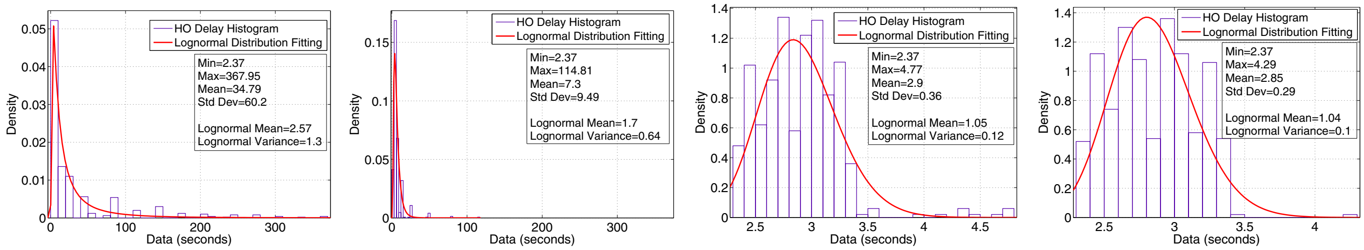

(a) without ARQ, high BER (b) with ARQ (one re-tx), high BER (c) without ARQ, low BER (d) with ARQ (one re-tx), low BER

Fig. 4. Delay density for Layer 2 and 3 handover with and without ARQ and for two different BER scenarios

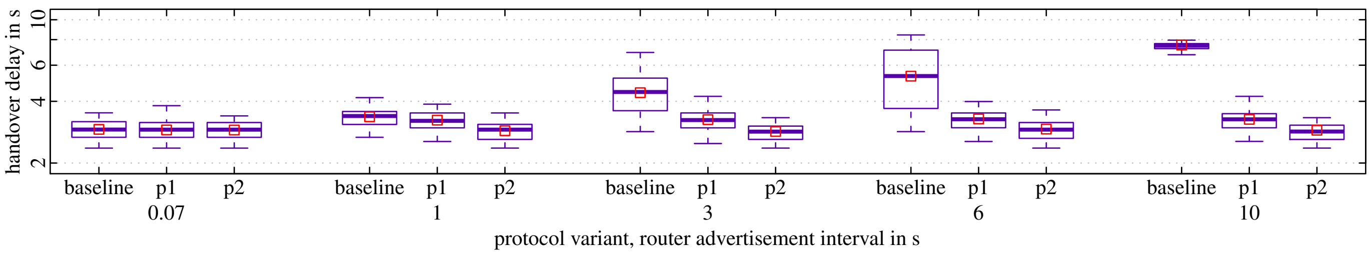

Fig. 5. Handover delay comparison: unsolicited RA vs. proposals 1 and 2

B. Proposal 2

The second proposal for increasing handover performance requires modifications to the BS. When it receives an unsolicited RA message from the connected AR, it now does not only send the message but also stores a copy in its local RA cache. The local copy is always updated with the most recent RA message. During the handover, when an a/c sends a CELL_RQST to the BS, the BS does not only send a CELL_RESP message, but it also sends the stored local copy of the RA message in the upcoming FL data slot. If the local copy is lost due to channel errors, the mobile should wait for a regular unsolicited RA message. Fig. 5 also shows the performance of this proposal: On average, it performs even better than proposal 1, further decreasing delays by about $0.4\,\mathrm{s}$.

C. Discussion

Although the achieved handover delay stays within a certain range in both discussed proposals, due to long service disruption time (around $3\,\mathrm{s}$) both proposals can not satisfy the specific application demands of, e.g., voice over IP. Similarly, considering TCP applications, packet losses during the handover will be considered as a sign of congestion by the TCP sender, which will result in unnecessary timeouts and retransmissions. In general, there are three main sources of the achieved handover delay, namely: DAD time for the care-of address generation, home registration procedure, and DAD time for the home address. The latter is not very critical since it occurs only during the first handover from home domain to foreign domain, however DAD for care-of address generation occurs at every layer 3 handover, so different approaches have been proposed to reduce this delay [17], [18]. Ignoring the DAD procedure, the only remaining component is the home registration delay which takes around $0.4\,\mathrm{ms}$ in the low BER case. Packet drops during this period can be prevented by using Fast Mobile IPv6 [18], so the next AR stores and delivers those packets to the mobile after the handover is completed. It needs to be mentioned that the achieved handover delay performance (around $3\,\mathrm{s}$) is not the final objective but a major step towards seamless handover in aeronautical networks. In addition, although the second proposal requires RS transmission in the RL and causes additional overhead, considering the large cell sizes and small handover rate, this overhead is negligible.

In the $0.07\,\mathrm{s}$ case, we could not see the real performance of the first proposal since before RS reaching to the AR (which will trigger solicited RA transmission), another unsolicited RA is already sent by the AR. Considering the second proposal, the $0.07\,\mathrm{s}$ case did not really affect the performance since RA is transmitted just after CELL_RESP message.

V. Speeding Up Handovers in Congested Cells

As mentioned in Section II-A, a BS provides a resource request slot to each registered a/c within the cell – no matter if those a/c will have some data to transmit or not. Using a CCCH slot, the BS notifies the a/c that have a right to send a resource request in the next upcoming DCCH slot. In Sections III-B and IV, we assumed the number of a/c in the next BS is always less than 52. However, if more than 52 a/c are attached to the BS, not all a/c are able to send their resource requests in every DCCH slot due to its limited size. For example, if we consider 416 a/c within a cell, each a/c will only get one resource request opportunity for every 8 multiframes (i.e. every $467\,\mathrm{ms}$). From a layer 3 handover perspective, this constitutes the worst case delay that a binding update transmission will suffer if an a/c enters such a congested cell.

In order to decrease the BU transmission delay in congested cells, we propose that the BS will allocate consecutive DCCH

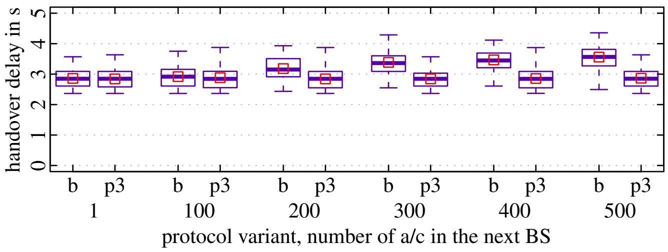

Fig. 6. Handover delay comparison: baseline vs. proposal 3

slots to the newly attached aircraft for certain duration. In our simulations we used 16 superframes (around $3.8\,\mathrm{s}$) since most of the handovers are completed in less than $4\,\mathrm{s}$ for low BER cases as mentioned in Section III-B2. By doing this, the BS allows the aircraft to send its resource request immediately when the BU message arrives at the L-DACS 1 queue. Fig. 6 shows the handover delay values for different numbers of a/c in the next cell. As shown in the figure, with our proposal, the handover delay stays constant no matter how many a/c are attached to the cell. If 500 a/c are attached to the BS our proposal can thus reduce handover delay by around $0.7\,\mathrm{s}$.

Our proposal requires modification to the CCCH slot structure which affects the DCCH slot allocations so that a BS is capable of assigning a DCCH slot to a desired a/c on demand within the cell. In the regular case, a BS assigns a/c to each DCCH slot based on the ordered subscriber access code.

It is good to mention that aircraft performing handover use the assigned consecutive resource request opportunities only for the transmission of the mobility signaling, not for user data. This is due to fact that RL capacity should be used by all users in equal amounts. Resource requests for the user data will be sent only in the regular dedicated DC slots as defined in the L-DACS 1 specification.

In addition, if we consider one a/c performing handover for certain duration, during this time, one less a/c will gain access to the DCCH slot. This is not very critical since that a/c will only be affected at most one multiframe duration, i.e. $58.32\,\mathrm{ms}$.

VI. Conclusion

In this paper, we analyzed the applicability of Mobile IPv6 in the context of ATN/IPS. We took into account all of the specific requirements of layer 2, i.e. of L-DACS 1. In particular, we investigated the benefit of ARQ on the handover delay performance. Based on our results, we can point out that in high BER scenarios the use of ARQ is indispensable in order to perform home registration within acceptable time. In low BER scenarios, on the other hand, the use of ARQ will not further improve handover delays. In that case, average handover delay values stay around 2.8–$2.9\,\mathrm{s}$.

Based on these findings and the observation that signaling overhead due to frequent transmission of RA messages has a significant impact on L-DACS 1 capacity in the FL, we propose two modifications to reduce this overhead. Our first proposal uses the functionality defined by the IEEE 802.21 standard with additional logic at the network layer. Although we have implemented some basic primitives of IEEE 802.21 standard in the first proposal, further analysis is required in order to implement the whole 802.21 stack for aeronautical environment. Our second proposal extends L-DACS 1 functionality by sending an RA message in the FL data slot following CELL_RESP message so that an a/c will not only enter a cell but also receive an RA message and perform address configuration. Compared to the first proposal, this provides much better performance (about $0.4\,\mathrm{s}$).

In the last section, we proposed a new method so that the BS can assign DCCH slot to connected a/c dynamically. By using this method, handover delay is reduced by $0.7\,\mathrm{s}$ in the worst case (i.e. 500 connected a/c).

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