Combining Space-Time Coding with Power-Efficient Medium Access Control for Mobile Ad-Hoc Networks

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***Abstract*— This paper investigates the impact of space-time coding on a power-efficient Medium Access Control (MAC) protocol in an IEEE 802.11a-based mobile ad hoc network (MANET). The new MAC protocol preserves energy by sending information at the minimal power required to reach the destination at the minimum power with a specified Packet Error Rate (PER). The analysis of space-time coding is conducted in practical environments, including spatial correlations between the fades between the transmitter and the receiver antenna elements. Combining improvements in the physical layer with the new MAC protocol leads to tremendous savings in power and increase in spatial reuse while maintaining a basic quality of service.**

I. Introduction

Wireless networks usually fall under two categories: infrastructure networks, with centralized control and Access Points, and infrastructure-less networks, with distributed control and no Access Points. The latter, known as mobile ad hoc networks (MANETs) are expected to see rapidly increasing use in meetings, conferences, disaster situations, etc. To ensure interoperability of products, IEEE finalized the 802.11 standard in 1997. Since then this standard has been extended to the 802.11b and 802.11a standards [1]. These are a potential framework for the operation of MANETs. Table I summarizes some important features of the approved 802.11 IEEE standards.

TABLE I
Approved IEEE standards for WLANs

802.11	802.11a	802.11b
July 1997	September 1999	September 1999
83.5 MHz	300 MHz	83.5 MHz
2.4-2.4835 GHz	5.15-5.35 GHz	2.4-2.4835 GHz
3 channels	12 channels	3 channels
1,2 Mbps	6, 9, 12, 18, 24 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps
FHSS, DSSS	OFDM	DSSS

In applying the 802.11 standard to MANETs, many problems remain unresolved. Some examples are poor transmission quality due to packet losses, battery constraints, mobility-induced re-routing, frequent network partitions and security. An efficient way to remedy some of these problems is to investigate improvements at the lower layers of the protocol stack, and develop new protocols at the higher layers to exploit physical layer improvements.

Recently, the use of multiple antenna elements at both the transmitter and the receiver to achieve diversity gains, commonly referred to as space-time coding (STC), has received considerable attention. The pioneering work in [2] has sparked wide research on efficient space-time codes. In this regard, Alamouti [3] proposed a technique for a two-elements array with remarkably simple encoding and decoding schemes. Previous studies have shown significant performance enhancement in applying STC to centralized networks with Access Points [4], [5].

The development of STC in [3] assumes independent fading between any two pairs of transmitters and/or receivers. This assumption is only approximately valid. The finite spacing between the elements of the array and the nature of multipath both lead to partially correlated fading. In cellular environments, the spatial correlation degrades the performance of STC [6]. In a MANET application, the element spacing is further constrained by the area of the mobile device. Two antenna elements will be used at both the transmitter and the receiver and, unlike previous attempts exploring the performance of IEEE 802.11a with STC [4], [5], the spatial correlation is modelled using the ”one-ring” model proposed by Jakes [7], and extended by Shiu et.al. [6].

In analyzing the performance of ad-hoc networks, the energy consumed per successfully transmitted data bit plays a crucial role. Much work has been done on finding efficient ways to preserve energy [8], [9]. These investigations have focused on the MAC layer independent of the physical layer. In [10], we proposed a MAC protocol based on sending the packets at the minimal power needed to achieve a threshold packet error rate (PER) at the receiver. The new MAC protocol solves other problems with prior approaches such as collisions while significantly increasing spatial reuse and reducing power consumption in mobile ad-hoc scenarios. In this paper, the benefits of combining improvements in the physical layer, based

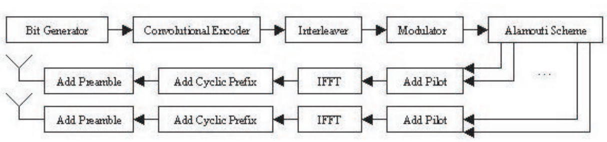

Fig. 1. Proposed Transmitter Design

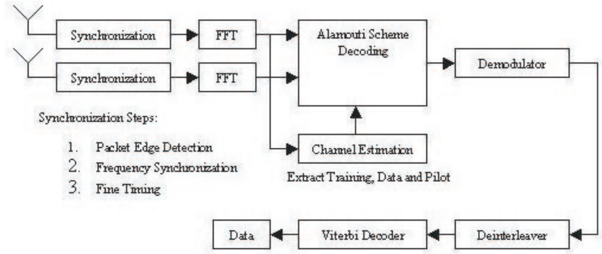

Fig. 2. Proposed Receiver Design

on Alamouti's space-time coding scheme, with improvements in the MAC protocol are quantified. This joint PHY-MAC approach is an effective and novel way to achieve power-efficient MANETs. The focus here is on the 802.11a standard.

Section 2 summarizes the physical layer design with STC added to IEEE 802.11a. This section also discusses spatial fading correlation and presents the model used to account for its effect on the performance of STC and presents some PHY layer results. Section 3 briefly explains the MAC protocol of [10]. Section 4 provides the results of combining the physical layer and MAC layer enhancements of Sections 2 and 3. This is the main contribution of this paper. Section 5 presents some conclusions.

II. Physical Layer Design

For signal transmission, data bits are generated by the binary source, input to a rate 1/2 convolutional encoder, which can be punctured to 2/3 or 3/4 for a particular data rate. The output is interleaved, then converted to BPSK, QPSK, 16-QAM or 64-QAM values depending on the modulation type of the data rate to be used. The resulting symbols are divided over the 48 data subcarriers, and 4 pilot subcarriers are added to form an OFDM symbol [1]. Alamouti's STC is applied to each symbol as shown in Figure 1.

For OFDM systems, space-time coding can be more appropriately named frequency-space coding. It is performed over the whole OFDM symbol which is coded in parallel across the 48 data subcarriers. If we denote two consecutive OFDM symbols by s_0 and s_1, then the two antennas transmit s_0 and s_1 is transmitted in the first symbol period, followed by $-s_1^*$ and s_0^* in the second symbol period. Before transmission, each antenna's signal is converted to the time domain by an Inverse Fast Fourier Transform (IFFT), the cyclic prefix is added and the preamble appended.

At the receiver, the reverse operations are performed after synchronization. The cyclic prefix is removed, and a Fast Fourier Transform (FFT) for every symbol recovers the values on the subcarriers. The channel is estimated using training symbols and pilot subcarriers. This allows the decoding of the STC symbols according to the combining scheme proposed by Alamouti [3]. These decoded symbols are then demodulated, deinterleaved and the Viterbi decoder identifies the data bits as shown in Figure 2.

A. Correlated Channels

At the physical layer, the most important factor limiting the performance of any scheme is the random channel between transmitting and receiving nodes. In an indoor setting, the channels may be modelled as Rayleigh tapped delay lines with an exponentially decaying average power profile [11]. The coherence time of the channels is assumed greater than the duration of an OFDM symbol, so the channel is assumed to be time-invariant for the duration of a single symbol transmission. In the analysis here, the rms delay spread set to 50ns, as a reasonable value for homes and offices [11].

In incorporating space-time coding into the 802.11a physical layer, the analysis here assumes two transmitting/receiving elements on each mobile node. For the results of the original Alamouti scheme to be valid, the four channels between any pair of transmitters and receivers must be statistically uncorrelated [3]. However, in practice, these channels are invariably correlated. While in an indoor setting, the impact of correlation may be minimal, any realistic simulations of the proposed scheme must account for possible correlation. To model fading correlation, we use the "one-ring" model proposed by Jakes [7] and extended by Shiu et.al. [6]. The spatial fading correlation can be determined from the physical parameters of the model such as antenna spacing, antenna arrangements, angle spread, and angle of arrival.

In the one ring model, if D is the distance between the transmitter and receiver, R the radius of the scatterer ring and Θ the mean angle of arrival at the receiver, the angles of incoming waves are confined within $[\Theta - \Delta, \Theta + \Delta]$ (Δ is the angular spread where $\Delta \approx arcsin(R/D)$). We define $d^T(p,q)$ as the distance between the transmitter antennas p and q, with $d_x^T(p,q)$ and $d_y^T(p,q)$ denoting the projections of $d^T(p,q)$ on the x- and y-axis, respectively. Similarly, we define $d^R(l,m)$ as the distance between the receiver antennas l and m, with $d_x^R(p,q)$ and $d_y^R(p,q)$ denoting the projections of $d^R(p,q)$ on the x- and y-axis.

If the uncorrelated channel is modelled as a vector $vec(H)$, where H is a 2x2 matrix, then the covariance matrix is given by $E[vec(H) \;\; vec(H)^\dagger]$, where † denotes the conjugate transpose. From Eqn. (6) in [6], assuming $d_x^T(p,q) = 0 \;\; and \; d_x^R(l,m) = 0$,

$$E \quad [H_{m,p} H_{m,q}^*] \approx J_0\left(\sqrt{(\Delta \frac{2\pi}{\lambda} \; d_y^T(p,q))^2 + (\frac{2\pi}{\lambda} \; d_y^R(l,m))^2}.\right) \quad (1)$$

In the rest of this paper, this matrix modifies the channel

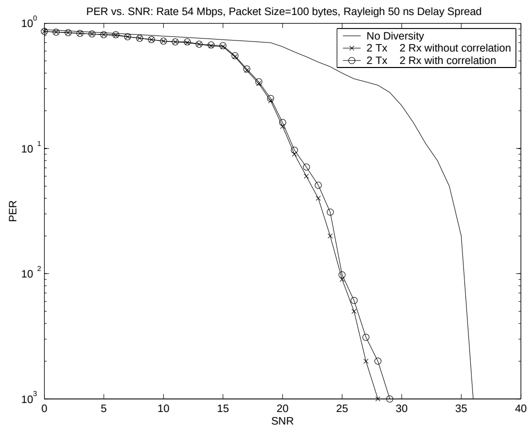

Fig. 3. PER vs. SNR at 54Mbps for correlated vs. uncorrelated fades

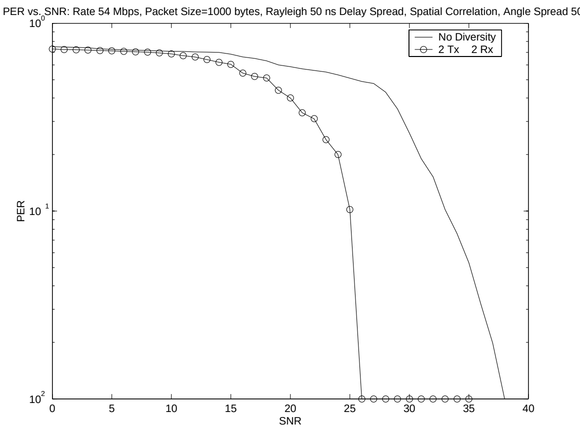

Fig. 4. PER vs. SNR at 54 Mbps for 1000 bytes packets

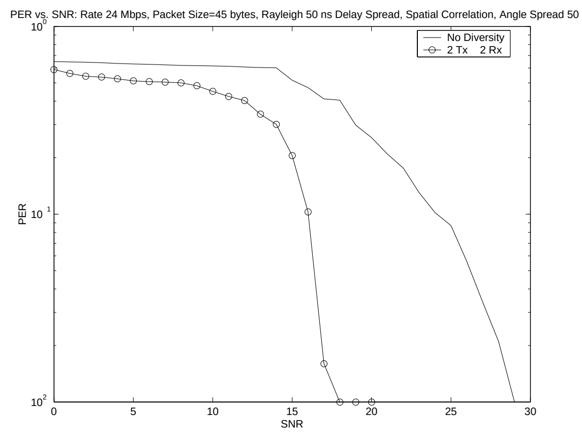

Fig. 5. PER vs. SNR at 24 Mbps for 45 bytes packets

impulse response so that spatial fading correlation is accounted for in the results.

B. PHY Layer Results

1) Spatial Correlation Effect on STC: To study the effect of STC in a correlated fading environment within the framework of the 802.11a standard, the measure of performance used will be the Packet Error Rate (PER). A received packet is considered to be in error if at least one bit is found incorrect after decoding. The simulation is based on Rayleigh faded channels with a 50ns rms delay spread. The spatial correlation is calculated for a $\lambda/2$ antenna element spacing at both the transmitter and the receiver, with an angular spread of $\Delta = 50°$. Figure 3 shows the average PER vs. signal to noise ration (SNR) for three cases: no diversity, STC without spatial correlation and STC with spatial correlation. As seen in the figure, the difference between the uncorrelated and correlated cases is minor. To obtain a 0.01 PER, an extra 1 dB is needed in the correlated STC case. In both the correlated and uncorrelated STC cases, the improvements compared to the no-diversity case are still considerable: around 11 dB for a PER of 0.1. For more realistic results, the spatial correlation will be accounted for when using STC in the remaining simulations, since this correlation may play an important role in other scenarios [6].

2) STC Effect on PHY layer: To transmit data at the lowest possible energy level, the MAC protocol requires the PER versus SNR curve for each transmission data rate. The protocol of [10] uses the control packets (RTS, CTS and ACK) defined in the IEEE 802.11 standard [1]. An additional confirmation control packet (CONF), similar in size and structure to RTS, is added. These control packets are sent only at one of the following three rates (6, 12 or 24 Mbps), depending on the data rate. The MAC protocol is tested for a video conferencing application, with a data transmission rate of 54 Mbps, data packet size of 1000 bytes and the control packet sizes fixed to 48 bytes for RTS, and to 42 bytes for CTS and ACK. Note that the header size (28 bytes) is added to the actual RTS (20 bytes) and CTS/ACK (14 bytes) packet sizes. The PER vs. SNR for this data packet size at a 54 Mbps rate and the PER vs. SNR for the mean control packet size (45 bytes) at a 24 Mbps rate are therefore needed.

As a function of SNR, Figure 4 compares the PER for 1000 bytes packets sent at 54 Mbps for the cases with and without STC. As expected, significant improvements are achieved by using Alamouti's scheme. To obtain a PER of 0.1, the gain is of 10 dB with Alamouti's STC as compared to the case without diversity. Figure 5 shows a similar plot for packets of 45 bytes sent at 24 Mbps. As seen in the figure, significant improvements are achieved by using Alamouti's scheme. To obtain a PER of 0.1, the gain is of 8 dB with Alamouti's STC as compared to the case without diversity.

III. Medium Access Control Layer Design

The MAC protocol proposed in [10], STC-MAC, is briefly summarized to show the role that STC can play in achieving additional power savings. The STC-MAC uses two channels, one for transmitting control packets and the other for transmitting data packets. Details on the spacing and bandwidth of these channels can be found in [10].

The sender initiates the exchange by sending RTS on

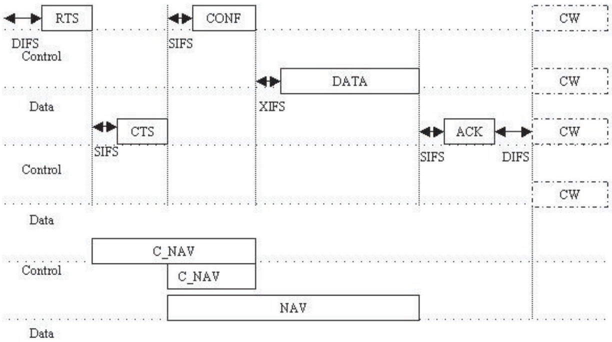

Fig. 6. MAC Protocol Design

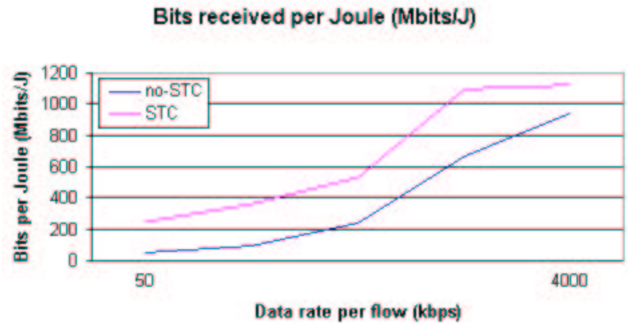

Fig. 7. Total data delivered per unit of energy consumption (Bits/J), with various network loads

the control channel at the maximum power Pt_{max} allowed by the 802.11a standard in its frequency band. Depending on the required received power P_{thres}, corresponding to a greatest allowed PER, the receiver calculates the minimum transmission power required $Pt_{min.des}$ at which CTS should be sent. Note that the benefit of space-time coding is to make this $Pt_{min.des}$ lower than the usual case, as the desired PER is obtained at a lower SNR. The receiver then sends CTS on the control channel at $Pt_{min.des}$. The sender sends a new control packet, CONF, at $Pt_{min.des}$ on the control channel to make sure no ongoing reception in its transmission range will be disrupted. The CONF packet is assumed similar in structure to the RTS packet. This packet is needed to ensure a collision-free protocol. The sender then waits for a short interval inter-frame spacing XIFS. XIFS has to be large enough to allow for propagation delay and frame processing time.

If a node has an ongoing reception in progress, with a data transfer on the data channel, and receives a CONF packet on the control channel, it sends a CANCEL packet at $Pt_{min.des}$ on the control channel, causing the new exchange to be delayed until the current ongoing transfer ends. The CANCEL packet is assumed similar in structure to the CTS packet. If the sender does not receive CANCEL during XIFS, it goes on to send the DATA packet at $Pt_{min.des}$ on the data channel. The receiver responds with an ACK packet at $Pt_{min.des}$ on the control channel, and the exchange is successfully ended.

Figure 6 shows the STC-MAC frame exchange sequence. As shown in [10], this protocol solves both the hidden terminal and exposed terminal problems in mobile ad-hoc networks.

IV. MAC Layer Results

The MAC protocol of [10] was simulated with and without space-time coding. The two cases are compared in terms of the total data delivered per unit of energy consumption (bits/J) and data throughput. The data delivered per unit consumed energy is given by:

$$\frac{S}{E_c} = \frac{S}{\sum_{i=1}^{K} P_i T_i + \sum_{j=1}^{M} P_j T_j}, \qquad (2)$$

where,
S: total number of successful data bits sent between source and destination,
K: total number of packets sent (including control packets) for the duration of the simulation (from all nodes including intermediate hops),
M: total number of packets received (including control packets) for the duration of the simulation (from all nodes including intermediate hops),
P_i: transmission power of packet i,
P_j: reception power of packet j,
T_i: time to transmit packet i,
T_j: time to receive packet j,
E_c: total energy consumption in the network,

Note that this formula accounts for both the power when the actual destination receives the packet and when any node hears a packet not destined for it.

The simulations used OPNET Modeler version 7.0B [12]. The data transmission rate is set to 54 Mbps. The control transmission rate is dynamically chosen based on the data channel rate, as specified in the standard [1]. The path loss exponent is set to 3.8, a reasonable value in an indoor environment [11]. The PHY layer results of Figures 4 and 5 are incorporated into OPNET, thereby accounting for fading and spatial correlation in the simulations and increasing the viability of the final results.

A typical peer-to-peer application, video conferencing, is used. This kind of application is well suited for an ad-hoc application, in meetings and conference rooms The packet load is varied with the packet size fixed to 1000 bytes, so that the results generated for the PHY layer can be used.

The first example simulates a *random* mobile topology, where 4 nodes move in a 20m $\times$ 20m area. The total data received per Joule consumed for both the STC and no STC case is measured with 4 random video conferencing flows starting at 25, 30, 35 and 40 secs. The simulations run for one minute. The flow rates take some values from 50 kbps to 4 Mbps. Due to the use of STC, the required transmission power from the nodes is lowered by 10-dB.

Figure 7 shows that the total data delivered per unit of energy consumed increases with the network load for both the MAC protocol with and without STC. As more data is being

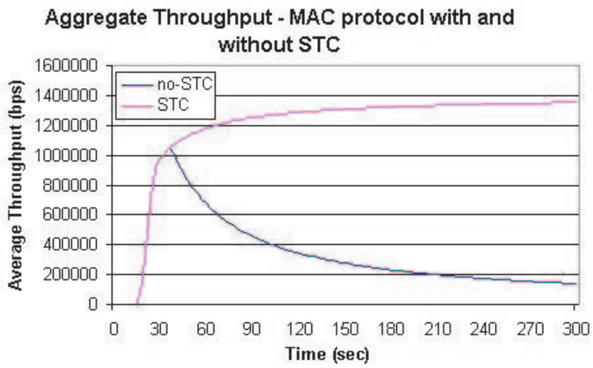

Fig. 8. Aggregate Throughput with/without STC

transmitted, the power savings increase, hence the total number of bits delivered per Joule increases. There exists a difference between the STC and the no-STC cases for a particular load, which shows that the use of STC at the PHY layer can yield additional power savings. When the load nearly overloads the network, the total number of bits delivered per Joule seems to reach a floor. Note that in this case, both configurations have the same overall network throughput, so only the savings due to the use of STC account for the power savings.

The second example illustrates the increased data throughput in dense networks due to space-time coding. Figure 8 shows the aggregate throughput of the overall network when the 4 nodes move in a 10m $\times$ 10m area, as opposed to the 20m$\times$20m area of the earlier example. Again, the 4 random video conferencing flows start at 25, 30, 35 and 40 secs. The simulation runs for five minutes. Due to the use of STC, the transmission power from the nodes is lower and hence reduces the interference level at the neighboring nodes. With the additional transmission power when STC is not used, it becomes difficult for simultaneous exchanges to occur. As the flows start, the throughput degrades due to the increased interference. In the STC case, the results are much better as the throughput increases gradually as more flows start. Therefore, the use of STC processing at the PHY layer makes STC-MAC's performance better in a dense environment.

V. Conclusion

This paper has studied the impact of space-time coding in a correlated fading indoor environment on a power-efficient MAC protocol. The paper establishes that STC results in lower energy consumption for a similar amount of data delivered. The combination of STC with the MAC power control protocol can provide large power savings. This is clearly an expected result, however requires a MAC layer protocol that *can exploit the resulting power savings*. The MAC protocol, coupled with STC at the physical layer also dramatically improves data throughput in dense terminal environments.

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