In-Band Transition of a Nationwide Air/Ground Radio System From an Analog to a Digital Architecture

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***Abstract*—The Next-Generation Air/Ground (A/G) Radio Communications System (NEXCOM) will provide a digital voice and data capability for air traffic control in United States airspace. The nationwide transition from today's all-voice analog system to NEXCOM will take several years. Since digital interference characteristics differ markedly from those of analog radios, most A/G radio circuits will need to change their operating frequencies when they are converted to NEXCOM, to avoid RF interference with neighboring circuits. The size and complexity of the system make it a challenging task to identify an incremental sequence of frequency changes that will enable a smooth, gradual, and cost-effective transition. In this paper, we present simulation results demonstrating the feasibility of a nondisruptive incremental transition to NEXCOM and identify specific measures for reducing the complexity of the transition and, thus, its overall cost.**

***Index Terms*—Aeronautical, air/ground, communications, digital, frequency assignment, interference, radio, spectrum, time-division multiple-access (TDMA), transition.**

I. INTRODUCTION

THE NATIONAL AIRSPACE SYSTEM (NAS) is critically dependent on the very high frequency (VHF) analog voice air/ground (A/G) radio system for air traffic control (ATC) communications and other air traffic services (ATS) throughout the United States [1]. The system operates in the 117.975–137.000 MHz band, which contains 760 carrier frequencies at 25-kHz intervals. Of the 760 frequencies, 509 were available for ATS in the year 2000, while up to 20 more were potentially available in the recently reallocated 136.000–136.475 MHz subband.

An ATS circuit comprises all the ground radios (GRs) that support communication on an assigned frequency between a given air-traffic controller and the aircraft being controlled or from an automated uplink-broadcast facility to its airborne users. The participating aircraft operate in a service volume (SV) whose horizontal footprint is either circular or polygonal. The SVs of today's ATS circuits, which number about 7000, are extremely diverse in their horizontal and vertical dimensions and highly nonuniform in their geographical distribution across the NAS.

The demand for new circuits is continually increasing, but the supply of frequencies is unlikely to grow much beyond 529 in the foreseeable future. It is becoming steadily more difficult for the Federal Aviation Administration (FAA) to assign frequencies to new A/G circuits while complying with all necessary rules for avoiding RF interference (RFI). The spectrum shortage has become a key constraint on the nationwide circuit capacity of the system [2]. Increasing the system's capacity is a primary objective of the planned transition to the Next-Generation Air/Ground Radio Communications System (NEXCOM).

The FAA is developing an architecture for NEXCOM in conjunction with the United States civil aviation community and the International Civil Aviation Organization (ICAO). NEXCOM will not only provide voice circuits, like the present system, but will also support data circuits as well.

The planned NEXCOM architecture is based upon the VHF Digital Link (VDL) Mode 3 (VDL3), described in [3]. VDL3 retains the present 25-kHz frequency spacing, but uses differential 8-ary phase-shift keying (D8PSK) modulation and a four-slot time-division multiple-access (TDMA) technique that allows up to four voice and/or data circuits to share a frequency by operating on separate slots in a single synchronized "bundle."

II. RFI AND THE TRANSITION TO NEXCOM

The change from analog to digital modulation will require new frequency-assignment criteria that are stricter in several ways than the rules used in today's system, to prevent RFI involving VDL3 circuits. The difficulties of an analog-to-digital transition—one aspect of which is documented in [4]—are magnified when (as in the NEXCOM transition) the newly converted digital circuits must coexist with the remaining analog circuits in a single frequency band for a prolonged period. This increases the potential for cochannel interference (CCI) and adjacent-channel interference (ACI) [5], [6] between the two classes of circuits. The following paragraphs present a preliminary set of criteria that have been proposed for use in NEXCOM planning efforts. The criteria are expected to evolve over time as data continue to accumulate from ongoing bench and flight tests of VDL3 radios. Any revisions to the criteria will be integrated into future NEXCOM analyses.

A. Intersite Interference

1) CCI: Under standard 4/3-earth atmospheric conditions [7], air-to-air CCI can propagate along unobstructed paths as long as 522 nmi between circuits that have 45 000-ft SV ceilings and are not in the same TDMA bundle. The potential existence

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of such long undesired signal paths severely limits frequency-reuse opportunities and exacerbates the spectrum shortage in the A/G radio band.

Cochannel protection ratios (CCPRs) have been defined or estimated for all four relevant undesired-to-desired pairs of radio types (analog-to-analog, VDL3-to-VDL3, analog-to-VDL3, and VDL3-to-analog). For analog-to-analog CCI, the FAA/ICAO experiential CCPR value of 14 dB [8] is used. Bench testing, performed in conjunction with subjective listening tests to ascertain thresholds of "unacceptable" interference, has yielded larger CCPR values, as cited in a prior Aeronautical Mobile Communications Panel (AMCP) study [9], [10], for the VDL3-related cases. These values are 20 dB for cases in which the desired signal is VDL3 and 30 dB when the undesired signal is VDL3 and the desired signal is analog. As a precautionary measure, we have also added a 6-dB margin to each VDL3-related CCPR, to allow for desired-signal fading, possible *negative* fading of the undesired signal, and variations in antenna gain functions as aircraft positions and orientations change.

2) ACI: For the analog-to-analog intersite-ACI case, we have used a time-tested FAA experiential rule whereby only the first adjacent channel (25 kHz away, carrier-to-carrier) need be protected, and then only when one circuit's GR or SV is within the other circuit's SV or less than 0.6 nmi outside it.

Our criteria for intersite-ACI cases involving VDL3 were based upon the AMCP study [9] and [10], which ascertained the distances at which a received undesired signal from a VDL3 transmitter using an FAA-approved spectrum mask would fall below a conservatively assumed −82-dBm desired-signal level by an amount equal to the relevant CCPR (20 or 30 dB, depending on whether the desired signal is VDL3 or analog). In the VDL3-to-VDL3 and analog-to-VDL3 cases, the criteria protect the second adjacent channel (50 kHz away) for very small values (less than 0.4 nmi) of undesired-signal path length, while the first adjacent channel is protected out to 1.28 nmi. The VDL3-to-analog case has the most stringent ACI criteria, with 5.09-nmi protection for the first adjacent channel and smaller distance values (1.28 nmi or less) for the second, third, and fourth adjacent channels (50, 75, and 100 kHz away, respectively).

B. Cosite Interference

It is currently assumed that the cosite criteria for VDL3 GRs that are "collocated" (which, in A/G radio frequency management, generally means not more than 1.0 nmi apart) and for mixed groups of collocated VDL3 and analog GRs, will be identical to those observed for collocated analog GRs in today's A/G radio system. Those criteria include a 500-kHz minimum frequency separation and avoidance of frequency combinations that could inflict second- or third-order intermodulation (IM) or harmonic interference upon collocated VHF or ultrahigh frequency (UHF) A/G radio receivers.

Commercial frequency modulation (FM) broadcast stations in the nearby 88–108-MHz band can operate at very high output powers and are sometimes close to A/G radio sites. VDL3 and GRs should continue to be protected wherever possible from two- and three-signal third-order IM products (IMPs) of FM broadcast signals. In this analysis, we have assessed such signals for significance on the basis of FM transmitter power and distance from the A/G radio site under consideration. Our IM criteria were based on an analysis that took into account the attenuation predicted for the signals by a smooth-earth propagation model, the out-of-band rejection they typically experience in a VHF GRs antenna and RF filter, and the characteristics of typical mixers in VHF A/G receivers. The resultant graduated IM criteria deem an FM transmitter a potential contributor to "significant" IMPs in VHF A/G radios if, for example, it operates above 100 MHz and radiates 1 kW at a distance of 4 nmi from an A/G radio site or 50 kW from 23 nmi away. When assessing FM signals below 100 MHz, we use higher power thresholds (e.g., 10 kW at 4 nmi for a signal near 90 MHz), because GR antennas and filters reject those lower-frequency signals more strongly than their counterparts above 100 MHz.

TABLE I
GUARD TIMES AND DELAY-RELATED DISTANCE LIMITATIONS FOR VDL3 BUNDLES

No. of Slots	Usable Guard Time (ms)	Delay-Limited Max. TDMA Distance (nmi)	Maximum Allowable G/A/G Distance (nmi)
3	7.524	609.0	1217.9
4	2.476	200.4	400.8

C. Interslot Interference

To protect the circuits within any VDL3 bundle against interslot message collisions arising from differential propagation delay exceeding the available guard time [11], they must meet the distance criteria in Table I. Each VDL3 circuit's SV must lie entirely within the *delay-limited maximum TDMA distance* (DLMTD) of each GR serving it. The sum of the ground/air (G/A) distance from the GR to any point in the SV and the A/G distance from that point to any other GR serving any other circuit in the same bundle, must never exceed the maximum allowable ground/air/ground (G/A/G) distance, which is equal to twice the DLMTD. This G/A/G rule is needed because the clock of each airborne radio (AR) is synchronized to the time-delayed signal arriving from the GR of the circuit in which it is participating, so that the G/A delay is added to the further delay that accumulates while the AR's own (undesired) signal travels to a "victim" GR in another circuit in the bundle.

III. SIMULATING THE TRANSITION

We have developed (in conjunction with our colleagues Dr. Snow and Dr. Monticone) an automated simulation tool for use as a spectrum-engineering "test bed" for NEXCOM. Fig. 1 presents an overview of this computer program's operation. The program analyzes characteristics of existing and/or future A/G circuits in a user-supplied environmental database, together with those of potential interferers lying outside the A/G radio bands. Depending on the options the user selects, the environment may contain analog radios using the baseline design, future radios using a postulated NEXCOM design,

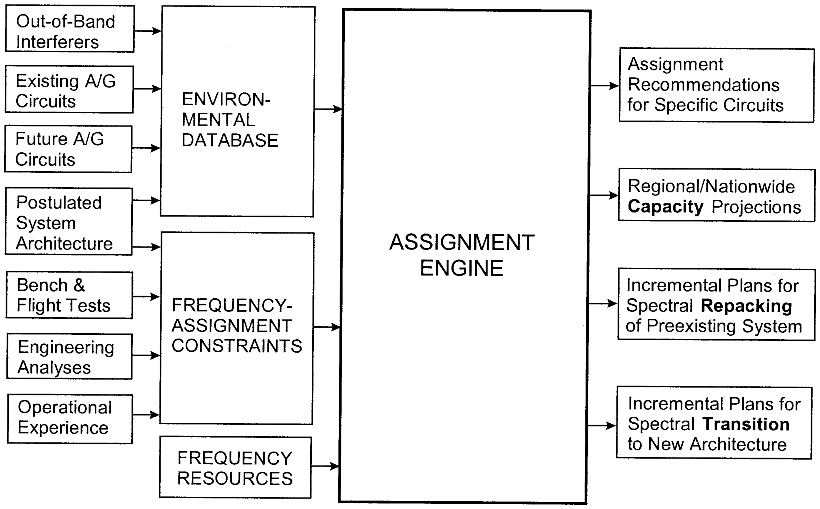


Fig. 1. Overview of automated simulation tool.

or a mixture of both kinds of radios (whose relative numbers gradually change when the program simulates an incremental transition to NEXCOM).

Using a predefined set of available "resource" frequencies, the program's assignment engine constructs or modifies a frequency plan for the A/G circuits in accordance with user-established assignment criteria. Automatically generating a nationwide frequency plan involving several thousand circuits requires that the program quickly and efficiently consider potential RFI problems involving tens of millions of circuit *pairs* and assign frequencies in a manner that avoids all such problems.

The resultant frequency plan is a sequential list of recommended frequency assignments or changes for some or all A/G circuits in the environment. Such plans can be used to assess the possibility of "liberating" particular blocks of spectrum by efficiently repacking the existing structure of assignments or (as in the simulations described in this paper) to identify a chronological sequence of assignments and reassignments that will allow a smooth transition to NEXCOM.

A. TDMA Simulation

When generating a frequency plan for a TDMA system, the program seeks and utilizes opportunities to combine circuits into TDMA bundles. Each bundle contains up to four circuits sharing a frequency but operating on separate time slots. The circuit using slot A is called the "host circuit" of the bundle. The bundle's other circuits are called "guest circuits" and use slots B, C, and D.

In VDL3, each TDMA bundle may be configured so that all of its circuits will share the GR(s) of the bundle's host circuit. The program models this by allowing (but not requiring) the user to stipulate that upon conversion to TDMA, every guest circuit will deactivate its own dedicated GR(s) and thereafter share its host's GR(s). Even when that stipulation is not made, the program always deactivates the nonbackup GRs of every guest circuit in which all such GRs, before conversion, were collocated with the host's GRs. Guest circuits of this kind are called "cosite guests." A bundle in which all the guests are cosite guests is called a "cosite bundle." The program's bundling algorithms favor the formation of cosite bundles wherever feasible, to reduce the eventual size of the nationwide NEXCOM ground infrastructure.

Fig. 2 illustrates the creation of a four-circuit TDMA bundle in a situation in which GRs are shared. In this example, each circuit covers an SV with a circular cross section and is served by a single GR before bundling. (Circuits with polygonal SVs and/or multiple GRs can also be bundled but have not been included in the example.) After conversion to VDL3, only one GR and one frequency remain in service. The host circuit, on time slot A, is still served from its original GR site, but with a new TDMA radio substituted for the original GR. The three guest circuits on slots B, C, and D share the host circuit's GR and frequency. Although the frequency of the host remains unchanged in this example, during a simulated nationwide transition the program typically alters many host frequencies to avoid potential RFI.

In any given TDMA simulation run, the user of the program can specify several constraints to control the bundling process. These include the following.

- Number (2–4) of time slots that are available for voice circuits in each bundle.
- Requirement (or prohibition) of intersite GR-sharing. This is GR-sharing by "intersite guest" circuits whose preconversion GRs are too far from those of their hosts to qualify them as cosite guests. Such sharing minimizes GR investment but requires potentially costly rerouting of land lines.
- Maximum number of nonbackup GRs that a circuit may contain before conversion, without being disqualified from later participation in a multicircuit bundle.
- DLMTD, which, as stated earlier, is used to avoid interslot interference.
- Loss-limited maximum TDMA distance (LLMTD). This is typically 160 nmi, but applies only if intersite GR-sharing is allowed. It limits the distance between any point in the SV of a guest "high-altitude" circuit (one whose maximum altitude is 30 000 ft or greater) and any GR that belongs to the host circuit. (Each *original* GR location associated with a guest *low*-altitude circuit—one

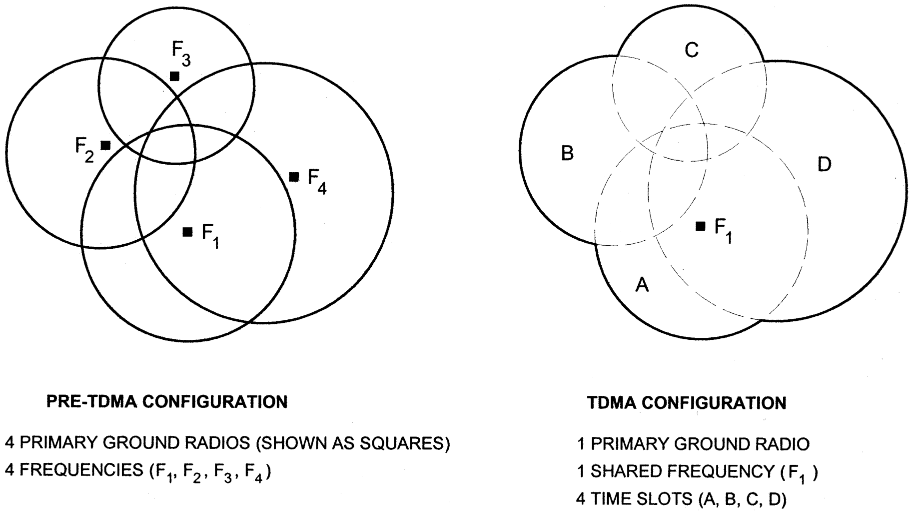


Fig. 2. Creating a four-circuit, GR-sharing TDMA bundle.

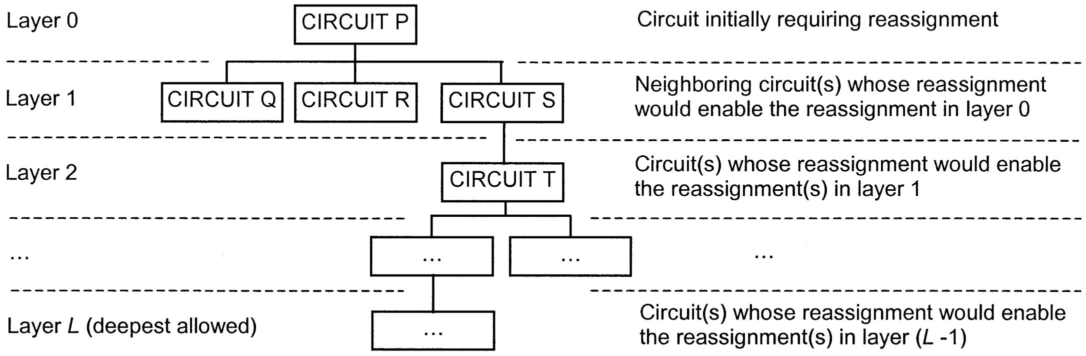


Fig. 3. Example of a neighbor-repacking reassignment tree.

whose ceiling is *below* 30 000 ft—must be within 5 nmi of each GR that belongs to the host circuit, to ensure full coverage of the guest circuit's relatively low-hanging SV "floor.")

Before putting any two circuits into the same bundle, the program's assignment engine verifies that they comply with all the above rules and also that they do not belong to separate TDMA-conversion subsets deemed unsuitable for mixing in a single TDMA bundle. For instance, the user may put circuits associated with different Air Route Traffic Control Centers (ARTCCs) into different subsets to avoid administrative complications that might result from interARTCC bundling.

B. Neighbor-Repacking

When the time comes to convert a particular circuit to VDL3, it may happen that *no* frequency can support the circuit's postconversion operation without violating one or more assignment rules, unless selective changes are made to neighboring frequency assignments beforehand, to create spectral room for the circuit about to be converted. The assignment engine has a *neighbor-repacking* capability that enables it to look one or more steps (or reassignment-search "layers") ahead in planning such changes. When no violation-free frequency is available for a particular circuit, the program may perform a preparatory repacking of neighboring circuits' frequency assignments in order to free up such a frequency. The resultant succession of circuit reassignments can be depicted as the multilayered *reassignment tree* of Fig. 3.

If the program initially cannot assign circuit P to a given frequency because of conflicts with the preexisting "blocking" assignments of neighboring circuits Q, R, and S, it can look for ways to reassign Q, R, and S to other frequencies to make room for a conflict-free assignment of P to the frequency in question. The program is also able, in situations where the blocking circuits Q, R, and/or S cannot be reassigned without causing a rule violation, to seek ways to break the logjam by changing some other preexisting assignment (of circuit T, say) that is blocking the reassignment of Q, R, or S. This process can continue until it reaches the deepest reassignment layer the program is allowed to probe.

The user can control the depth and breadth of the search by choosing values for certain key parameters at the outset of a simulation. Selecting proper values for these parameters is a tradeoff between computational speed and the thoroughness of the assignment search. Smaller values reduce the simulation time, but increase the risk of missing important assignment opportunities in the search. The most critical of these parameters are:

- L, the deepest reassignment layer;
- M, the maximum number of circuits in any single reassignment tree.

TABLE II
NOTIONAL EXAMPLE OF AN INCREMENTAL CONVERSION PLAN

Reassignment		Circuit [a]		Service Volume		Original Ground Radio Locations	Frequency/Slot Assignment [f]	
Tree	Layer	ID	Service Type	Radius (nmi) [d]	Ceiling (feet)		Old	New
1	0	1213[b]	High En Route	75	45 000	River City, IL	126.950	136.350A
2	0	8356[b]	Low En Route	60	30 000	Montezuma, MO [e]	118.025	136.350B
3	0	416[b]	High En Route	83	41 000	Bayou City, LA Crockett, AR	121.375	132.750A
4	1	5286[c]	Ground Control	2	100	Alexandria, IL	128.400	119.500
	0	4135[b]	High En Route	65	45 000	Burlington, IL	134.550	128.450A
5	4	2640[c]	Ground Control	3	100	Henderson, MI	134.475	134.450
	3	938[c]	Local Control	30	15 000	Elm Grove, MI	127.500	134.500
	2	3989[c]	Clearance Delivery	3	100	Triangle, IN	132.225	127.500
	2	6114[c]	Low En Route	95	23 000	Littlefield, OH Tallgrass, IN	132.250	118.550
	1	4218[c]	Approach Control	22	23 000	Grimsley, IN	120.375	132.250
	0	2334[b]	High En Route	55	45 000	Buchanan, IN	119.000	120.400A
6	0	2212[b]	High En Route	60	41 000	Budapest, KY [e]	124.525	136.350C
7	0	7501[b]	Low En Route	65	30 000	Southton, IN [e]	121.400	136.350D

a. All circuits and associated data shown in this notional example are fictitious, for illustrative purposes only.
b. "Convertible" circuit, selected by user for conversion to VDL3.
c. Neighboring circuit selected by program for repacking, without conversion.
d. For en route circuits, whose SVs have polygonal boundaries, radii of circumscribing circles are shown.
e. "Guest" GR location to be deactivated upon circuit conversion, since intersite GR-sharing is in effect.
f. VDL3 assignments include time slot (A, B, C, or D). Analog assignments do not have time slots.

All neighbor-repacking simulations discussed in this paper used values of $L = 4$ and $M = 20$. (In practice, however, the vast majority of reassignment trees are much shallower and smaller than those limits might seem to imply.)

The program's neighbor-repacking algorithms operate in a way that guarantees the sequential executability of the resultant frequency plan. If all the prescribed circuit conversions and preparatory enabling frequency changes (if any) to neighboring circuits are executed in the sequence specified in the plan, then none of those actions will cause rule violations involving any other frequency assignments existing in the environment at the moment the action is carried out. As much or as little time as desired may elapse between the execution of consecutive actions. (However, when the frequency of a multi-GR circuit or a previously formed TDMA bundle is changed, the circuit's or bundle's GRs must all be retuned simultaneously to the new frequency, to avoid service interruptions.)

C. Notional Example

The process of developing an incremental analog-to-digital conversion plan using neighbor-repacking is illustrated in the miniature hypothetical example of Table II. The user of the simulation program has chosen seven en route communications circuits to be converted to VDL3, specified the order in which those conversions are to be performed, and stipulated that intersite GR-sharing is allowed. The program does the rest. Its job is to find a postconversion frequency and time slot for each of the seven "convertible" circuits and to identify any necessary enabling reassignments of neighboring circuits. For each convertible circuit, the program establishes a reassignment tree. Each tree appears in the table as a succession of circuit reassignments, the last of which is a layer 0 reassignment for the circuit being converted. The prior reassignments (if any) within the tree all occur at deeper layers. Each such prior reassignment is performed for the sole purpose of creating necessary spectral room for the subsequent reassignment at the next higher layer.

The first three conversions shown in this example require no neighbor-repacking and, hence, no enabling reassignments, so trees 1–3 in Table II each consist only of a single reassignment at layer 0. Circuit 1213 becomes the host and, thus, the occupant of slot A in a new bundle at 136.350 MHz. Circuit 8356 is given a guest slot (B) in the same bundle and so, by the rules of intersite GR-sharing, its original (Montezuma) GR is deactivated and the circuit thereafter shares the River City GR of its host. Circuit 416, a two-GR circuit, is so far from the first two circuits that DLMTD and LLMTD constraints prevent it from joining the previously established bundle; instead, it becomes the host circuit of a new bundle at 132.750 MHz.

The fourth conversion (that of circuit 4135, at layer 0 of tree 4 in Table II) is the first in this example to require neighbor-repacking. Prevented by distance from adding circuit 4135 to either of the two VDL3 bundles previously begun and unable to find an interference-free frequency for that circuit's use as the host of a new bundle, the program creates an opening for it at 128.450 MHz by retuning neighboring circuit 5286 from 128.400 to 119.500 MHz to eliminate a potential second-ACI problem. Circuit 4135 is then assigned the host slot in a new bundle at the newly "cleared" frequency.

To accomplish the fifth conversion, that of circuit 2334, the program has to make five enabling frequency changes to neighboring circuits. Unable to insert 2334 into any previously formed bundle, the program seeks to make it the host of a new bundle at 120.400 MHz. This requires a previous layer 1 retuning of neighboring circuit 4218 to 132.250 MHz, to defuse a first-ACI problem. But to enable retuning of 4218, two prior layer 2 reassignments are needed: circuit 6114 must switch from 132.250 to 118.550 MHz to avoid CCI that would otherwise occur, while 3989 must change from 132.225 to 127.500 MHz to escape first ACI. To enable circuit 3989's frequency change to occur without CCI, a previous layer 1–4 switch of circuit 938 from 127.500 to 134.500 MHz is needed. And a prerequisite for the circuit 938 retuning is the layer 4 reassignment of circuit 2640 from 134.475 to 134.450 MHz, to prevent first ACI. Carried out either simultaneously or in the sequential order shown in the table, this series of layer 1–4 reassignments enables the conversion of circuit 2334 to be performed with no rule violations at any step.

The sixth and seventh conversions, those of circuits 2212 and 7501, are performed without the need for any prior neighbor-repacking. They are given guest slots C and D in the previously established 136.350-MHz bundle.

IV. NATIONWIDE TRANSITION SIMULATIONS

Current plans call for the VDL3 transition to commence with the conversion of en route circuits operating mainly in high-altitude airspace. To help plan this initial segment of the transition, the automated tool has been used in conjunction with an actual database of North American frequency assignments to simulate the nationwide transition of high-altitude VHF A/G radio circuits to VDL3. The objectives were as follows.

- Demonstrate that an incremental high-altitude transition is feasible within the available spectrum.
- Quantify the impacts of alternative sets of system parameters in various realistic scenarios and to guide future refinements to NEXCOM design and transition plans.
- Identify, for each scenario of major interest, a sequence of frequency changes achieving a spectrally efficient transition while avoiding unnecessary complexity of implementation.
- Reveal environmental obstacles to VDL3 conversion of specific circuits and indicate corrective measures.

A. Assumptions

A benchmark simulation was performed using the following standard set of assumptions.

- Several years of future growth in the NAS circuit population *before* the first of 497 high-altitude circuits (only 471 of which exist today) is converted.
- No use of new filters or new antenna sites to mitigate potential IM problems.
- Availability to VDL3 of 529 frequencies in the 118.000–136.475 MHz range, including all 20 from 136.000 to 136.475 MHz.
- All slots available for voice use if needed.
- *No* intersite GR-sharing.
- Neighbor-repacking with $L = 4$ and $M = 20$.

Several variations on the benchmark simulation were also performed to test the effects of changes in the above assumptions.

B. Metrics

We used the following metrics to evaluate the results of our simulations.

Success Rate: The percentage of candidate circuits successfully converted to VDL3. (Any circuits *not* converted remain analog and stay on their old frequencies unless neighbor-repacked later. The unconverted circuits act as embedded analog "pockets" around which the program constructs an otherwise all-digital high-altitude ATS frequency plan. The program logic ensures that rule violations involving such unconverted circuits never occur at any point in the transition.)

Bundling Factor: The average number of converted circuits per bundle. This measure of slot utilization has a maximum possible value of 4.00. (Unused slots, of course, are still available to support future system growth, eventual conversion of low-altitude circuits, and data service.)

Complexity: The average total number of GRs (in the converting circuit and its repacked neighbors) that must undergo frequency changes to enable conversion of a single circuit to VDL3. Such changes involve substantial administrative and site-engineering costs. For example, in a transition involving 497 high-altitude circuits and averaging 2.5-GR frequency changes per circuit conversion, there would be 1243 such changes in all. Each such change is labor intensive, often requiring travel to a remote site on a mountaintop or in some other relatively inaccessible place. Once at the site, the technician typically must retune not just the transmitter and receiver of the listed GR, but also a standby transmitter and receiver not explicitly listed in the United States assignment data and often cavity filters as well. This has a major impact on the overall cost of the transition and makes it desirable to keep the complexity as low as possible.

C. Findings

Table III summarizes the key results of our nationwide simulations. Each simulation, other than the benchmark, involved varying a single condition from the value assumed for it in the benchmark simulation. Since a few circuits in Alaska have SVs too large for VDL3 operation without self-inflicted interslot interference, 100% success was not observed in this series of simulations. However, splitting those oversized circuits into smaller ones would allow a 100% success rate to be achieved. Our findings are listed below.

- In every simulation about two slots were filled in the average bundle, with two slots typically left over for future use.
- If the transition could be carried out immediately, it would be less complex than a "delayed" one occurring after substantial future growth of the circuit population; this suggests a cost advantage to an early start.
- IM mitigation, by filters or resiting, at some congested ground locations will be essential for achieving a high success rate for circuit conversion.

TABLE III
NATIONWIDE HIGH-ALTITUDE SIMULATION RESULTS

Simulation	Success Rate*	Bundling Factor	Complexity
Benchmark (delayed transition, no IM mitigation, 529 frequencies, neighbor-repacking)	91.8%	1.95	2.2
"Immediate" transition of only the 471 *existing* high-altitude circuits	92.6%	2.03	**1.9**
IM mitigation by filters and/or resiting	**97.4%**	2.06	2.0
4 frequencies "lost" in 136–136.475 MHz range	90.5%	1.83	**2.8**
No neighbor-repacking	**65.2%**	2.01	1.6

* **Note:** A **100%** success rate can be achieved by subdividing a relatively small number of oversized circuits, in conjunction with IM mitigation at congested sites throughout the NAS.

- The denial to ATS of even 4 of the 20 frequencies in the 136.000–136.475 MHz range would significantly complicate the transition; as much of that "new" subband as possible should be set aside for ATS use during and after the transition.
- Neighbor-repacking will be essential to the transition, since *not* using it would greatly reduce the success rate.

V. CONCLUSION

The use of an automated simulation tool for NEXCOM spectrum-transition planning enables us to ascertain appropriate values for several interference-related system parameters and to identify a smooth transition path for the system. Results obtained with the tool demonstrate that a nondisruptive in-band high-altitude transition to a digital A/G communications system is feasible, but will require widespread neighbor-repacking. They also show that starting the transition as soon as possible and giving NEXCOM circuits access to as many frequencies as possible in the recently reallocated 136.000–136.475 MHz subband will reduce the complexity of the transition and, thus, tend to minimize its overall cost.

REFERENCES

[1] M. S. Nolan, *Fundamentals of Air Traffic Control*, 3rd ed. Pacific Grove, CA: Brooks/Cole, 1999, pp. 168–172.

[2] D. Phillips, "Radio crunch threatens air travel," in *The Washington Post* Washington, DC, 13 Nov. 2000, p. A1.

[3] "Signal-in-Space Minimum Aviation System Performance Standards (MASPS) for Advanced VHF Digital Data Communications Including Compatibility with Digital Voice Techniques," RTCA Special Committee 172, Washington, DC, RTCA Paper DO-224A, 2000.

[4] M. Benveniste, "Analog-to-digital transition: Selecting the optimal cellular radio mix," *IEEE Trans. Veh. Technol.*, vol. 48, pp. 1414–1420, Sept. 1999.

[5] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 1996.

[6] M. D. Yacoub, "Cell design principles," in *The Mobile Communications Handbook*, J. D. Gibson, Ed. Boca Raton, FL: CRC, 1996, pp. 328–331.

[7] "Electromagnetic wave propagation," in *Reference Data for Radio Engineers*, 6th ed. Indianapolis, IN: Sams, 1975, ch. 28.

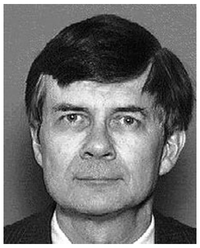
[8] "Attachment A: Considerations affecting the deployment of VHF communications frequencies," in *Aeronautical Telecommunications: Annex 10 to the Convention on International Civil Aviation, Volume V: Aeronautical Radio Frequency Spectrum Utilization*. Montreal, QC, Canada: ICAO, 1996.

[9] "Attachment D to Working Group B Report to AMCP/6," AMCP, AMCP-WG/B4, 1999.

[10] "Report on Agenda Item 3: Review of Current VDL System (RF) SARPs," AMCP, Montreal, QC, Canada, AMCP/6–WP/30, 1999.

[11] M. S. Roden, "Multiplexing," in *The Communications Handbook*, J. D. Gibson, Ed. Boca Raton, FL: CRC, 1997, ch. 7.

[12] F. Box and P. Long, "Spectrum planning for the transition to a digital air/ground radio system for air traffic control," in Proc. 19th Digital Avionics Systems Conference (DASC), Philadelphia, PA, Oct. 7–13, 2000.



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