

SIZING UP MIMO ARRAYS



Capacity Analysis Methodology and Performance Evaluation for Indoor Environments

Multiple-input multiple-output (MIMO) systems make use of multiple antennas at the transmitter and receiver sides to offer significant increases in data rates and link robustness at the same bandwidth and overall transmit power [1] as a single-input single-output (SISO) system in the presence of a scattering-rich environment. The performance of MIMO communication links is often evaluated using capacity as a performance measure [1], as it approximates the throughput in the presence of good error cor-

recting codes and adaptive modulation. Evaluation of the MIMO channel capacity requires knowledge of the wireless propagation channel, which can be obtained by carrying out channel measurements. In some cases, however, it is not possible to obtain channel measurements easily or there might not be sufficient channel data available to evaluate the MIMO channel capacity in that location. In this article, we describe a capacity evaluation methodology that relies on channel measurement data or output of ray-tracing simulations to obtain channel parameters, which can then be used to evaluate MIMO channel capacity. The available channel measurements (if

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any) can be used to validate results obtained from ray-tracing simulations.

In this article, we illustrate the proposed methodology by applying it to wireless deployment in aircraft, to reduce expenditure associated with the installation and maintenance of wires for seatback entertainment. The large data rates required can be easily supported by MIMO systems. However, the interior of an aircraft appears at first to be a hostile environment for MIMO communication. Specifically, it is unclear if the hollow-tube structure of the aircraft will provide the scattering-rich environment that is needed to make MIMO feasible in terms of performance gains. While one line of thought likens the airplane structure to a hollow waveguide that does not support scattering, another line of thought is that the multimodal structure of hollow tubes will cause sufficiently low spatial correlation between multipath components to make MIMO feasible. Unfortunately, due to limited aircraft availability because of tight construction and maintenance schedules, measurements cannot be easily taken in aircraft. We applied the proposed capacity analysis methodology to show that performance gains are indeed possible in aircraft. Ray-tracing simulations are carried out using electromagnetic software to evaluate capacity and optimize antenna placement locations and/or antenna configurations. For our analysis, we carried out the ray-tracing simulations in Site-Specific System Simulator for Wireless System Design (S^4W) (a three-dimensional (3-D) ray-tracing simulator developed at Virginia Polytechnic Institute and State University, Blacksburg, Virginia [2]), for a number of client antennas distributed throughout the aircraft. While this methodology is described for aircraft (for illustration), it is easily extended for evaluating capacity and optimizing antenna placements and antenna array configurations in any indoor environment. We adopt the free-space path-loss model for our illustration, due to the lack of a path-loss model in literature for aircraft environments. The methodology can be extended to suit any general indoor path-loss model.

The deployment of wireless devices and systems in airplanes has raised a lot of concerns about safety due to the possibility of interference caused by the devices to aircraft navigation [3]. There has been extensive research and testing carried out by Boeing, Qualcomm [4], and Lufthansa [5] to establish that the operation of a wireless local area network (WLAN) in an airplane is safe and does not hinder the navigation of the airplane.

This article is organized as follows. In the next sections, we present an overview of the proposed capacity analysis methodology and detail the channel model adopted, as well as list the measurements obtained in the aircraft. We then describe the ray-tracing approach used to obtain channel data like the number of clusters, the mean angles of arrival and departure, and angular

spreads of each cluster and evaluate the capacity using the free-space path-loss model. Finally, the proposed method is validated, the results of the capacity analysis methodology are presented, and a conclusion is given.

Proposed Capacity Analysis Methodology

Figure 1 shows that the inputs to the channel generator block include the channel parameters [number of clusters, the mean angle of arrival (AoA) and angle of departure (AoD), and angular spread (AS) per cluster], the number of antennas and the array configurations at the transmit, and receive sides. These input parameters can be obtained from channel measurement data or the output of ray-tracing software (S^4W). The inputs for the S^4W simulator include the transmitter and receiver locations, antenna array configurations, and the propagation environment model. The channel generator is used to generate multiple channel realizations by Monte Carlo simulations with the number of clusters, mean AoD (or AoA), and angular spread per cluster. These multiple realizations ensure randomness due to scattering. The inputs to the capacity evaluation block are the multiple channel realizations, number of transmit and receive antennas, and the appropriate path-loss model. We use this information to generate the capacity of each communication link as a function of the distance between the transmit and receive antennas.

In our specific example, we have channel measurements for a single communication link in the aircraft. We use these measurements to show that deploying MIMO in aircraft yields performance gains and also to validate the ray-tracing simulator— S^4W , used to evaluate the performance of different arrays in aircraft environment. We also use S^4W to select access point (AP) and client antenna (CA) placement locations from the candidate locations. Due to the absence of path-loss models for an aircraft environment, we used the free-space path-loss model. Note that this is merely for illustration purposes.

In the following, we explain each of the blocks in greater detail. We first describe channel modeling and the procedure to generate multiple channel realizations, using either measurements or S^4W outputs. We then advance into capacity evaluation methodology and finally present the results.

Channel Modeling

Realistic channel models are necessary to estimate the capacity of a MIMO communication link without having to go through the expense of directly measuring it. There is extensive literature available on wireless channel models, both indoor [6], [7] and outdoor [8], [9]. Like all practical channels, the channel in an aircraft exhibits spatial correlation. One of the most popular models that includes correlation is the clustered channel model. In [10], Ingram and Van Nguyen show that channel models disregarding cluster effects overestimate channel capacity.

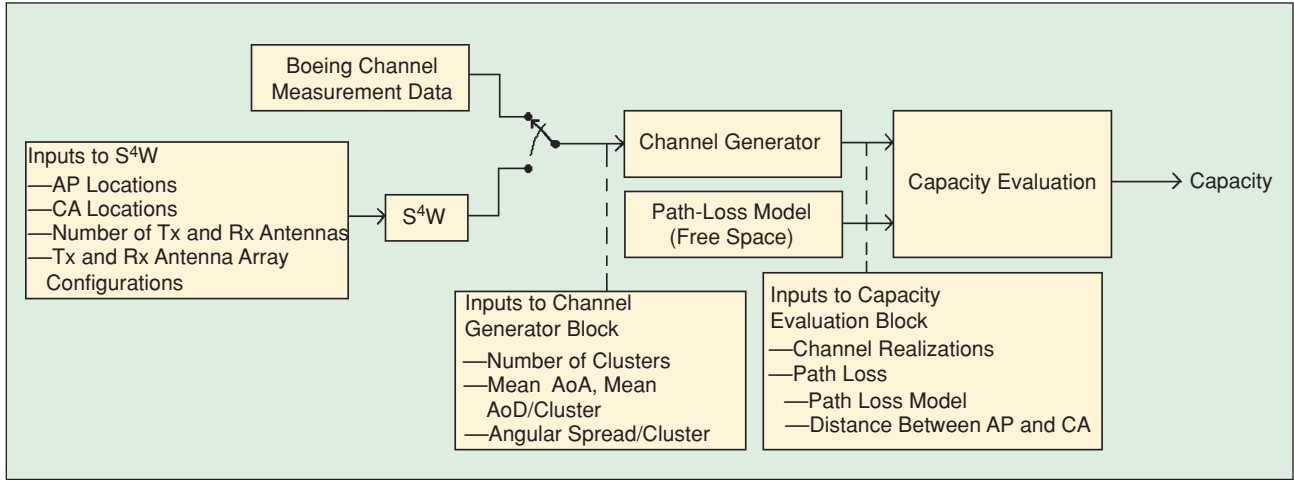


FIGURE 1 Capacity analysis methodology used for evaluating the MIMO system performance.

The earliest and most popular clustered indoor channel model was proposed by Saleh and Valenzuela and is called the Saleh-Valenzuela (SV) model [6]. In this model, received rays are grouped together in clusters, distinguished on the basis of time only. The SV model is only applicable to single antenna systems. It can be extended to multiple antenna systems through the use of both AoA (or AoD) and time to distinguish between clusters [11]. The proposed methodology makes use of the combined spatio-temporal clustered channel model to characterize the propagation environment within an aircraft.

Discrete-Time Propagation Modeling

The discrete-time impulse response of the clustered channel is found using a parametric approach. Ray tracing is used in the proposed methodology to predict the impulse response of the indoor wireless channel. Hence, the parametric model is the best option here. The discrete-time channel impulse response of a narrowband system is given by $\mathbf{H} = (1/\sqrt{L}) \sum_{l=0}^{L-1} \mathbf{H}_l$, where L is the number of clusters, and \mathbf{H}_l is the discrete-time impulse response of the l th cluster, given as

$$\mathbf{H}_l = \frac{1}{\sqrt{N}} \sum_{k=1}^N \alpha_k \sqrt{G_r(\phi_{kl}^r) G_t(\phi_{kl}^t)} \mathbf{a}_r(\phi_{kl}^r) \mathbf{a}_t^\dagger(\phi_{kl}^t), \quad (1)$$

where N stands for the number of rays in the cluster with k as the index, and α_k is the complex Rayleigh channel coefficient. The gains of the receive and transmit antennas at angles of ϕ_{kl}^r (AoA) and ϕ_{kl}^t (AoD) are given by $G_r(\phi_{kl}^r)$ and $G_t(\phi_{kl}^t)$, respectively, that can be obtained from antenna radiation pattern measurement campaigns. The receive and transmit array response vectors are given by \mathbf{a}_r and \mathbf{a}_t (given in [12]). Finally, $(\cdot)^\dagger$ stands for the Hermitian transpose. Note that (1) assumes that all the antennas in the array have the same radiation pattern. This can be easily generalized using more cumbersome notation.

The channel parameters required for this model are the number of clusters, the mean AoA, mean AoD, and angular spread per cluster. As shown in Figure 1, these parameters can be obtained from either channel measurements or from outputs of ray-tracing simulations.

Channel Measurements

Boeing provided channel measurement data, taken aboard the economy class of a Boeing-777 aircraft, for a single transmitter and receiver location, using monopole antennas. The channel parameters were obtained using angular delay spectrograms (angle versus time and power color plots) for both the transmit and receive sides using a measurement setup similar to that employed by Intel [13]. After empirically predicting clusters from the plots, parameters like AoD for the transmitter side, AoA for the receive side, and angular spreads were calculated. The results of the channel measurements are summarized in Table 1. (The channel parameters reported are obtained by truncating the actual parameters obtained from measurements.) We use this channel measurement data to show that performance gains are indeed possible in aircraft using MIMO systems.

We use the available limited measurement data to validate the proposed approach. In the absence of measurement data, channel parameters can be obtained using ray-tracing simulations as described in the next section.

TABLE 1 Channel Measurement Data from Boeing.

Cluster	AoD (Tx)	AS (Tx)	AoA (Rx)	AS (Rx)
Cluster 1	170°	20°	340°	20°
Cluster 2	180°	15°	350°	10°
Cluster 3	210°	20°	20°	10°
Cluster 4	10°	10°	340°	20°

Application of Ray-Tracing Software

In the event that measurements are not available or not sufficient, we can apply ray-tracing software to obtain channel parameters by the method described in this section. These channel parameters, after proper validation, can be used for applications like optimizing antenna placement locations for the access point and client antennas in the indoor environment, determining which antenna array configuration yields the best data rate, estimating coverage area, etc. We apply ray-tracing simulations to evaluate performance for the first two applications in the aircraft scenario.

There are four essential steps to obtaining channel parameters using ray-tracing software, as follows.

- 1) Ray-tracing software (S^4W , in our case) require a construction of the actual propagation environment. This is why they are known as site-specific models. In our case, we constructed 3-D models of the aircraft, complete with details like aircraft curvature, seat loca-

tions, and material properties for added accuracy. (The material properties of aircraft materials were provided to us by Boeing and cannot be disclosed due to a confidentiality agreement.) This is illustrated in Figure 2. Note that it is necessary to make the 3-D model as accurate as possible. It is also essential to define a reference frame for the coordinate axes in the model.

- 2) The second step is to place the access point and client antennas at the desired locations in the 3-D model. The details of the antenna locations are fed into the ray-tracing software using the coordinates of the locations in the 3-D model constructed. In the aircraft scenario, we place the access point and client antennas at the locations shown in Figure 3. We place 12 client antennas in a uniform fashion across the aircraft to obtain a distribution of the capacity across the aircraft. Figure 3(a) shows that there are four possible antenna placement locations. The squares and circles represent the access point and client antenna locations, respectively. Using the methodology we described in the “Proposed Capacity Analysis Methodology” section, we determine which of these four locations is the best option.
- 3) After ensuring that the simulation set-up is complete, we use the 3-D models generated to run S^4W simulations for each of the 12 client antenna locations. These simulations are run for each of the four

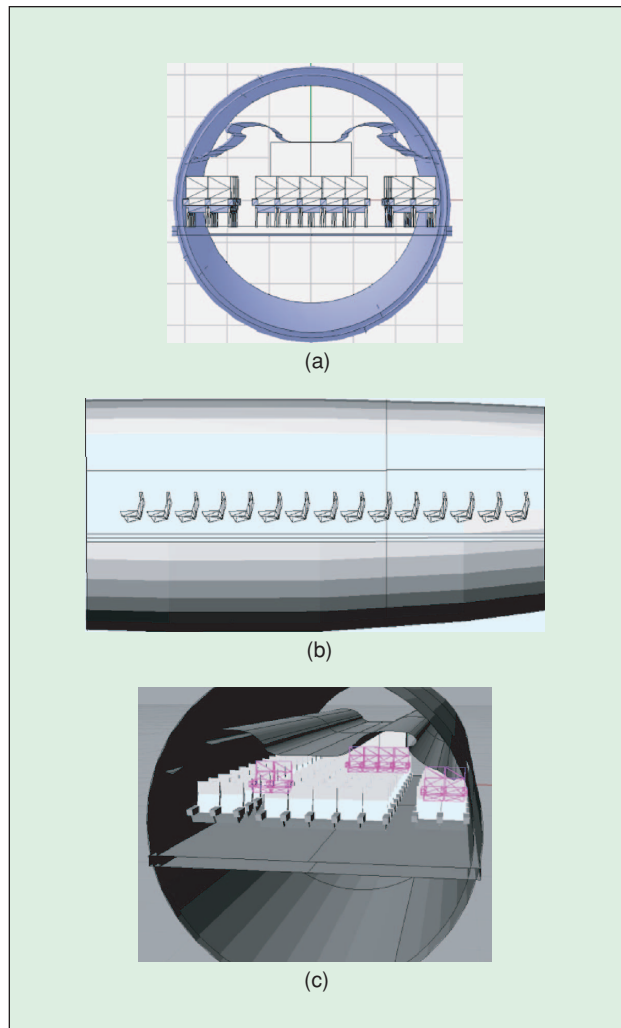


FIGURE 2 Different views of the 3D model constructed for simulations in S^4W . (a) Front view, (b) side view, and (c) perspective view.

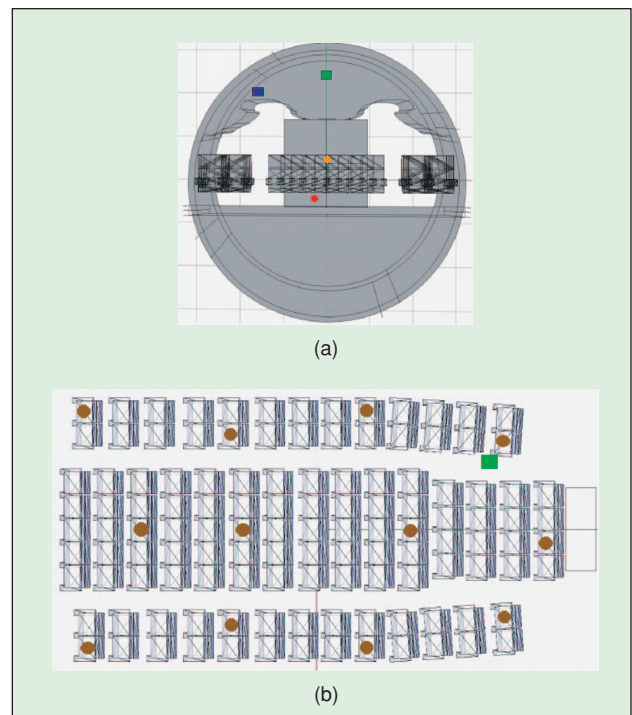


FIGURE 3 Simulation set-up, showing the (a) two AP and two CA candidate locations and (b) location of the access point (square) and 12 client antennas (circles) in a model of the economy class of Boeing-777.

possible access point–client antenna locations. The outputs of the S^4W simulations include the AoD, AoA, power, and time of arrival of each of the rays at the client antenna.

- 4) The S^4W outputs are then used to obtain channel parameters using the spatio-temporal clustered channel model that identifies clusters on the basis of both time and similar AoDs (or AoAs). For the aircraft scenario, we used the S^4W outputs of each of the 12 client antenna placements to generate power-angle-delay plots. An example of this plot is illustrated in Figure 4. It is clear from the figure that there are four distinct clusters. The mean AoA and AS of each of the clusters is obtained as a mean and standard deviation, respectively, of the AoAs within each cluster. For the example in Figure 4, we obtained the AoAs to be 275° , 260° , 230° , and 210° , with angular spreads of 20° , 20° , 20° , and 15° , respectively with respect to the broad-side of the array.

Capacity Analysis Methodology

Capacity has been used in the literature to evaluate the performance of MIMO arrays exploiting space, polarization, and pattern diversity in realistic spatially correlated channels [14], [15].

The inputs to the capacity evaluation block in Figure 1 are the channel realizations generated by (1), the number of transmit and receive antennas, and the path loss. By assuming that the process that generated the multiple channel realizations, over a particular location, is ergodic, the capacity of the MIMO systems is then evaluated as the ergodic mean of the capacity of the channel for each of these channel realizations.

The ergodic capacity is estimated by the sample mean given by

$$C(\rho) = \frac{1}{R} \sum_{r=0}^{R-1} \log_2 \det \left(\mathbf{I}_{M_R} + \frac{\rho}{M_T} \frac{\mathbf{H}^{(r)} (\mathbf{H}^{(r)})^*}{\frac{1}{RM_T M_R} \sum_{r=0}^{R-1} \|\mathbf{H}^{(r)}\|_F^2 L_o} \right) \frac{\text{b/s}}{\text{Hz}} \quad (2)$$

where ρ is the transmit signal-to-noise ratio (SNR), R is the number of channel realizations with r as the index, $\mathbf{H}^{(r)}$ is the r th channel realization and L_o is a loss factor in linear scale. In some cases, it might be necessary to evaluate the ergodic capacity that is only a function of channel quality and not a result of path-loss effects. To ensure a fair comparison with the independent identically distributed (i.i.d.) channel case, the normalization factor, $1/(RM_T M_R \sum_{r=0}^{R-1} \|\mathbf{H}^{(r)}\|_F^2 L_o)$ is included in (2). In

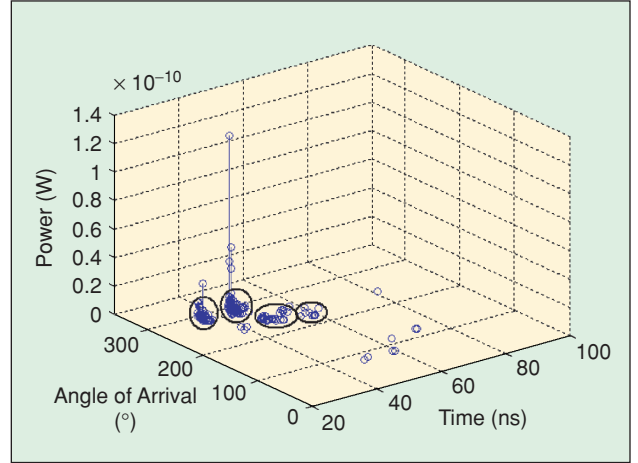


FIGURE 4 Example of a power-delay-angle plot used for estimating the number of clusters, the mean AoA and angular spread using S^4W outputs.

some other situations, like optimizing antenna placement locations, it is necessary to account for path loss. In such instances, we let the loss factor L_o be equal to the factor by which the transmit SNR will get reduced. When path loss is to be ignored, we use $L_o = 1$.

Path-Loss Model

Path-loss information in indoor channels is essential for determining the receive SNR and, hence, the coverage area. Thus, path-loss modeling is essential for selecting optimum antenna placement locations. Unfortunately, as there are no known verified path-loss models for an aircraft setting, we used the free-space path-loss model as a substitute. The free-space path loss is given by

$$PL = \frac{16\pi^2 d^2}{\lambda^2}, \quad (3)$$

where d is the distance between the transmitter and receiver in meters, and λ is the wavelength of the propagating wave. This is an extremely simplistic model that does not account for shadowing effects in the physical environment. We have used the free-space model for illustration purposes. For general indoor environments, the model can be replaced by any indoor path-loss model available in literature.

The impact of people on the performance of antennas for mobile phones has been studied in [16] and that of moving people on the channel impulse response in [17] for a WLAN. It has been shown in [16] that the received signal power was reduced by 3–4 dB when the impact of people was taken into account. This loss can be incorporated into the path-loss model. We will analyze the performance of MIMO systems, taking into account the effect of people seated and moving in the aircraft as a part of future work.

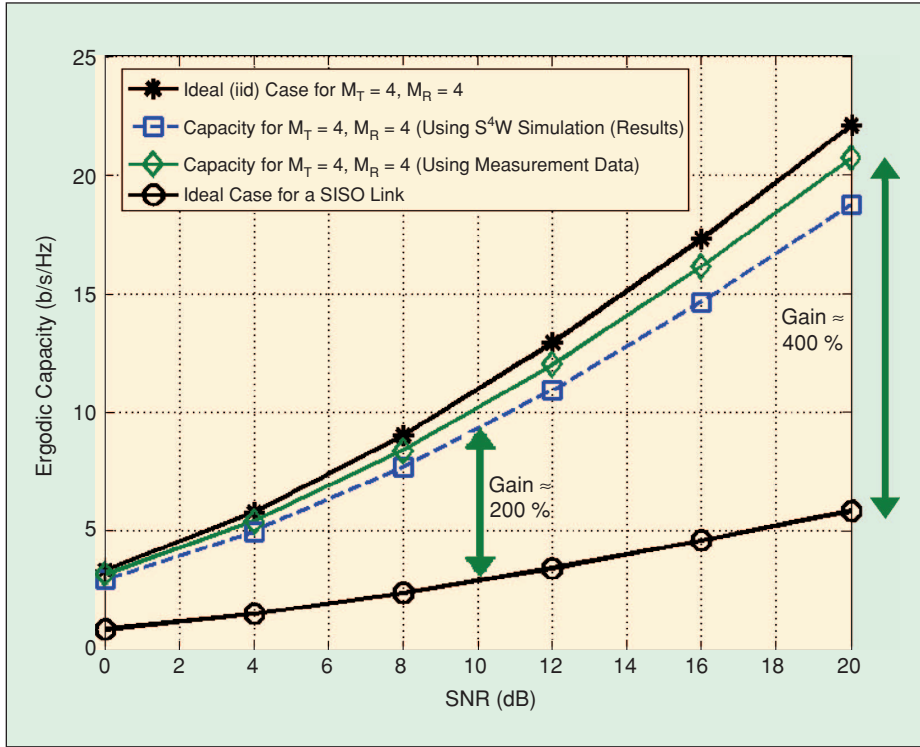


FIGURE 5 Capacity versus (transmit) SNR plot that shows the capacity gain for a 4×4 MIMO system over the SISO link. We can see that the capacity obtained using S^4W is in close approximation to that obtained from channel measurements.

Results

The results of the capacity analysis methodology described in Figure 1 are shown in this section for 4×4 MIMO systems. The antenna arrays employ vertically polarized monopoles. We consider the uniform linear, uniform circular and star array configurations mounted in the vertical plane.

Validation of the Ray-Tracing Approach

The single-link channel measurement data provided by Boeing is used to first show that capacity gains are attainable in aircraft using MIMO. The single-link measurements are then used to validate the ray-tracing approach detailed in the “Application of Ray-Tracing Software” section. In this section, we consider uniform linear arrays at the access point and client antennas, with an inter-element spacing of 1λ , where λ is the wavelength corresponding to the frequency of operation.

TABLE 2 Channel Parameters Measured Using S^4W for the Access Point and Client Antenna Locations Used by Boeing for Measurements.

Cluster	AoD (Tx)	AS (Tx)	AoA (Rx)	AS (Rx)
Cluster 1	155.25°	19.64°	29.52°	15.49°
Cluster 2	210.14°	9.83°	319.96°	39.48°
Cluster 3	139.56°	25.36°	49.06°	29.87°
Cluster 4	24.95°	18.29°	120.40°	20.07°

These data were first used to show that performance gains are possible in an aircraft. We compared the data rates obtained in the aircraft with that of the i.i.d. case and ignore path loss to make a fair comparison with the i.i.d. case. The results of the capacity analysis are shown in Figure 5. It is evident from the figure that implementing MIMO systems in aircraft yields significant gains (gains up to 400% at SNR = 20 dB) as compared to a SISO system.

We then proceeded to validate the results obtained from S^4W using the measurements provided. For the same link whose measurements were provided by Boeing, channel parameters were estimated using the approach described in the previous section (given in Table 2). Note that the values in Table 2 are obtained

using simulations, whereas the ones in Table 1 are actual measurements. They differ due to the approximations involved in the simulation process. The estimated channel parameters yield capacity shown by the dotted line in Figure 5. It is in close approximation to the one obtained from actual measurements. We thus validated the results obtained from S^4W using measurements taken aboard the aircraft.

Antenna Placement and Antenna Array Configuration

In this section, we provide the results of optimizing the antenna placement location and array configuration that involve simulations in S^4W to obtain channel parameters.

Antenna Placement Location

The optimum antenna placement location is chosen from among the four combinations of candidate AP-CA placement locations, as described previously. For each of the four combinations of the antenna placement locations, the receive SNR of the 12 MIMO communication links was calculated (using the free-space path-loss model, for a fixed transmit power of 20 mW) and used to evaluate the ergodic capacity of each link. The mean ergodic capacity and standard deviation of each AP-CA placement location are calculated as the average and standard deviation of the capacities of the 12 communication links shown in Figure 3 (listed in Table 3, for uniform linear arrays with four transmit and four receive antennas).

The optimum AP-CA placement is the location with the maximum mean and the lowest standard deviation. In our case, the optimum location for the AP and CA placement is above the ceiling panel and inside the display terminal, respectively. The values in Table 3 do not account for the attenuation effects of seats, ceiling panels, walls, etc. It is to be noted that the values obtained here are very high because the free-

space path-loss model does not take into account the shadowing effects caused by the seating arrangement. Also, in the free-space model, power decays as a function of the square of the distance. This may not be a true representation of the actual path-loss scenario in aircraft.

Antenna Configuration

We consider three commonly used array configurations—uniform linear array (ULA), uniform circular array (UCA) and the star configuration [12], using vertically polarized monopoles, as discussed previously. The interelement spacing for each of the configuration was selected to meet the maximum size constraints provided by Boeing. The maximum dimensions of the enclosure to house the anten-

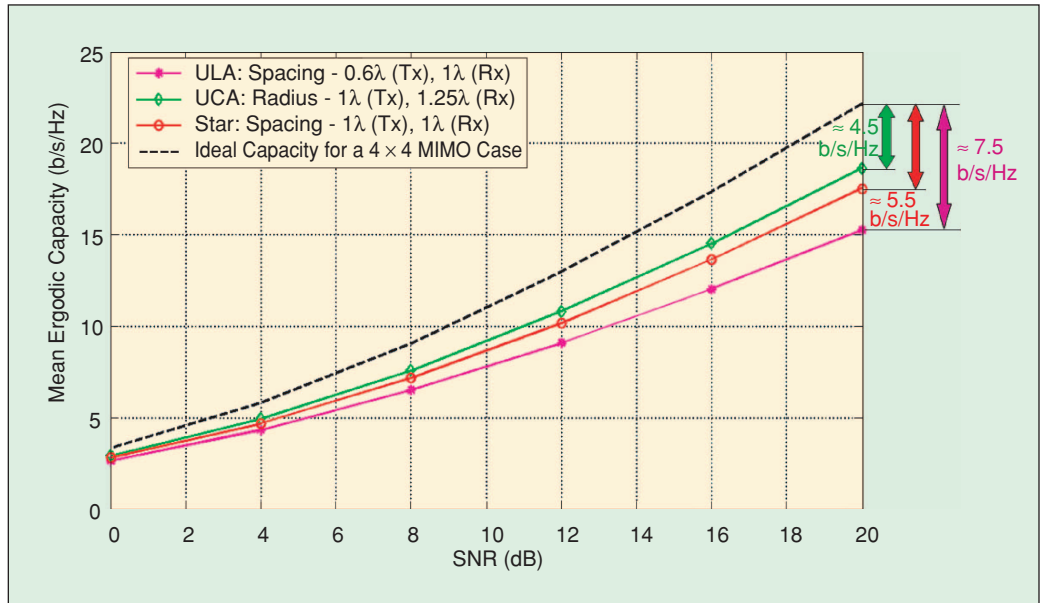


FIGURE 6 Comparison of the capacity obtained by using different array configurations at the AP and the CAs.

na arrays are given in Table 4. To estimate the actual array size permissible, we considered half of the dimension values given (so as to make space for wiring etc., as per Boeing specifications). The interelement spacing for each of the configuration was selected to meet these size constraints.

We choose the best antenna configuration for the transmit and receive antennas by placing the AP and CAs in Location 2 of Table 3, shown to be the optimum antenna placement location. The results of the simulations are shown in Figure 6 for symmetric configurations, i.e., the same antenna array configurations are used on the transmit and receive sides. Asymmetric configurations yield capacity curves that lie in between the ones shown. Figure 6 shows that the UCA gives the best rate gains as compared to the

TABLE 3 Results for AP and CA Placements.

Location	Access Point Location	Client Antenna Location	Mean Ergodic Capacity	Standard Deviation
1	Above ceiling panel	Below seat	26.61 b/s/Hz	10.23 b/s/Hz
2		Inside display terminal	32.37 b/s/Hz	8.82 b/s/Hz
3	Top of fuselage crown	Below seat	24 b/s/Hz	10.80 b/s/Hz
4		Inside display terminal	33 b/s/Hz	9.38 b/s/Hz

TABLE 4 Dimensions of Enclosures for the Antenna arrays (in inches).

Transmitter/ Receiver	Location	Dimensions	Comments
Transmitter	Ceiling panel	8 × 4 × 1	Large face against panel
	Fuselage crown	8 × 4 × 1	Large face against crown
Receiver	Below seat	12.5 × 9.4 × 2	Large face against seat legs
	Inside display terminal	9.4 × 7.4 × 1.4	Large face against seat back

other configurations, as it has the highest interelement spacing among the three configurations considered.

Conclusion

We proposed a capacity analysis methodology that can be used in situations where it is difficult to obtain measurements. This methodology, based on ray-tracing simulations, requires the construction of a realistic 3-D model of the propagation environment. We described a technique to obtain the parameters of a clustered channel model using the outputs of these ray-tracing simulations. We illustrated the given methodology for an aircraft scenario, where sufficient measurements were not available. We validated the proposed approach using single-link measurement data from a Boeing-777 aircraft.

Author Information

Ramya Bhagavatula (bhagavat@ece.utexas.edu) received her B.S. degree from Birla Institute of Technology and Sciences (BITS), Pilani-Dubai Campus in 2005. She received her M.S. degree in 2006 from The University of Texas at Austin in electrical engineering. She is currently pursuing her Ph.D. under the supervision of Dr. Robert W. Heath, Jr. in MIMO antenna design and channel modeling at the Wireless Networking and Communications Group, The University of Texas at Austin. She won the IEEE Best Student Paper award at the IEEE Vehicular Technology Conference, Spring 2007 in Dublin, Ireland. She was also the recipient of the Aileen S. Andrew Fellowship in 2007 and the David Bruton Jr. Fellowship 2007–2008.

Robert W. Heath Jr. (rheath@ece.utexas.edu) received the B.S. and M.S. degrees from the University of Virginia, Charlottesville in 1996 and 1997, respectively, and the Ph.D. degree from Stanford University, California in 2002, all in electrical engineering. He is currently an associate professor at The University of Texas at Austin and associate director of the Wireless Networking and Communications Group. He is the recipient of the David and Doris Lybarger Endowed Faculty Fellowship in Engineering and is a registered Professional Engineer in Texas. He is a Senior Member of the IEEE.

Sriram Vishwanath (sriram@ece.utexas.edu) received his B.S. at Indian Institute of Technology (IIT) Madras, M.S. from California Technical Institute (CalTech), and his Ph.D. from Stanford University, all in electrical engineering. He is currently at the University of Texas at Austin as an assistant professor in the department of Electrical and Computer Engineering. His research interests are in wireless systems and networks. His industry experience includes work at the National Semiconductor Corporation in California and at the Lucent Bell Labs, New Jersey. He received the ARO Young Investigator Award in 2007, the National Science Foundation Early CAREER award in 2005, and the IEEE Communications/ Information Theory Societies' Joint Best Paper Award in 2005.

Antonio Forenza (antonio@rearden.com) received the M.S. degree in telecommunications engineering from Politecnico di Torino, Italy, and Eurecom Institute, Sophia Antipolis, France, in 2001, and the Ph.D. degree in electrical engineering from The University of Texas at Austin in 2006. In 2001, he interned as a systems engineer at Iospan Wireless, Inc. over the summers of 2004 and 2005, as a research engineer at Samsung Advanced Institute of Technology (SAIT), Korea, and Freescale Semiconductor, Inc., Austin, Texas. Since June 2006, he has been working for Rearden, LLC, San Francisco, California, as a senior systems engineer. He authored the IEEE VTC'06 Best Student Paper and has published over 30 international journal and conference papers and standards contributions. His research interests include MIMO antenna design, adaptive MIMO transmission techniques, precoding methods for MU-MIMO, and smart antenna signal processing. He is a Member of the IEEE.

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