On the Use of Smart Antennas in Multi-Hop Wireless Networks

(Invited Paper)
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***Abstract*—**
Smart antennas include a broad range of antenna technologies ranging from the simple switched beam to the more sophisticated adaptive arrays and multiple input multiple output (MIMO) links. Their ability to exploit multiple degrees of freedom helps them operate in different strategies to achieve different objectives ranging from rate increase, range increase, transmission power reduction, and higher link reliability. While these antennas have been significantly researched at the PHY layer leading to results that are easily translatable to single-hop wireless networks, very little is understood about their use in multi-hop wireless ad-hoc networks. Specific unanswered questions in this context include: (i) what kind of performance improvements can the different technologies and their strategies provide? (ii) for each technology, which of the different possible strategies is the optimal strategy to employ for a given network condition? and (iii) for a given network setting, which of the different smart antenna technologies will deliver the best performance? In this paper, we systematically answer these questions by comprehensively evaluating the relative benefits of the different smart antenna technologies.

1. INTRODUCTION

Smart antennas possess sophisticated signal processing capabilities that help them deliver significant performance benefits such as increased spectral efficiencies, reduced power consumption, interference suppression, increased communication reliability, better connectivity, etc., over conventional omni-directional antennas. Not surprisingly, due to the above advantages, the use of such smart antennas in wireless networks has gained significant attention over the last few years. The term "smart antennas", in reality, represents a broad variety of antennas that consist of multiple-element arrays (MEAs) and include switched-beam antennas, steered-beam antennas, adaptive array antennas, and multiple-input-multiple-output (MIMO) links.

In addition to the different technologies, smart antennas, even for a given technology, can be operated using different strategies to achieve different performance objectives by exploiting the available gains in different ways: (i) to increase the capacity of the link, (ii) to increase the transmission range to reduce the number of hops for the flow and to increase connectivity, (iii) to increase the SNR or reduce the variance in SNR, thereby increasing the link reliability, and (iv) to perform power control and reduce the power consumption.

The focus of this work is to understand the performance trade-offs of the different smart antenna technologies and strategies in multi-hop wireless ad-hoc networks. Specifically, we attempt to answer the following question: *For a given ad-hoc network setting, which antenna technology and strategy is the ideal choice to employ to obtain the best performance?* While smart antennas have been significantly researched at the physical layer and hence their applicability and performance benefits in the context of one-hop cellular wireless networks has been well established, very little is understood in terms of the performance of smart antennas in ad-hoc networks. Although some recent work has focused on network protocols (especially at the medium access control layer) in ad-hoc networks with smart antennas, the technology considered has been predominantly that of simple switched beam or directional antennas [1], [2], [3] with MIMO gaining recent interest [4], [5]. At the same time, understanding the relative benefits of the different smart antenna technologies will help not only network designers in the appropriate design of ad-hoc networks for real applications, but also researchers developing network protocols for the environment.

Note that there does exist a total ordering of the antenna technologies in terms of sophistication - MIMO links being more sophisticated than adaptive arrays, which in turn are more sophisticated than switched beam antennas. However, the motivation for this work stems from the simple observation that the *extent to which the sophistication can be leveraged, and hence the performance itself, largely depends on network conditions*. For example, under certain network conditions, switched beam antennas (which are relatively simpler and cheaper) can provide better performance than even MIMO links. The contribution of this work is thus the identification of such trade-offs between the different smart antenna technologies with respect to different network conditions defined by factors including the number of antenna elements, load conditions, network density, and other environmental characteristics such as scattering and fading.

While the overarching goal of this work is to establish the performance trade-offs between the different technologies, we do so systematically through the following set of contributions: (i) we comprehensively evaluate the different antenna technologies, and their respective strategies with respect to the different network parameters, and identify performance trends; (ii) we draw inferences on which strategy proves to be optimal for the different settings for each technology; (iii) we then identify the technology that can deliver the best performance for a given network setting; and (iv) in the process, we also identify the relative performance "ordering" of the different strategies and antenna technologies.

1.1 Related Work

There have been several works at the PHY layer research that have identified the potential gains of the different antenna technologies [6], [7], [8].However, the effort in the direction of how these gains can be effectively leveraged at the higher layers of the protocol stack in ad-hoc networks has been premature. Most of the existing works in this area have focused on developing distributed MAC and routing protocols for a specific antenna technology, with the emphasis being on switched beam antennas predominantly [1], [2], [3], [9]. The throughput performance bounds for switched beam antennas in ad-hoc networks have also been studied in [10], [11]. Recently, MAC protocol design for MIMO links has been gaining significant interest [4], [5]. [12] is the first work that has made the effort of proposing a unified framework for medium access using the different antenna technologies. However, the focus there was not on the relative performance of the different antenna technologies and different strategies were not considered either.

The rest of the paper is organized as follows. In Section 2, we provide some background material on the different antenna technologies, their strategies and the respective gains leveraged. In Section 3, we present the details of the simulation model and algorithms used for the performance evaluation. Sections 4 and 5 evaluate the different strategies within a technology, and the technologies themselves respectively. Concluding remarks are presented in Section 6.

2. PHY LAYER BACKGROUND

In this section, we present background material on the different antenna technologies and their strategies considered in this paper.

2.1 Technologies

2.1.1 Switched Beam Antennas

In any MEA, the signal that is sent to each of the antenna elements is weighted in both magnitude and phase before being transmitted. The specific set of weights that are applied to the different antenna elements is responsible for the antenna (radiation) pattern formed. In the case of switched beam antennas, a pre-determined set of weights is used, each of which results in a beam pointing to a particular direction with a high gain referred to as the *directional* gain (G_d). In the case where both the transmitter and receiver know the direction of transmission to each other, this gain can be bounded by $G_d = G_t \cdot G_r = K^2$, where G_t and G_r correspond to the directional gains of the transmitter and receiver respectively [6]. K represents the number of elements at either ends of the link.Since the radiation pattern is fixed, when signals arrive with a large angular spread (scattering angle $>$ beam width) due to multi-path scattering, this leads to loss of signal energy and hence a degradation in performance in multipath environments. If the scattering anglesat the transmitter and receiver are assumed to be the same α, then

$$G_t = G_r = min(K, \frac{360}{\alpha}) \tag{1}$$

These antennas can suppress interference along the non-active beams, resulting in a directional spatial reuse (number of possible simultaneous transmissions) factor bounded by K^2 [10].

2.1.2 Fully Adaptive Arrays

Unlike the switched beam, the fully adaptive array antennas can adapt their weights so as to maximize the resulting signal-to-interference+noise ratio (SINR). This helps them cope with multi-path scattering by adaptively changing their radiation pattern. In addition to maximizing the gain for the desired signal, these antennas can also adaptively null interference. A K element antenna is said to possess K *degrees of freedom (DOFs)*, wherein it can adaptively null $K-1$ interferers even when they are uncorrelated with each other as long as they are uncorrelated with the desired signal. This results in a spatial reuse factor of K even in the absence of a strong line of sight (LOS) component as in switched beam. The maximization of SINR results in an *array* gain G_a, which can also be bounded by ([7]) $G_a = K^2$. While the gain from adaptive array antennas does not degrade with an increase in the degree of multipath scattering unlike switched beam antennas, yet, when angular spreads are significantly large at transmitter and receiver, the low correlation existing between different signal components bounds the gain asymptotically ([7]),

$$G_a = (2\sqrt{K})^2 = 4K \tag{2}$$

2.1.3 MIMO Links

A MIMO link employs digital adaptive arrays (DAAs) at both ends of the link. It is capable of operating in two modes, namely spatial multiplexing and diversity. Spatial multiplexing gain can be achieved when the transmit array transmits multiple "independent" streams of data, with each stream being transmitted out of a different antenna with equal power. Each transmitted stream generally has a different "spatial signature" due to rich multipath, and these differences are exploited by the receiver signal processor to separate the streams (eg. BLAST). This multiplexing gain can provide a linear increase in the asymptotic Shannon link capacity C, which is given by the following equation [13],

$$C_m \approx K \cdot C = K \log_2(1+\rho) \tag{3}$$

where ρ represents the average SNR at any one receive antenna.

Alternatively, the rich multipath can help the transmitter data streams fade independently at the receiver and hence the probability of all the data streams experiencing a poor channel at the same time is significantly reduced, thereby increasing the communication reliability. This contributes to the diversity gain. Diversity gain relates to the reduction in the variance of the SNR, which in turn depends on the diversity order. The maximum diversity order afforded by a MIMO link with M transmit antennas and N receive antennas is MN. At high SNR, this reduction in BER (p) as a function of the diversity order (d) can be given as [8],

$$p \approx \frac{1}{SNR^d} \tag{4}$$

2.2 Strategies

We consider the following four strategies with respect to each of the technologies.

2.2.1 RATE

For a given modulation scheme, the BER on the link is determined by its SNR. In this strategy, a gain in SNR (G) due to directional and array gains in switched beam and adaptive arrays respectively, is used to perform adaptive modulation, increasing the number of bits transmitted per symbol, while maintaining the BER at its original value. The increase in capacity can bounded as C_g, where

$$C_g \approx \log_2(1+\rho G) \tag{5}$$

In MIMO links, the capacity increase results directly from spatial multiplexing and is given in Equation 3.

2.2.2 RANGE

In $range$, the gain in SNR is used for increasing the range of communication r ($r \propto (\frac{1}{SNR})^{\frac{1}{p}}$, p = path loss exponent). Increased range reduces hop length and hence the multi-hop burden, but at the same time also decreases spatial reuse. In switched beam and adaptive arrays, the directional/array gains (say G) are used to provide a range extension factor of R_f given by,

$$R_f = (G)^{\frac{1}{p}} \tag{6}$$

In MIMO, the diversity gain (diversity order = $d = K^2$) can be exploited for range extension. However, since diversity gain relates to reduction in SNR variance, the slope of the BER-SNR curve changes for the link with extended range, making it difficult to translate the diversity gain (unlike directional/array gain) to a range extension factor. So we have evaluated the range extension factor that can be obtained from diversity gain through MATLAB experiments (bit-level simulations) and found it to be a linear function of elements ($R_f \approx K$), as a reasonable approximation.

2.2.3 REL

In rel, the gain in average SNR due to directional/array gains in switched beam and adaptive arrays, and the reduction in SNR variance in MIMO due to diversity gain, is retained to directly increase the link reliability and hence reduce the packet loss probability on the link (Equation 4). For switched beam and adaptive arrays with a diversity order of one, the BER decreases by a factor (p_f) of,

$$p_f = \frac{1}{G} \tag{7}$$

while in MIMO, it decreases by a factor of,

$$p_f = \frac{1}{\rho^{d-1}} \tag{8}$$

2.2.4 POW

In pow, the gain in SNR is exploited to perform power control and reduce the transmit power P_t on the link, such that the link reliability remains the same. In switched beam and adaptive arrays, the directional and arrays gains are exploited to reduce the transmit power by a factor, Pt_f,

$$Pt_f = \frac{1}{G} \tag{9}$$

In MIMO, the diversity gain is exploited for power control. If P_{t1} is the transmit power before applying the diversity gain, then the transmit power P_{t2} with diversity gain and power control (using Equation 4) is given by,

$$P_{t2} = (P_{t1})^{\frac{1}{d}} \tag{10}$$

3. Simulation Model, Metrics and Algorithms

We use the *ns2* network simulator for our evaluations by incorporating the necessary modules into it.

3.1 Antenna Model

While the beam pattern generated by the omni-directional, adaptive arrays and MIMO links are either omni-directional or dynamically tunable, the beam pattern of switched beam is fixed and must hence be modeled. The model is similar to the one used in [2] and incorporates front, side and back lobes. Further, front-side and front-rear ratios are assumed to be equal. The main lobe, front-side and front-back gains for switched beams with varying elements (beams) are assumed as provided in [2].

3.2 Channel Model

In addition to the free space, two-ray and shadowing path loss models considered in the *ns2* simulator, we incorporate the notion of Rayleigh fading into the channel model. Since the simulator works in the granularity of packets, we account for the packet loss probability arising from Rayleigh fading through a new collision model. The collision model captures the probability of packet errors for various configurations (locations, different antenna technologies and strategies used) of desired transmitters and interferers in the presence of Rayleigh fading. This is in turn derived from the BER statistics obtained from bit-level Matlab simulations of detailed physical layer modelling of the different antenna technologies and their strategies along with the required receiver processing techniques (zero forcing, interference cancellation, etc.) in the presence of Rayleigh fading. Thus, different tables of realistic packet drop probabilities for various combinations of antenna technologies, strategies and environments considered are generated and any given configuration of desired transmitter-receiver and interferers is indexed into the appropriate table to obtain the corresponding packet drop probability for the communication.

We have assumed typical parameter values corresponding to the 802.11 standard namely, frequency of operation to be 2.4 Ghz, transmit power to be 20 dBm, packet size to be 1000 Bytes, and the channel data rate to be 2 Mbps. The SINR threshold on the link is maintained at 10 dB with fade margins (SNR tolerance for fading) ranging from 0 dB till 10 dB. We have also assumed fast fading and consequently that its not correlated in time.

3.3 Network and Traffic Model

We consider a network of 100 nodes, randomly and uniformly distributed in a rectangular grid, and communicating using time division duplexing. The size of the network is varied to vary the node density, ranging from 400m by 400m (average node degree of 20), to 1000m by 1000m (average node degree of 3). Node degree is used as a measure to indicate the node density. The transmission range used by the nodes is set to 100m. The load in the network is varied by varying the number of flows from as low as 1 to as high as 50, where every node either acts as a source or a destination. The degree of multipath scattering considered in the network varies from 0 degrees (LOS) to 180 degrees (rich urban setting). The impact of node speed (upto 20 m/s) is incorporated in multipath fading through means of packet losses upto 30%. The number of elements possessed by each node determines the available *DOFs*; and is varied between 1 and 12 elements. The sources and destinations are randomly chosen in the network, resulting in a random traffic pattern. Each simulation is run for about 400 secs.

3.4 Metrics

3.4.1 Throughput

Throughput is measured as the number of bits successfully delivered from the source to the destination per unit time. We measure throughput/flow in our evaluations. However, in comparisons with $range$ in the presence of low node densities and low loads alone, aggregate flow throughput (throughput capacity) is considered to account for the difference in the number of flows existing in the network in the different strategies.

3.4.2 Throughput/Energy

Here, we measure the number of bits that can be successfully delivered to the destination per unit of Joule consumed. The different components determining the energy consumed per slot transmission are the communication energy (circuit-driving power P_c and transmit power P_t) and computational energy (mainly signal processing operations).

3.5 Protocols and Algorithms

Since the focus of the study is to obtain fundamental tradeoffs in the operation of the different antenna technologies, the impact of distributed inefficiencies of the protocols on performance is eliminated by considering centralized protocols for evaluation.

All the sources are assumed to be back-logged for the entire simulation duration. A shortest path routing algorithm (Djikstra's algorithm) is used to determine the routes for the flows based on the

$Routing$:
1 Estimate Scattering
2 If $(tech == \text{“}sw\text{”} || tech == \text{“}adap\text{”})$
3 Update dir/array gain
4 If $(strat == \text{“}range\text{”})$
5 Find_Txrange(tech, gain)
6 Run shortest path routing
7 Generate Flow Contention Graph, $G = (V, E)$

$Scheduling$:
8 $\forall\ i\epsilon V, res_i = K,\ alln_i = 0,\ service_i = 0$
9 While $(slot \leq 100,000)$
10 $\forall\ i, j\epsilon V\ \&\ (i, j)\epsilon E,$
11 Obtain channel matrix H_s with coefficients, h^s_{ij}
Obtain channel matrix H_{sr} with Rayleigh fading coefficients, h^{sr}_{ij}
LINK:
12 $\forall\ i\epsilon V$, If $(Is\_pkt(i))$
13 Register $(i, tech, strat, K_{tx})$
14 $R \rightarrow R \cup i$
15 If $(tech == \text{“}sw\text{”} || tech == \text{“}adap\text{”})$
16 $res_i = K_{rx}$ /* Update res_i based on scattering */

SCHEDULER:
17 Find $J \subseteq R$, such that, $\forall\ j\epsilon J,\ alln_j = 0$
18 & Check_self (j, K_{tx}, H_s) & Check_neighbor (j, K_{tx}, H_s)
19 While $(J \neq \emptyset)$
20 Find $k = arg[min(service(J))]$
21 Update_SINR $(strat, gain, F, h^s_{kk}, K_{tx})$
22 $alln_k = alln_k + K_{tx} \cdot R(strat, gain, K_{tx})$
23 $res_k = res_k - K_{tx}$
24 $\forall\ j\epsilon N(k)$
25 Update_SINR $(strat, gain, F, h^s_{kj}, K_{tx})$
26 $res_j = res_j - w_{kj} \cdot K_{tx}$ /* $w_{ij} = f(h^s_{ij})$ */
27 $energy_k = energy_k + E(strat, gain, SNR_k, d)$
28 Re-estimate J
29 $\forall\ i\epsilon V\ \&\ alln_i > 0$
30 Update_SINR $(strat, gain, F, H_{sr}, K_{tx})$
31 If Uniform (0,1) > PER_Table (SINR,Configuration)
32 $service_k = service_k + K_{tx} \cdot R(strat, gain, K_{tx})$
33 $slot++,\ alln_i = 0,\ res_i = K$

Check_self (i, K_{tx}, H)
34 If $(res_i \geq K_{tx}$ & Temp_SINR $(strat, gain, F, h_{ii}, K_{tx}) \geq SINR_{thresh})$
35 return 1;
36 else return 0;

Check_neighbor (i, K_{tx}, H)
37 $\forall\ j\epsilon N(i)\ \&\ alln_j > 0$
38 If $(res_j < w_{ij} \cdot K_{tx}$ || Temp_SINR $(strat, gain, F, h_{ij}, K_{tx}) < SINR_{thresh})$
39 return 0;
40 return 1;

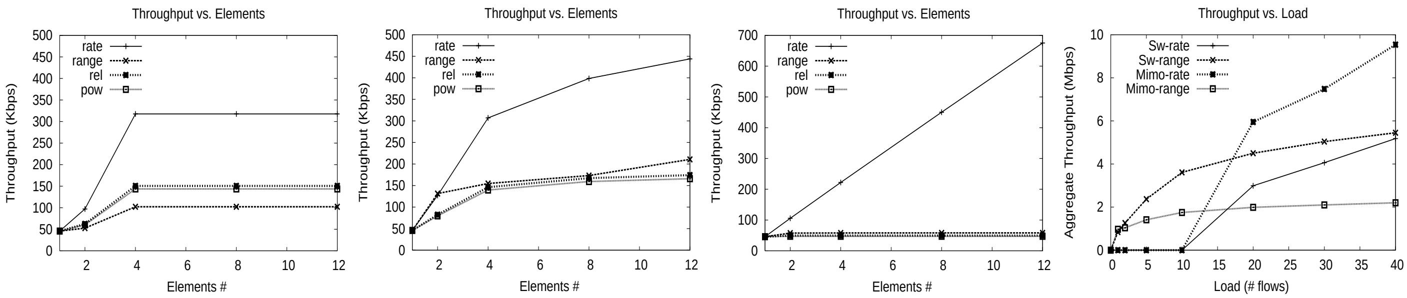
Figure 1. Pseudo Code for Centralized Algorithm

transmission range used by the nodes. The medium access control functionality is achieved by the presence of a centralized scheduler which performs max-min node fairness. To better understand the operation of the centralized scheduler, it helps to review some basic terminology: A *flow contention graph* ($G = (V, E)$) represents the interference existing between the different links in the underlying network. Hence, the vertices (V) in this graph represent the communication links in the network topology and an edge ($\in E$) between two vertices indicates that the two links interfere with each other when operating at the same time (assuming a single DOF). When determining if a link interferes with another, we assume bi-directional communication over the links, which is the case in most of the modern MAC protocols in ad-hoc networks. The weight of the edges is indicative of the amount of interference caused. A necessary condition for a *contention region* is one, where every link in the region contends with every other link in the same region. It can also be identified by determining the maximal cliques (complete subgraphs of maximal cardinality) in the flow contention graph.

The pseudo code for the centralized algorithm is presented in Figure 1. Once the routing protocol determines the routes (lines 1-7), the sources start pumping in traffic into the network. At the beginning of the slot, the channel coefficients with shadowing (H_s), and with both shadowing and Rayleigh fading (H_{sr}) are generated between every pair of communicating and interfering nodes (lines 10-11). If a node has a packet to transmit, it registers with the centralized scheduler (lines 13-14). The centralized scheduler determines the next-hop node and hence the link requesting for service. It also records the technology, the strategy, and the number of *DOFs* (resources, K_{tx}) with which the link would communicate. It also determines the impact of multipath scattering on the technology and if needed limits the gain and determines the effective number of resources K_{rx} that can be used by the link in its communication (lines 15-16). It then determines the set of links (J, lines 17 and 18) that can potentially transmit in the slot. A link belongs to the set if it has sufficient resources (DOFs) of the total effective available (K_{rx}) to go ahead with the transmission/reception and maintain the required SNR (based on the path loss, shadowing, fade margin F and gain from the antennas), after suppressing interference in all its contention regions due to links that have already been scheduled (lines 33-35). The scheduler also checks to see if the already scheduled links in the concerned link's contention regions will not have their SNR's degraded below their required threshold due to the scheduling of this link (lines 36-39). If both the checks are positive, the link is added to the set J. The link with the lowest service is then chosen from the set J to be scheduled with K_{tx} DOFs (line 20). The scheduled link as well as its neighboring links have their available resources then updated for the current slot to reflect the newly scheduled transmission (lines 21-26). The energy consumed by the scheduled link is also updated based on the strategy employed (line 27). Once all possible links have been scheduled based on their service, available resources, and SNR, the impact of multipath fading on the success of the communication is then incorporated. Based on the Rayleigh channels generated between the source, and the destination of the link as well as other interfering nodes, the new SNR on every scheduled link is calculated and checked to see if it still satisfies the required threshold (line 30). If so, the service obtained (bits/slot) by the link is updated based on the strategy employed (line 31). The scheduling then moves to the next slot.

The $rate$ strategies apply equations 3 or 5 to determine the additional bits that can be transmitted using their appropriate gains, when a link is scheduled successfully (function R). The impact of $range$ strategies is indirectly felt through the presence of lesser number of links and increased size of contention regions due to larger transmission range. The rel strategies use the gain for increased link SNR to counteract fading loss, reducing the probability of packet loss in the presence of fading as governed by equations 7 or 8 (functions $Update\_SNR$ and $Temp\_SNR$). Finally, the pow strategies apply their respective gains to reduce the energy consumption per slot as governed by equations 9 or 10 (function E).

Omni-directional antennas possess *a single DOF for both transmission and reception* ($K_{tx} = K_{rx} = 1$) and are not associated with any gain. Switched-beam antennas use *a single DOF for both transmission and reception* ($K_{tx} = K_{rx} = 1$), but by



a) Switched beam b) Adaptive c) MIMO d) Exceptions

Figure 2. Throughput - Strategies

virtue of directing transmissions, they avoid causing and incurring interference in directions other than their own beam direction. This is taken into account in the generation of the flow contention graph. The impact of side and back lobes is also taken into account in determining if the required SNR can be sustained on the link as well as on the active links in its contention regions. Adaptive arrays use *a single DOF for transmission but all available resources for reception and flexible interference suppression* using nulling ($K_{tx} = 1, K_{rx} = K$). MIMO links are capable of using *all DOFs for both transmission as well as reception*. However, only in spatial multiplexing and hence in $rate$ the used resources directly translate to multiple independent data streams ($K_{tx} = K_{rx} = K$). In diversity and hence in its $range$, rel, and pow strategies, the transmitted streams are dependent and hence do not translate to multiple data streams for generic STBC codes ($K_{tx} = K_{rx} = 1$).

4. Comparison of Strategies

Recall that each of the antenna technologies (switched beam, adaptive, MIMO) can be used with one of the four strategies ($rate$, $range$, rel, pow). While we have evaluated and compared each of the technologies operating in each one of these strategies (12 combinations in all excluding omni-directional antennas), we adopt a two-level discussion of the studies conducted for clarity.

First, we evaluate the different strategies in each antenna technology and identify the strategy that delivers the best performance with respect to a metric of interest for a given set of network parameters. Then using these insights, we evaluate the different technologies, each employing its best strategy that delivers the best performance for the given set of network parameters, and draw inferences on their relative performance.

The key components that impact throughput and throughput/energy are: number of active links/contention region (α), number of independent contention regions (m), and number of resources (K_{rx}) available in each contention region. While α depends on node density, load (number of flows) and hops/flow (h, determined by transmission range); m depends on network size and transmission range. The dependence of network capacity (N_c) on the network parameters can now be captured by, $N_c \propto min\{\alpha, K\} \cdot m$. For MIMO, the resources used in a contention region will always be K and are not limited by α or K_{rx}, unlike in switched beam and adaptive where every link uses a single DOF for transmission (and also for reception in switched beam). The throughput per link T_l, which directly impacts the throughput per flow T_f, is now captured by $T_l \propto \frac{N_c}{load \cdot h}$.

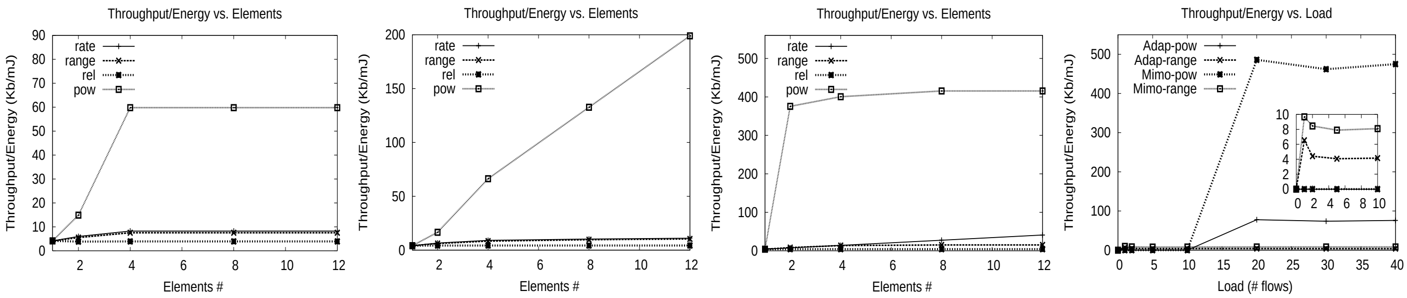
The default values for the parameters used in the results (when not varied) are: a node degree of 12 for density that ensures that the network is connected, a fading loss of 5% which is common in wireless ad-hoc networks, a load of 50 flows ensuring that every node is either a source or destination, array size of 4 elements that ensures easy deployment, and a small scattering angle of 25 degrees to isolate the impact of scattering on other parameters. These default values hold for both the comparisons of strategies as well as technologies in the subsequent section, unless specified otherwise.

4.1 Throughput

The throughput (T) results for the different strategies are presented in Figure 2. $rate$ performs the best amongst the four strategies under most conditions due to its ability to utilize the available gain from elements to directly increase throughput. In $range$, the decrease in spatial reuse reduces the throughput gain that can be obtained from the decrease in hop length. While rel is expected to be a good strategy at high loss rates, this happens only when losses are extremely high ($> 40\%$) and when small number of elements is used. This is because when losses are moderate or low, the reduction in throughput in $rate$ is not significant enough compared to its advantages. Further, most of the protection against losses is leveraged at smaller number of elements itself in rel and hence increasing elements further does not contribute to any significant additional gain. Finally, power control does not exploit the available elements to increase throughput and hence performs the worst. So the general trend[1] in throughput performance is $\{rate > rel > pow > range\}$ as can be seen in Figures 2 (a), (b) and (c), where a scattering angle of 90 degrees was considered.

However, the trend is violated under the following conditions: When density is low and hence the network is not connected, then $range$ can help more flows exist in the network and hence provide better aggregate throughput. Also, when load and hence the number of flows is already low, the decrease in spatial reuse due to increased range does not impact much. Though the number of flows existing in $rate$ is not as many as in $range$, its still possible for the directional/array/multiplexing gain available in $rate$ for those existing flows to outperform the aggregate throughput in $range$. Hence, the specific conditions vary with respect to the technology considered (Figure 2(d)). For switched beam, $range$ performs the best at low density; and moderate density with low loads. For adaptive arrays, the region is low density and low load; low density, high load but small-medium number of elements; and moderate density, low load with small-moderate number of elements. The reason for small-moderate number of elements in adaptive is because, unlike in switched beam where the directional gain in $rate$ is limited severely by scattering and scalloping loss, the array gain in adaptive's $rate$ increases significantly with elements

[1] We use the operator $>$ in $A > B$ to indicate that strategy (technology) A's performance is better than or similar to that of strategy (technology) B.



a) Switched beam b) Adaptive c) MIMO d) Exceptions

Figure 3. Throughput/Energy - Strategies

to outperform $range$. For MIMO, $range$ is best only at low density and low load since the large (linear) range extension resulting from diversity gain significantly reduces spatial reuse. This can be seen from the aggregate throughput in Figure 2(d), where a node degree of 3 was considered.

*Observation 1: For T, **rate** performs the best for all technologies under most network conditions, except at low densities where **range** performs the best.*

4.2 Throughput/Energy

In considering throughput/energy (TE) it becomes necessary to consider the relation between circuit driving power P_c and transmit power P_t. This is because, if $P_t \gg P_c$, then the pow strategy will help significantly improve TE since it directly exploits the available smart antenna gain to reduce P_t. However, if $P_t \sim< P_c$ (P_t less than or comparable to P_c), then no matter how large the gain is, power cannot be reduced beyond P_c in pow since P_c places a lower bound on the power and hence the energy consumed. Hence, the amount of reduction in ($P_t + P_c$) will provide diminishing returns with larger number of elements. Thus, the effectiveness of pow, which is on P_t, is significantly reduced in this case, thereby affecting the trend.

When $P_t \gg P_c$: The TE results for this case are presented Figure 3. pow performs the best under most conditions since power control directly helps exploit the gain in reducing P_t unlike the other strategies. The other strategies do not optimize energy and hence their TE depends on how well they can optimize their throughput. Thus, we have the following trend for TE performance: $\{pow > rate > range > rel\}$ (Figures 3 (a), (b) and (c); scattering angle = 90 degrees). However, at low loads and low densities, $range$ performs the best by virtue of it being able to allow all flows to exist in the network (miniplot in Figure 3 (d); node degree = 3).

When $P_t \sim< P_c$: The ability of pow to reduce energy consumption is significantly reduced. In addition, it also does not possess the ability to optimize throughput. Hence, the advantage of $rate$ and $range$ overshadow pow's energy reduction capability to result in the following trend $\{rate > range > pow > rel\}$ (results omitted due to lack of space). Once again, there exist some exceptions to this trend. $range$ performs the best at low loads and low densities for all technologies. Further, in MIMO, pow performs the best at low elements, low-moderate loads and high densities unlike in switched beam and adaptive arrays since the reduction in P_t is large even at small elements due to diversity gain and hence the net power P is reduced to almost P_c even at small elements (larger elements in diversity only provide diminishing returns). Further, $range$ does not have the advantage of improving connectivity at high densities. Hence, pow outperforms both $range$ and $rate$ in this region in MIMO.

*Observation 2: For TE, **pow** is the best strategy for operation when $P_t \gg P_c$, and **rate** is the best strategy when $P_t \sim< P_c$, for all technologies under most network conditions. At low densities, **range** is the best strategy in all cases.*

4.3 Inferences

We make the following inferences regarding the performance ordering of the different strategies.

For moderate-high network densities,

$$\begin{aligned} T &: rate > rel > pow > range \\ TE(P_t \gg P_c) &: pow > rate > range > rel \\ TE(P_t \sim< P_c) &: rate > range > pow > rel \end{aligned}$$

For low network densities,

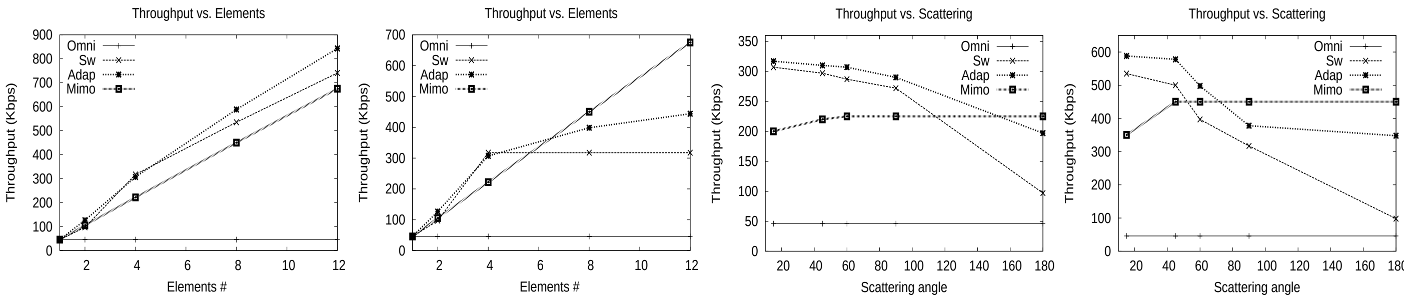
$$\begin{aligned} T &: range > rate > rel > pow \\ TE(P_t \gg P_c) &: range > pow > rate > rel \\ TE(P_t \sim< P_c) &: range > rate > pow > rel \end{aligned}$$

Thus, we find that the optimal strategy of operation varies not only with respect to the network conditions but also with respect to the performance objective. To the best of our knowledge, this is the first time all possible strategies possible with smart antenna technologies have been evaluated and their performance ordering has been obtained for multi-hop wireless networks. Further, we have also considered different possible network conditions as well as different performance objectives such as throughput and throughput/energy (taking into account both communication and circuit power for energy). This would help a network designer choose the best strategy of operation based on network conditions as well as the performance objective desired. Further, even if it is not possible for the network designer to operate his network using the best strategy (say, not being able to perform power control and hence use the pow strategy in connected networks with $P_t \gg P_c$), the ordering can help him determine the next best strategy to operate on ($rate$ strategy).

In the rest of our comparison of the different antenna technologies, we consider $rate$ for T, pow for TE when $P_t \gg P_c$, and $rate$ for TE when $P_t \sim< P_c$, as the default strategies unless otherwise specified.

5. Comparison of Technologies

We evaluate the different antenna technologies with respect to the five network parameters of density, elements, load, scattering and fading loss. However, not all parameters impact each other and hence its not necessary to evaluate the inter-play between all five parameters simultaneously. Recall that the key components that



a) T - Scattering: 25 degrees b) T - Scattering: 90 degrees c) T - Elements: 4 d) T - Elements: 8

Figure 4. Scattering and Elements

impact T and TE are: number of active links/contention region (α), number of resources available in each contention region (K), and number of independent contention regions (m). α is influenced by load and density; K is influenced by elements and scattering (in case of switched beam and adaptive); and m is influenced by density. Fading loss directly reduces T and TE and does not inter-play with any of the other parameters. Now, *since each of the components are atmost impacted by two parameters, evaluating the inter-play between every pair of parameters is sufficient*. However, note that α and K together determine the effective number of resources that can be used in any contention region. Hence, the study of the inter-play between parameters impacting both these components is also necessary. While we have evaluated the technologies with inter-play between the parameters for various combinations, we present results and discussions only for the important subset of the combinations that can be used to derive generic inferences and design rules.

5.1 Throughput

5.1.1 Scattering and Elements

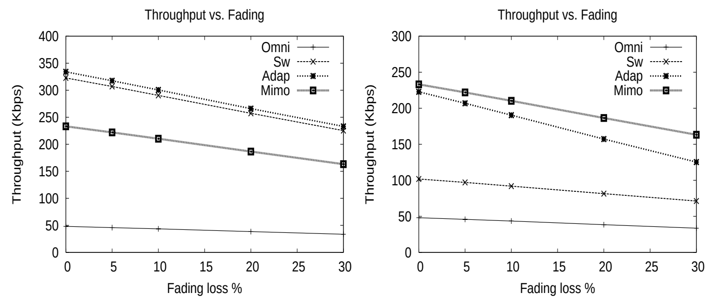
T decreases with an increase in scattering in switched beam and adaptive arrays due to the loss of energy in undesired directions, unlike in MIMO (Figures 4(c) and (d)). As number of elements increases, the available resources per contention region increases and hence improves T. Scattering limits the amount of gain that can be leveraged from the available elements in switched beam and adaptive (Figures 4(a) and (b)) and is hence more influential.

For increasing scattering angles, the trend in performance is $\{MIMO > adaptive > switched\}$ with the relative gain being more at larger number of elements (Figures 4(c)-(d)). But when scattering angles are low, MIMO suffers the most due to the lack of multipath scattering which is in fact essential for spatial multiplexing, resulting in $\{adaptive > switched > MIMO\}$. The improvement from switched beam to adaptive arrays is much more than the improvement from adaptive arrays to MIMO since scattering has a very significant (negative) impact on switched beam, a slight impact on adaptive arrays and almost no impact on MIMO. Further, the improvement over switched beam is more at large scattering angles and larger number of elements.

Observation 3: At large scattering angles, MIMO performs the best irrespective of load and density. However, at low-moderate scattering angles, high loads and high densities, adaptive performs the best.

5.1.2 Scattering and Fading

Throughput decreases with both multipath scattering and fading losses. While fading degrades performance in all technologies, the impact of scattering is relatively more in switched beam (Figures 6(a) and (b)).



a) T - Scattering: 45 degrees b) T - Scattering 180 degrees

Figure 6. Scattering and Fading

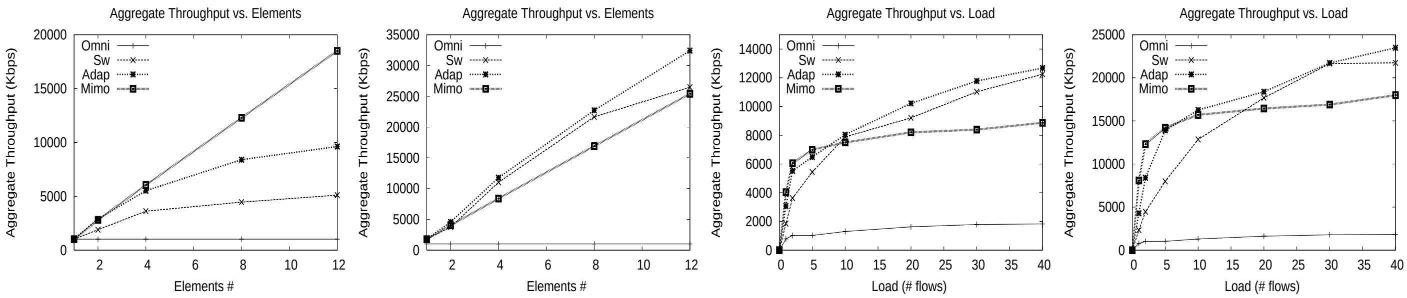
None of the technologies employing $rate$ have protection against fading and hence suffer a degradation in throughput. However, the degradation in throughput is not significant enough to shift the strategy to rel. In fact, as long as the fading is not highly time-correlated, semi-reliable MAC layers (eg. IEEE 802.11) will be able to recover from most of these losses, suggesting that the available gain should be wisely leveraged through $rate$. In this comparison, since the number of elements is moderate (four), when scattering angles are low, switched beam and adaptive outperform MIMO (Figure 6(a)). However, at larger scattering angles MIMO outperforms switched beam and adaptive (Figure 6(b)).

Observation 4: Fading impacts all $rate$ strategies alike. The choice of best technology in the presence of fading, is influenced by the other network parameters considered.

Fading does not have any influential effect on the other parameters in terms of affecting the trends. Also, since scattering limits the gain (in switched beam and adaptive), it has the same effect as reducing the effective available elements (resources) at each node. Hence, we do not present combinations of other parameters with fading and scattering in the rest of the discussions in this section, since their trends can be easily extrapolated from the individual results.

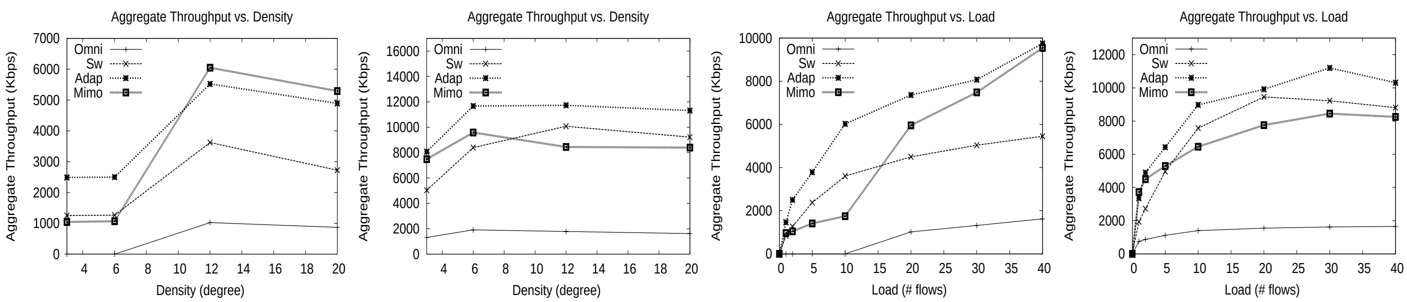
5.1.3 Load and Elements

Throughput increases with increasing load and number of elements (Figure 5). While both elements and load seem to be equally influential in switched beam and adaptive (load increases the number of flows and elements increase the throughput obtained by each flow), elements is the more influential component in MIMO since even at low loads, a MIMO link can use up all available resources in a contention region unlike in adaptive and switched beam.



a) T - Load: 2 flows b) T - Load: 30 flows c) T - Elements: 4 d) T - Elements: 8

Figure 5. Load and Elements



a) T - Load: 2 flows b) T - Load: 30 flows c) T - Node degree: 3 d) TE - Node degree 20

Figure 7. Load and Density

As load increases, T increases, as more and more network resources get utilized by the addition of flows. The trend in performance is $\{MIMO > adaptive > switched\}$ for low loads (Figures 5(a), (c) and (d)), where switched beam and adaptive are not able to use up all available elements ($\alpha < K$ and $\alpha < K^2$ respectively). The gain is especially more at larger elements due to high under-utilization in switched beam and adaptive (Figure 5(a)). But when load is high, the resources are not under-utilized in switched beam and adaptive and hence the directional/array gain helps them outperform MIMO in the presence of low scattering resulting in $\{adaptive > switched > MIMO\}$ (Figures 5(b), (c) and (d)).

Observation 5: MIMO performs the best at low loads and high densities even in the presence of low scattering, with the gain being more at larger elements, due to the under-utilization of resources in its counterparts.

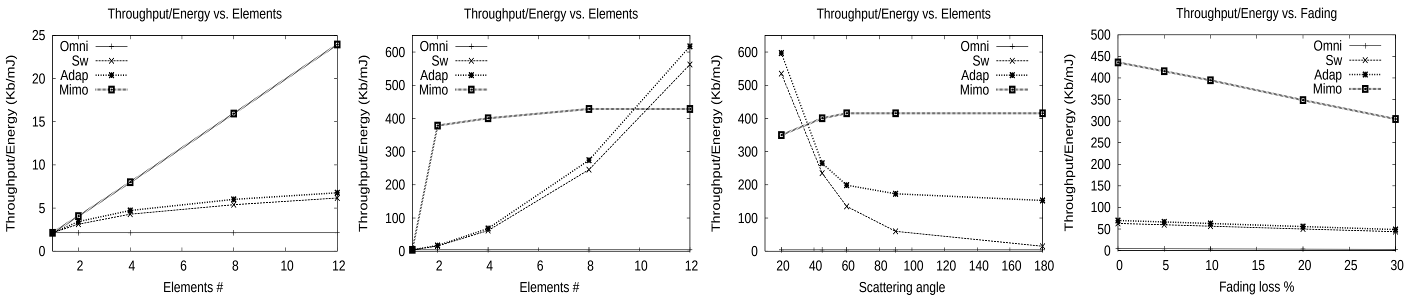
Since load and density, both impact the number of active links per contention region (α), their influence on the performance trends are similar. Hence, the combined variation of density and elements is not presented here.

5.1.4 Load and Density

As density increases (by decreasing network size), T increases initially due to increased number of connected flows but then starts to decrease once the network is connected wherein the impact of the decrease in spatial reuse is felt (Figures 7(a) and (b)). Further, if the elements are not sufficient to accommodate all the active links in the contention region, which in turn increases with density, then T will start to decrease. As load increases, T increases, and then starts to saturate when the available resources are exhausted (Figure 7(d)). Load is a more influential factor since it directly increases the number of flows that can utilize the resources in the network, especially at low densities (Figure 7(c)) and hence directly impacts the number of active links/contention region in the network.

MIMO performs the best for low loads and high densities, when the number of active neighboring links is less than the available elements, thereby resulting in under-utilization of resources in adaptive and switched beam (Figures 7(a) and (d)). For the rest of the cases, adaptive performs the best. As identified in Section 4, $range$ replaces $rate$ strategy for specific network conditions, namely, at low densities, and low load at moderate densities for switched beam and adaptive; and at low densities with low load for MIMO. We now have the following trends when using $range$ under specific conditions: $\{adaptive > switched > MIMO\}$ at low densities with low load (Figures 7(a) and (c)); $\{adaptive > MIMO > switched\}$ at low densities with high load (Figures 7(b) and (c)); and $\{adaptive > MIMO > switched\}$ at moderate densities with low load (Figure 7(a)). Thus, MIMO performs the best only at high densities with low loads. The reason for poor performance of MIMO at low densities with low load is that: when we move to low densities (with low load for MIMO) we need to shift to $range$ strategy which provides better T. However, *while the same directional/array gain is used in switched beam/adaptive for range extension, the diversity scheme needs to be used in MIMO, whose large range extension significantly reduces spatial reuse*. Further, diversity has code rates < 1 for $K > 2$ and uses up all degrees of freedom, whereby only one active link can transmit in any contention region. This degrades MIMO's performance worse than adaptive and switched beam. Further, adaptive ($range$) outperforms MIMO's best strategy ($rate$) at low densities with high load since the moderate range extension from array gain helps find routes for more flows and also reduces the hops/flow (which helps significantly at large loads) without significantly reducing spatial reuse. Note that, we have considered low scattering here. If however, scattering is large then MIMO will perform the best.

Observation 6: Unlike the case of low scattering and high densities, at low scattering and low densities, adaptive performs the best, while MIMO performs the worst owing to its ***range*** *strategy resulting in a large reduction in spatial reuse.*



a) TE - Load: 10 flows, $P_t \sim< P_c$ b) TE - Load: 10 flows, $P_t \gg P_c$ c) TE - Elements: 12, $P_t \gg P_c$ d) TE - Scattering: 90 degrees, $P_t \gg P_c$

Figure 8. Throughput/Energy

5.2 Throughput/Energy

The throughput/energy (TE) results are presented in Figures 8 and 9. TE shows an increasing trend with elements due to increased rate from directional/array/multiplexing gain (when $P_t \sim< P_c$, Figure 8(a)) or reduced power consumption from directional/array/diversity gain (when $P_t >> P_c$, Figure 8(b)). TE decreases with an increase in scattering angles in switched beam and adaptive arrays due to reduced antenna gains unlike in MIMO (Figure 8(c)). Increased fading losses directly degrade T and consequently TE (Figure 8(d)). TE decreases with increasing load and tends to saturate at large loads (Figure 9(b)). In fact, both T and energy decrease with increasing load, but the decrease in T is relatively more. This is because the energy associated with a flow is proportional to the product of its throughput and hop length; and as the load (# flows) increases, there is an increase in the average hop length initially, which in turn tends to saturate with larger number of flows (higher load). Finally, TE shows an increasing trend with density (reduced network size) since hops/flow decreases at high densities, thereby reducing the energy consumption (Figure 9(a)). At very high densities, the impact of decrease in spatial reuse is more than the decrease in hops/flow, thereby degrading TE slightly.

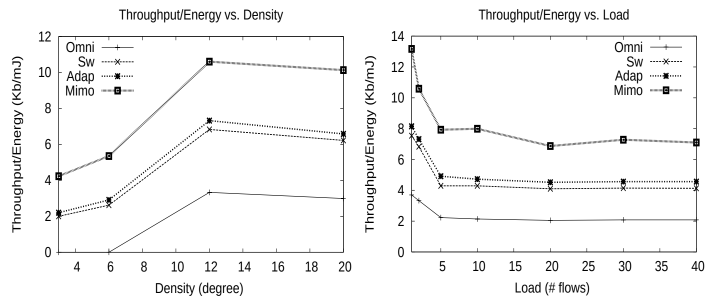
5.2.1 When $P_t \gg P_c$

pow serves as the operating strategy in all technologies. MIMO performs the best in most conditions due to its diversity gain contributing to large reduction in power, with the trend being $\{MIMO > adaptive > switched\}$ (Figure 8(b)). However, at small scattering angles and large number of elements, MIMO is outperformed resulting in
$\{adaptive > switched > MIMO\}$ (Figures 8(b) and (c)). This is because, *the diversity gain and hence power reduction diminishes with increasing elements unlike the array gain in switched and adaptive arrays* as can be seen in Equations 9 and 10. At low densities and low loads, $range$ is always the strategy employed by all the technologies. In these conditions, while switched beam and adaptive outperform MIMO in T due to the large reduction in spatial reuse (due to increased range from diversity - Figure 7(a)), MIMO performs the best with respect to TE due to the large reduction in hop length resulting from the same diversity gain (low density region in Figure 9(a)).

Observation 7: For TE, when $P_t \gg P_c$, MIMO performs the best with a large gain for most network conditions (including low densities, unlike in T) owing to its diversity gain. At low scatterings and large elements, adaptive performs the best.

5.2.2 When $P_t \sim< P_c$

$rate$ serves as the operating strategy in all technologies. MIMO performs the best in most conditions with the trend being



a) TE - Load: 2 flows, $P_t \sim< P_c$ b) TE - Node degree 12, $P_t \sim< P_c$

Figure 9. Throughput/Energy

$\{MIMO > adaptive > switched\}$ (Figure 8(a)). The main reason is that while switched beam (adaptive) can exploit directional (array) gain, and also potentially enable multiple parallel transmissions in their contention regions due to their K available resources (interference suppression gain), every transmission requires one unit of energy. However, in MIMO, K equivalent transmissions can take place on a link at the cost of one unit of energy due to the spatial multiplexing gain, resulting in power-efficient resource usage. This helps MIMO scale well in TE with respect to elements unlike switched beam and adaptive. Since multiplexing is used, MIMO does not suffer from diminishing returns from diversity gain and hence outperforms switched beam and adaptive even at low scatterings and large number of elements (compare Figures 8(a) and (b)).

Observation 8: For TE, when $P_t \sim< P_c$, MIMO performs the best in all conditions, showing good scalability (with elements) and gain due to the power-efficient resource usage in multiplexing.

5.3 Inferences and Implications

We now summarize the inferences with respect to the performance of the different smart antenna technologies.

We observe that smart antennas provide significant benefits compared to omni-directional antennas with respect to both T and TE in multi-hop wireless networks. We also observed MIMO to perform the best in the presence of significant scattering, while adaptive and switched beam tend to perform the best when scattering is low or moderate. Further, MIMO's diversity technique provides the best protection against multipath fading losses.

While the above set of inferences have parallels in PHY layer (cellular networks), the following inferences we identify are specific to multi-hop wireless networks, considering different networks parameters such as load, density, elements, etc. both individually as well as in conjunction.

5.3.1 Scalability

One of the key inferences is with respect to scalability. MIMO's spatial multiplexing provides the best scalability with respect to increasing elements (resources), due to its ability to use up all available resources efficiently unlike in switched beam and adaptive arrays where a single DOF is used for desired communication, with the remaining resources being used for interference suppression. Hence, the ability to use up all resources and hence scale, depends on the number of active neighbors available to a node in the case of switched beam and adaptive arrays. Thus, as long as number of neighbors ($\Theta(\log n)$) is small compared to the available resources ($K > \Theta(\log n)$ in adaptive and $K^2 > \Theta(\log n)$ in switched beam), there will be under-utilization, thereby limiting scalability. Hence, it is important for network designers to deploy smart antenna arrays with appropriate technology and number of elements based on the network topology and traffic pattern envisioned.

5.3.2 Exploiting Diversity

Another important observation is with respect to deploying large number of elements for diversity (and hence large diversity order) in MIMO. In the case of rel, large diversity order can reduce the link BER to arbitrarily small values. However, most applications only require that packet error rates satisfy a certain threshold, especially in the presence of FEC mechanisms and semi-reliable MAC layers such as IEEE 802.11 that employ re-transmissions (overcomes fast Rayleigh fading). Hence, a large diversity gain that comes at the cost of rate, is obviously un-necessary in such situations. Even worse, when diversity is exploited for increased communication range as in $range$, a large range extension than that required (say for connectivity) would significantly reduce the spatial reuse in multi-hop networks, thereby degrading throughput performance. Hence, it becomes necessary for network designers to devote only as many number of elements for diversity as required for the purpose (increased reliability, range, etc.) and use the remaining for spatial multiplexing, thereby employing a combination of both strategies on the link.

5.3.3 Performance Ordering

One would normally expect the relative performance between the technologies to follow $\{MIMO > adaptive > switched\}$ in rich multi-path environments and $\{adaptive > switched > MIMO\}$ in strong LOS environments based on PHY layer studies. However, we observe that the optimal technology and strategy not only depends on the environment conditions but also largely on (i) network parameters specific to multi-hop networks and (ii) performance objectives considered, thereby proving the importance of the conducted study. For eg., we find MIMO to suffer significantly in T at low densities even in the presence of large scattering where the use of large range extension from diversity significantly reduces spatial reuse. However, we find the same $range$ strategy of MIMO to perform the best in TE, due to the large reduction in hop length, which matters the most for TE. We also find adaptive arrays and switched beam to outperform MIMO in TE ($P_t >> P_c$) at large elements and low-moderate scattering angles where the diversity gain tends to saturate unlike the array and directional gains. However, when $P_t \sim< P_c$, MIMO performs the best even at low scatterings and large elements due to the efficient resource utilization of multiplexing in $rate$ and the large hop-length reduction due to diversity in $range$.

5.3.4 Adaptive Arrays vs. Switched Beam

Finally, considering the performance between adaptive arrays and switched beam, we find that adaptive arrays perform significantly better than switched beam at *large scattering angles and large elements*. Hence, unless scattering and elements are large, the gain of adaptive over switched beam may not justify the complexity and communication overhead incurred in adapting its beam-pattern and hence its deployment by network designers.

6. Concluding Remarks

In this work, we have identified the various strategies of operation of different smart antenna technologies and have evaluated them comprehensively for a variety of network conditions and performance objectives. We have used the studies to draw inferences on the optimal strategy and antenna technology to be used for specific network conditions as well as identify their relative ordering in performance. The inferences presented in this work will help a researcher working in the field of smart antennas in ad-hoc networks, better understand the relative performance benefits of the different strategies and antenna technologies and appropriately design efficient protocols. Further, it would also help a network designer better decide the antenna technology and strategy to be deployed in his network based on the metrics of interest.

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