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Automatic Dependent Surveillance Rebroadcast Technology Analysis

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May 2022

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Automatic Dependent Surveillance Rebroadcast Technology Analysis

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Summary

This paper discusses simulation results of modeling of communications success in a vehicular ad hoc network (VANET), that is, the spontaneous creation of a wireless communication network in the context of aircraft or drones. The technology of Automatic Dependent Surveillance Rebroadcast (ADS–R) combines the existing technology used with manned aerial vehicles (AVs) in the National Airspace System (NAS) with a "physical layer" of digital communications technology called flooding. Flooding allows the retransmission of the existing Automatic Dependent Surveillance Broadcast (ADS–B) AV flight information to "in the area" adjacent AVs, enabling communication to all AVs in the designated area with just a few retransmissions.

The theoretical basis of the modeling is the 2016 white paper by Saeed et al., "Analysis of Probabilistic Flooding in VANETs for Optimal Rebroadcast Probabilities." Modeling work was performed to independently verify the cases presented in that work using NASA-developed MATLAB® (The MathWorks, Inc.) models. The results presented here compare favorably with those of the white paper. Many different conditions are modeled, including various aircraft densities, mixtures of incoming and outgoing craft, and one-lane versus multiple-lane scenarios. Link-budgeted calculations are also investigated, including free space, air, and rain.

1.0 Introduction

In anticipation of increased air traffic in the National Airspace System (NAS) over the next 10 to 30 years, many technologies are being investigated for enhancing air traffic control (ATC). This increase in air traffic includes an increase in manned and unmanned aerial vehicles (AVs) of all sizes, at all altitudes, and of varying average speeds.

The technology of Automatic Dependent Surveillance Rebroadcast (ADS–R) combines the existing technology used with manned AVs in the NAS with a "physical layer" of digital communications technology called flooding. Flooding allows the retransmission of the existing Automatic Dependent Surveillance Broadcast (ADS–B) AV flight information to "in the area" adjacent AVs, enabling communication to all AVs in the designated area with just a few retransmissions.

This flooding technology is based on a white paper by Saeed et al. (Ref. 1) in which simulation and closed-form results were limited; thus, the interest in expounding on those results. This investigation adds additional capability to the existing ATC technology, ADS–B. ADS–R accommodates more traffic in the

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[*]Currently with L3Harris Technologies.

NAS and will allow for quick and more complete information on AVs in all levels (air to ground (A2G)) of airspace for all types of AVs, manned and unmanned, from large AVs to small drones (small unmanned aircraft systems). Thus, various scenarios need to be investigated to understand and quantify the required link budget power and network communication and throughput.

ADS–R technology is based on the speed adaptive probabilistic flooding (SAPF) algorithm outlined in Reference 2 and implemented in Reference 1. The SAPF algorithm initiates a message with a probability p that it will reach its adjacent vehicles (and a probability $1 - p$ that it will not), and ultimately the probability that the message will be received by all vehicles.

Symbols and acronyms are defined in Appendix A, Nomenclature. Additional terms are defined in Appendix B, Quantity Definitions.

2.0 Review of One-Lane Example From White Paper

It is desired to model the scenarios discussed in Reference 1. The first scenario in the white paper is presented here. Figure 1 (from Ref. 1, figure 1; used with permission) depicts the simplest one-lane example, showing the vehicles in a one-lane Bernoulli random graph SAPF. There are four nodes (n = 4) (vehicles to be reached) and two adjacent vehicles (K = 2) (vehicles within transmission range of the originating vehicle). The probability tree diagrams shown in Figure 2 and Figure 3 (from Ref. 1, figures 2 and 3, respectively; used with permission) depict results of the one-lane example (n = 4, K = 2) from the white paper.

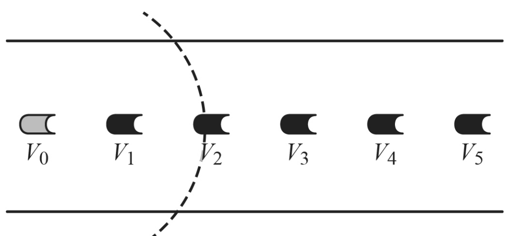

Figure 1.—One-lane scenario. Vehicle, V. Adapted from Reference 1 (figure 1); used with permission.

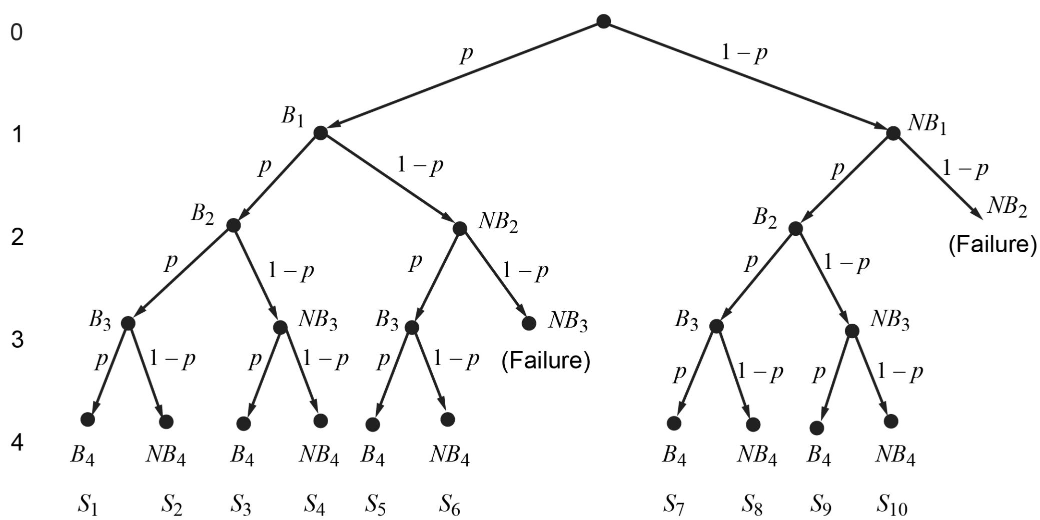

Figure 2.—Probability tree diagram for n = 4. Adapted from Reference 1 (figure 2); used with permission. Broadcast probability, p; probability not broadcast, $1 - p$; broadcast, B; not broadcast, NB; possible outcome, S_n.

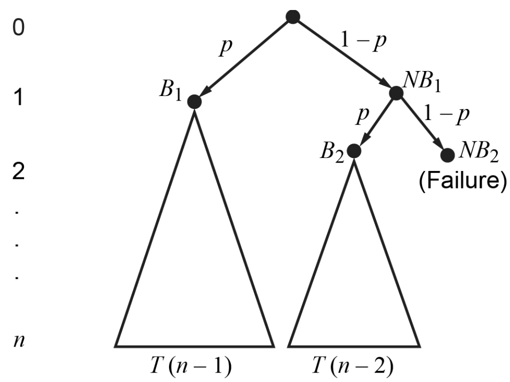

Figure 3.—Probability tree diagram for case of two vehicles in transmission range. Adapted from Reference 1 (figure 3); used with permission. Broadcast probability, p; probability not broadcast, $1 - p$; broadcast, B; not broadcast, NB; subtree, $T(n - i)$; number of nodes, n.

2.1 ADS–R MATLAB® Simulation Approach

It is desired to independently validate the models from the white paper (Ref. 1). The tool used for all simulations is MATLAB® (The MathWorks, Inc.). The approach for the MATLAB® simulations is as follows:

1. Validate algorithms and figures from the white paper (Ref. 1) using a static simulation of the AVs.
2. Code and implement an extended static ADS–R simulation, where extended analysis is used to extrapolate parameters and analyze them for scenarios that were not presented in the white paper.
3. Code and implement a dynamic ADS–R simulation for both lower altitude and slower velocity drones and for higher altitude and faster flying general aircraft.

The reason MATLAB® was selected for this project is to leverage a previous NASA project concerning ADS–B technology capacity simulations where the code had been written in MATLAB® (and has some already-coded *cmex* code, i.e., MATLAB® modules compiled into machine code for faster execution). The MATLAB® ADS–B simulation was reviewed for this project and was then optimized to accommodate all three approaches itemized above.

Broadly, the recoded MATLAB® ADS–R simulation (also known as the flooding simulation) utilizes parameter files in text format that capture simulation inputs. These are inputted into the MATLAB® code *AirplaneInputInfo_TEST.txt* within the *inputTextFiles* directory. These parameters include number of AVs, AV type, what percentage are incoming or outgoing, and so forth. The simulation's airspace is normalized such that one airport is centered at the origin [0,0,0]. The AVs are placed within the 500-nmi airspace according to the input files' parameters, and the simulation calculates real-time Monte Carlo values for an epoch of 1 s. The static simulation runs for 1 s and is used to implement approaches 1 and 2. The dynamic simulation runs for x minutes to understand the dynamics of AV velocities and the network congestion.

The simulation incorporates software hooks that will allow for air-to-air (A2A) and air-to-ground (A2G) transceiver communications analysis, including link budget calculations. No link budget calculations have been done within the simulation yet, as the flooding algorithm deals only with transceiver probabilities of closing the loop. The MATLAB® code also has output cartesian plotting that is used for debugging and visually capturing ADS–R scenarios for documentation and validation of simulation.

Table 1 shows the hierarchy of the MATLAB® ADS–R source files. The source files are described in Table 2.

TABLE 1.—MATLAB® ADS–R MODEL SOURCE FILE HIERARCHY

First tier	Second tier	Third tier
ADSRsim_main.m	*AV_Init_ADSR*	*radarRegionDetailed.m*
	LinkBudgetInit_ADSR.m	
	LinkBudgetInitGtoA.m	
	LinkBudget_GtoA.m	
	NewAVsCreated.m	*antennaRangeArray_c.c*
	Avupdate.m	*radarRegionDetailed*
	CalculateReceivedPower_ALL.m	*AVRadarRangeCheck_ALL_c.c*
		CalculateReceivedPower_100NM_c.c
		ADS_B_Radar_HeadOnDistance.m
	DEBUG_plot_most_intersect.m	
	DEBUG_Ploting_ComWindow_Output.m	
	DEBUG_Ploting_ComWindow_Output.m	
	DEBUG_ComWindow_LinkBudget.m	

TABLE 2.—MATLAB® ADS–R MODEL SOURCE FILE DESCRIPTIONS

File name	Description
ADSRsim_main.m	This is the main function to run simulation. Includes hooks to incorporate co-channel interference in the future.
AV_Init_ADSR.m	Sets up the input text file information from the file called *AirplaneInputFile_TEST.text*. This file sets up the major structure called *Avstruct*, which contains all initial data such as (1) incoming AV data across 4 radius-defined concentric circles; (2) outgoing AV data across radius-defined concentric circles 0 to 2, 2 to 5, 5 to 20, 20 to 100, and 100 to 500 nmi (original circles); (3) link budget parameters for ADS–B types and signal types per AV; and (4) the different ADS–B AV types per concentric circle range.
radarRegionDetailed.m	Creates the (approx.) 360° forward-looking ADS–B radar range detection for ADS–B parameters, such as ADS–B power/type, that give the head-on maximum perimeter related to airspeed.
LinkBudgetInit_ADSR.m	This is the air-to-air (A2A) link budget initialization file between AV communication in the NAS (not between ADS–B ground radar and AV communication; that is the air-to-ground (A2G) function).
LinkBudgetInitGtoA.m	Initialization file for computing the link budget between the radar and the AV receivers.
LinkBudget_GtoA.m	Computes the link budget between the radar and the AV receivers.
NewAVsCreated.m	Computes and sets latitude/longitude and other parameters for each AV.
antennaRangeArray_cc	This function determines perimeter per time increment and velocity. Velocity is hard coded and needs to be changed to be a parameter and thus more flexible for future simulation. Largest perimeter values are fixed and calculated as a function of velocity in a Microsoft® Excel workbook. The outputs of latitude and longitude are correct, but latitude is east to west (which is incorrect) while longitude is north and south (both should eventually be reversed). This module is compiled into *cmex* for faster execution.

TABLE 2.—Concluded.

File name	Description
Avupdate.m	This function iterates the *Avstruct* structure, updating the AV distance from the airport or the 500 nmi outer limit.
radarRegionDetailed.m	Updates radar region per AV.
CalculateReceivedPower_ALL.m	For A2A link budget calculations; to get the receiver in E_bN_o and gather statistics concerning performance of AVs.
AVRadarRangeCheck_ALL_c.c	This module determines if other AVs are within a particular AV's radar perimeter range, which is calculated using the AV's latitude and longitude. Compiled into *cmex* for faster execution.
CalculateReceivedPower_100NM_c.c	Rotates through all AVs that have other AVs in their respective ADS–B radar range and calculates the Multipath dB at receiver, and Multipath Delay if needed for future calculations.
ADS_B_Radar_HeadOnDistance.m	This function checks to see if concentric circle edges have been flown over to update minimum distances that are calculated via velocity values to be more flexible.
DEBUG_plot_most_intersect.m	Debug Radar Plot Files—Must be included to produce radar plots but makes simulation very slow.
DEBUG_ploting_ComWindow_Output.m	
DEBUG_ComWindow_LinkBudget.m	

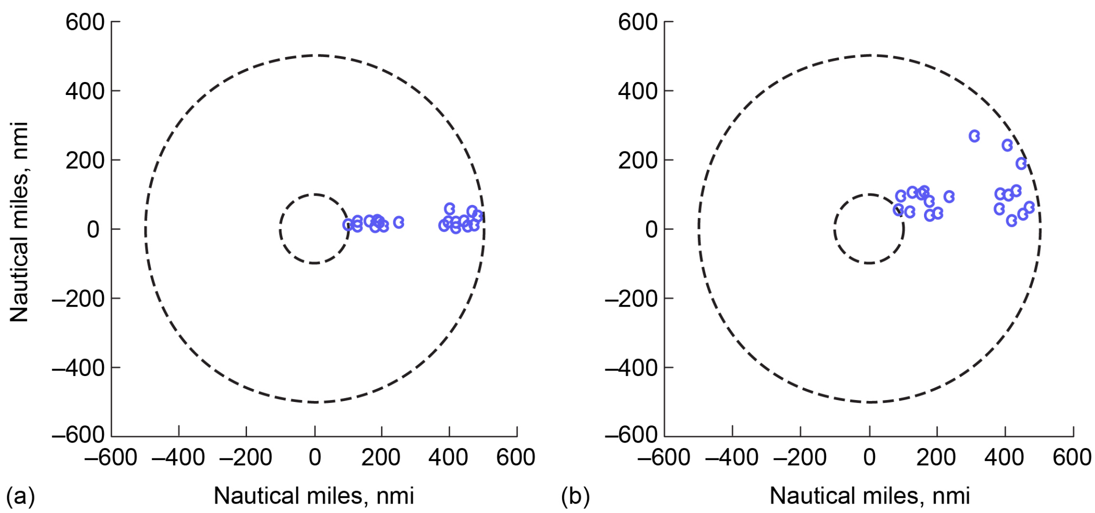

Figure 4.—Pie analysis,19 incoming AVs. (a) One-lane scenario. (b) Ten-lane scenario.

2.2 ADS–R Simulation Description

The normalized airspace for the ADS–R simulation is a circular topography where the center is the airport. The radial maximum distance is 500 nmi. Because the airspace is circular, we have renamed our ADS–R simulation a "pie analysis" to fit the various lane scenarios used in Reference 1.

Figure 4 depicts simulation results for two scenarios. Figure 4(a) is a one-lane scenario, and Figure 4(b) depicts a ten-lane scenario. The width of the lane is programmable in the simulation.

The simulation allows for incoming AVs (in blue) and outgoing AVs (in red), as shown in Figure 5. The circular boundaries for each AV are shown in each of the radar plots, but it is important to note that this is the Fresnel radar range, where the AVs are assumed to be flying at a higher speed. This still is good enough for implementation of the flooding algorithm technology, because the *K* definition is for the adjacent *K* to be in one direction.

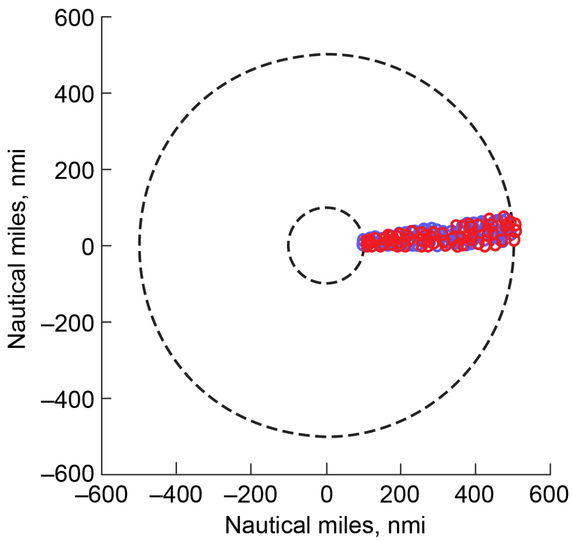

Figure 5.—Pie analysis, various lane configurations; radar perimeter range 100 to 500 nmi; 100 incoming AVs (blue); 92 outgoing AVs (red).

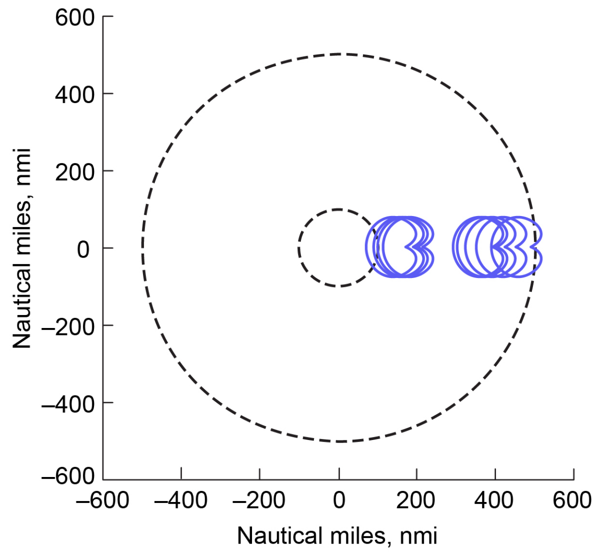

Figure 6.—One-lane example, 10 incoming AVs.

The intent here is not to fully show, step by step, how the simulation was validated, but to show the approach. A simple one-lane scenario of 10 incoming AVs was used. As seen in Figure 6, they are set up as a one-lane scenario. From there, communication of which AVs contacted which other AVs was used to determine when all of the AVs were contacted.

There is an array that holds all of the intersection data among all AVs within the simulation's scenario. Table 3 shows how the flooding logic works using this array.

All 10 AVs are rotated through separately, and the following logic is followed, starting with AV 1:

- AV 1 itself intersects 7 out of 10 AVs, as shown in the first row of Table 4.
- The algorithm then rotates through the other seven AVs and determines which AVs each of them intersects.
- In this case, by the time AVs 2, 3, and 5 have been iterated through, all AVs have been contacted with the initial message that AV 1 sent.
- Continuing with the remaining AVs, the additional intersections are ignored by the algorithm.

Table 4 illustrates visually how the logic of the flooding algorithm determines when communication to all AVs has been achieved.

The ADR–R simulation utilizes arrays of objects for each AV. It is important to note that as more AVs are added, this array gets very large, and processing time is greatly increased. As will be shown in a subsequent section, optimization methods were used to limit the number of AVs but with the ability to obtain higher densities along with larger *K* values.

TABLE 3.—INTERSECTION MATRIX

A[a] \ R[b]	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	1	0	1	0	0	1
2	0	0	0	1	0	1	0	0	1	0
3	1	0	0	0	1	0	1	0	0	1
4	0	0	0	0	0	0	0	0	0	0
5	1	0	1	0	0	0	1	0	0	1
6	0	1	0	1	0	0	0	0	0	0
7	1	0	0	0	1	0	0	0	0	1
8	0	1	0	1	0	1	0	0	1	0
9	0	1	0	1	0	1	0	1	0	0
10	1	0	0	0	1	0	1	0	0	0

[a]Originating AV.
[b]Retransmitting AV.

TABLE 4.—CONNECTIONS MATRIX

A[a] \ R[b]	1	2	3	4	5	6	7	8	9	10	Made connections to other AVs	New AV connection	Connections for each AV	Comments
1	0	1	1	0	1	0	1	1	1	1	2,3,5,7,8,9,10			
2	0	0	0	1	0	1	0	1	1	0	4,6,8,9	4,6	2,3,4,5,6,7,8,9,10	
3	1	0	0	0	1	0	1	1	1	1	6	1	1,2,3,4,5,6,7,8,9,10	
4	0	0	0	0	0	1	1	1	1	0	1,2,3,7,8,9,10			
5	1	1	1	0	0	0	1	1	1	1		2	1,2,3,5,7,8,9,10	Completed
6	0	1	0	1	0	0	0	1	1	0	1,2,3,5,6,8,9,10			
7	1	1	1	0	1	1	0	1	1	1	2,4,6,9	6	1,2,3,5,6,7,8,9,10	
8	0	1	0	1	0	1	0	0	1	0		4	1,2,3,4,5,6,7,8,9,10	
9	0	1	0	1	0	1	0	1	0	0				All AVs contacted by this point; additional intersections are ignored
10	1	1	1	0	1	0	1	1	1	0				

[a]Originating AV.
[b]Retransmitting AV.

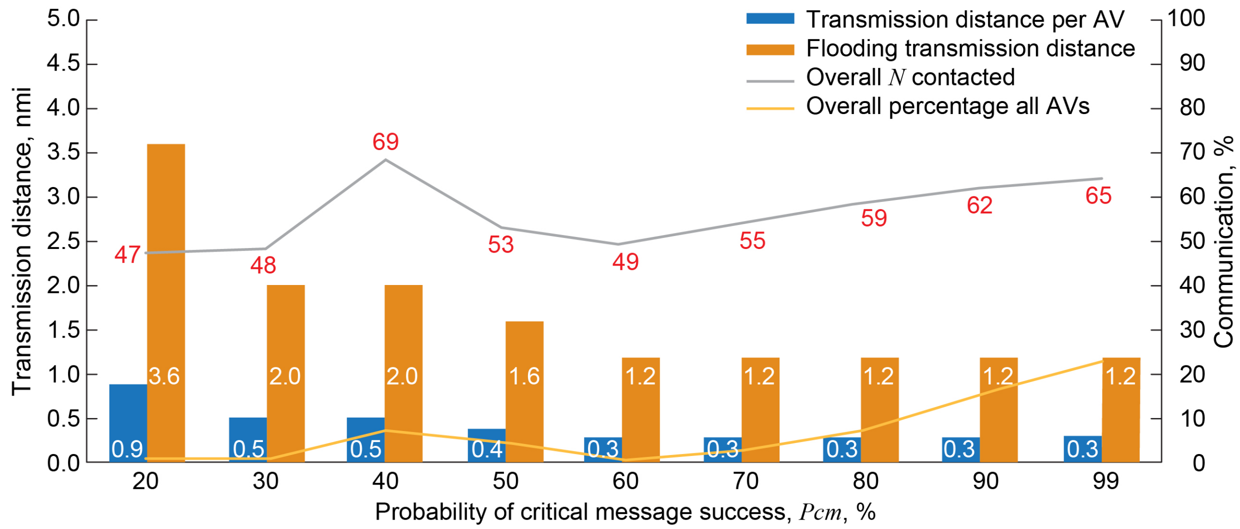

Figure 7.—Communication success; density 10 AVs/nmi^2, one-lane, 20 AVs, K = 4.

The analysis plot in Figure 7 illustrates transmission distances (d_t, nmi) for a scenario where all AVs have been contacted. The *Pcm* percentage is the probability of communication success, further described in the following list of simulation outputs:

- *Pcm* (percent)—Value identifying the optimized amount of critical message communication between transmitter and receiver within *Transmission Distance Per AV* distance of transmitter. Any communication above the *Pcm* will add unnecessary messaging between transceivers, thus overflooding the network.
- *Transmission Distance Per AV* (nmi).—The link-budget-determined distance that a transmitter has to send the signal.
- *Flooding Transmission Distance* (nmi).—The flooding effective transmission distance due to the *K* parameter (number of adjacent vehicles); for example, if the link budget transmission distance is 1 nmi for a transmitter, the flooding transmission distance (d_f) is K*1.0 nmi—in effect, allowing communication to additional linear and forward-looking adjacent AVs.
- *Overall N Contacted* (percent).—Percentage of AVs in a given area that have been contacted. This does not mean that all AVs have had the same message communicated to them yet; that occurs when the next parameter, *AVs Communicating to All AVs*, is at least > 0 percent.
- *AVs Communicating to All AVs* (percent).—Percentage of AVs in a given area that have fully communicated to all AVs within the area; for example, if there are 100 AVs in the entire area of interest and the value for this parameter is 1 percent, this means 1 AV of the 100 AVs currently flying in the area is communicating its message to all AVs in the area as a result of the flooding algorithm.

2.3 ADS–B Simulation Data Format

The simulation incorporates a total of 112 information bits per AV, which includes downlink (DL) format, capability, International Civil Aviation Organization (ICAO) AV address, type code, AV data (56 bits), and forward error correction (FEC) parity. The total radiofrequency (RF) BW is ~1 MHz. Approximately 3,800 time-division multiple access (TDMA) slots, thus 3,800 AVs, can communicate every second to each receiver; but again, that is with 58 bits of information for one AV.

3.0 Task 1 (February to May 2020): Basic ADS–R Flooding Scenarios

Reference 1's technical flooding algorithm is called speed adaptive probabilistic flooding (SAPF). Briefly put, SAPF initiates a message (like the ADS–B autonomous message of an AV's position), and with a probability of *p*, it will be received by its receiver neighbor. Using this approach creates what is commonly known as a Bernoulli random graph (Ref. 1).

The parameters used for the MATLAB® simulation to attempt to validate the results from Reference 1 are as follows:

- *n* is number of AVs.
- *K* is number of adjacent AVs to contact where each AV's maximum distance from others, or maximum spacing, is d_{ms}.
- d_{ml} is the ADS–R transmitter's maximum distance due to link budget allotted power.
- *p* is the probability that the message will make it through to the adjacent receiver.
- Density of AVs includes *n* within calculation; for this simulation, the density has three different topographies: horizontal–rectangular (*horiz–rect*), vertical–rectangular (*vert–rect*), and square–rectangular (*square–rect*). If considering only one lane, then the density only applies in one dimension, and thus if $n = 10$ AVs and lane = 1, and this is normalized to 1 km, then there are 10 AVs/km^2 for the lane = 1 case. This is where the ADS–R simulation will allow for extrapolation of Reference 1's results.
- Number of lanes is used in Reference 1, but when extrapolated to Reference 1's results, only density is considered.

Figure 8 recreates the first plot from Reference 1, which implements a Bayesian closed-form approach where just *n* and *K* are the inputs. The MATLAB® code's output (shown in Figure 9) matches the white paper's plot (Figure 8) correctly. *Pcm* is the critical message probability, defined as the most optimal probability of the transceiver sending the signal out without adding additional messaging to the nearby network traversing these messages between AVs. The topic of critical value message is initially mentioned in a paper by Krishnamachari, Wicker, and Bejar (Ref. 3). Reference 1 found that as *K* neighbors increase, the *Pcm* of reaching all its nodes diminishes as *p* increases.

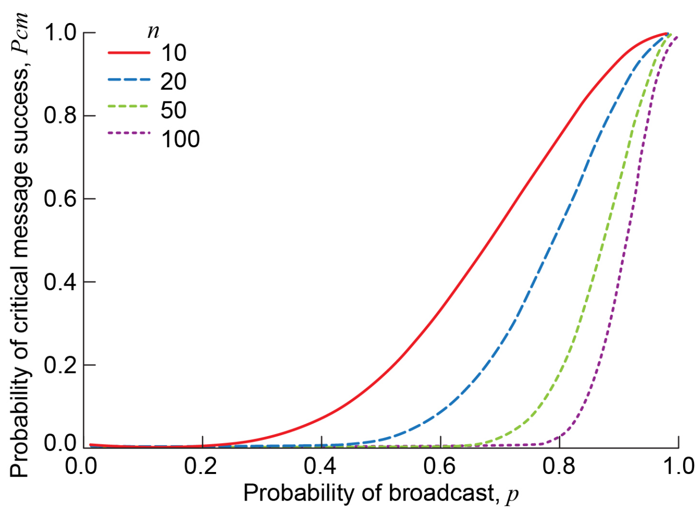

Figure 8.—Probability of critical message success versus probability of broadcast, for various values of *n*. Adapted from Reference 1 (figure 4); used with permission.

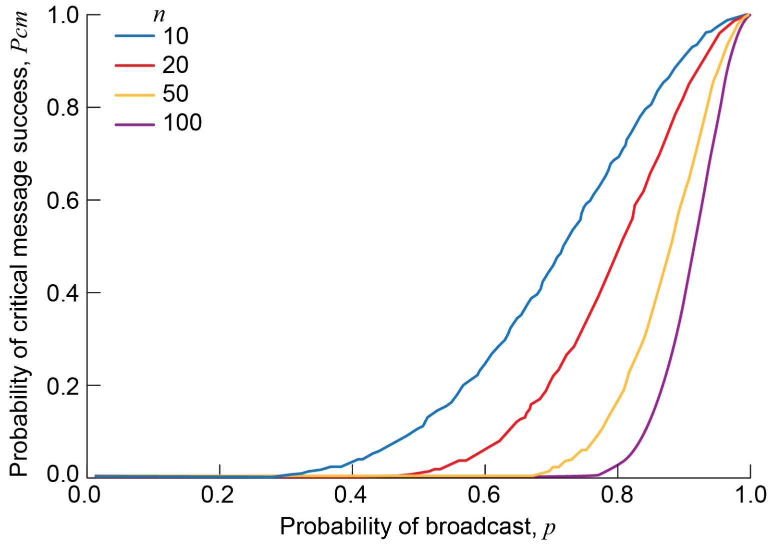

Figure 9.—Probability of critical message success versus probability of broadcast, K = 2, one lane, for various values of n, from the simulation.

Figure 10 reproduces a plot from Reference 1 that has n = 10 but varies the flooding algorithm's K value. Likewise, the simulation is for one lane, where visually means that each AV is separated from other AVs a distance of d_{ms} and all AVs are aligned back to back in a straight line. Of course, this is not a real-world approach, in general, for the ADS–R simulation work. Again, this effort sought to reproduce the white paper's results first before extrapolating results that are not in the white paper.

Notice that the curves of the two plots (Figure 10 and Figure 11) are not exactly congruent. This is likely due to the Reference 1 simulations using somewhat different methodology than the ones developed here. However, the results are close.

This plot is essentially showing that there is a probability of receiving a message, denoted as p, that is input by the user into the flooding algorithm, where an *optimal* probability of receiving a message is met per a certain number of AVs = n at a certain K. This optimal probability is denoted as Pcm. What this optimal probability really indicates is that the transceiver that is sending that message does not need to always send its particular message at a high probability in order to achieve flooding, that is, transmitting the message to all AVs in the area. The probability can be lower where less congestion within that area of AVs can be reduced to assist in wasted additional communication between transceivers. If the density of AVs in the area is high, this can impact overall bandwidth (BW) of the system.

As shown in Figure 11, the higher the K, with a fixed number of AVs (for one-lane topography—what this paper calls *horiz–rect* topography), a lower p is needed to communicate to all AVs (in this case, 10 vehicles). For example, consider when K = 2, where the probability of broadcast p range is between 0.6 and 0.8 percent, and the y-axis Pcm is between 0.3 to 0.8 percent. Pcm also depends on d_t, which is not part of this figure. But as will be shown later, there is an optimal Pcm for a specific d_t, K, and vehicle density (AVs/km^2).

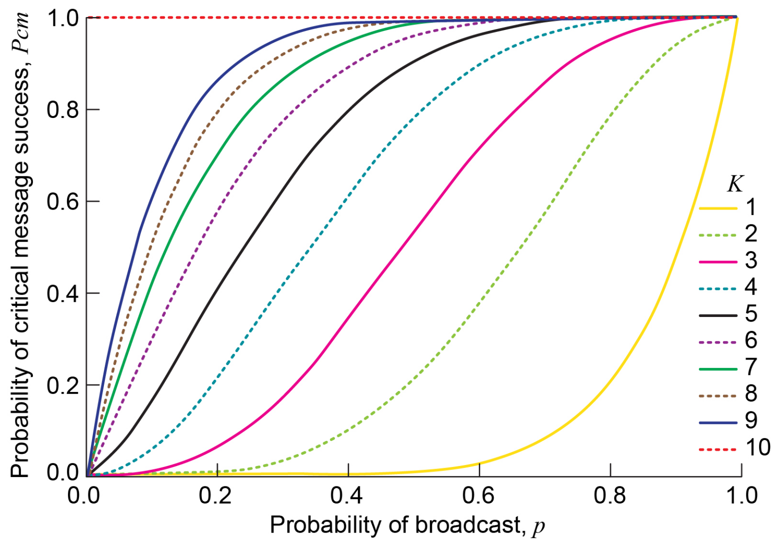

Figure 10.—Probability of critical message success versus probability of broadcast, various values of *K* and *n*; adapted from Reference 1 (figure 7); used with permission.

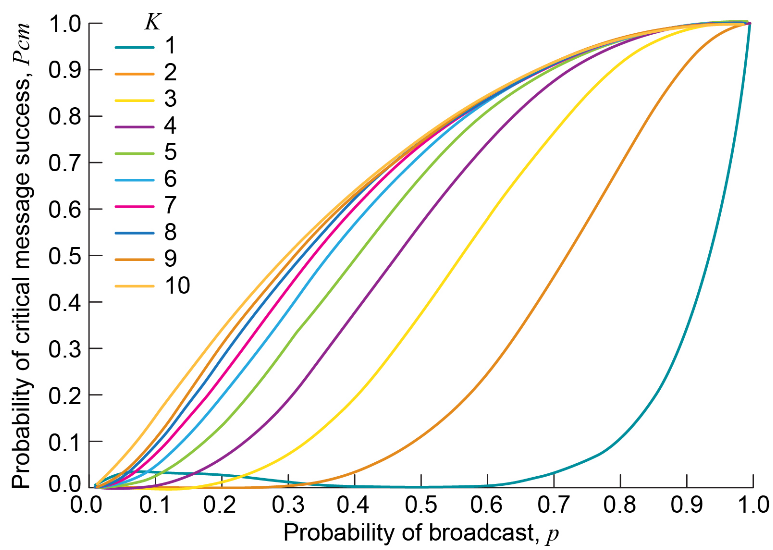

Figure 11.—Probability of critical message success versus probability of broadcast, n = 10, various values of *K*.

Figure 12 provides a comparison of a plot from Reference 1 and the same plot reproduced by the project simulation. Instead of *K*, Figure 12(a) alters *n* when altering *p* on the x-axis. Because it is a one-lane model, density is equivalent to *n* per linear km. What this plot shows is similar to Figure 10; as the number of AVs increases (or density increases) for a one-lane scenario, a smaller *Pcm* is needed to meet the flooding algorithm's purpose of communicating to all AVs within the area with an optimal probability of messaging. Again, the transmission distance parameter is left out of this plot.

Figure 12(b) shows the plot produced by the project simulation and is very similar to the plot from Reference 1.

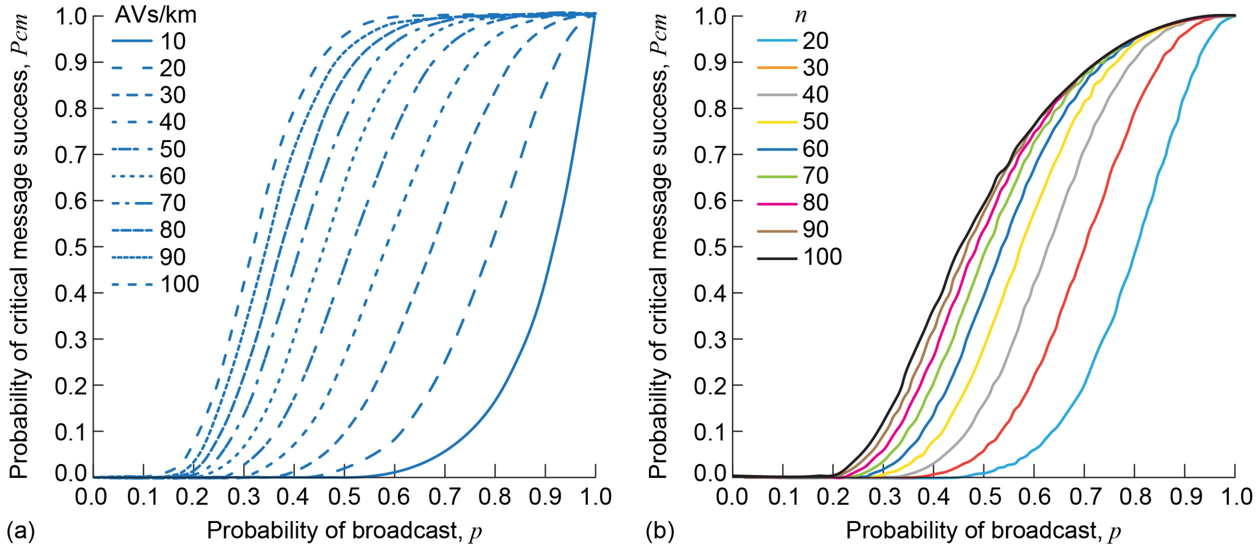

Figure 12.—Probability of critical message success versus probability of broadcast, various vehicle densities on 1-km road. (a) Adapted from Reference 1 (figure 11); used with permission. (b) From the simulation.

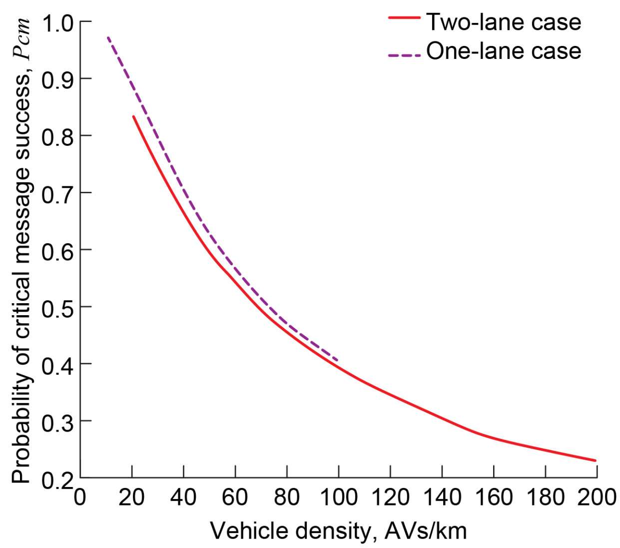

Figure 13.—Probability of critical message success versus vehicle density for one- and two-lane cases. Adapted from Reference 1 (figure 12); used with permission.

Figure 13 recreates figure 12 from Reference 1. Parameters such as transmission distance or *K* per density are not given. To generate the plot shown in Figure 13, three steps were performed. First, a Bayesian probability analysis was done to determine the inverse probability of the flooding function. The second step was to simulate it; this is where the curve in Figure 14 was generated. Arbitrary *K* and *n* values were chosen for a one-lane scenario: $K = 3$ and $n = 30$, thus density was 30 AVs/km. As shown in Figure 14, the peak of the curve is approximately the *p* value of 0.23, resulting in $(1 - p)$ of approximately 0.77. This point was then plotted at x-axis = 30 AVs and y-axis $Pcm = 0.77$, as shown in Figure 13.

The final step was to run the simulation for $n = 20$ through 100 and *Pcm,* plotted in Figure 15. The plot is very close to what is shown in Reference 1 and reproduced in Figure 13. Only a one-lane scenario was plotted, as a two-lane scenario is similar to one-lane scenario. Most important for future MATLAB® simulation, this plot indicates that even though the number of lanes may be increased, the *Pcm* changes very slowly. This will be confirmed in a later section. Another observation from Figure 15 is that as AVs increase (density for lanes >1), the needed *Pcm* for the flooding algorithm to communicate to all AVs decreases. Also, as the number of AVs is increased, the d_t needed also will go down. This saves power and still results in communication to all AVs in the area—the main objective of the flooding algorithm. This will also be shown in a later section.

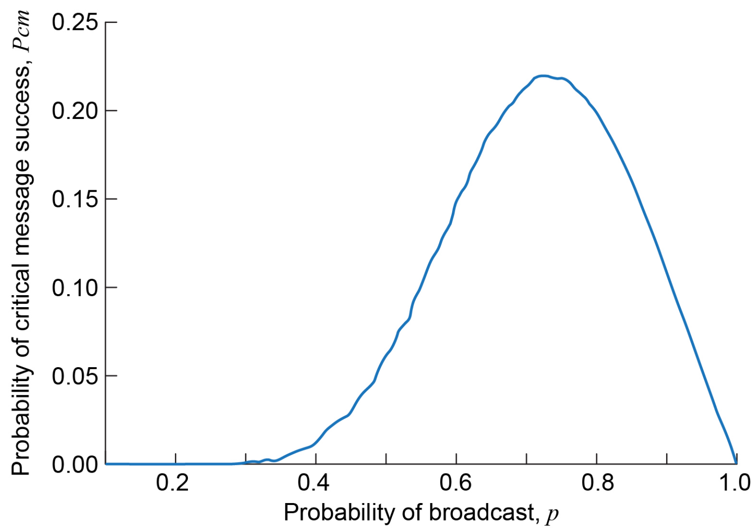

Figure 14.—Probability of critical message success versus probability of broadcast; n = 30, K = 3.

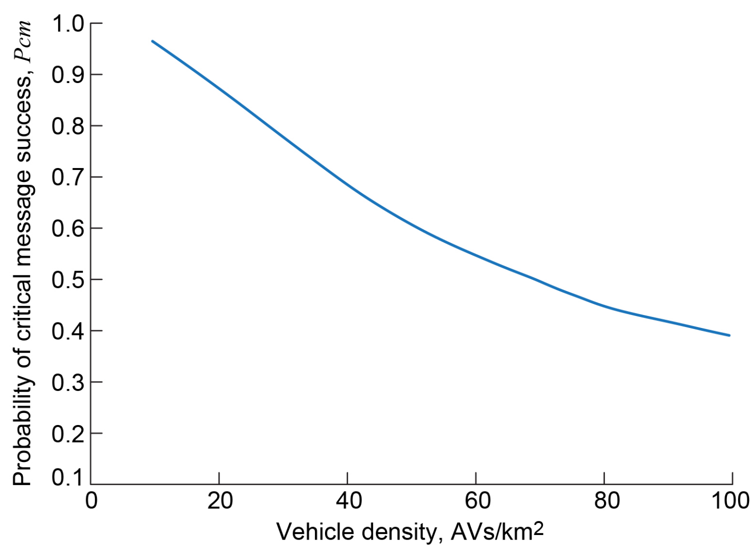

Figure 15.—Probability of critical message success versus vehicle density; n = 20 through 100 AVs/km^2.

Figure 16 reproduces figure 13 from Reference 1 and shows that as the number of neighbors *K* increases, the *Pcm* gets lower. (*K* is proportional to the flooding transmission distance ($K*d_t$).) Again, this illustrates the power of the flooding algorithm itself, as more neighbors allows for greater opportunities for message retransmission and thus lower critical probability needed to achieve flooding.

Figure 17, reproduced from Reference 1, shows that when the number of vehicles is increased while keeping the transmission range fixed ($K = 3$), there is a need for higher rebroadcast probability to achieve the desired *Pcm*. This is acceptable, because the current AVs transmit at a very high probability of connectivity within their designed distance. This was duplicated in the simulation, as shown in Figure 18.

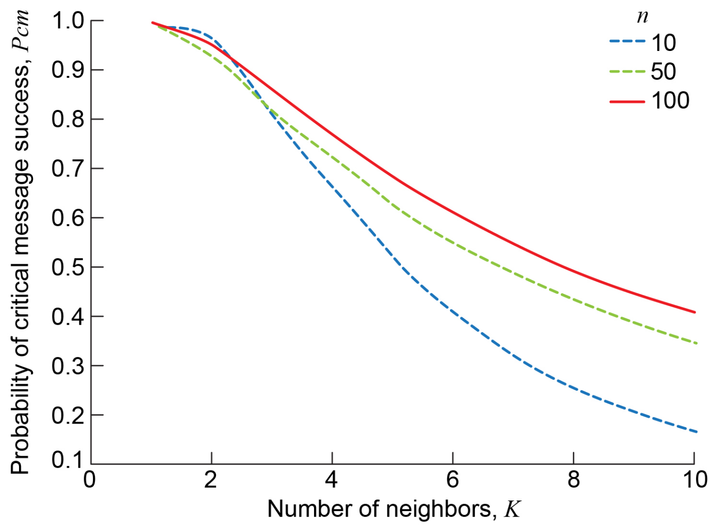

Figure 16.—Probability of critical message success versus number of neighbors in transmission range. Adapted from Reference 1 (figure 14); used with permission.

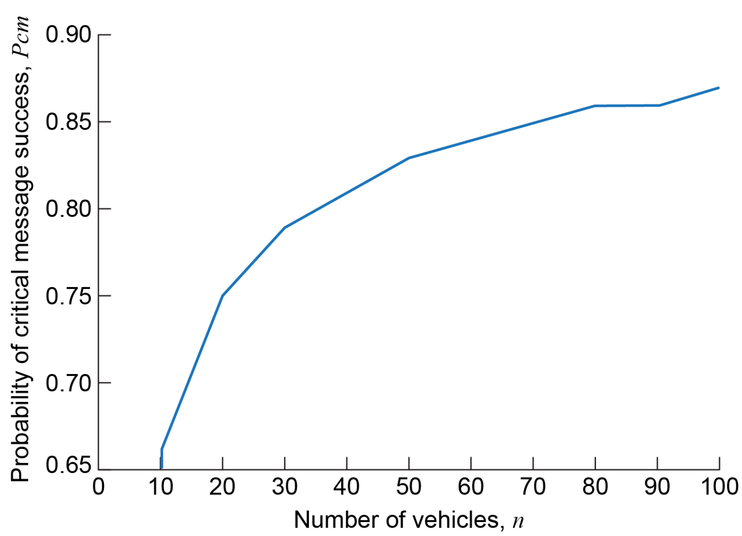

Figure 17.—Probability of critical message success versus number of vehicles. Adapted from Reference 1 (figure 14); used with permission.

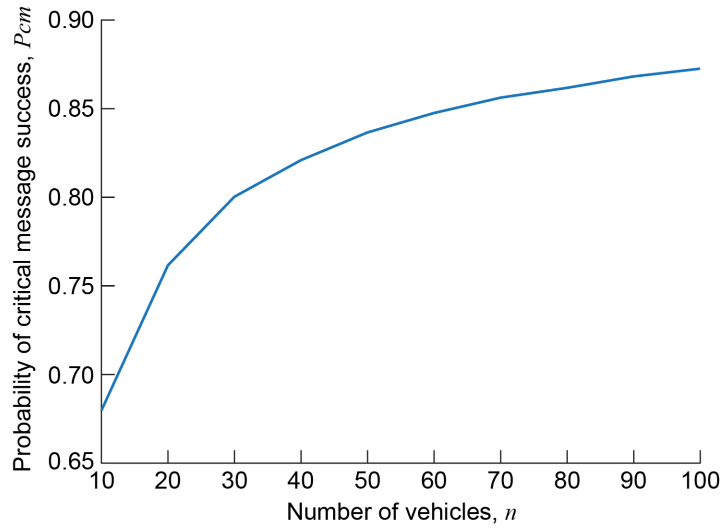

Figure 18.—Probability of critical message success versus number of vehicles, from simulation.

So, if there is a higher density of AVs in the area, this indicates that the value of K need not be as large, because the AVs' probability of successful communication is very high (>90 percent), thus deterring additional localized network traffic, and being able to use a smaller framing size to carry additional AV information from AV to AV, as K is much smaller. This is a design issue that needs to be addressed when implementing this flooding technology.

Now that the foundational coding and analysis of Reference 1 is complete, the next step is to investigate extrapolated scenarios that Reference 1 was not able to address at that time. This will be done using the previous ADS–B code but now adding the ADS–R flooding algorithm, where this new simulation will be called *ADSR_sim* (directory). The MATLAB® source file names and descriptions can be found in Table 1 and Table 2.

4.0 Task 2 (May 2020 to January 2021): Code and Implement an Extended Static ADS–R Simulation

Reference 1 defines density in terms of AVs/km^2. The original ADS–B simulation, now ADS–R, used miles, so the calculations need to be transformed. Table 5 shows the initial lane calculations that were done. A one-lane slice was arbitrarily chosen to be 0.0157 rad, where 100 slices make up a quarter of the circle, or 90° (π/2). It should be noted that the definition of a "lane" in this study's MATLAB simulations differs somewhat from the definition used in the white paper. Here, a lane is essentially a slice width, and not necessarily a single-file line of AVs. This table was created to understand how many AVs per lane are needed for a density of 10 AVs/km^2. It is important to note that the simulations, run on a laptop, maxed out at ~1,200 AVs, where each simulation took about approximately 2 h. A better way to simulate higher lanes and AVs/km^2 was investigated; this improvement will be shown in a later section. Eventually, this data should be excluded from any white paper, but it is shown here for proof of how the simulation was incrementally implemented.

The static MATLAB® statistics were run for a fixed time interval (1 s of simulated time) and for multiple time intervals (many seconds of simulated time) where the AVs did not move to compare the statistics. It was found out that one iteration produced statistics similar to multiple overall averaged statistics; thus, the one-iteration results shown in Figure 19 may be considered representative. All the statistics and output data shown for the static simulation are for a one-time run where there is no velocity movement of the AVs. This approach will be shown to match the Reference 1 results, along with allowing for more extrapolated scenarios than Reference 1 was able to show.

Figure 19 shows data for a one-lane scenario where $K = 4$ and density = 10 AVs/nmi^2 where there are 157 AVs in total. *Pcm* is at 40 percent for this scenario, transmission distance per AV is 0.3 nmi (shown in blue), and flooding transmission distance is K*0.3 = 1.2 nmi (orange).

TABLE 5.—INITIAL LANE SCENARIOS
[Inner radius is 498 nmi; outer radius is 500 nmi.]

Lane	Angle, rad	Angle, deg	Inner radius arc length, nmi	AVs/ nmi	AVs/ km	Area, nmi^2	Area, km^2	AVs/ nmi^2	AVs/ km^2	Percent circumference
1	0.0157	1	8	20	--------	16	40	1.3	-----	0.2
1	0.0157	1	8	157	400	16	40	10.0	10.0	0.2
2	0.0314	2	16	314	800	31	80	10.0	10.0	0.5
3	0.0471	3	23	470	1,200	47	120	10.0	10.0	0.7
4	0.0628	4	31	626	1,600	63	160	10.0	10.0	1.0
5	0.0785	5	39	782	2,000	78	200	10.0	10.0	1.2
10	0.1570	9	78	1,564	4,000	156	400	10.0	10.0	2.5
25	0.3925	23	195	3,910	10,000	391	1,001	10.0	10.0	6.2
50	0.7850	45	391	7,830	--------	782	2,002	10.0	-----	12.5
100	1.5700	90	782	15,650	--------	1,564	4,003	10.0	-----	24.9

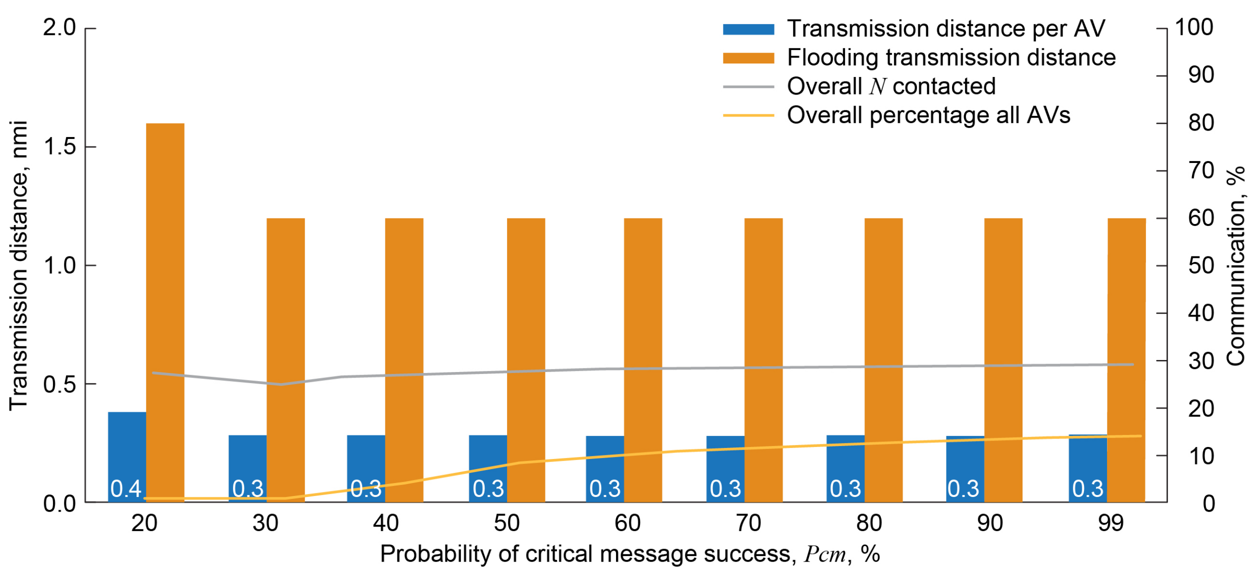

Figure 19.—Communication success; one lane, $K = 4$, density 10 AVs/nmi^2, 157 AVs total.

For scenarios with up to five lanes, the following results were notable:

- Each time the number of lanes increases (from 1 to 2, 2 to 3, etc.), the transmission distance increases by 0.2 nmi—a major finding found by simulating more than one lane. As noted earlier, the one-lane slice was arbitrarily chosen to be 0.0157 rad (slightly less than 1°), where 100 slices make up a quarter of the circle, or 90° (π/2).
- The *Pcm* goes down as the lane count goes from 1 to 2 lanes—from 60 to 30 percent. This does not match the closed-form figure 12 of Reference 1. This is because the simulation is not a strict one-to-two-lane simulation due to the randomizing of the AVs within the pie cut—another major finding found by simulating more than one lane as compared with Reference 1.
- The *Pcm*, in general, is 30 percent. What this means is that the closed-loop connection or communication that occurs, say every second between transmitter and receiver of adjacent AVs, can be inefficient in connecting 30 percent of the time within the given transmission range.
- For $K = 4$ at a lower AV area density, d_t ranges from 0.3 to 1.1 nmi for lanes up to five.

Next, simulations were rerun for densities of 10 AVs/km^2. Table 6 shows the lane calculation and range. Note two cases were run with nmi and km units, with different densities for each.

Figure 20 shows the random placement of AVs for lanes 3, 4 and 5. These MATLAB® output graphics were created using the flags for plotting within the MATLAB® code. It is important to note that the topography makes a difference in output statistics. The topography areas shown in Figure 20 are *vert–rect* topography.

The ADS–R simulation has a circular geography with a maximum radius of 500 nmi, where the center of the circle is the airport. All randomly placed AVs radially-linearly traverse in or out from the center of the circle. It was arbitrarily chosen that there will be 100 lanes per 1/4 circle (π/2 rad) where the angle size per lane is 0.0157 rad. Parameters are shown in Table 7.

Table 8 shows the rollup results for density in square kilometers for one through five lanes where $K = 4$.

TABLE 6.—LANE CALCULATION: DENSITY = 10 AVs/km^2
[Inner radius is 490 nmi; outer radius is 500 nmi.]

Lane	Angle, rad	Angle, deg	Inner radius arc length, nmi	Outer radius arc length, nmi	AVs per nmi	AVs per km	Area, nmi^2	Area, km^2	AVs per nmi^2	AVs per km^2
1	0.0157	1	7.69	7.85	16	40	1.6	4	10.2	10.0
2	0.0314	2	15.39	15.70	32	80	3.1	8	10.2	10.0
3	0.0471	3	23.08	23.55	48	120	4.7	12	10.2	10.0
4	0.0628	4	30.77	31.40	64	160	6.3	16	10.2	10.0
5	0.0785	5	38.47	39.25	80	200	7.9	20	10.2	10.0

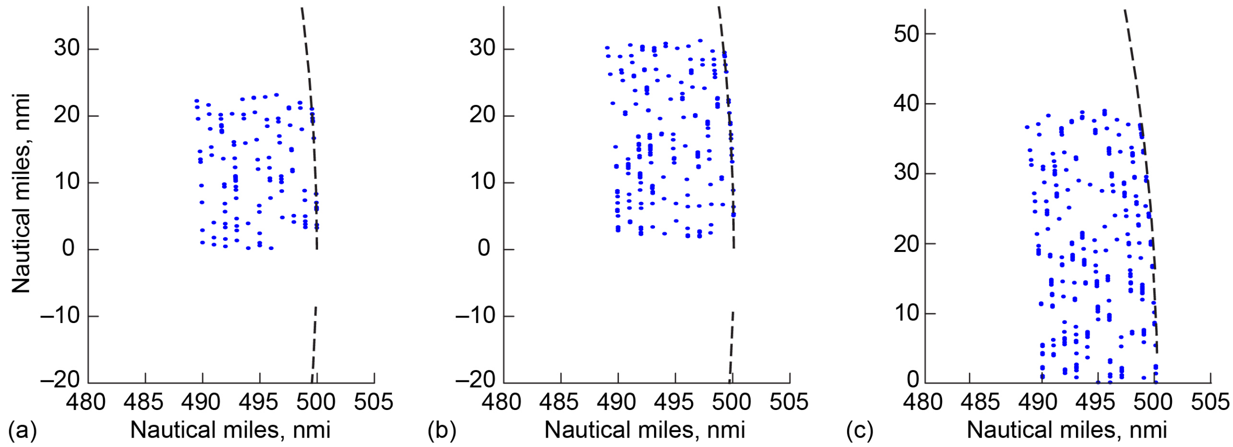

Figure 20.—Zoomed-in MATLAB® radar plots. (a) 120 incoming AVs. (b) 160 incoming AVs. (c) 200 incoming AVs.

TABLE 7.—SIMULATION PARAMETERS

Circle circumference, rad	6.28
1/4 circle, rad	1.57
Slices per 1/4 circle	100
Radians per lane	0.0157

TABLE 8.—SIMULATION RESULTS: DENSITY = 10 AVs/km^2
[K = 4, Pcm = 50.]

Lane	Transmission distance per AV, km	Flooding transmission distance, km	Ave no. all AVs contacted	Max no. all AVs contacted
1	1.6	6.4	4	12
2	1.9	7.7	6	13
3	3.0	12.2	13	35
4	3.2	12.8	14	32
5	3.7	14.7	16	41

The following definitions apply to Table 9 and later tables:

- *Ave Iterations, AVs Communicate to All*.—Number of iterations for AVs within the area to communicate to all AVs on average, meeting the flooding expectation. If the optimized *Ave* is 10, this means that on average there will be 10 iterations to contact all AVs.
- *Max Iterations, AVs Communicate to All*.—Greatest number of iterations to communicate to all AVs, thus, the worst-case communication timeframe.
- *Min Iterations, AVs Communicate to All*.—Least number of iterations to communicate to all AVs, thus, the best-case communication timeframe.

Table 9 shows results for densities of 10, 20, and 50 AVs/km^2, static mode, and *horiz–rect* topography where K = 4. These results are novel and were not part of Reference 1.

TABLE 9.—SIMULATION RESULTS: DENSITY = 10, 20, AND 50 AVs/km^2
[K = 4, Pcm = 50.]

Density, AVs/km^2	Lanes	Transmission distance per AV, km	Flooding transmission distance, km	Overall N contacted, percent	AVs communicating to all AVs, percent	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
10	1	1.6	6.4	70	5.0	8	18	1
10	2	1.9	7.7	58	1.9	9	22	1
10	3	3.0	12.2	57	0.4	17	37	1
10	4	3.2	12.8	72	5.9	29	71	1
10	5	3.7	14.7	70	1.0	35	96	1
20	1	1.6	6.4	70	5.0	8	18	1
20	2	1.9	7.0	58	1.9	9	22	1
20	3	3.0	9.6	57	0.4	17	37	1
20	4	3.2	12.8	72	5.9	29	71	1
20	5	3.7	14.7	70	1.0	35	96	1
50	1	1.6	6.4	85	46.0	9	18	1
50	2	1.9	7.0	65	1.0	10	24	1
50	3	3.0	9.6	65	0.7	14	31	1
50	4	3.2	11.5	71	1.0	18	41	1
50	5	3.5	14.1	75	0.4	23	57	1

4.1 Detailed Simulation Analysis

The detailed simulation analysis revealed the following observations:

1. The transmission distance increases as number of lanes increases.
2. The transmission distance is similar per lane as densities increased from 10 to 20 to 50 AVs/km^2.
3. Comparing lanes, the average time of communication stayed the same as well; thus, density does not make a difference for the flooding communication algorithm. K increases needed network transmissions, which increased delay of when all AVs are contacted and thus affected digital differential analyzer (DDA) algorithms for higher density AVs.

An analysis was done to determine whether there is any statistical difference if the AVs are all incoming or are a mix (50/50) of incoming and outgoing. Table 10 and Table 11 show the results. Overall, it was found that for the static model, there is no statistical difference between the two scenarios.

A goal of analysis at this stage of the project was to capture what can be called vicinity statistics. *Vicinity contacted* means the number of AVs per $K*d_t$ (maximum flooding distance) that one AV has contacted in its general cartesian area. These statistics can be used to understand how much additional localized network data the flooding algorithm will add.

TABLE 10.—SIMULATION RESULTS: ALL AVs INCOMING
[K = 4, Pcm = 50.]

Density, AVs/km^2	Lanes	Transmission distance per AV, km	Flooding transmission distance, km	Overall N contacted, percent	AVs communicating to all AVs, percent	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
10	1	1.6	6.4	70	5.0	8	18	1
10	2	1.9	7.7	58	1.9	9	22	1
10	3	3.0	12.2	57	0.4	17	37	1
10	4	3.2	12.8	72	5.9	29	71	1
10	5	3.7	14.7	70	1.0	35	96	1
20	1	1.6	6.4	70	5.0	8	18	1
20	2	1.8	7.0	58	1.9	9	22	1
20	3	2.4	9.6	57	0.4	17	37	1
20	4	3.2	12.8	72	5.9	29	71	1
20	5	3.7	14.7	70	1.0	35	96	1
50	1	1.6	6.4	85	46.0	9	18	1
50	2	1.8	7.0	65	1.0	10	24	1
50	3	2.4	9.6	65	0.7	14	31	1
50	4	2.9	11.5	71	1.0	18	41	1
50	5	3.5	14.1	75	0.4	23	57	1

TABLE 11.—SIMULATION RESULTS: 50 PERCENT AVs INCOMING, 50 PERCENT OUTGOING
[K = 4, Pcm = 50.]

Density, AVs/km^2	Lanes	Transmission distance per AV, km	Flooding transmission distance, km	Overall N contacted, percent	AVs communicating to all AVs, percent	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
10	1	2.4	9.6	80	7.5	8	20	1
10	2	2.2	9.0	72	3.1	9	28	1
10	3	2.7	10.9	77	9.2	18	45	1
10	4	3.2	12.8	75	4.7	27	65	1
10	5	3.8	15.4	75	0.5	33	89	1
20	1	1.6	6.4	80	7.5	8	20	1
20	2	1.9	7.7	72	3.1	9	28	1
20	3	2.6	10.2	77	9.2	18	45	1
20	4	3.2	12.8	75	4.7	27	65	1
20	5	3.7	14.7	75	0.5	33	89	1
50	1	1.4	3.6	84	26.0	6	14	1
50	2	1.9	4.8	76	10.0	10	24	1
50	3	2.2	5.6	62	2.0	10	27	1
50	4	3.0	7.6	68	3.0	18	40	1
50	5	3.7	9.2	71	1.6	23	54	1

The forward-looking transmission perimeter is shown in Figure 21; the elliptical transition perimeter is $K*d_t$. The transmission of the signal was initially modeled after large, high-flying manned AVs traveling 300 to 500 nmi/hr, consistent with the ADS–B simulation. Due to physics, the isotropic antenna transmission pattern of a high-flying AV is more forward looking, as shown in Figure 21.

To understand the flooding perimeter that leads to vicinity-flooding statistics, the example diagram may be better explained as a scenario example: $K = 4$, transmission distance = 0.9 nmi; then overall linear (one-lane) flooding transmission distance $d_f = 3.6$ nmi. However, the simulation is a real-world simulation, where AVs are not arranged in one lane. The AVs are randomly placed within the geographic area, thus a planar (two-dimensional) distance needs to be calculated. For example:

- sin (~45°) * 3.6 = 2.5. Thus, the planar distance between AVs is $(3.6^2 + 2.5^2)^{0.5} = 4.4$.
- Thus, the distance is larger than the one-lane case distance ($K*d_t$) as a result of the AVs being arranged in two dimensions.

Figure 22 shows the first-pass results of vicinity flooding for one lane, $K = 4$, where the topology was *square–rect*.

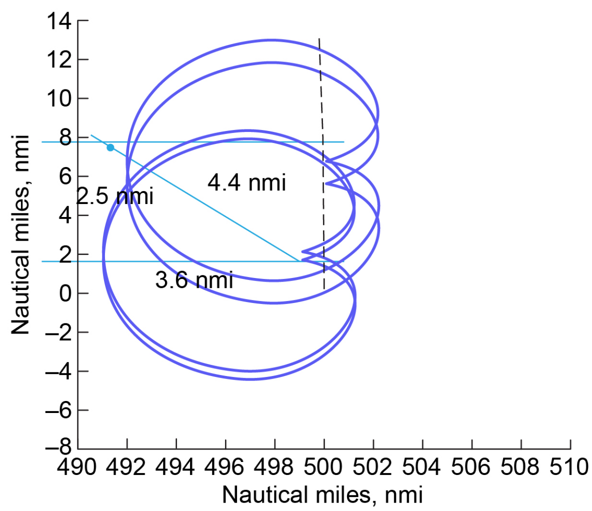

Figure 21.—Pie analysis; four incoming AVs.

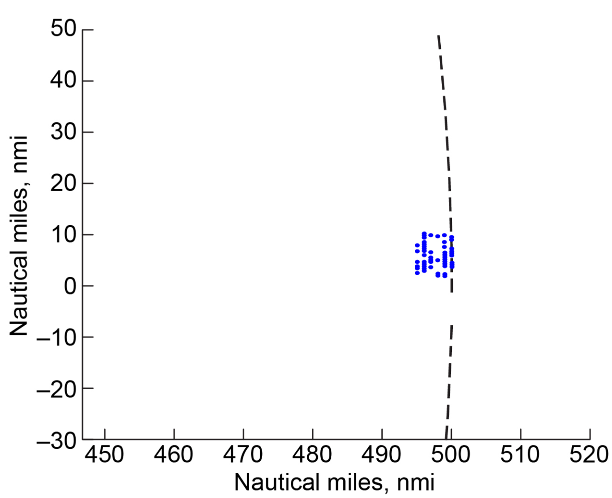

Figure 22.—Simulation run with 50 outgoing AVs, one lane, $K = 4$, *square–rect* topology.

It is desired to express the region in question, shown in Figure 23, in square kilometers so the density can be expressed in AVs per km². The following equation is used:

$$(500 \text{ nmi} - 495.0 \text{ nmi}) * 1.6093 \times (7.850 \text{ nmi}) * 1.6093 = 8 \text{ km} \times 12.6 \text{ km} = 100.5 \text{ km}^2 \quad (1)$$

Therefore, with 50 AVs, density = 0.50 AVs/km².

To obtain higher densities, the inner radius is made larger, enabling densities up to 50 AVs/km² for comparison, as shown in Table 12.

The simulation was run for one to five lanes with the lower *K* values of 2, 4, and 8; respective results are shown in Table 13 to Table 15. Recall that the vicinity statistics capture the average, maximum, and minimum number of AVs that one AV contacts per the flooding distance. It is desired that vicinity statistics be similar for all AVs. Definitions for parameters are found in Appendix B.

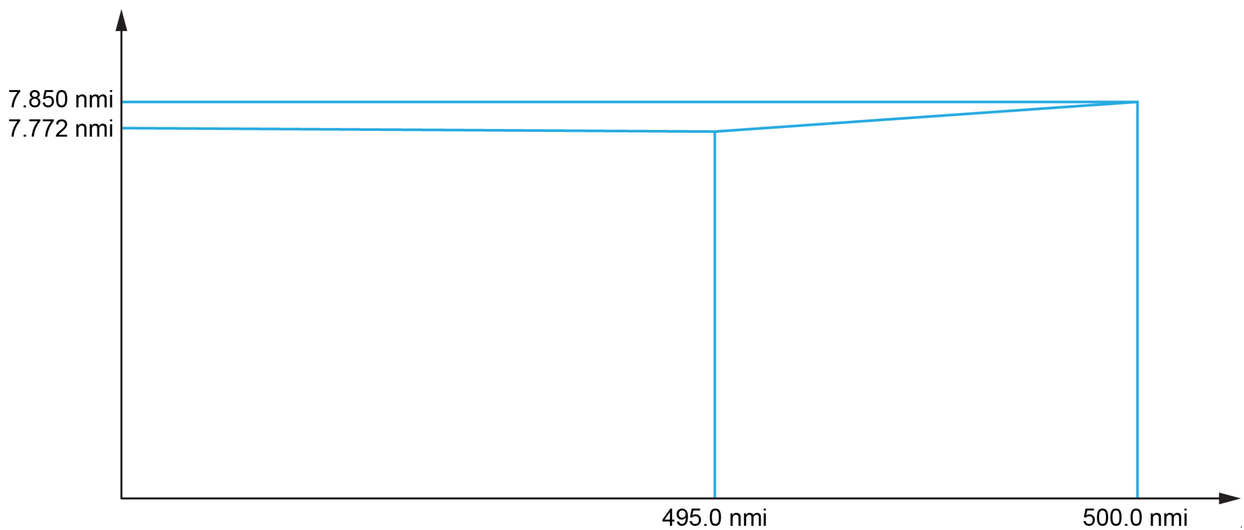

Figure 23.—Density illustration.

TABLE 12.—SIMULATION USING VARIOUS AV DENSITIES FOR ONE LANE
[Angle, 0.0157 rad (0.9°); inner radius 499 nmi; outer radius 500 nmi; inner radius arc length 7.834 nmi; outer radius arc length 7.850 nmi.]

AVs/km	Area, km²	AVs/km²
20	20	1.0
100	20	5.0
200	20	10.0
402	20	20.0
1,002	20	50.0

TABLE 13.—SIMULATION RESULTS: LANES 1 TO 5, K = 2, AVs/km^2 = 0.5

			Vicinity measurements (per AV)						All AVs contacted		
Lane	Transmission distance per AV, km	Best linear flooding transmission distance d_f for In/Out radar perimeters, km	Ave no. AVs in vicinity contacted per AV	Max no. AVs in vicinity contacted per AV	Radius of max vicinity AV, nmi	Min no. AVs in vicinity contacted per AV	Ave d_f, km	Max d_f, km	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
1	1.9	3.8	9	16	795	3	3.1	6.7	8	17	1
2	2.2	4.4	13	26	794	3	3.7	8.4	10	24	1
3	3.0	6.0	19	39	794	5	4.6	10.9	14	31	1
4	3.6	7.2	24	45	794	6	5.3	12.1	18	41	1
5	4.8	9.6	32	54	792	9	6.2	13.7	23	57	1

TABLE 14.—SIMULATION RESULTS: LANES 1 TO 5, K = 4, AVs/km^2 = 0.5

			Vicinity measurements (per AV)						All AVs contacted		
Lane	Transmission distance per AV, km	Best linear flooding transmission distance d_f for In/Out radar perimeters, km	Ave no. AVs in vicinity contacted per AV	Max no. AVs in vicinity contacted per AV	Radius of max vicinity AV, nmi	MIN no. AVs in vicinity contacted per AV	Ave d_f, km	Max d_f, km	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
1	1.4	5.8	10	20	792	3	3.4	7.9	9	18	1
2	1.9	7.7	13	26	794	3	3.7	8.4	10	24	1
3	2.2	9.0	19	39	794	5	4.6	10.9	14	31	1
4	3.0	12.2	24	45	794	6	5.3	12.1	18	41	1
5	3.7	14.7	32	54	792	9	6.2	13.7	23	57	1

TABLE 15.—SIMULATION RESULTS: LANES 1 TO 5, K = 8, AVs/km^2 = 0.5

			Vicinity measurements (per AV)						All AVs contacted		
Lane	Transmission distance per AV, km	Best linear flooding transmission distance d_f for In/Out radar perimeters, km	Ave no. AVs in vicinity contacted per AV	Max no. AVs in vicinity contacted per AV	Radius of max vicinity AV, nmi	Min no. AVs in vicinity contacted per AV	Ave d_f, km	Max d_f, km	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
1	0.8	6.4	10	20	792	3	3.4	7.9	9	18	1
2	1.0	7.7	14	28	794	4	3.8	8.8	10	25	1
3	1.3	10.2	20	42	794	5	4.8	11.3	15	34	1
4	1.4	11.5	24	45	794	6	5.3	12.1	18	41	1
5	1.8	14.1	32	54	792	9	6.2	13.7	23	57	1

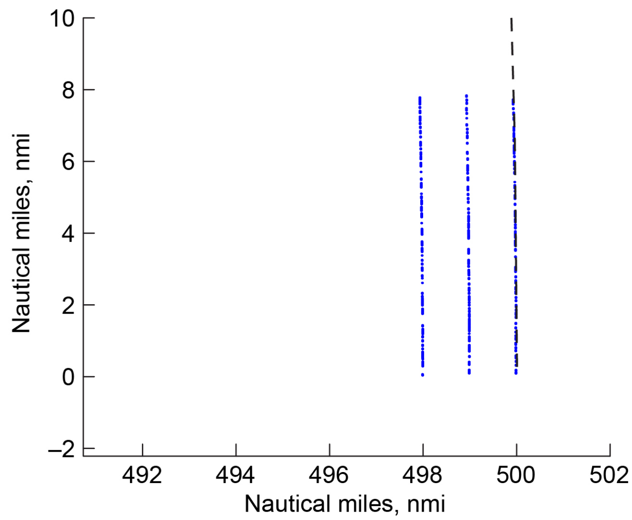

Figure 24.—Zoomed-in radar plot, 400 incoming AVs.

Basically, as *K* increases, the transmission distance (and thus power needed at transmitter) is less, which makes sense. This is what the flooding algorithm is all about—decreasing needed power to communicate to all AVs. The downside, however, is latency; this is the tradeoff. When looking at the vicinity measurements, on average, the number of iterations per *K* and number of lanes is not significant. In other words, for lanes = 5 where $K = 2$, 4, or 8, an average of 23 iterations will be needed to contact all AVs. This may or may not be optimal, depending on the spacing of the AVs and their velocities. Improvements will be addressed in later sections and will become more apparent in the dynamically created ADS–R simulation.

The static *horiz–rect* topography simulation shown in Figure 22 was redone for a higher density of 10 AVs/km^2; results are shown in Figure 24.

4.2 *Vert–Rect* Initial AV Layout for 50 AVs/km^2

Table 16 illustrates the 50 AVs/km^2 simulation, with 1,000 AVs; it took between 1 and 2 h to run, depending on parameters.

For this analysis, focus on $K = 4$:

- Notice there is an optimal transmission distance for *Pcm*, which is 0.8 km = d_t, thus flooding transmission distance (d_f) = 4*0.8 = 3.2 km.
- As d_t increases, so does the average number of AVs contacted; thus, it is important to find the optimal *Pcm*.
- Focus trend for all *K*s—that flooding transmission distance d_f is around 3.2 to 3.8 km, where all remaining vicinity statistics are the same.
- This trend may allow us to limit the number of simulations and understand the trend as we increase or decrease *K* per d_t.

This simulation raises the following questions:

- What effect does having a larger *K* have on the system?
- Is a larger frame needed to keep more information due to more AVs being contacted?
- Are more or fewer slots needed in the ADS–B design?

It is known that the larger the *K*, the smaller d_t needed, thus less power needed for transmitter. This is seen with link budget and added millimeter-wave attenuation; d_t with rain in closing loop is maximum at 1 km with either much higher power or directional antennas.

As *K* is increased, it is assumed that the near-distance AV's information bits are also loaded in frame for the flooding algorithm, thus the frame at minimum from 56 to $K \times 56 \times 3,800$ information data bits, thus increasing BW. Increasing BW also increases the number of TDMA slots required. The transmission distance is directly related to transmission power, which is directly calculated from the link budget. Table 17 is an A2A link budget table that varies the transmission power.

To meet the $K = 2$ d_t for a density of 10 AVs/km^2 for the static *horiz–rect* topology scenario, a d_t of 1.9 km is needed. Thus, for a free-space link budget model, only 1 W is needed. (Free space may be defined as a RF link with no atmosphere or rain present.) As the results in Table 16 show, when *K* is increased to 8, only enough power to transmit 0.5 km is needed to communicate to all AVs in the area. This can be accomplished with just 100 mW, which is a feasible power level for an AV. Thus, the trend for *K* is that as distance increases by 2 times, the distance needed to transmit also halves—this distance went from 1.9 to 0.8 to 0.5 km. However, an understanding of latency and additional network communication is needed to ensure ADS–R works well in real life. Next, vicinity statistics for this are examined.

TABLE 16.—SIMULATION RESULTS, ONE LANE: 1,000 AVs, AVs/km^2 = 50, K = 2, 4, 8
[Radians slice = 0.0157 (0.9°); max radius 1 = 800 km; max radius 2 = 792 km;
Pcm = 50 percent; min flooding distance = 0.00043 km.]

K	Transmission distance per AV, nmi	Transmission distance per AV, km	Flooding transmission distance d_f, km	Overall *N* contacted, percent	Overall all AVs contacted, percent	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all	Ave d_f, km	Max d_f, km	Radial position of flooding, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Radial position of starting AV for max, km	Min no. AVs in vicinity contacted	Simulation time to run, s
2	1.2	1.9	3.8	53	8	72.12	149	1	2.1	4.4	792.0	87	151	792.0	17	2,191
4	1.0	1.6	6.4	91	66	196	382	12	3.3	8.1	793.6	211	396	793.6	58	N/A
4	0.8	1.3	5.1	58	15	124	238	1	2.8	6.2	792.0	133	250	792.0	24	6,922
4	0.7	1.1	4.5	57	12	84	172	1	2.3	4.7	796.8	99	173	792.0	20	3,926
4	0.5	0.8	3.2	53	8	72.12	149	1	2.1	4.4	792.0	87	151	792.0	17	2,359
8	0.3	0.5	3.8	53	8	72.12	149	1	2.1	4.4	792.0	87	151	792.0	17	2,150

TABLE 17.—MAXIMUM DISTANCE VERSUS TRANSMIT POWER

AV transmit power			Max distance	
W	dB	dBm	km	nmi
5.000	7.0	37.0	4.8	2.9
3.000	4.8	34.8	3.7	2.2
1.000	0.0	30.0	2.1	1.3
0.500	–3.0	27.0	1.5	0.9
0.200	–7.0	23.0	1.0	0.6
0.100	–10.0	20.0	0.7	0.4

4.3 Next Evolution of Simulation—Results Not in White Paper

To speed up simulation, AV placement is randomized within the designated area. Figure 25 presents an example of one lane before and after randomization of 100 AVs between 495 and 500 nmi of normalized circular airspace. Table 18 illustrates the geometry of the lane/slice.

The *vert–rect* area (AVs clustered in a 7.85- by 5.00-nmi rectangle) is 39.25 nmi^2, which is equivalent to 100.48 km^2.

The static *vert–rect* topography is run using a randomized AV placement approach as opposed to the lined-up lane approach used previously. The practical limit using a laptop is ~1,000 AVs before the simulations take too long to run, so a scenario of up to 50 AV/km^2 will be implemented, as seen in Table 19.

The next logical step is to understand the three different topologies and their differences in order to efficiently run future simulations.

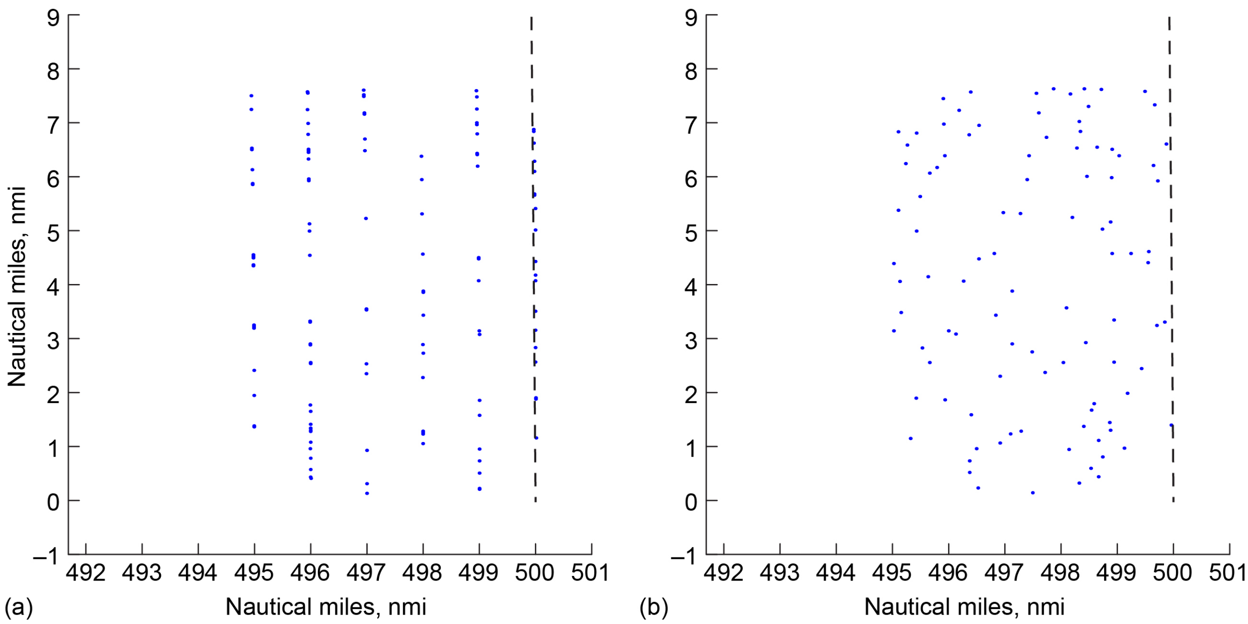

Figure 25.—Zoomed-in radar plot; one lane, 100 incoming AVs. (a) Before randomization. (b) After randomization.

TABLE 18.—SIMULATION RESULTS: ONE LANE, 100 AVs

Angle, rad	Angle, deg	Inner radius, nmi	Outer radius, nmi	Inner radius arc length, nmi	Outer radius arc length, nmi	AVs	Area, km^2	AVs/km^2
0.0157	1	495	500	7.772	7.850	100	99	1.0

TABLE 19.—SIMULATION FOR VARIOUS AV DENSITIES, ONE LANE
[Angle = 0.0157 rad (0.9°); inner radius = 499 nmi; outer radius = 500 nmi; inner radius arc length = 7.834 nmi; outer radius arc length = 7.850 nmi.]

AVs/km	Area, km^2	AVs/km^2
20	20	1.0
100	20	5.0
200	20	10.0
402	20	20.0
1,002	20	50.0

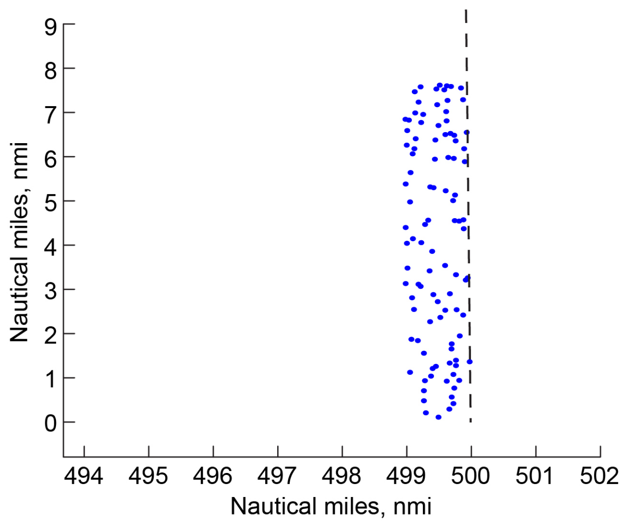

Figure 26.—Zoomed-in radar plot; *vert–rect* topology.

4.3.1 *Vert–Rect* Topology

Figure 26 shows the rollup results for densities from 1 to 50 AVs/km^2 for K = 2, 4, and 8 for static, *vert–rect* topology, all incoming AVs.

Table 20 presents simulation results for the *vert–rect* topology. Important observations include the following:

- For this *vert–rect* topology, as density increases while K stays the same, d_t stays the same for all densities.
- As K increases geometrically by the power of 2, no matter the density, d_t gets divided by 2. This indicates that for this *vert-rect* topology, K is the parameter that will assist in reducing transmission power when needed.
- As density increases, average flooding distance remains the same. This makes sense, as there is a maximum communication distance for flooding before all AVs are contacted.

TABLE 20.—SIMULATION RESULTS: *VERT–RECT*, $K = 2, 4, 8$
[AVs = 20 to 1,000; *Pcm* = 50.]

Total AVs	AVs/km^2	*K*	Transmission distance d_t per AV, nmi	d_t per AV, km	Flooding transmission distance d_f, km	Ave d_f, km	Max d_f, km
20	1.0	2	1.00	1.8	3.5	1.6	2.9
100	5.0	2	1.00	1.6	3.2	1.3	2.8
200	10.0	2	1.00	1.6	3.2	1.3	2.9
400	20.0	2	1.00	1.6	3.2	1.3	2.9
1,000	50.0	2	1.00	1.6	3.2	1.3	2.9
20	1.0	4	0.60	0.96	3.8	1.7	3.1
100	5.0	4	0.50	0.8	3.2	1.3	2.8
200	10.0	4	0.50	0.8	3.2	1.3	2.9
400	20.0	4	0.50	0.8	3.2	1.3	2.9
1,000	50.0	4	0.50	0.8	3.2	1.3	2.9
20	1.0	8	0.30	0.48	3.84	1.7	3.1
100	5.0	8	0.30	0.48	3.84	1.5	3.3
200	10.0	8	0.25	0.40	3.20	1.3	2.9
400	20.0	8	0.23	0.368	2.94	1.2	2.7
1,000	50.0	8	0.21	0.336	2.69	1.2	2.7

4.3.2 *Horiz–Rect* Topology

Figure 27 shows rollup results for static*, horiz–rect* topography with all incoming AVs.

Table 21 presents results for the static *horiz–rect* topography simulation. Important observations include the following:

- The statistics are very similar to those of the *vert–rect* simulation, thus all assumptions are the same.
- As density increases while *K* stays the same, d_t stays the same for all densities (except density <20 AV/km^2).
- As *K* increases geometrically by the power of 2, no matter the density, d_t gets divided by 2. *K* is thus the parameter that will assist in reducing transmission power when needed.
- As density increases, average flooding distance remains the same for all *K* variations, which makes sense, as there is a certain communicating maximum distance for flooding until all AVs are contacted.

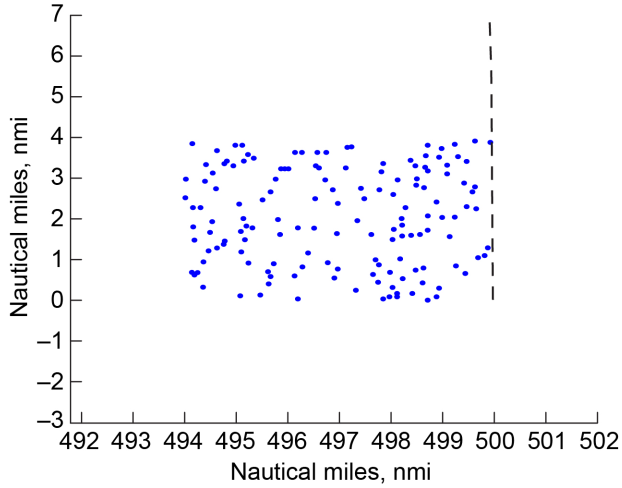

Figure 27.—Zoomed-in radar plot, static *horiz–rect* topography; 150 incoming AVs.

TABLE 21.—SIMULATION RESULTS: *HORIZ–RECT*, $K = 2, 4, 8$
[AVs = 20 to 1,000; *Pcm* = 50.]

Total AVs	AVs/km^2	K	Transmission distance d_t per AV, nmi	d_t per AV, km	Flooding transmission distance d_f, km	Ave d_f, km	Max d_f, km
20	1.0	2	1.30	2.1	4.2	1.6	2.9
100	5.0	2	1.00	1.6	3.2	1.3	2.8
200	10.0	2	0.90	1.4	2.9	1.3	2.9
400	20.0	2	0.90	1.4	2.9	1.3	2.9
1,000	50.0	2	0.90	1.4	2.9	1.3	2.9
20	1.0	4	0.70	1.1	4.5	1.7	3.1
100	5.0	4	0.60	1.0	3.8	1.3	2.8
200	10.0	4	0.50	0.8	3.2	1.3	2.9
400	20.0	4	0.50	0.8	3.2	1.3	2.9
1,000	50.0	4	0.50	0.8	3.2	1.3	2.9
20	1.0	8	0.40	0.6	5.1	1.7	3.1
100	5.0	8	0.30	0.5	3.8	1.5	3.3
200	10.0	8	0.30	0.5	3.8	1.3	2.9
400	20.0	8	0.25	0.4	3.2	1.2	2.7
1,000	50.0	8	0.25	0.4	3.2	1.2	2.7

4.3.3 *Square–Rect* Topology

Table 22 shows the rollup results for densities 1 to 50 AVs/km^2 for $K = 2$, 4, and 8 for static, *square–rect*, all incoming AVs. Important observations from this simulation include the following:

- The statistics are not similar to the *vert–rect* and *horiz–rect* topology statistics.
    - As density increases, average flooding distance decreases.

- Transmission distance, d_t, is approximately 40 to 50 percent less than *vert–horiz* topography for densities >20 AVs/km^2.
- The *square–rect* topology statistics are similar to the *vert–rect* and *horiz–rect* statistics in these ways:
  - As density increases while K stays the same, d_t stays about the same for all densities above 10 AV/km^2.
  - As density increases above 10 AV/km^2, average flooding transmission distance remains the same for all K variations, which makes sense, as there is a certain communicating maximum distance for flooding until all AVs are contacted.
- Using the *square–rect* topology, there is a skewed improvement in transmission distance power when compared with the *horiz–rect* and *vert–rect* topographies.
- For densities greater than 100, d_t stays the same for no matter what density for all topographies.

As the number of AVs are limited for simulation runs on a laptop due to simulation time, it is desired to extrapolate behavior for higher densities.

Next, network traffic and delay from the flooding algorithm as a function of K, density, and type of topology is examined.

TABLE 22.—SIMULATION RESULTS: *SQUARE–RECT*, K = 2, 4, 8
[AVs = 20 to 1,000; *Pcm* = 50.]

Total AVs	AVs/km^2	K	Transmission distance d_t per AV, nmi	d_t per AV, km	Flooding transmission distance d_f, km	Ave d_f, km	Max d_f, km
20	1.0	2	1.90	3.04	6.08	2.03	4.82
100	5.0	2	0.70	1.12	2.24	1.19	2.58
200	10.0	2	0.60	0.96	1.92	1.02	2.40
400	20.0	2	0.60	0.96	1.92	1.01	2.37
1,000	50.0	2	0.60	0.96	1.92	1.02	2.40
20	1.0	4	1.00	1.60	6.40	2.17	4.82
100	5.0	4	0.40	0.64	2.56	1.35	3.09
200	10.0	4	0.30	0.48	1.92	1.02	2.40
400	20.0	4	0.30	0.48	1.92	1.01	2.37
1,000	50.0	4	0.30	0.48	1.92	1.02	2.40
20	1.0	8	0.50	0.80	6.40	2.17	4.82
100	5.0	8	0.17	0.27	2.18	1.16	2.58
200	10.0	8	0.17	0.27	2.18	1.13	2.63
400	20.0	8	0.17	0.27	2.18	1.13	2.71
1,000	50.0	8	0.13	0.21	1.66	0.90	2.09

TABLE 23.—SIMULATION RESULTS: NETWORK TRAFFIC AND DELAY, *VERT–RECT*
[*Pcm* = 50.]

Total AVs	AVs/km^2	*K*	Transmission distance d_t per AV, nmi	d_t per AV, km	Flooding transmission distance d_f, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted
20	1.0	2	1.10	1.8	3.5	3	7
100	5.0	2	1.00	1.6	3.2	15	29
200	10.0	2	1.00	1.6	3.2	31	49
400	20.0	2	1.00	1.6	3.2	62	99
1,000	50.0	2	1.00	1.6	3.2	160	235
20	10.0	4	0.60	1.0	3.8	4	8
100	5.0	4	0.50	0.8	3.2	15	29
200	10.0	4	0.50	0.8	3.2	31	49
400	20.0	4	0.50	0.8	3.2	62	99
1,000	50.0	4	0.50	0.8	3.2	160	235
20	1.0	8	0.30	0.5	3.8	4	8
100	5.0	8	0.30	0.5	3.8	18	31
200	10.0	8	0.25	0.4	3.2	31	49
400	20.0	8	0.23	0.4	2.9	56	88
1,000	50.0	8	0.21	0.3	2.7	137	211

4.3.4 Network Traffic and Delay

Table 23 presents *vert–rect* simulation results for network traffic and delay. Note that for smaller densities, there is a smaller number (on average) of adjacent AVs contacted.

To illustrate, consider the following example:

- *K* = 2, 4, or 8; density = 10 AVs/km^2; and the average time elapsing before all AVs know where all other AVs are located will be 31 s. This latency depends on the velocity of the AVs; if AVs are traveling at 500 nmi/hr, this may be too slow. However, for AVs that are at least d_f away, this should be acceptable.

As the density gets higher, latency increases, but so does the network traffic, which needs to be taken into consideration. It is important to note that the value of *K* is not significant.

4.3.5 Summary of Results for All Three Topologies

Table 24 presents a summary of simulation results for all three topologies. Important observations include the following:

- The statistics for both *vert–rect* and *horiz–rect* are similar for average number of AVs in vicinity contacted. *Square–rect* topology results in a 10-percent reduction in total number of AVs that need contacting. This is useful knowledge because this topology may be used in an urban area.
- The average latency (i.e., the number of iterations the algorithm needs to achieve flooding) increases as AVs increase. Average latency can be calculated to be 15 percent of the total AVs in the air, whereas the maximum latency can be double that number.

- Up to 30 percent of AVs in the air need to communicate to 15 to 20 percent of the total AVs flying in the designated density area. This is the case for all densities greater than 100 AVs/km^2. This is a very important finding to understand nearby smaller networks around one AV.
- So on average, assuming the matched transmission distance, d_t, is met, 15 percent of the AVs in the radial area around the AV in question will need to be contacted at a *Pcm* of 50 percent (most efficient to meet “All AVs contacted”) to achieve flooding.
- A maximum 30 percent of total AVs in the air for “AVs in vicinity contacted” by origin AV is a good basis for making simulation arrays somewhat smaller to allow for larger AV simulations.
- Using the *square–rect* topology, there is a marked improvement in percentage of nearby AVs contacted by the original AV—10 percent of total AVs in air, down from 15 percent. This is useful data to make simulation arrays somewhat smaller to allow for larger AV simulations with reasonable execution time.

The next step is to investigate results for higher K with lower density. Table 25 shows simulation results for K = 8.

TABLE 24.—ALL RESULTS: *VERT–RECT, HORIZ–RECT, SQUARE–RECT*
[K = 2, 4, 8; Pcm = 50.]

			Vert–Rect						*Horiz–Rect*						*Square–Rect*					
Total AVs	AVs/km^2	K	Transmission distance d_t per AV, nmi	d_t per AV, km	Flooding transmission distance d_f, km	AVE no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Ave percent AVs in vicinity contacted	d_t per AV, nmi	d_t per AV, km	d_f, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Ave percent AVs in vicinity contacted	d_t per AV, nmi	d_t per AV, km	d_f, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Ave percent AVs in vicinity contacted
20	1.0	2	1.10	1.8	3.5	3	7	17	1.30	2.08	4.16	4	9	22	1.90	3.0	6.1	3	6	13
100	5.0	2	1.00	1.6	3.2	15	29	15	1.00	1.60	3.20	16	31	16	0.70	1.1	2.2	7	15	7
200	10.0	2	1.00	1.6	3.2	31	49	15	0.90	1.44	2.88	28	51	14	0.60	1.0	1.9	11	28	5
400	20.0	2	1.00	1.6	3.2	62	99	16	0.90	1.44	2.88	56	98	14	0.60	1.0	1.9	22	44	6
1,000	50.0	2	1.00	1.6	3.2	160	235	16	0.90	1.44	2.88	147	234	15	0.60	1.0	1.9	58	104	6
20	1.0	4	0.60	1.0	3.8	4	8	20	0.70	1.12	4.48	5	9	25	1.00	1.6	6.4	3	6	14
100	5.0	4	0.50	0.8	3.2	15	29	15	0.60	0.96	3.84	16	31	16	0.40	0.6	2.6	9	21	9
200	10.0	4	0.50	0.8	3.2	31	49	15	0.50	0.80	3.20	33	63	17	0.30	0.5	1.9	11	28	5
400	20.0	4	0.50	0.8	3.2	62	99	16	0.50	0.80	3.20	67	114	17	0.30	0.5	1.9	22	44	6
1,000	50.0	4	0.50	0.8	3.2	160	235	16	0.50	0.80	3.20	174	285	17	0.30	0.5	1.9	58	104	6
20	1.0	8	0.30	0.5	3.8	4	8	20	0.40	0.64	5.12	6	11	31	0.50	0.8	6.4	3	6	14
100	5.0	8	0.30	0.5	3.8	18	31	18	0.30	0.48	3.84	21	42	21	0.17	0.3	2.2	7	15	7
200	10.0	8	0.25	0.4	3.2	31	49	15	0.30	0.48	3.84	44	82	22	0.17	0.3	2.2	13	30	7
400	20.0	8	0.23	0.4	2.9	56	88	14	0.25	0.40	3.20	67	114	17	0.17	0.3	2.2	27	54	7
1,000	50.0	8	0.21	0.3	2.7	137	211	14	0.25	0.40	3.20	174	285	17	0.13	0.2	1.7	46	81	5

TABLE 25.—SIMULATION RESULTS, 0.5 LANE: K = 8, DENSITY = 10 AVs/km^2, TOTAL AVs = 100
[Radians slice, 0.003925 (0.9°); in/out percent 100/0; max radius 1 = 800 km; max radius 2 = 796.8 km; transmission distance d_t per AV = 0.17 nmi; min d_t per AV = 0.27 km; flooding transmission distance d_f = 2.18 km; ave d_f = 1.1 km; max d_f = 2.6 km; min d_f = 0.1 km.]

Pcm, percent	Radial position of flooding max, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Radial position of starting AV for max, km	Min no. AVs in vicinity contacted	Overall *N* contacted, percent	Overall all AVs contacted, percent	Ave iterations, AVs communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
40	797.1	10	23	797.4	1	64	2	9	20	1
50	796.9	13	30	797.4	1	70	12	11	26	1
90	796.9	24	43	797.3	4	77	20	20	39	1

Observations:

- For K = 8, the most efficient *Pcm* is 40 percent. As K goes up, *Pcm* goes down.
- The minimal distance to meet the flooding algorithm for the K = 8 simulation parameters is 0.17 nmi, no matter the *Pcm*. Again, the *Pcm* is the optimal probability of transmission of the transceiver. Any probability above this optimum value results in unnecessary messaging placed on the network.

Next, higher K values are investigated. Table 26 shows simulation results for the following parameters:

- K = 16 and 32
- *Square–rect* topology
- Low density of AVs: 10 AVs/km^2
- Varied *Pcm*

Observations:

- For K = 16, the most efficient *Pcm* is 30 percent; for K = 32, this is 25 percent. As K goes up, *Pcm* goes down—the same trend seen in the previous simulation.
- The minimal distance to meet the flooding algorithm for these simulation parameters is 0.09 nmi for K = 16, and this is approximately halved for K = 32, which follows the same trend seen in the previous simulation.
- As *Pcm* goes to 90 percent, it increases the number of unnecessary messages from the flooding algorithm, thus adding more network congestion.

The next example maps transmission distance to power needed for link budget for K = 8, with transmission power kept at 50 mW. This is illustrated in Table 27. For ADS–B, closing the loop at bit error rate (BER) 1×10^{-6} requires an E_sN_o (symbol energy per noise spectrum density, a measure of signal-to-noise ration) of 5.5 dB. The next step is to design for a worst-case scenario where atmospheric air absorption and rain fade are present within the link distance of 272 m. Table 27 shows the link budget for all three types of link budgets (free space, air, and rain).

TABLE 26.—SIMULATION RESULTS: K = 16, 32; DENSITY = 10 AVs/km^2; TOTAL AVs = 100
[Radians slice, 0.003925 (0.225°); 0.5 lane; in/out percent 100/0; max radius 1 = 800 km; max radius 2 = 796.8 km; min flooding transmission distance 0.1 km.]

K	Pcm, percent	Transmission distance d_t per AV, nmi	Minimum d_t per AV, km	Flooding transmission distance d_f, km	AVE d_f, km	Max d_f, km	Radial position of flooding max, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Radial position of starting AV for max, km	Min no. AVs in vicinity contacted	Overall N contacted, percent	Overall all AVs contacted, percent	Ave iterations, AVS communicate to all	Max iterations, AVs communicate to all	Min iterations, AVs communicate to all
16	30	0.09	0.14	2.30	1.2	2.8	797.2	9	23	797.4	1	60	3	7	16	1
16	40	0.09	0.14	2.30	1.3	3.1	796.9	10	26	797.4	1	71	7	8	21	1
16	90	0.09	0.14	2.30	1.1	2.5	797.7	22	39	797.3	4	73	19	18	38	1
32	25	0.05	0.08	2.56	1.3	3.1	796.9	8	22	799.0	1	64	2	7	19	1
32	30	0.05	0.08	2.56	1.3	3.1	796.9	10	26	797.4	1	71	7	8	21	1
32	90	0.05	0.08	2.56	1.3	3.1	796.9	30	52	797.4	8	90	42	25	57	1

TABLE 27.—LINK BUDGET FOR RAIN PLUS OXYGEN, OXYGEN, AND FREE SPACE

	Rain + oxygen	Oxygen	Free space
Frequency, GHz	90	90	90
Wavelength, λ, m	0.00333	0.00333	0.00333
Distance, m	272	272	272
Free-space path loss (FSPL), dB	120.2	120.2	120.2
Transmission power, W	0.05	0.05	0.05
Transmission power, dB	–13	–13	–13
Transmission power, dBm	17	17	17
Rain attenuation, α_{rain}, dB/km	4	0	0
Actual α_{rain}, dB	1.088	0	0
Oxygen attenuation, α_{oxy}, dB/km	0.2	0.2	0.0
Actual α_{oxy}, dB	0.1	0.1	0.0
Aeronautical fade margin (a loss factor)	2.0	2.0	2.0
Transmitter gain, G_{tx}, dBi	0	0	0
Receiver gain, G_{rx}, dBi	0	0	0
Receiver signal power, dBm	–106	–105	–105
Noise figure (NF) receiver, dB	1	1	1
Data rate, R, bps	3.00×10^{6}	3.00×10^{6}	3.00×10^{6}
System noise temperature, T_s, K	290	290	290
Boltzmann constant, k	1.38×10^{-23}	1.38×10^{-23}	1.38×10^{-23}
Quadrature phase-shift keying (QPSK) waveform, k_{BPS}	3	3	3
Data rate, R, symbols/s	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}
Energy per bit, E_s, dB	–166.4	–165.3	–165.2
Noise density, N_o, dB	–173.0	–173.0	–173.0
Normalized signal-to-noise ratio, E_sN_o, dB	6.61	7.69	7.75

Table 28 presents a comparison using higher *K* values of 8, 16, and 32.

Again, as *K* increases, the distance needed to communicate to all AVs within a square area with a density of 10 AVs/km^2 goes down, thus less power is needed to close the loop for the ADS–R receiver. Notice that keeping the power the same for increasing value of *K* significantly increases the required power needed at the receiver.

The next example, shown in Table 29, illustrates link budget power needed for different values of K and transmit power.

For example, with $K = 8$, the link budget E_sN_o for oxygen plus rain is less than the 5.5-dB "closing-the-loop" limit. However, because *Pcm* is at 40 percent, the flooding algorithm may still allow for successful communication with one iteration of the algorithm (which is 1 s with a simulation step size of 1 s). This type of analysis needs to be added to the simulation for a better understanding, as all AV transceivers have a 99-percent probability of transmission when in power range.

From a network messaging perspective, the lower the density, the lower the number of AVs in the network area to communicate. It was found that the average number of AVs contacted before all AVs are contacted (the flooding algorithm) is very low—9—which means within 9 s all 100 AVs are contacted (density of 10 AVs/km^2).

TABLE 28.—LINK BUDGET ROLLUP FOR STATIC, *SQUARE–RECT* TOPOGRAPHY, TRANSMIT POWER = 50 MW
[Density = 10 AVs/km^2; all incoming AVs.]

Simulation parameters		Link budget inputs		E_sN_o, dB		
Pcm, percent	*K*	d_t, m	Transmit power, mW	Free space (FS)	FS with oxygen	FS with oxygen + rain
40	8	272	50	7.75	7.69	6.61
30	16	144	50	13.24	13.24	12.67
25	32	80	50	18.38	18.36	18.04

TABLE 29.—LINK BUDGET ROLLUP FOR STATIC, *SQUARE–RECT* TOPOGRAPHY, VARYING TRANSMIT POWER
[Density = 10 AVs/km^2; all incoming AVs.]

Simulation parameters		Link budget inputs		E_sN_o, dB		
Pcm, percent	*K*	d_t, m	Transmit power, mW	Free space (FS)	FS with oxygen	FS with oxygen + rain
40	8	272	30	5.53	5.48	4.39
30	16	144	9	5.80	5.80	5.22
25	32	80	3	6.16	6.15	5.82

Assume that all 10 AVs are equally spaced within a square 100 m on each side (or approx. 140 m diagonal), all at the same altitude, and flying at a velocity of 100 km/h (28 m/s). In this case, in the 9-s timeframe (i.e., nine iterations with a simulation step size of 1 s), the farthest an AV will travel is 9 s × 28 m/s, or 250 m, which does not give the AV time enough to react from a DDA perspective; this is why a dynamic simulation is needed. So, we either increase power per *d* or reduce *K* to meet the DDA time to react.

The next scenario considered is a more realistic modern scenario where density is 0.5 AVs/km^2. The analysis shown in Figure 28 and Table 30 includes the best *Pcm*, efficiency, and probability of closing the loop transmission, because that is where most current transceivers for both drones and higher flying AVs.

The minimal distance to meet the flooding algorithm for these parameters is 0.5 nmi (0.8 km), no matter the *Pcm.*

Table 31 presents results for a simulation using the same density but higher *K* values of 16 and 32.

Observations:

- The most efficient *Pcm* is 40 percent for both *K* = 16 and *K* = 32. However, the granularity is not as good, as there are only 10 AVs in total.
- The minimal distance to meet the flooding algorithm for these parameters is 0.25 nmi for *K* = 16; this is approximately halved for *K* = 32. This follows the same trend observed in previous simulations.
- As *Pcm* increases to 90 percent, the number of unneeded messages from the flooding algorithm increases, thus adding more network congestion, but this may extend the transmission distance a certain amount; this needs further investigation.

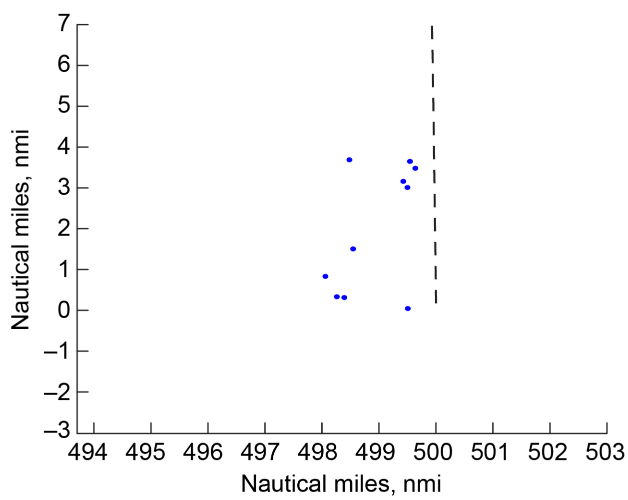

Figure 28.—Zoomed-in radar perimeter run, 10 incoming AVs.

TABLE 30.—SIMULATION RESULTS, 0.5 LANE: $K = 8$, AVS CONTACTED
[Radians slice, 0.00785 (0.45°); in/out percent 100/0; max radius 1 = 800 km; max radius 2 = 796.8 km; total AVS = 10; AVs/km^2 = 1.0; transmission distance d_t per AV, 0.05 nmi; min d_t per AV, 0.80 km; flooding transmission distance d_f 6.40 km; min d_f 0.2 km; radial position of starting AV for max, 796.9 km.]

Pcm, percent	Transmission distance d_t per AV, nmi	Ave flooding transmission distance d_f, km	Max d_f, km	Radial position of flooding max, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Min no. AVs in vicinity contacted	Overall *N* contacted, percent	Overall all AVs contacted, percent	Ave	Max	Min
40	0.50	2.2	4.8	797.4	3	5	1	83	20	2	4	1
50	0.50	2.2	4.8	797.4	3	6	1	87	30	2	5	1
90	0.50	2.5	5.1	796.9	5	9	2	100	100	5	9	2

TABLE 31.—SIMULATION RESULTS: AVS CONTACTED, $K = 16, 32$
[Radians slice = 0.00785; 0.5 lane; in/out percent = 100/0; max radius 1 = 800 km; max radius 2 = 796.8 km; total AVS = 10; density AVs/km^2 = 1.0; min flooding distance = 0.2 km; radial position of starting AV for max = 796.9 km.]

K	*Pcm*, percent	Transmission distance d_t per AV, nmi	Minimum d_t per AV, km	Flooding transmission distance d_f, km	Ave d_f, km	Max d_f, km	Radial position of flooding max, km	Ave no. AVs in vicinity contacted	Max no. AVs in vicinity contacted	Min no. AVs in vicinity contacted	Overall *N* contacted, percent	Overall all AVs contacted, percent	Ave iterations, AVs communicate to all AVs	Max iterations, AVs communicate to all AVs	Min iterations, AVs communicate to all AVs
16	40	0.25	0.40	6.40	2.2	4.8	797.4	3	5	1	83	20	2	4	1
16	50	0.25	0.40	6.40	2.2	4.8	797.4	3	6	1	87	30	2	5	1
16	90	0.25	0.40	6.40	2.5	5.1	796.9	5	9	2	100	100	5	9	2
32	40	0.12	0.19	6.14	2.2	4.8	797.4	3	5	1	74	2	2	4	1
32	50	0.12	0.19	6.14	2.1	4.8	797.4	3	6	1	83	2	2	5	1
32	60	0.12	0.19	6.14	2.4	5.1	796.9	5	9	2	100	5	5	8	1

4.3.6 Summary of Findings of Static ADS–R Simulations

- As *K* increases by a factor of 2, d_t is approximately halved (consistent with higher density scenarios).
- The higher the density, the more network communication that occurs (consistent with higher density scenarios).
- For lower densities, 1 to 8 AVs/km^2 may utilize DDA algorithms for AVs traveling on average 100 km/h.
- For lower density AV scenarios, the flooding algorithm can work in the frequency range of 90 GHz.

5.0 ADS–R Link Budget

Every telecommunications system has a link budget where it displays the losses and gains (in power ratios called dB/dBm/dBi) of a communications signal as it traverses from a transmitter to a receiver through a channel (in this case, air).

The ADS–R A2A transceiver is a line-of-site type of communication. In other words, there are no buildings, trees, or barriers obstructing the path. As AVs are flying at high speeds at higher altitudes, there are other channel attenuations that affect the signal, but in general, there are no large barriers as there might be for lower altitude AVs, such as small unmanned AVs (drones).

The RF link budget is slightly different than a Long-Term Evolution (LTE) link budget, a satellite link budget, or a radar link budget. Thus, each portion of the RF link budget will be itemized and explained. As a double check, and to illustrate that there are multiple ways of doing link budgets, two approaches are shown.

5.1 ADS–R Link Budget Approach 1

The ADS–R technology is not yet fully defined. It is estimated that the technology will be used in the 80- to 90-GHz RF frequency range, where the current ADS–B RF frequency is at 1 GHz. Likewise, the current ADS–B BW is ~1 MHz, whereas the ADS–R BW is flexible and undefined currently and, due to the flooding algorithm, is estimated to take up to 10 MHz BW. For this link budget, the ADS–R BW will be kept at 1 MHz.

Another attribute of the ADS–R transceiver is that the typical AV maximum transmit power level is 5 W and the minimum is 100 mW, even though current ADS–B transmit power can be as high as 250 W.

Finally, like ADS–B, the ADS–R sync signal comes from the Global Positioning System (GPS), where it is assumed all ADS–R transmitters will transmit at the same epoch time, every second, where at this time, only one isotropic antenna will be on each AV, thus the antenna gain for both transmit and receive antennas is 0 dBi.

The ADS–R transmitter portion of the link budget, also known as the effective isotropic radiated power (EIRP), is shown in Table 32.

It is important to note that the ADS–R transmitter's noise figure (NF) is assumed to be modeled after a typical satellite receiver RF transmitter. This parameter can be altered once the ADS–R transmitter is designed and more information is known.

The next part of the link budget is to look at the receiver side of the equation. It assumed the same or similar ADS–R transceiver is used on the receiving AV, thus the AV NF is the same as the transmitter's. The calculation for noise density—general channel thermal noise normalized to Hz—is shown in Table 33.

TABLE 32.—ADS–R LINK BUDGET: TRANSMITTER SIDE

Parameter	Transmitter parameters	Comments
AV transmit power	5.0 W	Main input parameter for link budget
	7.0 dB	
	37.0 dBm	
AV antenna gain	0 dBi	Omnidirectional antenna
AV noise figure (NF)	1 dB	Typical satellite receiver NF
Effective isotropic radiated power (EIRP)	38.0 dBm	

TABLE 33.—NOISE DENSITY CALCULATION

Boltzmann constant, *k*, J/K	1.38×10^{-23}
Temperature, *T*, K	290
Bandwidth, *BW*	1
kTBW	4.00×10^{-21}
kTBW, dB	–203.98
kTBW, dBm	–173.98

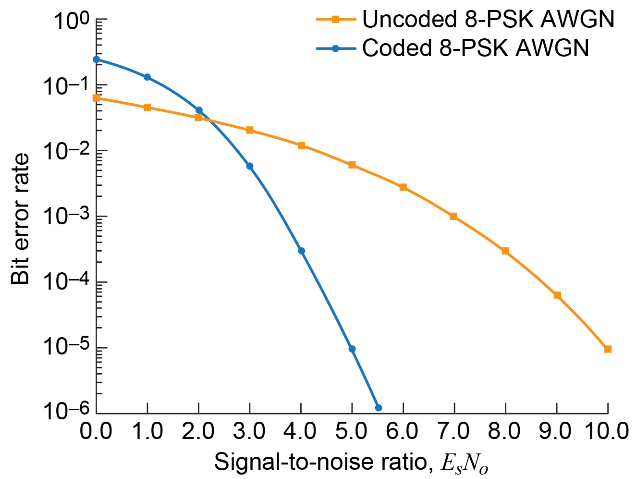

Figure 29.—Bit error rate versus normalized signal-to-noise ratio, E_sN_o. Phase-shift keying, PSK; phase-additive white Gaussian noise, AWGN.

The current ADS–B waveform is 8-DPSK (differential phase-shift keying) with a FEC where its close-the-loop BER of 1×10^{-6} is at signal-to-noise ratio (SNR) 5.5 dB. (SNR normalized to one symbol is defined as E_sN_o, also known as SNR per symbol.) This is shown in Figure 29.

Because the transmitter and receiver antennas are omnidirectional, there is no gain with each antenna. Likewise, it is assumed no multiple-input/multiple-output (MIMO) technology is being used for this version of ADS–R. Thus, there is no line item for MIMO gain, but this may be added in the future. Because there is not much cabling between receiver and antenna, a 1-dB loss is assumed in the cabling.

When all gains and losses identified are added, the receiver's sensitivity = –106.5 dBm. Table 34 shows the receiver sensitivity calculation.

Now assume a worst-case fade margin due to a Fresnel coefficient of 2 dB. When EIRP, the AV sensitivity, and the fade margin are added, the maximum allowable path loss (MAPL) is obtained, which is inputted into the Friis free-space path loss (FSPL) equation (Ref. 4), as in Table 35.

Using the Friis free-space equation, the maximum distance of communication between transmitter and receiver is calculated, Table 36. The Friis free-space equation is

$$\text{FSPL(dB)} = 20\times\log_{10}(d\,(\text{in km})) + 20\times\log_{10}(f\,(\text{in GHz})) + 92.45 \quad (2)$$

Without altering any values in the link budget other than the transmitter's wattage, Table 37 shows the maximum coverage distance per transmitter watts using the Friis free-space equation.

TABLE 34.—RECEIVER SENSITIVITY CALCULATION

Parameter	Receiver	Comments
Thermal noise density	–174.0 dBm/Hz	
AV noise figure (NF)	1 dB	Typical satellite receiver NF
Bandwidth (BW)	1.00×10^{-6} MHz	
Noise BW	60 dBHz	
Noise power	–113.0 dBm	
Normalized signal-to-noise ratio per bit, E_bN_o, at 1×10^{-6} BER for ADS–B	8.5 dB	
Transmission mode	8-DPSK	
Signal-to-noise ratio	5.5 dB	
AV receiver sensitivity—Step 1	–107.5 dBm	
Antenna gain	0 dBi	Omnidirectional antenna
Cable loss	1 dB	
Antenna diversity gain	0 dBi	Assume only one antenna
AV receiver sensitivity—Step 2 Final	–106.5 dBm	

TABLE 35.—MAXIMUM ALLOWABLE PATH LOSS

Parameter	Value
Effective isotropic radiated power (EIRP)	38.0 dBm
Aeronautical fade margin (a loss factor)[a]	2 dB
Maximum allowable path loss (MAPL)	38.0 dBm

[a]Due to flying in air will be added by Fresnel dB impact.

TABLE 36.—MAXIMUM DISTANCE TRANSMITTER TO RECEIVER CALCULATION
[Friis Free-Space Path Loss Model.]

Free-space path loss	142.5 dB
Radiofrequency carrier frequency	90 GHz
Free-space distance calculation	39.08 dB
Constant for km	92.45
Calculation 1	0.5
Maximum distance to communicate	3.5 km
Maximum distance to communicate	2.1 nmi

TABLE 37.—MAXIMUM DISTANCE PER TRANSMITTER WATTS

AV transmit power			Max distance	
W	dB	dBm	km	nmi
5.000	7.0	37.0	3.5	2.1
3.000	4.8	34.8	2.7	1.6
1.000	0.0	30.0	1.6	1.0
0.500	–3.0	27.0	1.1	0.7
0.200	–7.0	23.0	0.7	0.4
0.100	–10.0	20.0	0.5	0.3

For these E-band frequencies, there are three more attenuation parameters that need to be taken into consideration: (1) oxygen (atmospheric), (2) rain, and (3) scattering near the surface of the receiving antenna on the aerial vehicle.

Figure 30 shows the dB/km effect for oxygen. Because this is in the 80 to 90 GHz range, a worst-case effect of 0.2 dB/km has been chosen. Adding this impairment lowers the maximum distance slightly to 3.25 km.

Table 38 shows the maximum communication distance (in nmi and km) for free space, air, and rain.

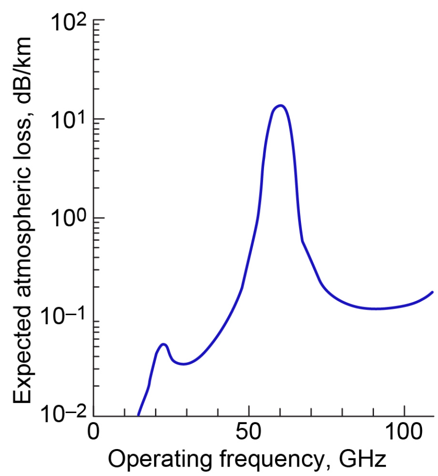

Figure 30.—Atmospheric path versus frequency.

TABLE 38.—MAXIMUM COMMUNICATION DISTANCE: RAIN, OXYGEN, FREE SPACE

	Rain + oxygen	Oxygen	Free space
AV receiver sensitivity, dBm Step 2 Final	–106.5	–106.5	–106.5
Aeronautical fade margin (loss), dB	2	2	2
Expected maximum distance, km	3.5	3.5	3.5
α_{rain}, dB/km	5	0	0
Actual α_{rain}, dB	17.5	0	0
α_{oxy}, dB/km	0.2	0.2	0
Actual α_{oxy}, dB	0.7	0.7	0
Maximum allowable power loss (MAPL), dB	–124.3	–141.8	–142.5
Now that MAPL is established, determine maximum distance in free space.			
Free-space path loss (FSPL), dB	124.3	141.8	142.5
RF carrier frequency, GHz	90	90	90
Free-space distance calculation, dB	39.08	39.08	39.08
Constant for km	92.45	92.45	92.45
Calculation 1	–0.4	0.5	0.5
Maximum distance to communicate, km	0.43	3.25	3.52
Maximum distance to communicate, nmi	0.26	1.95	2.11

Another cause of signal attenuation that must sometimes be taken into consideration is rain. It is important to note that rain effect will not occur beyond ~10,000 ft in altitude, so depending on AV type, this may not be an issue. At our frequency of interest, 90 GHz, and a moderate rainfall rate of 4 mm/hr, attenuation of around 5 dB/km can be expected based on established data for rain attenuation versus frequency and rain rate (Ref. 5). This drastically reduces the maximum transmission range to 0.43 km.

5.2 ADS–R Link Budget Approach 2

There is another free-space equation used for vehicle-to-vehicle E-band link budget calculations that is based on empirical data (Ref. 6). The curve fit closed-form equation is

$$L_p(\text{dB}) = 20 \times \log_{10}\left(\frac{4\pi d}{\lambda}\right) \tag{3}$$

where L_p is path loss, λ is wavelength (in meters), and d is distance.

The Friis free-space equation used in Approach 1 is the standard free-space equation used for most RF link budgets to date. Likewise, Approach 2 starts by first finding the MAPL = FSPL = L_p in dB per distance and wavelength as inputs, as shown in Table 39.

As will be shown shortly, using the FSPL equation shows that 3.52 km will meet the 5.5-dB “closing-the-loop” ADS–B limit.

Once the FSPL is set, the link budget is backtracked to find receiver sensitivity, which includes path loss, EIRP, and gain line items, as shown in Table 40.

TABLE 39.—ADS–R LINK BUDGET APPROACH 2

	Rain + oxygen	Oxygen	Free space
Frequency, GHz	90	90	90
Wavelength, λ, m	0.003	0.003	0.003
Distance, d, m	3,520	3,520	3,520
FSPL, dB	142.5	142.5	142.5

TABLE 40.—LINK BUDGET: RAIN, OXYGEN, FREE SPACE

	Rain + oxygen	Oxygen	Free space
Transmission power, W	5	5	5
Transmission power, dB	7	7	7
Transmission power, dBm	37	37	37
α_{rain}, dB/km	5	0	0
Actual α_{rain}, dB	22	0	0
α_{oxy}, dB/km	0.2	0.2	0
Actual α_{oxy}, dB	0.9	0.9	0.0
Transmitter gain, G_{tx}, dBi	0	0	0
Receiver gain, G_{rx}, dBi	0	0	0
Receiver signal power, dBm	–130	–108	–107

For contrast, three different path loss sensitivities are shown to assist in understanding how each channel attenuation affects receiver sensitivity. The higher the sensitivity, the better the receiver's performance, which allows for longer distance in connecting with the transmitter.

Once we know received signal power, P_o (dB), and symbol rate (assume ADS–B symbol rate of ~1 MHz), we can determine energy per symbol, E_s. Next, the one-sided noise power spectral density, N_o, at the receiver is calculated:

$$N_o = NF \text{ (receiver noise figure)} \times k \text{ (Boltzmann constant)} \times \text{K (temperature in Kelvin)} \quad (4)$$

Having E_s and N_o, we now can get the energy per symbol, E_sN_o, needed to meet the distance requirement for that E-band frequency, which for 4.4 km at 90 GHz will close the loop at 5.6 dB for FSPL, as seen in Table 41.

As the two final attenuations of atmosphere and rain are determined by the distance, Figure 31 can be used to quickly determine the distance per attenuation scenario per "closing the loop" SNR as related to the FSPL equation.

TABLE 41.—E_sN_o CALCULATION

	Rain + oxygen	Oxygen	Free space
Noise figure (NF) receiver, dB	1	1	1
Data rate, R, bps	3.00×10^{6}	3.00×10^{6}	3.00×10^{6}
System noise temperature, T_s, K	290	290	290
Boltzmann constant, k	1.38×10^{-23}	1.38×10^{-23}	1.38×10^{-23}
Quadrature phase-shift keying (QPSK) waveform, k_{BPS}	3	3	3
Data rate, R, symbols/s	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}
E_s, dB	–185.8	–168.2	–167.5
N_o, dB	–173.0	–173.0	–173.0
E_sN_o, dB	–12.8	4.8	5.5

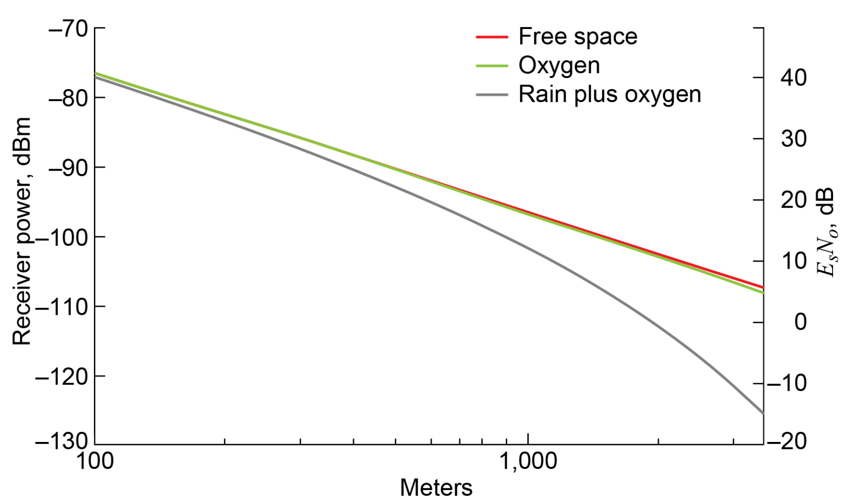

Figure 31.—90-GHz attenuation versus distance showing effect of rain; 5-W transmit power link budget.

TABLE 42.—COMPARISON OF TWO LINK BUDGET APPROACHES

Design	Approach 1			Approach 2		
	Distance, km			Distance, km		
	Free space	Oxygen	Rain + oxygen	Free space	Oxygen	Rain + oxygen
5 W	3.52	3.27	1.47	3.52	3.27	1.64
250 W	24.89	16.90	3.35	24.78	16.82	3.35
5 W + transmitter gain G_{tx} + receiver gain G_{rx} = 10 dBi	35.20	21.50	3.75	35.04	21.41	3.74
	Distance, nmi			Distance, nmi		
5 W	2.1	2.0	0.9	2.1	2.0	1.0
250 W	14.9	10.1	2.0	14.9	10.1	2.0
5 W + G_{tx} + G_{rx} = 10 dBi	21.1	12.9	2.3	21.0	12.8	2.2

To capture some design extremes for the two attenuation parameters, one design approach adjusts the transmitter gain from 5 to 250 W, the point at which the current ADS–B technology is optimal. Another design approach is to keep the transmit power at 5 W, but add directional antennas to both the transmitting and receiving sides of 10 dBi. Table 42 shows the distances per link budget approach, per link budget design approach.

As seen in Table 42, the maximum distances for oxygen and oxygen plus rain differ between the two approaches. The reason is that Approach 1 keeps the maximum distance constant across the free-space length, whereas Approach 2 allows for adjustments. Thus, Approach 2 is the more accurate approach, unless one were to go back and alter the maximum distance for rain attenuation to the correct distance.

5.3 ADS–R Link Budget Approach 3

Within the MATLAB® Communications Toolbox is a graphical user interface (GUI) satellite communications toolbox that can be used as a double check for a RF transceiver link budget. Table 43 shows the parameters for this approach. Table 44 shows the values used for both rain and oxygen fading (using the fourth design simulation from a previous section) and is used to double-check the results from the first two approaches. This double check is only for the DL. But for an RF link, A2A, the DL and uplink (UL) generally have the same parameters, thus the same link budget.

The fourth design is for an AV RF link budget where 5 W at the transmitter is used, as for the design 1 baseline, but this time 3-dBi isotropic antenna gains are added for both transmitting and receiving antennas. This isotropic antenna design is a new design that may be used for isotropic antennas for smaller AVs. This is not MIMO.

First, the free-space MAPL = FSPL = 148.5 dB for the ADS–R model. This is also calculated using the MATLAB® Satellite Link Budget model.

Second, increasing the antenna gains increased the free-space maximum distance to 7 km. This is shown in both models; in Approach 2, FSPL output is 7,000 m.

For the satellite link budget, the final signal to noise (S/N, also known as SNR and E_sN_o) only shows the final oxygen-plus-rain value of –33.17 dB, which is very close to the –30.9 value in the ADS–R model. Further investigation is needed to determine why the rain attenuation dB/km seems to be different with the MATLAB® model than with the ADS–R rain fading model.

TABLE 43.—ADS–R LINK BUDGET:
MATLAB® TOOLBOX APPROACH

Parameter	Transmitter
AV transmit power	5.0 W
AV transmit power	7.0 dB
AV transmit power	37.0 dBm
AV antenna gain	3 dBi
AV noise figure (NF)	1 dB
EIRP	41.0 dBm
Parameter	**Receiver**
Thermal noise density	–174.0 dBm/Hz
AV NF	1 dBb
Bandwidth (BW)	1.00×10^{-6} MHz
Noise BW	60 dBHz
Receiver noise power	–113.0 dBm
E_b/N_o at 1×10^{-6} BER for ADS–B	8.5 dB
Transmission mode	8-DPSK
Signal-to-noise ratio	5.5 dB
AV receiver sensitivity—Step 1	–107.5 dBm
Antenna gain	3 dBi
Cable loss	1 dB
Antenna diversity gain	0 dBi
AV receiver sensitivity—Step 2 Final	–109.5 dBm
Aeronautical fade margin (a loss factor)	2 dB
Maximum allowable path loss (MAPL)	–148.5 dB

TABLE 44.—E_sN_o FOR RAIN, OXYGEN, FREE SPACE:
MATLAB® COMMUNICATIONS TOOLBOX APPROACH

	Rain + oxygen	Oxygen	Free space
Frequency, GHz	90	90	90
Wavelength, λ, m	0.00333	0.00333	0.00333
Distance, m	7,000	7,000	7,000
Free-space path loss (FSPL), dB	148.4	148.4	148.4
Transmission power, W	5	5	5
Transmission power, dB	7	7	7
Transmission power, dBm	37	37	37
α_{rain}, dB/km	5	0	0
Actual α_{rain}, dB	35	0	0
α_{oxy}, dB/km	0.2	0.2	0
Actual α_{oxy}, dB	1.4	1.4	0.0
Aeronautical fade margin (loss)	2.0	2.0	2.0
Transmitter gain, G_{tx}, dBi	3	3	3
Receiver gain, G_{rx}, dBi	3	3	3
Receiver signal power, dBm	–144	–109	–107
Noise figure receiver, dB	1	1	1
Data rate, R, bps	3.00×10^{6}	3.00×10^{6}	3.00×10^{6}
T_s, K	290	290	290
Boltzmann constant, k	1.38×10^{-23}	1.38×10^{-23}	1.38×10^{-23}
Quadrature phase-shift keying (QPSK) waveform, k_{BPS}	3	3	3
Data rate, R, symbols/s	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}
E_s, dB	-203.8	–168.8	–167.4
N_o, dB	–173.0	–173.0	–173.0
E_sN_o, dB	–30.9	4.1	5.5

5.4 ADS–R Link Budget Summary

From an ADS–R flooding distance perspective, as wattage is decreased, K must be increased to ensure all AVs are contacted. The current simulation work is trying to determine how much K is needed, and for what densities of AV.

The initial three link budget design approaches show the extremes of the ADS–R link budget; these extremes should be taken into consideration when determining which d_t and K values to simulate.

Further work is needed to add the scattering and/or Fresnel fading attenuations for high-flying AVs and multipath fading for lower flying drones to the model to get a more precise link budget.

6.0 Concluding Remarks

A versatile methodology to verify Automatic Dependent Surveillance Rebroadcast (ADS–R) communications success with diverse topologies and vehicle densities was demonstrated. Moving forward, it is desired to apply this methodology to future NASA projects, including aerial vehicle (AV) detection and avoidance and enhanced situational awareness using the flooding algorithm for AVs two or three times beyond direct line of sight, all using the NASA spectrum at 81 GHz.

Appendix A.—Nomenclature

Symbols

B	broadcast
BW	bandwidth
d	distance
d_f	flooding transmission distance
d_{ml}	maximum distance due to link budget allotted power
d_{ms}	maximum spacing distance
d_t	transmission distance
E_b	energy per bit
E_bN_o	normalized signal-to-noise ratio per bit
E_s	energy per symbol
E_sN_o	normalized signal-to-noise ratio (scaled to one symbol)
f	frequency
G_{rx}	receiver gain
G_{tx}	transmitter gain
K	adjacent vehicles
k	Boltzmann constant
k_{BPS}	bits-to-symbols multiplier for QPSK modulation
L_p	path loss
n	number of nodes
N_o	noise density
NB	not broadcast
p	probability of broadcast
P_o	received signal power
Pcm	probability of critical message success
R	data rate
S	possible outcome
$T(n-i)$	subtree
T_s	noise temperature
V	vehicle
α	attenuation
λ	wavelength

Acronyms

A2A	air to air
A2G	air to ground
ADS–B	Automatic Dependent Surveillance Broadcast

ADS–R	Automatic Dependent Surveillance Rebroadcast
ATC	air traffic control
AV	aerial vehicle
AWGN	additive white Gaussian noise
BER	bit error rate
BW	bandwidth
DDA	digital differential analyzer
DL	downlink
DPSK	differential phase-shift keying
EIRP	effective isotropic radiated power
FEC	forward error correction
FSPL	free-space path loss
GPS	Global Positioning System
GUI	graphical user interface
ICAO	International Civil Aviation Organization
LTE	Long-Term Evolution
MAPL	maximum allowable path loss
MIMO	multiple-input/multiple-output
NAS	National Airspace System
NF	noise figure
PSK	phase-shift keying
QPSK	quadrature phase-shift keying
RF	radiofrequency
SAPF	speed adaptive probabilistic flooding
SNR	signal-to-noise ratio
TDMA	time-division multiple access
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
UL	uplink
VANET	vehicular ad hoc network

Appendix B.—Quantity Definitions

Ave Flooding Distance (nmi).—Average distance, using the flooding algorithm, that a message propagates.

Ave Iterations, AVs Communicate to All.—Number of iterations for AVs within the area to communicate to all AVs on average, meeting the flooding expectation. If the optimized *Ave* is 10, this means that on average there will be 10 iterations to contact all AVs.

Ave No. AVs in Vicinity Contacted Per AV.—Average number of AVs, using the flooding algorithm, that a specific AV transmitter has transmitted to within K^*d_t flooding transmission cartesian area.

AVs Communicating to All AVs (percent).—Percentage of AVs in a given area that have fully communicated to all AVs within the area; for example, if there are 100 AVs in the entire area of interest and the value for this parameter is 1 percent, this means 1 AV of the 100 AVs currently flying in the area is communicating its message to all AVs in the area as a result of the flooding algorithm.

Flooding Transmission Distance (nmi).—Flooding effective transmission distance due to the *K* parameter (number of adjacent vehicles); for example, if the link budget transmission distance is 1 nmi for a transmitter, the flooding transmission distance (d_f) is K*1.0 nmi—in effect, allowing communication to additional linear and forward-looking adjacent AVs.

Max Flooding Distance (nmi).—Longest distance an AV message is propagated via the flooding algorithm in a simulation.

Max Iterations, AVs Communicate to All.—Greatest number of iterations to communicate to all AVs, thus, the worst-case communication timeframe.

Max No. AVs in Vicinity Contacted Per AV.—Maximum number of AVs, using the flooding algorithm, that a specific AV transmitter has transmitted to within K^*d_t flooding transmission cartesian area.

Min Flooding Distance (nmi).—Minimum distance a message is propagated using the flooding algorithm. This quantity should never be zero, as that would indicate a problem with the simulation, but it could be a very small distance due to one AV being very close to another.

Min Iterations, AVs Communicate to All.— Least number of iterations to communicate to all AVs, thus, the best-case communication timeframe.

Min No. AVs in Vicinity Contacted Per AV.—Minimum number of AVs, using the flooding algorithm, that a specific AV transmitter has transmitted to within K^*d_t flooding transmission cartesian area.

Overall N Contacted (percent).—Percentage of AVs in a given area that have been contacted. This does not mean that all AVs have had the same message communicated to them yet; that occurs when the next parameter, *AVs Communicating to All AVs*, is at least >0 percent.

Pcm (percent).—Value identifying the optimized amount of critical message communication between transmitter and receiver within *Transmission Distance Per AV* distance of transmitter. Any communication above the *Pcm* will add unnecessary messaging between transceivers, thus overflooding the network.

Radial Position of Flooding Max (nmi).—Radial position of the AV that has the *Max Flooding Distance*. This was captured to see if any trends are observed in certain topology densities as to where the largest flooding distance is occurring.

Radial Position of Starting AV for Max Per AV (nmi).—Radial position of the originating AV, as measured from the airport, for maximum number of AVs contacted in the K^*d_t flooding transmission cartesian area.

Transmission Distance Per AV (nmi).—Link-budget-determined distance that a transmitter has to send the signal.

Vicinity Contacted.—Number of AVs per K^*d_t (maximum flooding distance) that one AV has contacted in its general cartesian area.

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