Networked Airborne Communications Using Adaptive Multi-Beam Directional Links

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***Abstract*—Advances in digital arrays provide new techniques for increasing throughput in airborne adaptive directional networks. By adaptive directional linking, we mean systems that can dynamically change both the transmit and receive spatial patterns used for a link on a packet-by-packet basis. Using several arrays at each node, and several beams per array, these systems are able to both focus transmit energy in favorable directions, and reject interference at reception. Our problem space overlaps considerably with Multiple Input Multiple Output (MIMO) systems and distributed MIMO, but differs in several important ways. First and foremost, our links are largely line of sight, and as such, typically have a maximum rank of one and little time variation; hence, point-to-point multi-stream and diversity techniques have little benefit. We do however consider multiple transmissions at each transmitting array face, not to a common receiver, but to several distributed receiving nodes. As we will show, the primary driver of network performance becomes geometry and array technology rather than channel phenomenology. We explore the utility of various spatial processing strategies both on the receive and transmit side of the networked links, and the gains associated with multiple simultaneous transmissions.**

I. Introduction

Adaptive multi-beam directional communication techniques can dramatically increase the capacity in airborne networks. Advances in digital array technology are beginning to put these gains within reach for the first time [1][2]. Although the individual techniques are straightforward—array processing, beamforming, interference suppression, and random access—together they yield impressive gains.

This paper is the first to investigate the tradeoff between different physical-layer algorithms and network-layer capacity in airborne networks. Physical-layer techniques range from simple naturally-weighted beamforming [3] to complex space-time adaptive processing [4]. Much of the foundational work on network performance, see [5], [6] for example, postulated networks of nodes that were omnidirectional, which leads to fairly simple scaling laws. The preferred metric there is transport capacity, measured in bit-meters per second, which is a distance-weighted average rate achieved for any randomly chosen source-destination pair, potentially hopping over several links. In these situations, throughput can be shown to scale as $1/\sqrt{n \log n}$ if interference is to be strictly avoided. Later works introduce more sophisticated channel models, and route selection by a method called percolation [7], [8]. For these examples, throughput can be shown to scale as $1/\sqrt{n}$. We will borrow the main idea of the percolation method, which is essentially a nearest neighbor routing strategy, to motivate our approach.

It is difficult to derive analytical results for network metrics as a function of the physical-layer beamforming technique; hence, we take a numerical analysis approach with high-fidelity simulations. Our numerical tools can compute with high accuracy the signal levels and interference contributions at each array (each node has several arrays) due to every other node in the network. Array processing algorithms can be implemented in a modular fashion at each receiving terminal. Together with detailed link budgets, communications rates can be computed, and other related network performance benchmarks.

For each simulation case, we compile statistics on three metrics: individual link rates, network sum capacity, and average network connectivity. We do not compute a network throughput, which would require evaluating message routing protocols. We define the network sum capacity as the sum of all active individual links and we define the average network connectivity for a given case as the percentage of all Monte Carlo trials where the airborne nodes and links between them form a connected graph.

The paper is organized as follows: first we visit the primary features of the simulation model we use. Second, we discuss the laydown of nodes, the link budget used to compute signal powers, and the issue of interference modeling. We then present the results of a series of simulation runs designed to reveal the interplay of the fundamental parameters influencing network performance. Network performance is measured by the sum capacity of the links formed and by the connectivity of the network. Finally, we will state our conclusions.

II. Network Modeling

In this section, we describe the procedure for laying down nodes, forming links between nodes, generating link budgets, computing interference, and computing the metrics.

A. Node Position Lay Down

We randomly position nodes within a box geometry where the z-axis extent is 1% of the x and y axis extents. For

Distribution A: Public Release. This work is sponsored by the Assistant Secretary of Defense for Research and Engineering under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government. This is in accordance with DoDI 5230.29, January 8, 2009.

example, at an altitude of 10 km, the horizon to horizon distance is about 700 km, and our vertical extent would be 7 km. To avoid unusual statistical anomalies associated with a pure Poisson point process, we have developed a node laydown procedure whereby *orderly* distributions of nodes is preferred, such as when a flight of communicating nodes are spread out to cover a certain territory, or perhaps when they are each maintaining a prescribed standoff range. The anomalies we hope to avoid are when unrealistically short range links dominate the statistics. We first determine the location and configuration of each node, and then determine which links will be active for that laydown. Our method of analysis will be to generate large ensembles of such laydowns and observe the statistics generated by a chosen set of parameters. These parameters are given in Table I.

TABLE I
LAYDOWN PARAMETERS

parameter	value	units
N_s	Number of nodes	
extent	x-y extent of laydown	Nmi
randFact	Parameter that controls randomness of laydown, 1 is a Poisson point process, 3 reserves space around each node	
nSector	Number of array faces at each node, symmetrically oriented in the horizontal frame	
f_c	Center frequency	MHz
ldType	Type of laydown, currently supporting *random* and *hex*	
totPower	Total power at each array face, will be shared amongst nBeam multi-beams	W
nBeam	Max number of multiple simultaneous transmit beams per sector	
pctXmit	Percentage of array faces designated as transmitters prior to link establishment	

The laydown algorithm starts by generating a collection of N_s nodes, distributed in x, y, z coordinates. The coordinate system is set up such that x is cross range, y is down range and z is elevation oriented up. The nodes will be contained in an extent by extent box in horizontal azimuth (x, y), and by extent/100 in vertical elevation. An oversampling algorithm is used to keep any pair of nodes from being too close. This works by generating *randFact* nodes, and then recursively removing nodes involved in the closest pair-wise distances until the desired number N_s nodes remain.

B. Link Formation

Each node has several array faces, situated in the horizontal frame uniformly about the node. The array face orientations are then set (relative to a zero degree heading), and then the potential links established. The algorithm visits each node and

- Assigns each array face as either *t* or *r*, transmit or receive
- Assigns a random (uniform in azimuth) heading to the node
- Computes the range and angle in the master reference frame to all the other nodes
- Determines which array face is best oriented toward each of the other nodes
- Computes the local azimuth and elevation in the array face coordinates pointing to each of the other nodes
- Does a link budget for each potential link, for the ideal case of both array faces pointing exactly at each other.

After this is accomplished, the algorithm revisits each node, looks at each of its neighbor nodes (all other nodes for now) and determines the array face at the receiving end. Once this is accomplished, each of these potential links can be identified as *tr* (transmit to receive), *rr* (receive to receive), etc, and as such, many will not be suitable for link formation.

Once all the potential links have been determined, they are pruned to keep links that would achieve a minimum rate, and also to adhere to a limit on the maximum number at each transmitting array face. Receiving array faces can have any number of links. At time of pruning, our algorithms collect all of the unused links to later compute secondary interference. This interference is due to transmissions from an unlinked node still in view of a receiving array face.

A second pruning called *mudPruning* can be used to remove one of a pair of transmitting signals too close in angle, which eliminates the need for multi-user detection techniques. In practice, this pruning will keep the adaptive beamforming algorithms from generating ill-poised beams when nulls are placed too close to desired transmit directions. On the receive side, pruning cannot be used, and the simulation simply accepts the high interference case. The links involved in these cases will have a signal to interference plus noise ratio (SINR) near 0 dB regardless of transmit power, and correspondingly lower rates. In practice, we anticipate that many of these cases would be handled by a multiuser detection strategy, however this has been left to future development of our analysis.

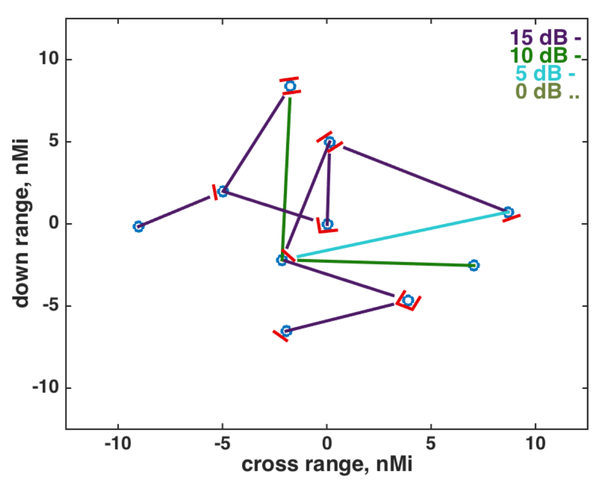

Fig. 1. **Example laydown of ten nodes, links are connected at transmitting end. Red surfaces indicate receiving array faces. Centrally located nodes typically receive several links at lower SINR.**

Our methods generate laydowns such that the distribution of inter node distances are correlated. As the number of nodes increase within a certain bounding box, nodes tend to have several nearest neighbors with similar ranges. The most important feature of this family of distributions is that it is bounded to the left, smaller ranges are discouraged.

C. Link Budget

A simple link budget is used to compute the signal and noise powers present at any receiver in the laydown. This budget computes the ideal signal to noise ratio present for two array faces pointed exactly at each other, at a standoff range of d meters. Our baseline total transmit power is 1 Watt, and the center frequency, $f_c = 22$ GigaHertz. The signal to noise ratio will be

$$\gamma(d) = \frac{P_t}{N_{ktb} N_b} G_t G_r \left(\frac{\lambda}{4\pi\eta(d)d} \right)^2, \tag{1}$$

where our losses are summarized in η,

$$\eta(d) = 10^{(L+0.01\cdot d/1000)/20}. \tag{2}$$

In Equation 2, the link budget is further summarized by the parameter L, which has been set at $L = 12$ dB. (see Table II.) Note that the pointing mismatch and the implementation mismatch are explicitly handled in the simulation by array and geometry pertubations, and not used in this loss computation. The remaining relevant parameters are N_b the number of simultaneous transmit beams, and $G_t = G_r = \pi N_{ele}$ which are the array transmit and receive gains.

TABLE II
LINK PARAMETERS

Parameter	value	Units
Atmosphere loss	0.01	dB/Km
Rain margin	2	dB
pointing mismatch	sim	dB
feed loss	1	dB
polarization mismatch	2	dB
implementation mismatch	sim	dB
cable/conversion losses	2	dB
noise figure	5	dB
total loss	$L = 12$	dB

D. Interference Modeling

From this link budget, we derive the signal to noise ratio present at the output of a receive beamforming terminal, when the transmitting and receiving arrays are pointed directly at each other. To complete the model, the effect of off axis response must be accounted for at both sides of the link. Many cases arise in the analysis,

1) **Point-to-point:** A data stream uses its intended spatial beam at the transmitter and is received at a receive node on its intended beam. Both beams are steered as accurately as possible toward each other.
2) **Cross-talk** A data stream using its intended spatial beam at the transmitter couples into an unintended beam at the transmitter and is received at a receive node listening to that unintended beam.
3) **Main-Beam Interference** A data stream using its intended spatial beam at the transmitter is received off axis at every receiver in its sector, and couples into every receive beam at each.
4) **Side-Lobe Interference** A data stream coupling into an unintended spatial beam at the transmitter is received at every receiver in its sector, and couples into every receive beam at each.

Our simulation tracks and includes the effect of each of these signal sources in the computation of signal to noise ratio and signal to noise and interference ratio. To do so, the raw signal to noise ratio at the beamformer output $\gamma(d)$ is converted to linear units considering the noise power to be unity. The interference sources can then be power summed to obtain an SINR. To include the effect of off axis coupling onto unintended directions, for each link or interference pair we compute the signal amplitude as follows

$$\begin{aligned} a_{i,j}(k_i, l_j) = &\beta(k_i, q_{i,j}) \cdot 10^{(\gamma(d_{i,j})/20)} \\ &\cdot \beta(l_j, q_{j,i}). \end{aligned} \tag{3}$$

In Equation 3 node i is the transmitting node, node j is the receiving node, k_i indicates which user and beam is under consideration at the transmitter, and k_j accordingly at the receiver. The βs are the coupling of the data onto the link,

$$\beta(k_i, q_{i,j}) = \langle w_{i,k}, q_{i,j} \rangle \tag{4}$$
$$\beta(l_j, q_{j,i}) = \langle w_{j,l}, q_{j,i} \rangle . \tag{5}$$

Here, $w_{i,k}$ are the beamforming weights at array i for user k normalized for a maximum plane wave response of one, and $q_{i,j}$ is the plane wave response vector in the local coordinate system of array i, in the direction of array j. The planewave responses are also normalized to one such that the maximum coupling onto any steered direction is $\beta = 1$.

Computation of SINR with these preliminaries in place is straightforward. At the receiving side of each link, retrieve the signal amplitude a from Equation 3. The couplings for this amplitude will generally both be near $\beta = 1$. Secondly, for every array face in the field of view of this receiving array, retreive all of the signal amplitudes due to every active transmit beam and every active user, as they couple into the receive beam in question. Power sum these, add in one for the thermal noise, and compute the interference plus noise level. The signal to interference plus noise level will be the ratio of the desired power level to the interference plus noise level. Since we are considering only linear reception (no Multiuser Detection for now), the rate achieved will be

$$R_{i,j}(k_i, l_j) = \log_2(1 + \text{SINR}_{i,j}(k_i, l_j)). \tag{6}$$

III. ANALYSIS

To verify our our combined physical-layer and network simulator is working properly, we compare its results using a simple structured (hexagonal) lay-down model to a derived closed-form solution. Figure 2 shows the laydown, and the labeling of some of the nodes we will use to analyze the performance of the corresponding network. For this case only, each node gets six arrays, each faced toward one of the six nearest neighbors. Each node is allowed to transmit one signal only, if it can find the correct pairing of 'tr' as we have described. The node spacing and power are fixed such that the highest possible rate is 2 bits per second per Hz for a node communicating with a nearest neighbor without interference.

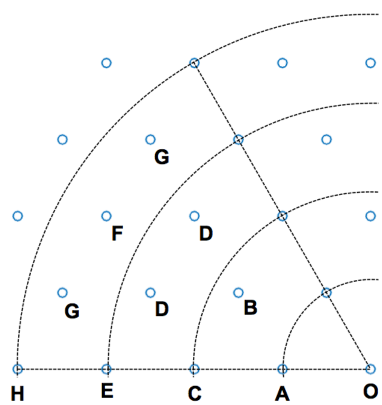

Fig. 2. **Hex Laydown with Primary Nearest Neighbors Labeled**

Table III fills out the geometry and rates we would expect. From the left, this chart starts with normalized range to the origin node O, angle in degrees, the signal to noise ratio (dB, interference free) if that neighbor is a communicator, and the rate for that SNR, in bits per second per Hertz. The case we have chosen here is for a 22 GigaHertz system, 16 MegaHertz of bandwidth, with 48 element arrays at 1 Watt total. For these parameters, a 2 bits per second per Hertz link can be made at 68.8 Killometers, and the post beamformed SNR is 4.77 dB.

TABLE III
HEXAGONAL LAYDOWN

node	distance	angle	SNR	rate	prob
A	1	0	4.77	2.00_A	.822
B	$\sqrt{3}$	30	-0.50	$.919_B$	.146
C	2	0	-1.93	$.714_C$	.026
D	$\sqrt{7}$	19.1, 40.9	-4.81	.412	.005
E	3	0	-6.14	.314	-
F	$\sqrt{12}$	30	-7.72	.225	-
G	$\sqrt{13}$	13.9, 27.5	-8.16	.205	-
H	4	0	-9.33	.159	-

The probability of our origin node choosing each of the nodes A, B and so forth as a nearest neighbor can be computed. To do this exactly, the edge nodes would have to be treated differently, but we will presently consider only interior nodes. Starting with the nodes at a normalized distance of 1, the origin node will query each corresponding array pair to find a transmit receive condition of 'tr'. If there is more than one, one will be selected randomly. The probability of finding this pair is $p = 1/4$, so the probability of finding a nearest neighbor of unit normalized distance is

$$p_A = 1 - (1-p)^6 = .822. \tag{7}$$

Conditioning on the probability of not finding a unit distance neighbor, the probability of finding the next neighbor B (there are six of those as well) would be $p_B = p_{\overline{A}} \cdot (1 - (1-p)^6)$. The remaining probabilities can be filled out accordingly, and have been entered onto Table III. Past the node C which has only a 2.6 percent chance of being chosen, there is very little probability. For an edge node with perhaps only 3 sectors pointing into the network, the probabilities are more uniform, extending to nodes D and E at normalized distances to 3.

We wish to also characterize the interference situation and probabilities in the network. This proves much more difficult, but at least the simplest cases (and most common) can be analyzed. Suppose a link is up from A to O, and we wish to compute the probability it is being interfered with by a link from C to A. We wish to compute the probability that node C chose a unit length link, *and* it is the one of the six pointed also at node O. This can be computed using the binomial probability. In fact, our probability p_A, the probability that a unit distance link is chosen is the sum of the binomial probabilities for $k = 1, 2, \cdots, 6$ successes, and conditioning on each of these outcomes, the probability of choosing the co-linear link is $1/(N-k+1)$. Summarizing, the probability of a co-linear link C to A interfering with a link A to O is

$$p_{int} = \sum_{k=1}^{6} \binom{6}{k} \frac{p^k (1-p)^{6-k}}{7-k} = .165. \tag{8}$$

A similar analysis of the probability of co-linear interference of node F on B in communication with O give only 2.9 percent of the length $\sqrt{3}$ cases suffering interference.

We can now fill out a table with likely interference situations and probabilities. Our anaylsis means that each of the entries of Table III will be separated in two, some interference free, and some with interference. Table IV shows the result. Some of the probabilities have been left out (vanishingly small), but the rates computed for reference.

TABLE IV
INTERFERENCE CASES FOR NODES COMMUNICATING WITH ORIGIN NODE O

node	int node	rate	prob
A	none	2	.686
A	C	1.500	.136
C	A	.214	-
A	E	1.77	-
E	A	.085	-
B	none	.919	.142
B	F	.816	.004
F	B	.123	-

Figure 3 presents the probability distribution generated by our simulation, of individual link rates for a fifty node hexagonal network. The curve has been labeled to indicate the type of link present, and agrees well with our analysis. Since this simulation also involves computation of array responses and spatial losses, the peaks are spread out in rate slightly but do scale with the probability mass function we have predicted. Since the nodes are capable of steering beams, this figure is essentially identical for the case when the headings of the nodes are also randomized.

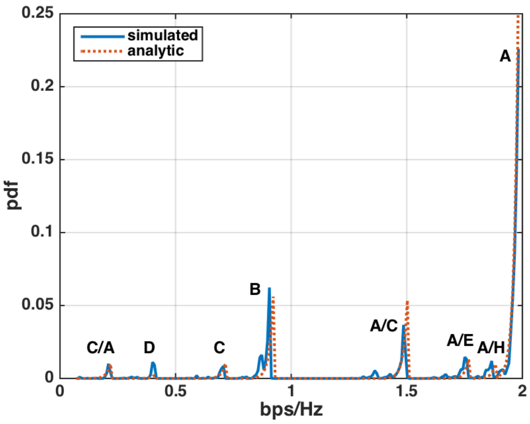

Fig. 3. **Communication Rates for a 50 Element Hexagonal Laydown. Nearest neighbor is node A, communicating at a rate of 2 bits/sec/Hz. Interference cases are labeled as communicator / interferer.**

A. Random Laydowns

We now examine the network capacity for a collection of nodes randomly layed out in a fixed area. We return to our primary case of interest, nodes with four array faces, with a fifty fifty split between transmitters and receivers. The node powers will be 1 Watt, and the extent E_x of the simulation 25 by 25 nautical miles. A quick computation of the rates we would expect is in order. First, a typical area surrounding each node would be $A = g(E_x * 1852)^2/N$ square meters, and radius to the edge $r = \sqrt{A/\pi}$. The parameter g is Gauss' packing ratio for optimal packing, $g = \pi/(3*\sqrt{2})$. This means a typical communications range would be

$$d_{ref} = 2 \cdot \sqrt{\frac{A}{\pi}} = 2\sqrt{g} \cdot \frac{(E_x * 1852)}{\sqrt{\pi N}}, \tag{9}$$

with some pairs closer and some more separated. For example, with $N = 12$ nodes laid out, a typical nearest neighbor range would be $d = 15.1$ killometers, and the signal to noise ratio would be, by our link budget at 22 GigaHertz, $\gamma(d) = -25.1$ dB. The single link rate at that SNR would be $C = 0.025$ bits per second per Hertz.

We can now characterize the distribution of rates in our network. To do so, we use an analytic result for the distribution of distances for randomly arranged nodes. Following [9], the probability distribution function of internode distances in a square area is

$$p(\xi) = \begin{cases} 2\xi(\xi^2 - 4\xi + \pi) & 0 \le \xi < 1, \\ 8\xi\sqrt{\xi^2-1} - 2\xi(\xi^2+2) & \\ \quad +4\xi\left[\sin^{-1}(1/\xi) - \cos^{-1}(1/\xi)\right] & 1 \le \xi < \sqrt{2}, \end{cases} \tag{10}$$

where ξ is distance normalized to the edge of the square. Using standard formulae for the distributions of ordered statistics based on this density function [10], the distribution of the nearest K neighbors can be computed, along with the most likely distance for each. If we normalize these distances by our Equation 9 reference distances, we can generate a spectrum of likely of normalized distances $d_n(k)$. We can also compute the likelihood that any of these neighbors become the nearest link. In our hexagonal case, there were rings of six and twelve neighbors each with equal distance neighbors, now we have individual nodes. The probabilities are simpler now, the likelihood that the first node is chosen is $p_1 = 1/4,$ and the likelihood that the linked node is any node past node one is $p_{1+} = 1 - p_1 = 3/4$. The probability that the linked node is past the k^{th} node is

$$p_{k+} = (1 - p_1)^k. \tag{11}$$

Armed with this pdf of likely normalized link ranges, for a given extent E_x and reference range d_{ref} we can run the distance spectrum through our link budget, and obtain a probability mass function (PMF) on likely link rate. We can also normalize this data by computing a reference rate $r_{ref} = \mathsf{L}(d_{ref})$ using the reference distance and our link budget. Here the operator $\mathsf{L}(d) = \log_2(1 + \gamma(d))$ represents the link budget, which returns a rate for a distance. This normalization is possible because the normalized distance spectrum is nearly constant past approximately 15 nodes or so. Our single node normalized rate PMF is therefore

$$p(r) = \sum_{k=1}^{N_k} \frac{1}{4} p_{(k-1)+} \cdot \delta(r - \frac{\mathsf{L}(d_n(k) \cdot d_{ref})}{\mathsf{L}(d_{ref})}). \tag{12}$$

Figure 4 shows the form of this function, again for numbers of nodes exceeding 15 or so. With probability 25 percent, a node will link with a neighbor at 1.34 times the reference rate, and so forth. Our simulation runs will use network sum rate as a primary metric of performance. Our final step in creating a reference rate will be to summarize the Equation 12 PMF with a mean and standard deviation and use the central limit theorem to compute the approximately normal pdf of the sum rate. Since we are interested in the ninety fifth percentile of rate, we then compute the lower rate bound that 95 percent of all rates will exceed. This curve will be part of our analysis, a reference curve for interference free plane wave beamforming when each node forms one link only with a neighbor.

IV. Simulation Results

In this section, we investigate through Monte Carlo simulation the following two questions:

- What are the relative pay-offs for increasing complexity or sophistication of the PHY algorithms used by the nodes?
- Is it worthwhile to have individual arrays simultaneously transmit multiple signals?

The key statistics for comparison are the network sum rate, typical individual link rate, and network connectivity, as we have described. Table V gives a summary of the simulations. The *run type* column indicates the array processing algorithms used in the simulation. The N_{sect} column indicates the number of sectors per node, each sector has one array. The N_{beam} column indicates the maximum number of transmit beams per sector.

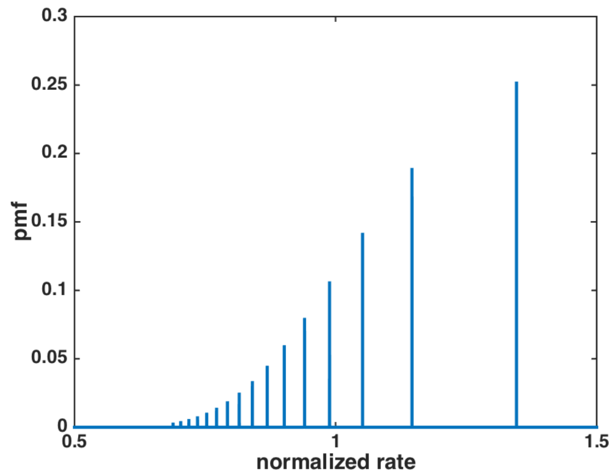

Fig. 4. **Normalized Interference Free Rates of First Sixteen Nearest Neighbors in a Fifty Element Network, Random Laydown**

TABLE V
SIMULATION RUNS

run type	notes	N_{sect}	N_{beam}
omni	Both transmitting and receiving nodes are omni-directional. No array gain.	1	1
fullSector	Both transmitting and receiving nodes are directional within a given sector of view.	4	1
planeWave	Both transmitting and receiving nodes are directional (plane wave model), with a 48 element array.	4	1
mBeam	Same as planeWave case, but multiple transmits allowed. Each transmission gets $1/N_{beam}$ of the power.	4	2-4
gsc	Same as mBeam case, but the transmitters and receivers use generalized sidelobe canceling (GSC) nulling. [11]	4	2-4

Figures 5 through 7 summarize our results along with the reference we have described. Examining first the network sum rate curves on Figure 5, we see that the type of spatial processing employed has a strong influence on the network sum rate. The generalized sidelobe canceller (top two curves) is the only method to exceed the reference curve, and outperforms the multibeam method (cyan and green, nearly coincident) by approximately 50 percent. Both methods are multibeam methods, but the GSC method is adaptive and can steer spatial nulls. Note also that even though multiple beams of data are attempted for the multibeam (non adaptive) case, the ideal interference free reference cannot be exceeded. The remaining curves are near the bottom, well below the reference sum rate. If we look at Figure 7, the gsc and multibem methods exceed 90 percent connectivity, above 95 percent when four links per array face are allowed. For our present purposes, we define connectivity as the percentage of simulations with all nodes connected into one group. Connection means that each node is touched by either a transmit or receive end of a link.

Table VI tabulates the result for 25 nodes, the reference sum rate for this case is 226 bits per second per Hertz. The GSC performance, in terms of network sum rate is 157% of the rate obtained by plane wave beamforming. Values in boldface are those cases plotted on the figures.

TABLE VI
NETWORK PERFORMANCE FOR 25 NODES ON A 25 BY 25 NAUTICAL MILE LAYDOWN.

algorithm	lpn	mBeam	link rate	sum rate	cnct
omni	1	1	**0.01**	**4.3**	**0**
full sector	3	1	**0.13**	**33.42**	**68.0**
-	4	1	**0.12**	**33.83**	**74.4**
plane wave	1	1	1.87	137.6	2.44
-	2	1	1.34	171.8	54.6
-	3	1	0.89	186.1	69.9
mBeam	3	2	0.43	192.5	90.9
-	3	3	**0.31**	**191.2**	**94.7**
-	4	2	0.42	198.6	95.7
-	4	3	**0.26**	**195.9**	**97.5**
GSC	3	2	1.57	274.7	92.0
-	3	3	**1.24**	**284.8**	**94.2**
-	4	2	1.43	292.3	93.8
-	4	3	**0.90**	**307.7**	**97.0**
-	4	4	0.74	311.4	97.7
reference	1	1	-	226.0	-

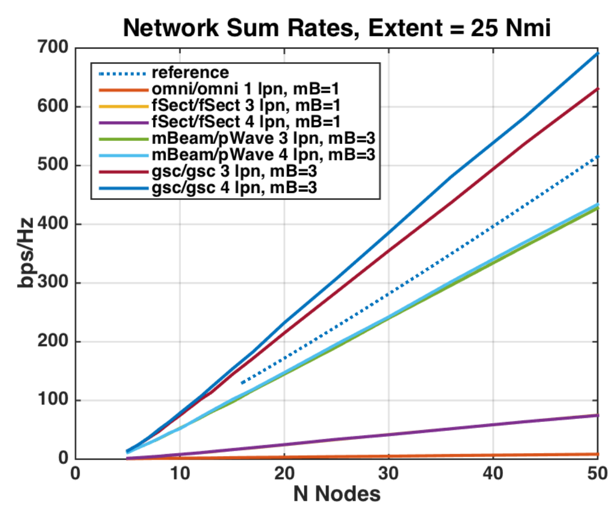

Fig. 5. **Comparison of the Network Sum Rates (95th percentile) Realized by a Variety of Methods, on a 25 by 25 Nautical Mile Area**

V. CONCLUSION

We have developed and validated a detailed physical layer model that can accurately compute the rates available to a networked communication system. Many types of media access layer (MAC) protocols can be coupled to our model to predict real world communications rates rather than idealized

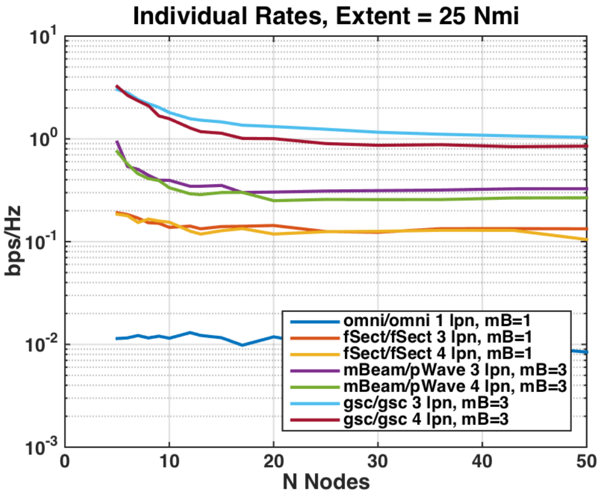

Fig. 6. **Comparison of the Individual Link Rates (95th percentile) Realized by a Variety of Methods, on a 25 by 25 Nautical Mile Area**

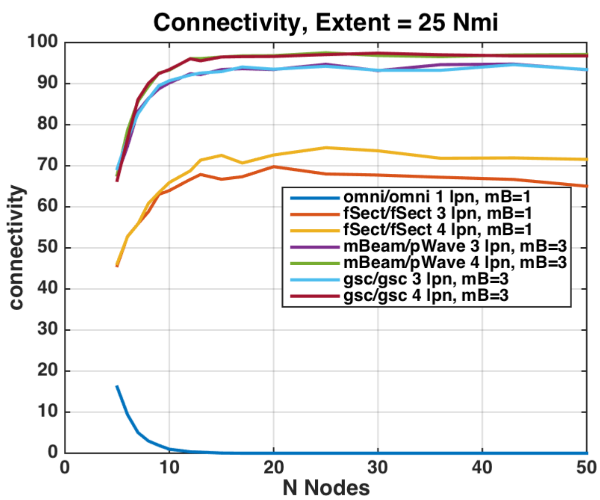

Fig. 7. **Comparison of the Network Connectivity Realized by a Variety of Methods, on a 25 by 25 Nautical Mile Area**

network capacity. With a typical MAC strategy taken from the literature, we have demonstrated the utility of various spatial processing algorithms along with the benefit of multiple simultaneous transmission at a single array face. The benefits of adaptive processing are clear, and also open the gateway for multiple beam transmission. Our networks, connected by multiple beam transmission, achieve near perfect connectivity with an ad-hoc nearest neighbor MAC layer.

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