A low-delay MAC solution for MIMO Ad Hoc Networks

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***Abstract*—Beamforming is regarded as a key element for multiantenna ad hoc networks. However, it cannot simultaneously provide the omnidirectional and long-range coverage required by broadcast transmissions [1]-[4], a problem known as the Asymmetry in Gain. We propose a scheme for control packet exchange over an extended radio coverage based on a Space Time Code technique. This solution is shown to solve the Asymmetry in Gain issue, and is proposed as part of a MAC protocol for MIMO ad hoc networks, whose performance benefits include increased throughput and reduced delay and energy consumption.**

***Index Terms*—Space Time Coding, MIMO, Ad hoc networks, MAC protocols**

I. INTRODUCTION AND PROBLEM STATEMENT

BEAMFORMING [5] has been the main ingredient of many multiantenna ad hoc network MAC protocols [1]-[4], [6], [7]. Unicast data packets especially benefit from its ability to increase coverage and reduce interference. On the other hand, control packets (like RTS/CTS frames) or multicast/broadcast transmissions (such as routing information) need to be distributed omnidirectionally and with increased range, in order to reach as many neighbors as possible. If these packets are transmitted directionally, coordination between nodes can become very poor [4], [8]. This asymmetry between the possibility to achieve a high (but directional) gain and the need for an omnidirectional transmission has been called the gain asymmetry and, if not properly addressed, may lead to poor performance at the MAC layer, where directional transmission of data packets and omnidirectional transmission of control packets coexist [1]-[4]. One of the main ideas to solve this issue so far has been the concept of Circular RTS (C-RTS),[1] where a control packet is successively beamformed in adjacent sectors, so that the whole horizon is swept by means of multiple transmissions. This approach extends the transmission range while also retaining omnidirectionality, but comes at the price of additional delay. A longer handshake increases the contention time, thus reducing the efficiency of the handshake itself and the overall performance. Finally, the usage of multiple packets increases interference and energy consumption.

Moreover, a closely related problem is that the majority of the proposed MAC protocols for MANET with smart antennas [2], [4], [6], [8], as well as the studies of broadcast techniques [9], [10], assume that omnidirectional reception must have unit gain, so that the transmitter-receiver pair is effectively turned into a MISO (rather than MIMO) system. This is due to the erroneous belief that there is always a trade-off between beamforming gain and beamwidth. While this is certainly true at the *transmitter*, where sending on two beams simultaneously requires twice the power and is therefore impossible in the presence of a power constraint, at the *receiver* this is not the case, because starting from the baseband samples at the output of the antennas it is possible to form as many receiving beams as desired by just using signal processing (i.e., no additional power is needed to implement more beams, as long as the processing power consumption can be considered as negligible). This misinterpretation of the beamforming process at the receiver has led some authors to designing schemes that take into account a constraint that does not exist.

While the asymmetry in gain has been identified and addressed for directional antennas [1]-[4], protocols designed for MIMO networks do not deal with it [7], [11]-[13]; these papers explore the interaction between MIMO PHY and MAC, and they assume that the coverage of directional and omnidirectional communications is the same, because the network is geographically small. Or in some other cases [13] unicast and broadcast packets are transmitted by the same space time architectures (STBC in that case). This approach is suboptimal, because it does not consider the possible directionality inherent in antenna arrays even when it could be useful. On the other hand, studies for broadcast in multiantenna networks [9]-[10] focus on designing MAC protocols that exploit directivity, but again directional and omnidirectional transmission ranges are the same, because the power for directional communications is lowered.

The problem that we want to solve is to employ a known MIMO technique for packets that have to be processed by all neighbors, such that it 1) achieves the same performance as [2] in terms of increased coverage, 2) provides a major reduction of the delay (sending the packet as few times as possible), 3) is an open loop technique, and 4) is not applicable to directional data transmissions. The last condition can be motivated as follows. A solution suitable for transmission of both control (omnidirectional) and data (directional), such as for example traditional channel coding or TCM, would benefit them equally and hence would not reduce the asymmetry. Therefore our goal has been to design an efficient protocol component by means of existing PHY techniques.

Manuscript received June 17, 2006; revised September 23, 2006, January 16, 2007, June 3, 2007 and October 15, 2007; accepted July 16, 2008. The associate editor coordinating the review of this letter and approving it for publication was Dr. S. Shen.

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The material in this paper was presented in part at IEEE ICC 2006, Istanbul (Turkey) [17]. This work is supported in part by the U.S. Army Research Office under the Multi-University Research Initiative (MURI) grant no. W911NF-04-1-0224

Digital Object Identifier 10.1109/TWC.2008.080662.

[1] The technique of C-RTS was originally proposed in [2] and later extended (under the name of Circular RTS and CTS MAC, CRCM) in [3]. While our comparisons refer to the latter and more advanced version, we will use both terms (CRCM and C-RTS) interchangeably.

The contribution of this letter is a novel control packet exchange method that provides extended as well as omnidirectional coverage while not suffering from the long delays incurred by C-RTS, and the design and performance evaluation of a new MAC protocol based on it. Our goal is not to propose a new MIMO technique, but rather to use existing multi-antenna schemes in the design of high-performance protocols which exploit the opportunities offered by antenna arrays. Our scheme includes for the first time some MIMO techniques that, while well established in the PHY community, have not yet been considered in the *protocol design* for MIMO ad hoc networks [7], [11]-[13]. We show that some existing and well studied MIMO techniques are sufficient to overcome the asymmetry in gain. The upshot is a 40% delay reduction and 15% throughput improvement over state-of-the-art protocols.

The rest of the paper is organized as follows: The models for the wireless channel and the Space Time codes are analyzed in Section II; Section III describes the protocols and compares their PHY. OPNET simulations in Section IV measure the performance of the two protocols at the MAC layer, while Section V draws the conclusions.

II. ANTENNA AND CHANNEL MODELS

In this paper, plain letters (i.e., x) denote scalars, overlines (i.e., $\overline{x}$) denote column vectors and capital bold letters with an overline (i.e., $\overline{\mathbf{X}}$) denote matrices.

The MIMO channel is regarded as Ricean flat fading, slowly varying in time. The baseband (complex) channel gain from the α-th input to the β-th output is denoted by $h_{\alpha,\beta}, \alpha, \beta \in \{1, 2, ..., N\}$, where N is the number of antennas at each node. We consider here a Space-Time Block Code (STBC) model [14], in which a block of K complex data symbols (arranged in the vector $\overline{x} = (x_1, x_2, ..., x_K)^T$, $x_i = x_i^r + jx_i^i$) is transmitted in $L \geq K$ symbol intervals (K/L is the code rate). In the ℓ-th interval of each L-symbol group, the N antennas send linear combinations of the K data symbols, computed according to two weighing $N \times K$ matrices: $\overline{\mathbf{W}}_\ell^r$ for the real part and $\overline{\mathbf{W}}_\ell^i$ for the imaginary part. The output of the baseband equivalent of the receiver antennas in the ℓ-th symbol interval (neglecting interference from other users) can be written as:

$$\overline{r}(t) = \overline{\mathbf{H}} \left(\overline{\mathbf{W}}_\ell^r \overline{x}^r + j\overline{\mathbf{W}}_\ell^i \overline{x}^i\right) + \overline{n}(t) \tag{1}$$

where $\overline{n}(t)$ is a zero-mean, spatially and temporally white Gaussian noise. A set of complex matrices $\overline{\mathbf{W}}_\ell^r, \overline{\mathbf{W}}_\ell^i, \ell = 1, \ldots, L$ defines an STBC. For instance, for the Alamouti code [15] and QAM modulation, two data symbols are transmitted every two symbol intervals, so that $K = L = 2$ and $\overline{\mathbf{W}}_1^r = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\overline{\mathbf{W}}_2^r = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, $\overline{\mathbf{W}}_1^i = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, $\overline{\mathbf{W}}_2^i = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.

Finally, the Ricean statistics describes each channel gain by a constant coefficient and a complex circularly symmetric Gaussian random variable:

$$\overline{\mathbf{H}} = \sqrt{\frac{\kappa}{\kappa+1}} G\overline{a}(\theta_t)\overline{a}(\theta_r)^T + \sqrt{\frac{1}{\kappa+1}} \overline{\mathbf{H}}_w \tag{2}$$

where κ is the Rice parameter, and θ_t and θ_r are respectively the direction of the receiver with respect to the line perpendicular to the transmitter's array and viceversa. The first part is the LOS component. The coefficients $\overline{a}(\theta_t)$ and $\overline{a}(\theta_r)$ can be derived by geometric reasoning ([5], [16], Section III) and depend only on the array geometry and the transmission/reception directions. $\overline{\mathbf{H}}_w$ is a matrix composed by complex circularly symmetric Gaussian random variables, and models fading.

We assume that the receiver has perfect Channel State Information (CSI, e.g., obtained by training based estimation), while the transmitter only knows the function $\overline{a}(\theta_t)$ (which depends only on θ_t and requires no feedback from any receiver). This asymmetry is due to the fact that in multicast it is typically impossible for the transmitter to have CSI for all the receivers (whose number and identity may even be unknown).

III. PROTOCOL MODEL

In the following we outline our protocol and a modified CRCM that is more robust to fading.

1) STBC based broadcast: In our previous research [17], we showed that (in agreement with other results from array processing theory [5] or information theory [18]) in a MISO setting the asymmetry in gain cannot be eliminated, because there is an intrinsic tradeoff between coverage and packet delivery delay. Thus the receiver's degrees of freedom must also be used in order to overcome this impairment. The performance gap with respect to CRCM can be bridged using Maximum Ratio Combining (MRC) at the receiver and a space time block code [14] with full rate (to keep the delay as short as possible) and full diversity (to improve the outage behavior of the scheme). These features can be found in the STBC proposed in [19] (called ABBA), refined by constellation rotations [20], which also provides some coding gain. The decoding is performed by a twice iterated MMSE-PIC. That is to say, all symbols are first decoded by an MMSE filter, then each stream is decoded after the contribution from the other symbols is cancelled. The computational complexity is about twice as large as that of linear MMSE detection, but the performance in terms of BER vs SNR is close to optimal. We opted for an already existing coding strategy, because our purpose is to use known PHY solutions to enhance a MAC protocol, rather than to advance space time processing theory itself.

Therefore, our proposal is to employ this class of STBC to transmit control packets; we prove by Bit Error Rate (BER) simulations (reported at the end of this Section) that a suitable MIMO technique (the ABBA code properly enhanced) can provide the same performance as the beamforming technique of [3] in terms of range extension and omnidirectionality, without the delay and energy costs associated to multiple transmissions. Thus, a brief description of the protocol is as follows:

- Medium access is controlled by conventional carrier sense;
- RTS/CTS packets are transmitted by means of the ABBA STBC. The CTS includes the channel right eigenvector corresponding to the largest singular value;

- Unicast packets (data/ACK) are sent by closed loop beamforming. The weight vector was included in the CTS;
- If no feedback is received (i.e, CTS or ACK), another attempt is performed after a binary exponential backoff, or the packet is discarded if the maximum number of retransmissions has been reached.

Unicast packets may employ spatial multiplexing or beamforming. While an application of the former is, for example, [11], we focus on the latter. In conclusion, we study CSMA/CA where control packets use the ABBA STBC, and evaluate the network performance benefits provided by this space time architecture.

2) Modified CRCM: The original CRCM [3] would follow the same protocol model outlined in the previous subsection, except for the transmission scheme for RTS/CTS packets. In [3] an RTS/CTS frame would be sent by a sweep of directional communications in order to emulate a broadcast transmission, while the Data/ACK exchange is directional. The radiation pattern adopted in studying CRCM followed the pie-slice model, and selection diversity was assumed at the receiver [2]. While this might be quite realistic for LOS conditions, the presence of a highly scattering medium would break the regularity of the pattern, so that CRCM would present unacceptable performance. Instead, one of the desirable features of our system is that it offers robust performance with respect to the degree of fading. Therefore it is a suitable choice for both LOS environments and Rayleigh fading conditions.[2] Therefore, for a fair comparison, we have modified the scheme in [3] by the inclusion of an STBC.[3] In addition, the required method must be flexible enough to reduce to a conventional beamforming scheme if CSI is available at the transmitter. The scheme proposed in [21] associates the Alamouti STBC [15] with equal gain combining in a frequency flat environment, and has been chosen because of its simplicity and effectiveness. The difference between the modified CRCM and our scheme lies in the type of STBC and in the number of transmissions for each RTS. In its original form, the scheme is designed for a system with 2 transmit antennas, but it can be readily generalized to encompass any number N of antennas. In this type of STBC, the transmitter is assumed to know the phase difference between the channel coefficients, so as to perform equal gain combining beamforming. In [21] this quantity is fed back by the receiver. However, in a broadcast environment this kind of information is not available, thus the transmitter simply assumes the channel vector $(h_1\; h_2\; ...\; h_N)$ towards direction θ_t (with respect to the direction orthogonal to the array axis) to be proportional to $(\hat{h}_1\; \hat{h}_2\; ...\; \hat{h}_N) = (1,\, e^{j\phi},\, e^{2j\phi}, ..., e^{j(N-1)\phi})^T$ where $\phi = \pi d\ sin\theta/\ell$, which are the coefficients of classic linear beamforming schemes [5] (d is the array pitch, ℓ is the carrier wavelength, θ is the actual direction of the receiver with respect to the transmitter). The choice of θ_t is exactly the same as in [2]: $2\pi k/M$, where M is the total number of control packets needed to sweep the whole horizon and k is the number of control packets sent so far in the sweep. Thus also this scheme is open-loop. Since the ABBA code does not require any feedback from the receiver, both systems are open-loop.

Moreover, the original scheme in [21] includes a parameter, λ, which is a distribution coefficient for allocating power between the two transmitted symbols. The choice of this parameter should mirror the correlation between the estimated and the actual coefficients. In our case, the closer the scenario to the LOS condition, the higher the correlation. Since the power of the LOS component is proportional to $\kappa/(\kappa+1)$, λ is taken to be equal to $1-\kappa/(\kappa+1)$. Provided that the Rice constant is known,[4] the beamforming matrix can be built as follows:

$$\begin{pmatrix} 1 & 0 \\ v\sqrt{1-\lambda} & \sqrt{\lambda} \end{pmatrix}$$

where v is equal to $e^{-j\cdot arg(h_2 h_1^*)}$, that is to say the phase difference between the first and the second columns of the channel matrix. In a broadcast scenario, this (unknown) information is replaced by $e^{-j\cdot arg(\hat{h}_2 \hat{h}_1^*)}$. If perfect CSI were available at the receiver, this scheme would yield an equal gain combining beamforming. Therefore, for a circular broadcast of RTS/CTS packets, each time a certain direction is taken as reference and the channel coefficients are estimated according to that bearing.

For $N > 2$ antennas at the transmitter, the system can be generalized as follows. The STBC is still Alamouti, but each symbol is sent by a block of $N/2$ contiguous antennas. Finally, this system could be extended to include a higher diversity STBC, but it would lose orthogonality and that would entail more complicated signal processing.

A brief comparison of the BERs achieved by the two systems is reported in Fig. 1 when both transmitter and receiver have 4 antennas. Fig. 1 shows that the usage of the ABBA STBC with MRC does provide enough coding gain to overcome the asymmetry in gain. The powerful ABBA code yields a very robust behavior with respect to different channel variabilities (the two curves for STBC basically overlap). Even in the AWGN case (the scenario CRCM is designed for) STBC outperforms CRTS. The reason is as follows: the performance would be very close if the receiver were always at the center of the main beam. However, this may not be the case, since its position is random inside the beam. Therefore, the C-RTS may not always provide as high a gain as possible, and this causes the 1 dB performance loss observed in Fig. 1 for the AWGN case. The STBC does not rely on any LOS component or directionality, and this offers a smooth performance with respect to the transmitter-receiver mutual position.[5] These BER simulations show that the STBC method achieves at least

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[2] Most of the cited protocols work in LOS conditions only. However, there are some protocols designed for highly scattering conditions, e.g., [7]-[12]

[3] We remark that our previous work [17] simulated C-RTS by a highly idealized model, where the transmitter had perfect CSI toward any receiver. The modified version here is a more realistic implementation of C-RTS for a fading channel.

[4] It may be estimated by averaging the channel coefficients in time and space, because the channel statistics is assumed to be time invariant in both dimensions.

[5] The value of about 1 dB may be predicted by computing the average gain of a 4 antenna linear uniform array in broadside configuration inside its 3 dB beamwidth. This integral mean is equal to 3.24, which corresponds to a loss of 0.91 dB with respect to the peak value (equal to 4).

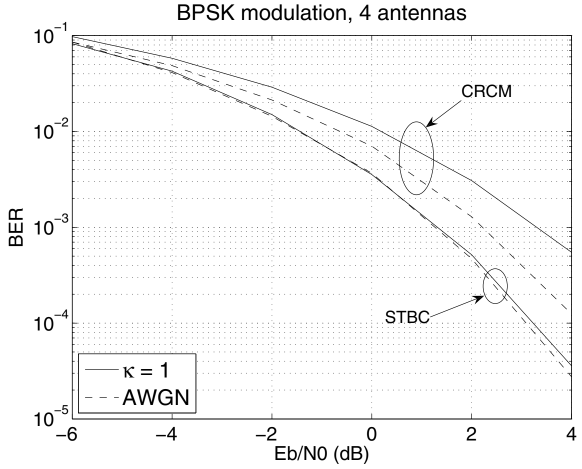

Fig. 1. BER Comparison for CRCM and STBC

the same coverage as CRCM for the shown array sizes, since for the same SNR BER$_{STBC}$ $\leq$BER$_{CRCM}$. For even larger array sizes (10 antennas or more) the beamforming array gain cannot be provided by modified STBC. In this case, the packet has to be transmitted twice or more to match the power gain. However, these large arrays are not of practical importance for ad hoc networks. In our setting, a single transmission is enough to provide as good a coverage as CRCM.

In conclusion, the main differences between our scheme and CRCM are:

- Our scheme uses STBC ABBA, CRCM employs beamforming (hybrid STBC/beamforming in its modified version);
- Our scheme needs to transmit a packet only once for moderate array sizes N, CRCM needs at least N transmissions;
- Our scheme is completely open loop, CRCM needs to estimate the Rice constant.
- Our scheme uses the ABBA STBC, while CRCM employs beamforming (or hybrid STBC/ beamforming in its more advanced version) for handshake packets;
- Our scheme manages to broadcast a packet in a single transmission for moderate array sizes, CRCM needs at least N transmissions;
- Our scheme is completely open loop, modified CRCM needs to estimate the Ricean constant.

IV. MAC PROTOCOL SIMULATION RESULTS

The two schemes in Section III can be employed in modified IEEE 802.11 MAC protocols, where the control packets are sent according to one of these two methods and the data packets by directional beamforming. In order to assess their actual impact on network behavior and performance, CRCM and our protocol have been compared using OPNET 11.5. The network is a 200m × 200m square, where 12 nodes are uniformly randomly placed. The simulation time is 240 seconds, long enough to stabilize the metrics, and the results are averaged over 30 independently generated random topologies, which provide the desired statistical confidence.

The maximum transmission power (0.25 mW) has been chosen large enough to let every node transmit a data packet (8336 bits) to any other node in an AWGN channel with an outage probability of 10% only if they both transmit and receive directionally with 4 antennas each.[6]

Therefore, this is a single-hop network with no hidden nodes. This scenario, where all nodes may simultaneously contend for the channel, is designed to test the ability of the protocol to exploit spatial re-use and to reduce channel contention. MIMO ad hoc networks can provide increased parallelism, but the physical layer capacity improvement must be coupled with an adequate degree of coordination, or otherwise performance may be even worse than conventional 802.11 [8]. Our study has focused on the use of STBC to improve channel access. The impact of these techniques for multihop networks is an interesting problem.

There are four types of packets: RTS, CTS, DATA and ACK. Their sizes are, respectively, equal to 240, 240, 8336 and 120 bits per packet. The CTS is as large as the RTS because it carries the estimated coefficients of the transmit beamforming vector. In CRCM, each RTS/CTS is sent 5 or 10 times, for a 4 or 8 antenna array [17]. The packet arrivals are described by a Poisson process, whose rate takes values between 10 and 100 packets/s. This rate has been increased until saturation.

Each node is equipped with a linear antenna array, comprising 4 or 8 antennas. The Rice factor κ is equal to 1 or ∞ (AWGN). These two values have been chosen to test almost opposite environments, i.e., nearly Rayleigh or LOS. For our system, the rotation angle of the STBC has been chosen to be half the characteristic angle of the PSK modulation. While this is not always optimal, the performance is often close to the maximum [20]. Moreover, the channel is never purely Rayleigh. If fading followed a Rayleigh statistics, CRCM performance would drop to a very low level, because no LOS component is present, while CRCM needs some predictable LOS component to beamform and achieve array gain. We have avoided this scenario, in which CRCM would be too penalized, and haven chosen $\kappa = 1$ instead as representative of a heavily faded channel. Finally, the channel bandwidth is 1 MHz and the modulation is BPSK, and thus the data rate is equal to 1 Mbps.

Three metrics (aggregate throughput, packet delivery latency and transmit power consumption) will be evaluated. The first metric is the aggregate throughput, defined as the total number of data bits successfully acknowledged, normalized by the product of the channel bandwidth and the simulation duration. This quantity is depicted against the aggregate load,[7] which is computed as the total number of transmitted bits, including both data and control packets, also normalized by the bandwidth-duration product. Whenever this quantity is larger than 100%, then spatial reuse is effectively in place, because more bits than the duration-bandwidth product are sent. Hence

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[6] Our simulations show that both approaches make the network fully connected. This indirectly proves that they achieve the same coverage, since this network is single hop only if sufficient array gain can be obtained also for handshake packets.

[7] We shall use the expression effective load as a synonym. This term is meant to also highlight that we take into consideration the bandwidth actually used by the users, not the nominal load given by the traffic generated at the packet sources.

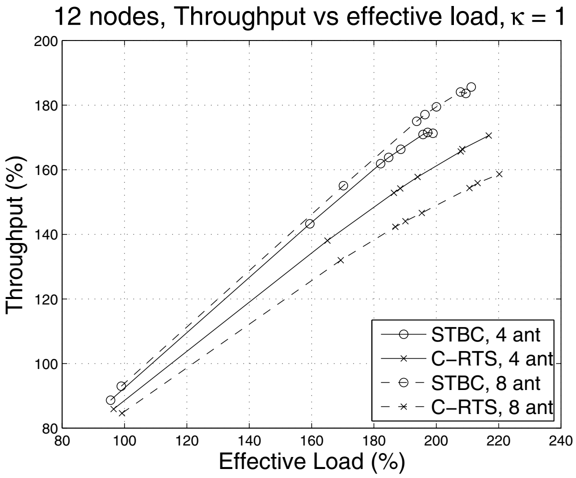

Fig. 2. Throughput vs effective load, 12 nodes

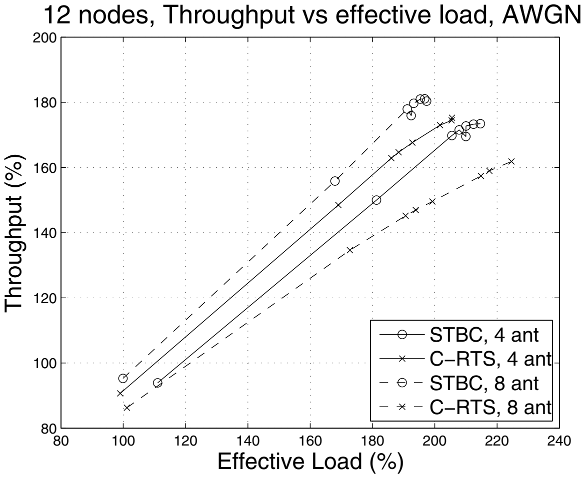

Fig. 3. Throughput vs effective load, 12 nodes

this load (and not the nominal load) actually proves whether antenna arrays enable spatial reuse, and is thus more informative for this class of MACs. The results are reported in Figs. 2 and 3. A few observations are in order. First of all, Figs. 2 and 3 analyze the same networks; in the former, the Rice constant is 1, in the latter ∞. For a scenario close to Rayleigh fading, our system outperforms CRCM for both array sizes (gaining 15% and 25% in throughput, respectively). In addition, the performance of CRCM actually becomes worse for a larger number of antennas (losing 5% in throughput), because of the increased RTS/CTS overhead and interference. In such a case, handshakes fail more often and since their duration is longer the loss in throughput is more noticeable. The phenomenon is particularly remarkable in the AWGN case: in the 4 antenna case CRCM delivers the same performance as STBC but with slightly smaller load. However, in the 8 antenna case the relative order is reversed, with a performance gain as large as 25%, showing that our scheme can better exploit the benefits of antenna arrays. With 4 antennas, CRCM slightly outperforms our protocol because each hadshake packet is sent out 4 times, and thus these frames can enjoy a limited amount of time diversity. For a small number of antennas and the AWGN channel, CRCM does not incur a large overhead and its RTS/CTS have additional robustness due to the repeated retransmissions. However, CRCM performs better than the STBC solution only in terms of throughput and only for LOS channels, that is to say the situation it has been designed for. On the other hand, our approach is more robust to the channel environment parameters, since it is not greatly affected by the specific value of the Rice constant. Incidentally, we point out that the metric shown on the x-axis of the plots is the effective load, and therefore the expected saturation effect is not shown in the graphs, because for higher nominal loads both aggregate load and throughput decrease.[8] Therefore, points in the graphs reach a maximum in the top-right corner and then both coordinates scale down.

More importantly, thanks to the much more efficient RTS/CTS exchange, our scheme achieves a significantly reduced packet delivery delay (Figs. 4 and 5). In the comparison, we considered the latency between the start of MAC contention and the correct reception of the ACK. The delay reduction is between 17 and 20% for 4 antennas and between 32 and 37% for 8 antennas. In addition, this advantage is more noticeable for a larger number of antennas, as expected, and in the AWGN case the 8-antenna system outperforms the 4-antenna network because of the increased interference suppression, which leads to fewer retransmissions. Instead, CRCM's latency is affected by the circular RTS delay. Doubling the array size from 4 to 8 antennas results in twice as many transmissions of RTS and CTS packets (from 5 to 10 times each). Each of them takes 240 μs, leading to an additional delay of 2.4 ms. In fact, the CRCM curves in Fig. 4 are approximately the same but shifted upwards by about 2.8 ms, which is in fair agreement with this estimate. The difference is due to a worse protocol efficiency, as the longer handshake time slightly exacerbates the problems outlined before (such as increased collisions). In conclusion, the STBC based packet distribution takes advantage of the greater number of antennas in any propagation environment, which is not the case for CRCM; moreover the shorter handshake eases problems of coordination, whereas the opposite happens in CRCM.

Finally, another important metric is transmit energy consumption, computed as the total transmit energy divided by the number of information bits successfully acknowledged, and plotted against throughput in Fig. 6. We assumed that handshake packets are sent at the maximum power, while unicast frames (data and ACK) are subject to power control. This fact is essential because otherwise a data exchange (which lasts for a long time with respect to a control packet) would create a great deal of interference and would also capture many receivers in the area, preventing further communications. Therefore unicast frames have a limited weight in this metric, and the control (broadcast) packets contribute to the majority of the energy consumption. Since our scheme needs significantly fewer transmissions for a control packet, savings can be very high, as Fig. 6 shows. In addition, the increased number of collisions in CRTS makes the gap between the two

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[8] We note that when the generated traffic is large, collisions become more likely and nodes spend a significant fraction of their time in backoff. This fact reduces the available time for transmission, and thus the effective load.

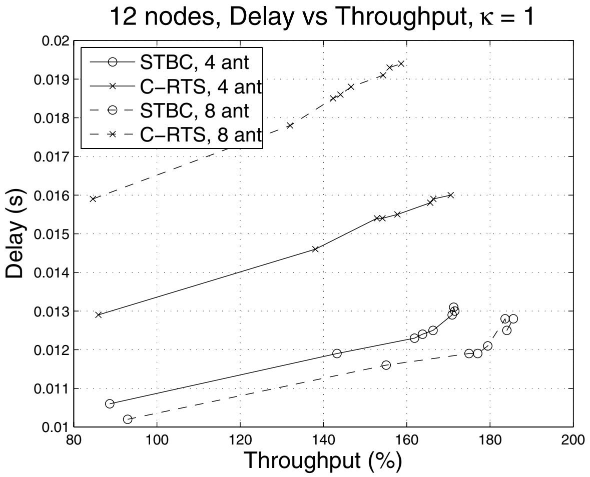

Fig. 4. Delay vs Throughput, 12 nodes

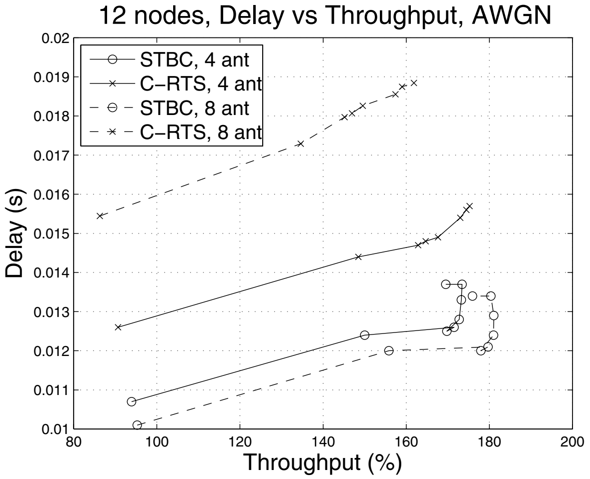

Fig. 5. Delay vs Throughput, 12 nodes

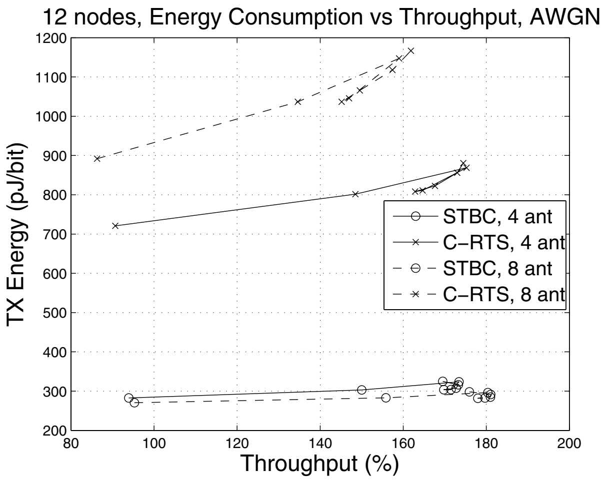

Fig. 6. Energy per information bit vs Throughput, 12 nodes

sets of curves even wider.

V. CONCLUSIONS AND FUTURE WORK

The issue of the gain asymmetry in ad hoc networks has been described and some of its consequences have been discussed. The solution proposed in [2], [3] has been reviewed. The major problem of this technique is the significant delay and energy consumption due to the circular distribution of the control packets. Building on theoretical considerations, in this paper we have applied Space Time Block Codes combined with Maximal Ratio Combining for the transmission of handshake packets, and have shown that a suitable STBC can provide the required performance in terms of coverage and omnidirectionality without any delay penalty. The performance benefits when this scheme is incorporated into a MAC protocol for MIMO ad hoc networks have been documented by simulation results. Interesting extensions of this work include rate adaptation and multihop.

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