ERLANG B/C LINK AVAILABILITY/BLOCKAGE FOR DATA AND VOICE OVER VDL MODE 3

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Abstract

This study looks into the blockage and availability of Digital VHF Mode 3 link. Using future predicted voice and CPDLC data traffic loads, the Erlang B and Erlang C formulas were utilized to measure the availability / blockage of the two applications over VDL Mode 3. The results here, along with previous cell capacity calculation on the number of frequency channels available done as part of separate study, can give a measure of the maximum overall system capacity. This study shows sufficient availability (or acceptable blockage levels) for worst case traffic loads. It is found that overall, the voice communications will reduce the system availability the most, followed by the Management accessing portion of the data which in turns limits the CPDLC capability. The most significant reduction of ideal maximum capacity is probably the limitation of the controller's human capability to handle a large group of aircrafts within a sector. Also it is found that requiring at least a single voice channel within each 25 Khz frequency channel, and requiring each controller to have a single voice channel, limits the data capability considerably even for 3 voice, 1 data shared configuration.

Introduction

At the present time, all communications between pilots and controllers take place using the analog VHF voice technology. The FAA [1] is planning with the help of other government and industry partners (such as NASA [2]) to modernize the air space and introduce digital and networking technologies that will help alleviate many of the capacity, and delay problems occurring in our present system. Every year approximately 300 new frequency channels have to be assigned so that to accommodate the growth of the air traffic [3]. At that growth rate (approximately 4% yearly), it is expected that the system will reach its operating capacity by a decade time frame hence making the modernization effort a crucial one. A small but important part of this effort is the introduction of the Very High Frequency Digital Link (VDL) Mode 3 to replace the analog voice. The VDL Mode 3 provides Aeronautical Telecommunication Network (ATN) data and digital voice services. It replaces a single 25 KHz channel with four logical independent channels with each used for voice or data transfer Among the applications that will be supported by the VDL Mode 3 link will be in addition to digital voice, the Controller Pilot Data Link Communications CPDLC traffic. CPDLC supports efficient Clearances, Flight Plan Modifications, and Advisories (including Hazardous Weather Alerts).

Although the VDL Mode 3 introduction will increase the available national system capacity from two to four times that of the analog system depending on the configuration used, it is found in previous studies that such an increase is still not sufficient at certain altitudes and in certain air space sectors [4]. Nevertheless this is only true if each user occupies the allocated TDMA slot for the entire flight which is not expected to be the case. This short study attempts to analytically measure the number of users that can share a single TDMA slot given the applications being fed through the links and the density of the air space. The use of the Erlang B and Erlang C is utilized for that purpose keeping in mind several variables. The next four sections will cover the CPDLC, voice, and VDL 3 specifications,

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the Erlang B Erlang C computations, the results of availability and blockage, and the conclusions.

Voice and CPDLC applications on VDL Mode 3

The VDL Mode 3 link general specifications are shown in Table 1 [5]. It uses Time Division Multiple Access (TDMA). To divide up the 25 KHz channel over 2,3 or 4 users. Up to seven configurations of voice and data sharing are defined. VDL Mode 3 uses a Differential 8 Phase Shift Keying (D8PSK) modulation scheme at a data rate of 31.5 kbps.

CPDLC is the designated data application to be utilized with the VDL 3 digital links. This is in addition to the voice capability. The voice communications will generally occupy a single TDMA slot for the time the voice communications is taking place. The data on the other hand will occupy a given number of TDMA slots that are sufficient to send the data packets, and then give way for other user data packets or same user new packets.

The CPDLC application future predicted traffic load is obtained from [6], and from [7]. Compared to other aeronautical applications (not planned to go on VDL Mode 3 link) the CPDLC data traffic is on the low side. CPDLC messages are preformatted and will be used only on needed bases by pilots and controllers to communicate efficient Clearances, Flight Plan Modifications, and Advisories (including Hazardous Weather Alerts). As such more messages are expected as aircraft come closer to the airport area than En Route.

The voice communications will be necessary as well as data although data is the preferable mode of pilot to controller communications as it is better optimized with use of CPDLC.

VHF band for Aeronautical use	760*25 kHz total 524*25 kHz ATC only
Number of VDL-3 TDMA slots	3 max data/voice channels (3T) 4 max voice 2 voice,2 data 3 voice, 1 data (4 other configurations)
VHF channel bandwidth	25 kHz
M burst, M channel, or M slot	DL used for link access and status. UL used for timing and network configuration.
25 KHz channel data rate, with total overhead (coding, etc)	31.5 Kb/s
Modulation type	D8PSK
VDL TDMA slot period.	120 milliseconds total (4 TDMA slots) with M portion 30 milliseconds per TDMA slot (120ms /4 slots per frame)
Information bits/TDMA slot	496 data bits/ one TDMA slot 576 voice bits /one TDMA slot
Service data rate for data messages μ per TDMA slot	μ=496/120=4.13 Kbits/s (data) μ=576/120=4.8 Kbits/s (voice)
Tower Transmit power	10 Watts
Airplane Transmit power	10 to 20 Watts
Required Signal to Co-channel interference ratio	20 db (26 db max, 14 db min)
CPDLC Frame Size	Using a crude average of 500 bits (includes overhead of 150%). Specific values vary for En route,Terminal, and Airport and different message types.

Table 1: VDL 3 System and application Parameters

Voice will be used for functions not covered by the CPDLC or by other data services not using VDL Mode 3. The traffic load for the voice shown in Table 2 was also obtained from [6].

$\lambda \equiv$ application demand rates (data and voice)	**For CPDLC data**
Obtained from [6] for year 2015 projected traffic loads.	3.4 Kbits/s airport uplink, or 3.4/192 = 0.0177 Kbits/s per aircraft. 2.9 Kbits/s airport downlink, or 2.9/192 = 0.0151 Kbits/s per aircraft.
Aircraft Peak traffic loads for year 2015 for all classes (1,2,3) (over a designated sector) [6]:	1.3 Kbits/s terminal uplink, or 1.3/137 = 0.0095 Kbits/s per aircraft. 0.9 Kbits/s terminal downlink. or 0.9/137 = 0.0066 Kbits/s per aircraft.
192 aircraft for airport	1.1 Kbits/s En Route uplink, or 1.1/500 = 0.0022 Kbits/s per aircraft.
137 aircraft for terminal	1.3 Kbits/s En Route downlink, or 1.3/500 = 0.0026 Kbits/s per aircraft.
500 aircraft for Enroute	**Digital Voice:** 23.0 Kbits/s airport uplink, or 23/192 = 0.1198 Kbits/s per aircraft.
	10.56 Kbits/s airport downlink, or 10.56/192 = 0.0550 Kbits/s per aircraft
Note: airport and terminal domains are defined over a 10 minute period (600 seconds), while en route is defined over a 50 minute window.	4.8 Kbits/s terminal uplink,or 4.8/137 = 0.0350 Kbits/s per aircraft 4.8 Kbits/s terminal downlink, or 4.8/137 = 0.0350 Kbits/s per aircraft 10.56 Kbits/s En Route uplink, or 10.56/500 = 0.0211 Kbits/s per aircraft 2.88 kbits/s En Route downlink, or 2.88/500 = 0.0058 Kbits/s per aircraft.

Table 2: CPDLC and Voice Future Traffic Loads

For both voice and data calculation, a projected peak air traffic density was used in [6] with various message intervals and sizes depending on the airspace sector being used. The peak traffic (using 10 minute window) at the busiest airport was quoted as 192 aircrafts, while at terminal it was 137 aircrafts, and at the busiest En Route sector using 50 minutes window, it was 500. The voice data was given in [6] by call usage time over observation time and was converted in this paper to Kbits/s using a 4.8 Kbit/s Vocoder assumption. Note the voice VDL3 TDMA service rate was designed to meet that 4.8 Kbits/sec Vocoder specification.

The VDL mode 3 will use within each TDMA time slot, a management portion where the aircrafts will be sending request data messages. The service rate of request data processing can range from 0.2 Kbits/sec up to 2 Kbits/sec depending on the number of M slots (each slots service rate is 0.2 Kbits/sec). The request message sizes are only 48 bits each, and it was assumed that the frequency of the messages is equivalent to the frequency of the CPDLC messages (and voice to a lesser extent, hence not included) in the downlink direction. Only downlink requests for time slots occur from the aircraft to the ground. However, for every uplink CPDLC message from the ground, the aircraft transport protocol layer needs to send an acknowledgment, and to do that it needs to send a request for a time slot, hence adding to the frequency of required request. As such a reasonable frequency can be obtained by simply taking the combined down link and uplink CPDLC data rates in each domain, and dividing by a 500 bit CPDLC average packet size (for a conservative result). For example in the en route, we would have (0.0022e3+0.0026e3)/500=0.0096 CPDLC messages per second. Hence on an average bases we would have at least 0.0096 request messages per second per aircraft. Using the 48 bit request message size this gives us a rate of 0.0096*48=0.4608 bits/sec. Similarly the request bit/sec rates for the other domains can be computed and Table 3 summarizes it.

Service data rate for request messages **μ** per M burst slot	μ=0.2 Kbits/sec with up to 10 M bursts available for 3T configuration and from 2 to 3 for 1v1d group as an example.
Request message Frame Size	48 bits
Request message data rates in the down link direction	Airport domain 3.1488 bits/sec per aircraft Terminal domain 1.5456 bit/sec per aircraft En Route domain 0.4608 bits/sec per aircraft

Table 3: VDL mode 3 management channel (portion of each TDMA time slot), and aircraft request messages size and demand rates

Erlang B and Erlang C computations of Availability

Given the type of application, and the information in the previous section on the application demand rates, the airspace density, and the TDMA slot data rate capability, it is possible to compute the availability of the communication link per TDMA digital channel (or slot). To do that two formulas are used the first is for the Erlang B and the second is the Erlang C. The Erlang B assumes that a request for service must be serviced immediately or else dropped immediately. The Erlang B formula (based on an M/M/c loss system) gives the probability that a new block is denied service given no buffering capability. The formula is given by [8]:

$$B(c,a) = \left(\frac{\frac{a^c}{c!}}{\sum_{n=0}^{c} \frac{a^n}{n!}} \right) \tag{1}$$

$$a = \lambda / \mu \tag{2}$$

Where a is defined as the average traffic intensity in Erlang given by the ratio of the average service demand rate λ in bits/second over the average user link rate μ also in bits/second. Note this is also called offered load.

The Erlang C on the other hand is obtained from an infinite queue M/M/c system. The Erlang C, also called Erlang delay formula gives the probability that a customer (or data packet for data services) being sent by the application, would be required to queue for service. This is the same as the probability that there are c or more customers (data packets) in the system already by the time the sent packet arrives. The formula for the Erlang C and its variations are given by [8]:

$$P(N \geq c) = C(c,a) = \frac{\frac{a^c}{c!}}{\left((1-\rho) \sum_{n=0}^{c-1} \frac{a^n}{n!} + \frac{a^c}{c!} \right)} \tag{3}$$

$$L_q = \frac{\rho C(c,a)}{1-\rho} \tag{4}$$

$$W_q = L_q / \lambda \tag{5}$$

$$W_s = 1/\mu \tag{6}$$

$$W = W_q + W_s \tag{7}$$

$$W_q(t) = 1 - C(c,a) \exp^{-\mu t(c-a)} \tag{8}$$

$$W(t) = \begin{cases} a \neq c-1 \\ 1 - \frac{(a-c+Wq(o))}{(a+1-c)} \exp^{-\mu t} - \frac{C(c,a)}{(a+1-c)} \exp^{-c\mu t(1-\rho)} \\ a = c-1 \\ 1 - (1 + C(c,a)\mu t) \exp^{-\mu t} \\ Wq(o) = 1 - C(c,a) \end{cases} \tag{9}$$

$$\pi_q(r) = \frac{W_s}{c(1-\rho)} \ln\left(\frac{100C(c,a)}{100-r} \right) \tag{10}$$

where the parameters Lq,Wq correspond to the mean queue size in packets, and mean waiting time in queue in seconds. Similarly Ws corresponds to the mean service time, while W corresponds to the mean system time (service and queue). Wq(t) and W(t) correspond to the queueing time distribution, and the system waiting time distributions respectively. Finally $\pi_q(r)$ correspond to the r^{th} percentile delay in the queue. A formula also exists for the r^{th} percentile delay in the system, but was not used since the results are obtained directly from the data in the waiting time distribution W(t).

The availability is generally defined as the probability that an at least one empty TDMA slots is available when a packet is ready to be sent , which is one of the parameters of interest. For the Erlang B, and Erlang C computations, it is given by the next two equations:

$$A_B = 1 - B(c,a) \tag{11}$$

$$A_c = 1 - C(c,a) \tag{12}$$

A variation or the Erlang C is used in this study. Here, the availability is defined in terms of an acceptable maximum waiting time in the system (Outage definition time T_{od}) beyond which a packet is deemed worthless. In that case and regardless if the c channels are full or not, it would be equal to the probability that a packet has to wait in the system for longer than the outage definition time, and is only applicable for the data analyses (as oppose to the voice).

$$A_{cw} = 1 - W(T_{od}) \tag{13}$$

The Erlang B computations are more appropriate for the voice application since users will be sharing the available channels in party line scenario and calls do not have the waiting option that the data has. Also the M channel and request for time slots is best analyzed with the Erlang B as will be explained later.

The Erlang C and its variation are more appropriate for the data CPDLC application since it allows for queuing. The assumption that there are an infinite size queue is acceptable since there is plenty of capability on board the aircrafts, and on ground to store CPDLC messages until they are due to be sent. If on the other hand a queue limit has to be imposed which is small (below 10 CPDLC frames for example, which is highly unlikely), then a more appropriate model would be the M/M/c/K. That system was also tested although it was felt that the infinite queue model is more appropriate. Other parameters observed using the M/M/c model included the waiting time in queue and in the system, as well as the 95^{th} percentile delay.

In this study, the availability is computed independently for voice, data (including CPDLC, and Management requests). No attempt was done to strictly combine the different availability figures (other than to discuss the limiting factors of one to the other). This was mainly because no requirement was readily available in the strictest sense and hence it was more beneficial to study each and then tie them all together. None the less, if a strict combination is needed then a multiplication of all versions can be considered such as:

$$A_{total} = A_B A_{CW} \cdots \tag{14}$$

Availability and blockage results

Making use of the formulas in the previous section, and the input data of Table 1,2, and 3, we can compute the availability (or blockage) of the voice and CPDLC application in uplink and downlink directions and over the three different airspaces, airport, terminal, and En Route.

The voice application used the Erlang B formula since voice calls are not queued, and are effectively dropped if no channel is available. The results for the voice are shown in Figure 1.

Note since the uplink and downlink will be sharing the same channels, the two are combined for each of the airspace types. Combining the two is equivalent to adding together the demand rates in the two directions.

Since one controller will be managing a single sector with each sector covered by a single voice channel, it was interesting to look at the availability in terms of a single voice channel (c=1). Figure 1 represents that case. The relationship is not linear and hence can not be easily deduced from Figure 1 directly.

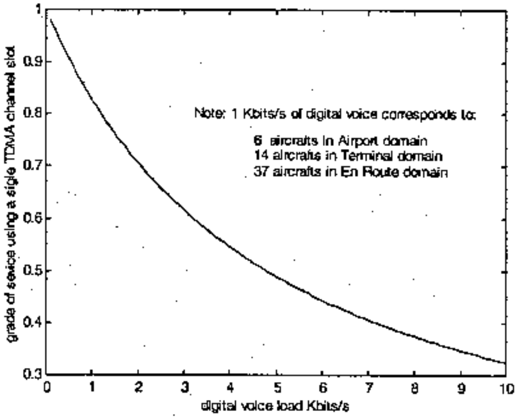

Figure 1: Availability of voice services for a range of data rate using Erlang B using a single TDMA time slot.

From Figure 1, it can be seen that 1 Kbits/s of voice digital load is supported with a grade of service of approximately 0.83. If such a grade of voice service is acceptable then a single TDMA slot can support up to 6, 14, and 37 aircrafts in the airport, terminal, and en route domain respectively. If on the other hand a grade of service of 0.9 is needed then those numbers are approximately reduced in half to 3, 7, and 18 respectively. If for the sake of experimenting with having 2 channels available to share, which means 2 controllers accommodating the same pool of aircrafts (an unlikely scenario), it can be shown that a four to six times improvement is achieved in that case. For example for the 0.83 grade of service approximately 24, 56, and 148 aircrafts are supported for airport, terminal, and en route domains respectively while for a grade of service of 0.9 at least 18, 42, and 111 can be supported. Having 2 voice channels independently (one per controller for each sector) would simply provide 2 times that of the single channel and hence less than that by the sharing scenario.

Next, investigating the data services of the CPDLC, over the VDL Mode 3 link, we used the formula for the availability corresponding to the waiting time distribution in the system. This is done to measure the 95% probability that a CPDLC data message would wait in the system (queuing as well as service times) given by equation 9. The requirement was given to be as " 0.95 probability that a high priority message of 192 bits to be delivered within 1 second [5]". Figure 2 shows the system waiting distribution over a 3 second window for data loads ranging from 0.4 up to 4 Kbits/sec using a 0.4 Kbits/sec increment. Although the requirement was in terms of a 192 bit CPDLC message, a 500 bits size message was used in Figure 2 for a more general case. The 192 bit case would provide even better results.

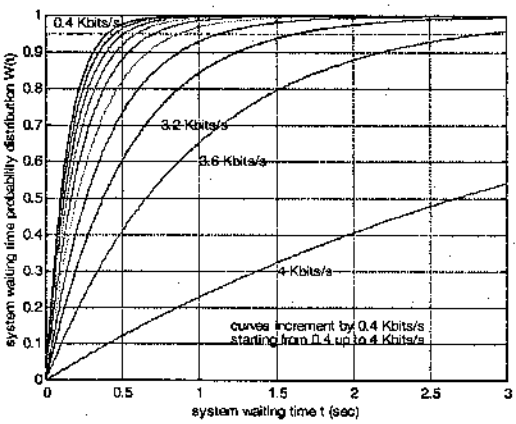

Figure 2: System waiting time distribution curves W(t) for a single data slot channel (c=1), with a CPDLC frame size of 500 bits, using a range of data rate starting from 0.4 Kbits/sec up to 4 Kbits/sec. Each graph increments in order by a 0.4 Kbits/sec step.

Observation of Figure 2 indicates that a waiting time in the system of less that 1 second and with a 0.95 probability can be achieved with data loads up to 6*0.4=2.4 Kbits/sec (sixth curve from left to right). As such using the 2.4 Kbits/sec, and the uplink and downlink data rates per aircraft shown in Table 2, we can determine an ideal capacity of a data TDMA slot. For example at the airport, 2.4 Kbits/sec corresponds to 2.4/(0.0177+0.0151)=73 aircrafts, while for terminal it is 2.4/(0.0095+0.0066)=149 aircrafts, and finally for en route it is 2.4/(0.0022+0.0026)=500 aircrafts. Using a 129 bit message size we get 97, 198, and 667 aircrafts for airport, terminal, and en route respectively such that the 0.95 probability is met. Using more data channels such as two or three (c=2, c=3) improves those numbers considerably and was obviously beyond the need or the capability of the controller processing to be worth while to investigate. None the less, as will be pointed out next, the accessing done via the Management bursts within the M portion of the TDMA slots limits the capacity considerably and looking at c=2, and c=3 can give an idea of the comparison between the two and where the ideal configurations should and can be.

To study the accessing or management portion, we utilize the data in Table 3. Since management channels are embedded within TDMA slots with up to 10 available depending on the configuration, we first look at the capability of a single one. An M/M/c loss model is best suited to approximate request behavior since request packets get lost when they collide. Also since the assignment of an M burst slot is done at random (uniformly) when aircrafts wish to transmit, adding more M slots does not match up with adding more c channels in the M/M/c loss model. Rather, because of the random assignment to the M slots, the system would look more like a set of M/M/1 loss models in parallel with up to the number of available M slots. This is a draw back in terms of capacity as adding more channels to an M/M/c loss system (i.e. c being equal to the channels available) would produce a much larger capacity than a set of c M/M/1 loss models in parallel. The obvious reason for that is because the M/M/c loss model (as well as all other queuing models in general) assume that new packets go to the empty servers (as oppose to randomly getting assigned to a server which could be in use or not), and hence a much more optimal usage of the servers capability is done that way. None the less, we are limited to the M/M/1 loss parallel case, and we estimate capacity of more than one M slots by simply multiplying the results of the M/M/1 loss system with the number of available M slots. Note this is not the case with the data portion of the CPDLC analyses since there the ground intelligence place data slots into empty TDMA slots when available and hence an M/M/c model is more realistic (as oppose to c M/M/1 models in parallel). Figure 3 next shows the capacity of a single M slot given a range of data loads (or λ). Again the Erlang B is appropriate with a slight difference from the actual system due to lack of repeated requests when a collision occurs which can account for some difference but not as significant to warrant the use of a much more customized system for a first study.

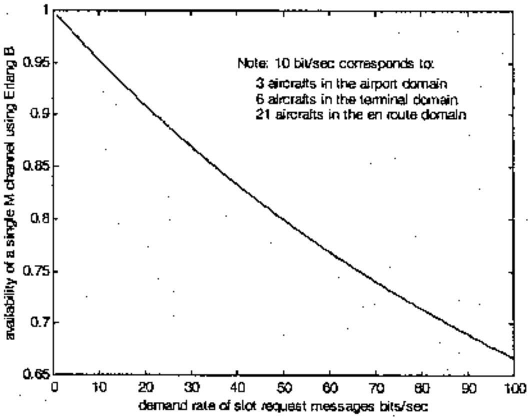

Figure 3: Availability of the Management channel (a portion of a single TDMA slot) for a range of request messages data rates λ using Erlang B and a single M time slot (M channel) with a 0.2 Kbit/sec channel service rate

From Figure 3, we can conclude that for a single M channel, we can have up to 6 aircrafts (10 bits/sec) accommodated in the terminal domain at a 0.95 grade of service (or 5% chance of being blocked or colliding). Similarly for the 0.95 grade of service up to 3 aircrafts can be accommodated in the airport domain, and 21 in the en route domain. If we use a 0.9 grade of service then the numbers approximately double to 6,12, and 42 aircrafts in the airport, terminal, and en route domains respectively. Hence for example if a 2v2d configuration is used, then each group (or single controller group) will have 1 voice and 1 data channels (TDMA slots) with each containing an M burst logical channel. Hence for a 0.9 grade of service the accessing will be limited to 2 times the numbers in Figure 3, or basically 12, 24, and 84 aircrafts for airport, terminal, and en route domains. In the 3T configuration we have up to 10 channels which leads to 60, 120, and 420 aircrafts for a 0.9 grade of service, and 30, 60 and 210 aircrafts for a 0.95 grade of service in the airport, terminal, and en route domains respectively. Based on those results it is evident that the capabilities of the data services are limited by the access channels rather than by the CPDLC data portions. Those results were also verified with detailed simulations done in [9] for a 3T configuration with all data. In order to combine the accessing and traffic channels, it is possible to compute the combined availability of the two and also include the re-transmits advantage. The way that would be done is to look at the probability of getting service within a total required time such as the outage definition time T_{od}. That would include the chance of getting service within that time from the first try, plus the chance in the second try (if the first try was blocked), plus the third try (if the first two tries are blocked) and so on. At some point, it will not be possible to try again due to the time reaching its maximum allowed T_{od}. Hence the first time the probability of getting service would be equal to the product of the probability of getting access to the M channel (Figure 3) with the probability that the service time will be less than T_{od} (from Figure 2). If a second try is needed and is possible, then a second term is added corresponding to the probability that service would be provided within T_{od} minus the time it took until the second try took place, multiplied by the probability of getting access on the second try. The probability of getting access on the second try is in turn equal to the probability of getting access (same as in the first try and all other tries if we assume a finite population of aircrafts), multiplied by the probability of trying for a second time which is equal to the probability of being blocked the first time. In a similar way, the next sequence of tries are computed with the main difference being the probability of trying which would decrease considerably since for example if the blocking on the first try is 0.1, then probability of trying the second time is 0.1, while for the third time is 0.1*0.1=0.01, and fourth is 0.001 and so on. As the number of retries increases (i.e. we allow for a larger T_{od} or we reduce the time between retries) it would be possible to reduce the access channel blockage probability considerably and hence increase the number of supported aircrafts. However, as the number of allowable retries increases, that will also increase the request data traffic load (i.e. traffic load in Table 3), and hence will then start to have the opposite effect of reducing the number of possible aircrafts to support. Hence, the retries have a significant advantage initially (for example allowing for 2 or 3 retries is much better than one) but much higher is not recommended and can cause worse results. Finally when doing the combined analyses, it should be noted that the same number of aircrafts for both the M and the Data channels should be used when getting numbers from Figure 2 and 3 so as to be consistent. For example we may use a 0.95 requirement that data packets have to be received within 1 second time frame, and figure out the number of aircrafts that will produce a total probability that is equal to the 0.95 given all tries possible using Figures 2, and 3 data as well the probability of trying. This combined probability was studied and the results showed better number of aircrafts than looking at the access channel alone, but a worse one based on the data channel as expected. A future study will show the numbers more formally but interested readers can do the computations simply by following the procedure above and using data given from the plots of the last two figures. It was found that a 1 second T_{od} with up to two tries possible and with the use of 3 data channels and 8 access channels, will give an approximate number of 25 to 35 aircrafts that can be supported using worst case scenarios with service rates half of that in Table 1 to accommodate the random wasted slot spaces in the real system due to shorter packets occupying full slots. Again the access channels produced the greatest limitation as it compared to the 3 data channels which could have accommodated many more aircrafts if it was not for the accessing limitation. This is evident from the result stated earlier on the 149 aircraft capacity in the terminal area using only a single data channel but without looking into the access channel limitation. Increasing the accessing channels is the simplest way to accommodate more traffic on the M channels. Again this was compared to an actual simulation and in the study to follow this it will be elaborated on in much more details.

Conclusion

This study involved the computation of availability/blockage of voice and data over VDL Mode 3 data link. The Erlang B was used for the voice and the access data channels, while the Erlang C was used for the data services (with CPDLC traffic) to compute the availability of each. Several parameter that effect the availability results were studied including the system wait time, range of service data, number of available TDMA logical channels, and packet size. The results show very good availability of the data portion of the TDMA slots which service the data CPDLC traffic. This availability was though tied also to the Management channels availability where request for TDMA slots are sent. That availability was considerably less hence limiting the overall system data capability. This is true even with the retry chances on the M channels. Voice on the other hand provided the least capacity and as such is a more significant limiting factor than the access channels if a voice channel have to be accompanied by a data channel (such as in the 2v2d configuration). Since the controllers are managing the same set of aircrafts via voice and data, the lower capacity of the two is the determining factor as such a sharing of a single data channel between more than one controller each having a single voice channel is more optimal. At present only up to 3 controllers are allowed to share a single data slot with each using a single voice channel such as in the 3v1d configuration. Even so, from the numbers shown it appears that more can be done with a single data channel than 3 voice channels combined and hence a waste in system capacity is eminent. This will be much more pronounce if in the future voice traffic will be much reduced given more reliance on data and CPDLC specifically. Finally, the controller capability to observe and manage a limited number of aircrafts in its sector (a number of 15 aircrafts is common), is probably the most limiting factor compared to the communications links capabilities. This is also the case because of the requirement of having one voice channel per controller.

Previous studies [4] on available frequency channels given Co-channel interference requirements can be linked with this study to show the overall system capacity and availability. It can be concluded from the two studies that the use of multiple frequency channels, is the obvious option to provide more TDMA logical channels and that the combination of the available frequency channels and the capability of a single channel (done in this study) can provide sufficient support for future traffic loads. None the less, this study attempted to point out where the limiting factors are and where improvements can possibly be applied if more capacity is needed in the future.

Finally it is worth pointing that many more results can be obtained based on the formulations of this study in a simple way that can serve the purpose. For example any future variations in traffic loads, requirements, can be accounted for by simply varying the appropriate parameters of the traffic data rates while using the same availability curves and accounting for a different number of aircrafts. Similarly a change in an availability waiting time requirement, or voice grade of service can be accounted for by simply observing the same curves shown here but extracting data at different point.

For future recommendation or enhancements, a few items can be thought of which include: using priority queuing systems for different priority levels; accounting for repeated requests in a more formal way; including other delay factors such as propagation although those are minimal; investigating the total availability in a more strict sense; investigating ways to optimally use the access channels (as oppose to the random method) so that to come closer to M/M/c loss type models rather than M/M/1 in parallel; investigating improvement or variations in the transport layer that can reduce data loads in general; Investigate the difference in efficiency losses caused by the actual system that are due to not using portions of the data slots (when a CPDLC message occupied a portion of the slots); Investigating unconventional ideas such as the advantages of reducing voice traffic, and also the possibility of sharing channels of data and voice with a voice preemption capability such that to not allocate voice channels when not used (or to use quite times for data transmissions)

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