Energy-Efficient Protocols for Wireless Networks with Adaptive MIMO Capabilities

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Abstract

Transmission power control has been used in wireless networks to improve the channel reuse and/or reduce energy consumption. It has been mainly applied to single-input single-output (SISO) systems, where each node is equipped with a single antenna. In this paper, we propose a power-controlled channel access protocol for MIMO-capable wireless LANs with two antennas per node. Our protocol, called E-BASIC, extends the classic CSMA/CA access scheme by allowing for dynamic adjustment of the transmission mode and the transmission power on a per-packet basis so as to minimize the total energy consumption. By transmission mode we mean one of the four possible transmit/receive antenna configurations: 1×1 (SISO), 2×1 (MISO), 1×2 (SIMO), and 2×2 (MIMO). Depending on the transmitter-receiver distance, any of the four modes can be the optimal one in terms of minimizing the *total* energy consumption. We study the performance of E-BASIC in both ad hoc and access point topologies. We also incorporate E-BASIC in the design of a power-aware routing (PAR) scheme that selects minimum-energy end-to-end paths. Our adaptive designs are first conducted assuming fixed-rate transmission, but later extended to multi-rate systems. To account for the energy-throughput tradeoff in our designs, we impose a constraint on the average packet delivery time. Simulations indicate that the proposed adaptations achieve a significant reduction in the overall energy consumption relative to non-adaptive MIMO systems.

Index Terms

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Power control, MIMO, ad hoc networks, CSMA/CA, IEEE 802.11, power-aware routing, energy efficiency.

I. INTRODUCTION

The vast majority of currently deployed wireless local area networks (WLANs) are based on the IEEE 802.11 standard [1]. Channel access in this standard is performed according to a variant of CSMA/CA with an optional virtual carrier sensing (VCS) mechanism, i.e., request-to-send/clear-to-send (RTS/CTS) exchange. By default, packets are transmitted at a fixed power level. Several studies of WLANs and ad hoc networks have demonstrated the inefficiency of the fixed-transmission-power strategy in terms of energy consumption and spatial reuse in the channel (e.g., Gupta et. al [2], Minks et. al [3], Wu et. al [4]). Accordingly, several transmission power control (TPC) protocols have been proposed (see Krunz et. al [5] for a survey)[1], some of which are aimed at energy conservation (e.g., Agarwal et. al [6], Gomez et. al [7], Jung et. al [8]) while others are throughput oriented (e.g., Monks et. al [3], Muqattash et. al [9], Muqattash et. al [10], Wu et. al [4]). By "throughput oriented" we mean that the primary design goal of power control is to *increase the network throughput* by allowing for more concurrent transmissions to take place, i.e., increase the spatial reuse of the channel. Such a goal is in contrast to energy-oriented designs, where the primary goal is to save energy without necessarily impacting throughout (or sometimes at the cost of reduced network throughput). For example, in the BASIC protocol by Jung et. al [8], RTS and CTS packets are transmitted at a fixed power ($P_{\max}$), while data and ACK (acknowledgment) packets are transmitted at the minimum power level that guarantees the required signal-to-noise ratio (SNR). This leads to a reduction in the total energy consumption in the network, but does not improve the channel's spatial reuse. The POWMAC protocol by Muqattash et. al [10] addresses the channel reuse issue by redefining the role of the RTS/CTS exchange, making it possible for multiple pairs of neighboring nodes to communicate provided that the selected power levels do not cause the SNR at any receiver to fall below the required threshold. Other protocols improve the performance by using busy-tones (e.g., Wu et. al [4]) and prioritized back-off (e.g., Xiao [11], Xiao [12]).

Thus far, much of the emphasis has been on TPC techniques for single-input single-output (SISO) wireless networks, where each node uses a single antenna for transmission and reception (with the transceiver typically operating in a half-duplex mode). Significant improvement in network performance can be achieved by employing multi-input multi-output (MIMO) techniques (Paulraj et. al [13]), whereby multiple transmit and/or receive antennas are exploited to achieve spatial diversity. Cui et. al [14] showed that MIMO-based communication consumes much less *transmission power* than SISO-based

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[1] Another approach to conserve energy is to put inactive nodes to sleep. Such an approach is complementary to TPC, and is not considered in this paper.

communication for the same throughput. Sundaresan et. al [15] presented a new MAC protocol for ad hoc networks with MIMO links. The application of MIMO techniques in mobile ad hoc network (MANET) protocols was explored by Hu et. al [16]. The spectral efficiency of a MIMO ad hoc network was studied by Chen et. al [17]. Various architectures of MIMO systems and their features (including those proposed for the IEEE 802.11n standard) were discussed by Gilbert et. al [18]. Sundaresan et. al [19] proposed a routing protocol called MIR for ad hoc networks with MIMO links. This protocol leverages the various characteristics of MIMO links to improve the network performance. A novel connectivity metric for MIMO-equipped ad hoc networks was introduced by Jafarkhani et. al [20] based on probabilistic analysis of the achievable capacity of random topologies. Aniba et. al [21] formulated the scheduling problem in MIMO-equipped networks as a generalized assignment problem, and advocated a new cross-layer design for the scheduling of users and the assignment of their corresponding data to available transmit antennas.

As alluded to earlier, for a given target bit error rate (BER), a multi-antenna transmission requires less RF power than a SISO transmission. However, it also requires more circuit power at both ends of the link. As a result, a distance-dependent tradeoff emerges between transmission and circuit powers (Cui et. al [22]): For relatively small distances, circuit power is dominant, and hence a SISO mode is more energy-efficient than a multi-antenna transmission. As the transmitter-receiver distance increases, the tradeoff shifts in favor of the multi-antenna modes (SIMO, MISO, or MIMO). Joint optimization of transmission/circuit powers was considered in several previous studies (e.g., Cui et. al [22], Min et. al [23], Schurgers et. al [24]), although the focus has been on SISO systems. Cui et. al [14] proposed a joint energy minimization strategy for MIMO-based systems, but only for a single link under a fixed MIMO strategy.

In this paper, we investigate the feasibility of using adaptive multi-antenna modes in a multi-user wireless packet network. Each node is assumed to be equipped with two antennas, allowing a link to operate using one of the four possible *transmission modes*: 1×1 (SISO), 2×1 (MISO), 1×2 (SIMO), and 2×2 (MIMO). We propose a channel access scheme called Enhanced-BASIC (E-BASIC), in which the transmission mode and power are jointly adapted on a per-packet basis such that the total energy consumption is minimized. E-BASIC is an extension of BASIC, a power-controlled MAC protocol that was developed for SISO-based ad hoc networks by Jung et. al [8]. As in BASIC, E-BASIC uses a variant of CSMA/CA with VCS for channel access. We integrate E-BASIC in the design of a power-aware routing (PAR) protocol for MIMO-capable ad hoc networks. In contrast to the standard min-hop routing, PAR attempts to compute *energy-efficient* end-to-end paths. Our channel access and routing protocols are first designed with the assumption of a fixed transmission rate, but later extended to allow for rate adaptation by additionally optimizing the order of the modulation scheme (i.e., the constellation size). Because energy-oriented designs often come at the cost of reduced network throughput, we further conduct the joint transmission mode/power/modulation optimization under an additional constraint on the average per-hop packet delay, which we use to indirectly control the tradeoff between energy consumption and network throughput.

The rest of the paper is organized as follows. After reviewing some basic MIMO concepts, we present in section II E-BASIC and its integration in the design of a PAR protocol for MIMO-capable MANETs. In the same section, we study power/MIMO mode optimization with adaptive-rate systems, where we also optimize the modulation order on a per-packet basis. Optimization subject to a constraint on the average packet delay is studied in subsection II-E. The performance of E-BASIC, PAR/E-BASIC, E-BASIC under adaptive modulation, and E-BASIC under a delay constraint is studied via simulations in section III. Section IV summarizes our main findings.

II. MIMO ADAPTIVE CHANNEL ACCESS AND ROUTING PROTOCOLS

A. Spatial Gains in MIMO Systems

MIMO technology offers three types of gains: *array*, *diversity*, and *multiplexing* (Paulraj et. al [13]). The array gain is achieved either at the transmitter through directional alignment of the transmitted signal or at the receiver by coherently combining the multiple copies that are received over independently fading paths. Diversity gain is interpreted as the slope of the average BER curve versus SNR, which is proportional to the number of independent paths (in the best case, this number is equal to the product M_tM_r, where M_t and M_r are, respectively, the numbers of transmit and receive antennas). To realize this gain, space-time coding is used to encode the signal and transmit it over the M_t antennas. Multiplexing gain is obtained when different signals are transmitted over the M_t antennas for the purpose of increasing the total transmission capacity of the link. In our work, we focus on the array and diversity gains, leaving the exploitation of the multiplexing gain for future research. For the array gain, we only explore the receiver-side array gain, which requires channel state information (CSI) only at the receiver. The two gains (diversity and array) can be used to achieve higher link reliability (i.e., lower BER), longer communication distance, or a reduced SNR requirement. We focus on the last benefit, whereby a target BER, say p_b, is set and the signal transmission power is minimized to achieve a given SNR threshold.

B. Energy Consumption Model

Before introducing our MIMO-adaptive protocols, we first describe the energy model used in the paper. For now, we assume a fixed-rate system that uses BPSK modulation. We later extend the treatment to variable-rate systems.

We consider a wireless network in which each node is equipped with two antennas that can be used separately or jointly to transmit or receive, giving rise to four possible modes for each packet transmission. Following Cui et. al [14], the power consumed for sending a packet consists of transmission (RF) and circuit powers. The transmission power is adjustable and is given by $P_t = (1+\psi)P_{out}$, where ψ is a factor that depends on the *drain efficiency* of the power amplifier and the underlying modulation scheme (Cui et. al [22]), and P_{out} is the total transmit power at the air interface. P_{out} can be expressed as:

$$P_{out} = \gamma(M_t, M_r) N_o B N_f G_o M_l d^k \tag{1}$$

where $\gamma(M_t, M_r)$ is the required SNR at the receiver when M_t and M_r antennas are used for transmission and reception, respectively, N_o is the single-sided thermal noise power spectral density (PSD), B is the passband bandwidth, N_f is the receiver noise figure ($N_f \overset{\text{def}}{=} \frac{N_r}{N_o}$, with N_r being the PSD of the total effective noise at the receiver input), G_o is a constant that depends on the transmitter and receiver antenna gains, M_l is a link margin that compensates for hardware variations and other sources of interference, k is the path-loss exponent (we take $k = 4$), and d is the transmitter-receiver distance. Note that γ depends on the target error probability (p_b) and the specific transmission mode.

As for the circuit power (P_c), it is given by Cui et. al [14]:

$$P_c \approx M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} + M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}) \tag{2}$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, and P_{syn} are the power consumption values for the digital-to-analog converter, the mixer, the low noise amplifier, the intermediate frequency amplifier, the active filters at the transmitter and the receiver sides, the analog-to-digital converter, and the frequency synthesizer, respectively.

Accordingly, the total energy consumption per bit is:

$$E_{bt} = \frac{P_t + P_c}{R_b} \tag{3}$$

where R_b is the bit rate (for BPSK modulation, $R_b \approx B$ bits/sec). Using (1) and (2), E_{bt} can be written in terms of d, M_t,

M_r, and R_b as follows:

$$E_{bt} = \frac{C_1 \gamma(M_t, M_r) d^k + C_2 M_t + C_3 M_r + C_4}{R_b} \tag{4}$$

where C_1, C_2, C_3, and C_4 are circuit-specific constants. For the same value of p_b, the smaller the values of M_t and M_r, the larger the required SNR (γ), i.e., $\gamma(1,1) > \gamma(2,2)$, making MIMO more favorable in terms of RF power. However, for sufficiently small distances, circuit power is dominant, and hence a SISO mode is more energy-efficient than a multi-antenna transmission. As the transmitter-receiver distance increases, the tradeoff shifts in favor of the multi-antenna modes (SIMO, MISO, or MIMO).

Note that for the purpose of optimizing the antenna mode and the modulation order, it is sufficient to focus on minimizing E_{bt} under each of the four modes. Accounting for retransmission-related energy consumption will not change the optimality point. However, when determining P_t that corresponds to the "minimum" E_{bt}, we actually account for the impact of collisions and retransmissions through the link margin $M_l > 1$, which provides a cushion against unexpected interference, such as interference from "out-of-range" sources as well as new sources that were not silenced by the CSMA/CA mechanism (e.g., due to the hidden-terminal problem). Such a factor is sometimes known as the "load factor" or the "interference margin," and is commonly used in the design of cellular and power-controlled ad hoc networks.

An important point that should be noted is that although this paper focuses on the less-than-two transmitting antenna cases, the proposed methodology is actually applicable to any $M_t \times M_r$ antenna system. However, to establish an *analytical* framework for the arbitrary $M_t \times M_r$ case, one needs a general expression for E_{bt} as a function of the BER. Unfortunately, such an expression does not exist, given the non-uniform structures of orthogonal space-time codes for general $M_t \times M_r$ systems. For example, for $M_t \leq 2$, we could easily deploy uniform rate-1 Alamouti codes; whereas for $M_t > 2$, no uniform code structures exist for a given rate. Tarokh et. al [25] proposed a methodology for designing rate-half orthogonal space-time codes with arbitrary M_t and M_r values. However, finding the code itself and analyzing its E_{bt} are still case-dependent, so it is still not possible to write a universal analytical relationship between the BER and E_{bt} that is parameterized by M_t and M_r. A number of studies focused on designing codes with higher-than-half rates and $M_t > 2$, but at the cost of sacrificing orthogonality. For example, a rate-1 non-orthogonal code was proposed by Tirkkonen et. al [26] for $M_t = 3$. Quasi-orthogonal codes were also proposed by Sharma et. al [27] to improve the BER for the cases $M_t = 4$ and $M_t = 8$. For a more general discussion on space-time code design, please refer to Paulraj et. al [13].

To summarize, in order to apply the design methodology proposed in this paper to arbitrary antenna configurations, we could *numerically* construct an (M_t, M_r)-indexed table that quantifies the relationship between the BER and E_{bt} for all known $M_t \times M_r$ space-time codes. Such a table can be used for the MIMO-based adaptive control at the cost of an additional table-lookup time. In this paper, to provide a meaningful *analytical* comparison between various antenna modes (as opposed to a table-lookup design), we fix the code structure (orthogonal and uniform rate-1 Alamouti codes) and vary M_t and M_r within the permissible range. For this reason, our reported results are limited to $M_t \leq 2$ and $M_r \leq 2$.

C. E-BASIC Protocol

E-BASIC is a MIMO-adaptive CSMA/CA-based channel access protocol that aims at minimizing E_{bt} with respect to the transmission power, the number of transmit/receive antennas, and the modulation order. For an ad hoc network with two-antenna nodes, the operation of the protocol is as follows. When a node X wishes to send a packet to another node Y, it first senses the channel. If the channel is idle, X starts a timer with a randomly chosen period of time. The timer duration is decremented when the channel is idle and is frozen otherwise. Once the timer expires, node X can start its transmission. As in the 802.11 and BASIC protocols, an optional virtual carrier sensing (i.e., RTS/CTS exchange) is used when large data packets are to be transmitted. The RTS and CTS control packets are transmitted at a fixed (maximum) power, $P_{\max}$, using the 2-by-2 MIMO mode, which ensures the farthest reception for these packets. Upon receiving the RTS packet, node Y computes the optimal antenna mode, transmission power, and modulation order for the ensuing data packet from X to Y. Node Y already knows the transmission power of the RTS, and it can measure its received power. Accordingly, it can estimate the channel gain and use it to determine the minimum required transmission power for the subsequent data packet. As shown in (1), this power depends on the transmission mode through γ. So, node Y determines the optimal antenna configuration[2] and corresponding transmission power that minimize E_{bt}. For systems that support adaptive modulation, node Y can also optimize the modulation order b. Note that b impacts the energy consumption E_{bt} through the SNR threshold γ and the transmission rate R_b. In principle, a higher value of b necessitates a higher γ, i.e., more required transmission power. However, it also means a higher rate R_b, i.e., lower transmission time, which in turn reduces the energy consumption (see (3)). The confluence of the two effects determine the optimal modulation order (b^*). As shown in Figure 1, b^* generally decreases with the transmitter-receiver distance, as transmission energy becomes more dominant.

If the transmission power computed by node Y is less than $P_{\max}$, node Y responds to X with a CTS that contains the optimal mode, transmission power (to be used by node X), and the modulation order. Following the RTS/CTS exchange,

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[2] The feasibility of changing the antenna mode on a per-packet basis was demonstrated in several experimental MIMO platforms [28].

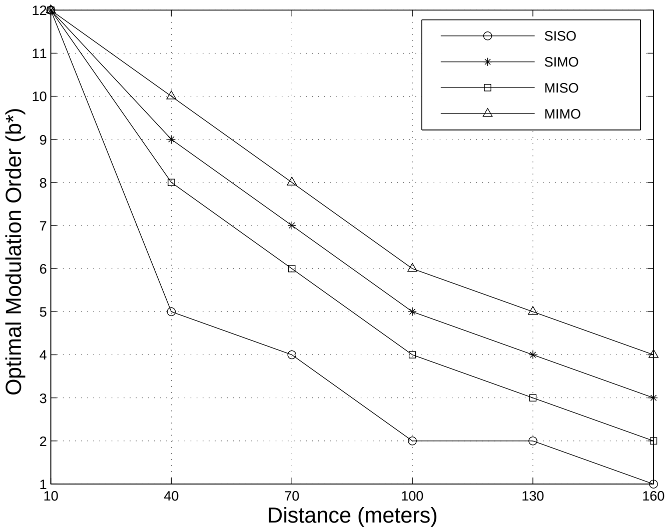

Fig. 1. Optimal modulation order (b^*) versus distance for various (fixed) antenna configurations.

node X sends its data packet to Y at the parameters specified in the CTS. If the transmission is successful, node Y responds back with an ACK packet that is sent using the same transmission power, mode, and modulation order as the data packet.

Note that the version of BASIC that we adopt in our work does not allow for oscillating the transmission power while transmitting a data packet. As illustrated by Jung et. al [8], such a simple version has a deficiency with regard to ACK receptions. Specifically, the reduction in the transmission power for the data packet is accompanied with a reduction in the carrier-sensing range for the transmitting node. Thus, some of the receiver's relatively far neighbors who would otherwise sense the transmitter's carrier will not be able to do so under a reduced transmission power approach, leading to potential interference with the reception of the ACK packet. To address this issue, Jung et. al [8] (who also proposed the simple version of the BASIC protocol) suggested a modified version of BASIC, in which the transmission power of the data packet is periodically raised to its maximum value for a short time period (i.e., within the transmission time of the packet) so as to alert potentially interfering nodes and avoid a reduction in the carrier-sensing range. While this periodic oscillation of the transmission power will enhance the performance for both BASIC and E-BASIC (or any transmission power control to that matter), it involves *intra-packet power control*, which is very hard to implement in real systems. For this reason, our implementations of both BASIC and E-BASIC do not account for this feature.

D. Power-Aware Routing Under MIMO-Adaptive Channel Access

Power-controlled multi-hop transmission is known to reduce the end-to-end *transmission* energy (Krunz et. al [5]). This is attributed to the nonlinear attenuation behavior of the electromagnetic signal over the RF channel. However, the relationship between energy consumption and the hop count is less obvious when circuit energies at the transmitter and receiver are taken into account. Specifically, in contrast to transmission energy, circuit energy does not depend on the distance between two communicating nodes, so it generally increases (almost linearly) with the hop count.

To reap further benefits from adapting the antenna mode, we incorporate E-BASIC into a PAR scheme. This scheme determines the end-to-end path that minimizes the total energy consumption among all possible paths between two nodes. The algorithm consists of two steps. In the first step, we determine all pairs of nodes that can communicate directly at power $P_{\max}$ using at least one of the four antenna modes. For a given pair, we establish as many parallel links as the number of feasible antenna modes between the two nodes (see part (a) of Figure 2). We then prune the graph and keep only the one with the least required E_{bt} value (see part (b) of the figure). In step 2, we run a modified version of Dijkstra's algorithm, where the weight of a link is taken as its E_{bt} value determined from step 1. The returned path has the minimum sum of E_{bt} values among all possible paths between the source and destination nodes. Similar to other PAR protocols in the literature (e.g., Das et. al [29], Lee et. al [30], Banerjee et. al [31]), ours can be supported using either proactive (link-state or distance-vector) or reactive routing mechanisms. For link-state-based proactive routing, a node can, for example, disseminate to other nodes the weight (i.e., the minimum E_{bt} value) of the link between itself and each of its neighbors. In the case of reactive routing, protocols such as AODV or DSR can be easily extended to enable the on-demand discovery of the most energy-efficient end-to-end path.

E. Antenna Adaptation Subject to a Delay Constraint

Our previous adaptations are aimed at minimizing the overall energy consumption via optimal selection of the antenna mode, transmission power, modulation order, and routing strategy. Such adaptations, however, do not attempt to improve the network throughput (i.e., channel's spatial reuse). For a one-hop transmission, the throughput is not influenced by the transmission power of the data packet or by the antenna mode,[3] as the spatial reuse is determined by the range of the RTS/CTS packets (fixed in our protocols). However, the throughput is affected by the modulation order; the higher the

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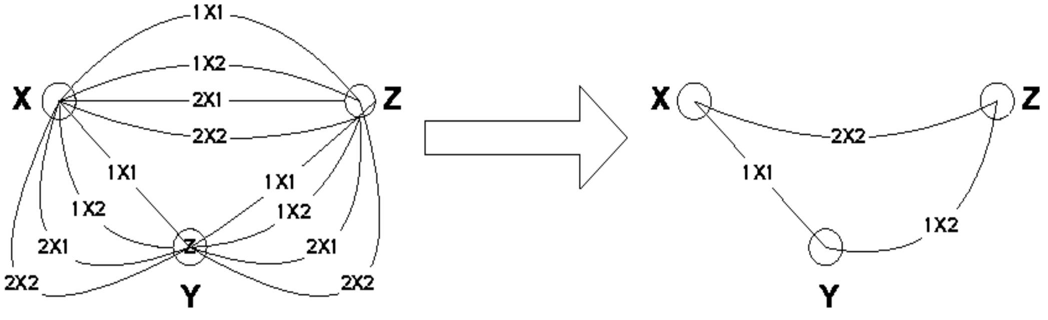
[3] This is true only when MIMO technology is employed to achieve diversity gain. The situation is different in the case of multiplexing gain, which we do not address in this paper.



(a)

(b)

Fig. 2. Topology representation in PAR with adaptive antennas (the link label represents the antenna mode used).

modulation order, the smaller is the packet transmission time, and hence the higher is the throughput. The throughput is also impacted by the routing strategy: Whereas multi-hop transmission (with power control) generally plays a positive role in reducing the overall energy consumption, it is less clear that it will lead to improved throughput. In fact, in our setting, because the transmission floor reserved through the RTS/CTS exchange is fixed, increasing the number of hops will likely have a negative impact on the overall network throughput.

In this section, we extend our previous PAR/E-BASIC design to consider throughput. This is done by optimizing the per-link modulation order (b) subject to a constraint on the *average* end-to-end packet delivery time. Let D_{tot} be the end-to-end delay for an arbitrary packet. Then, $D_{\text{tot}} = N_h \tilde{D}$, where N_h is the hop count and $\tilde{D}$ is the per-hop average packet delivery time, defined as $D + Q$, where D is the time elapsed from the moment the packet reaches the head of the transmitter's queue until a positive ACK is received or the packet is dropped, and Q is the queuing delay at the transmitter. For a given N_h, imposing a constraint on D_{tot} amounts to imposing a constraint on $\tilde{D}$. Accordingly, for a data packet, we require that

$$E[\tilde{D}] = E[D] + E[Q] \leq D_{\max} \tag{5}$$

where $D_{\max}$ is a given constant. Note that the above equation is essentially used to determine the optimal modulation order b for a given antenna mode of a given link. Thus, Q is directly measurable by the transmitter, and $E[Q]$ can be simply replaced by a moving average of the observed queueing delay, denoted by Q_{avg}.

It should be noted that even if the queueing delay is obtained from measurements while the transmission delay is obtained from analysis, this in itself does not preclude that the two quantities are correlated (which they are). More specifically, the measured queueing delay depends on the various system parameters (load, node density, etc.), which are also parameters that impact the transmission delay.

We now focus on expressing $E[D]$ as a function of b. Recall that in CSMA/CA, a station that is ready to transmit must first sense the channel. If the channel is idle, the station backs off for a uniformly distributed random period after which the station can commence with its transmission (provided the channel is still sensed to be idle). If a collision occurs following a transmission attempt, the station doubles its maximum backoff interval, samples a new backoff value, and repeats the process. In practical systems, this so-called exponential backoff mechanism is implemented as follows. The sampled backoff interval is converted to an integer number of fixed-length time slots, and channel sensing is conducting at the beginning of each slot. A timer with a timeout value that equals the length of the backoff period (in fixed slots) is set. If in a given slot, the channel is sensed busy, the station freezes its backoff timer. The timer is decremented only when the channel is idle. Once the timer reaches zero, the packet can be transmitted.

Chatzimisios et. al [32] studied the average packet delay ($E[D]$) and expressed it as follows:

$$E[D] = E[X]E[l] \tag{6}$$

where X is the number of timer decrements (i.e., the initial backoff value), and l is the time interval between two consecutive backoff time counter decrements.

Let W be the minimum contention window size, m be the maximum backoff stage, and p be the collision probability. According to Bianchi [33], $E[X]$ can be computed as follows:

$$E[X] = \frac{(1-2p)(W+1) + pW(1-(2p)^m)}{2(1-2p)(1-p)} \tag{7}$$

Let p_{tr} be the probability of having one or more transmissions in a duration of l time units, p_s be the probability of having a successful transmission, T_s be the average time that the medium is busy due to a successful transmission, T_c be the average time that the medium is busy due to a collision, and σ be the time needed at any station to detect the transmission of a packet from any other station. $E[l]$ can be computed as follows (Bianchi [33]):

$$E[l] = (1-p_{tr})\sigma + p_{tr}p_sT_s + p_{tr}(1-p_s)T_c \tag{8}$$

The expressions for p_{tr}, p_s, T_s, and T_c are given by Bianchi [33]:

$$p_{tr} = 1 - (1-\tau)^n \tag{9}$$

$$p_s = \frac{n\tau(1-\tau)^{(n-1)}}{1-(1-\tau)^n} \tag{10}$$

$$T_s = T_{RTS} + T_{SIFS} + \delta + T_{CTS} + T_{SIFS} + \delta + T_H + T_P + T_{SIFS} + \delta + T_{ACK} + T_{DIFS} + \delta \tag{11}$$

$$T_c = T_{RTS} + T_{DIFS} + \delta \tag{12}$$

where n is the number of contending nodes, τ is the transmission probability, T_{RTS}, T_{CTS}, T_{ACK}, T_{SIFS}, and T_{DIFS} are the time required for the RTS, CTS, ACK, SIFS, and DIFS, respectively, δ is the propagation delay, $H = PHY_{hdr} + MAC_{hdr}$ is the packet header, T_H is the packet header over the bit rate, and T_P is the transmission time for the data packet, which depends on the transmission rate and the packet size. It should be noted that the impact of retransmissions is directly accounted for in the derivations of the average delay per hop.

Bianchi's analysis assumed a saturated-traffic scenario. Malone et. al [34] extended this analysis to the non-saturated case. They found that the throughput expression is the same as in the saturation case. Furthermore, the expressions for p_s and p_{tr} are the same for both cases. However, the two cases give rise to different τ and p. More specifically, τ and p for the non-saturated case are given by Malone et. al [34]:

$$\begin{aligned} \tau &= b_{(0,0)e}\frac{q^2}{1-q}\left(\frac{W}{(1-p)(1-(1-q)^W)} - (1-p)\right) && (13) \\ p &= 1-(1-\tau)^{n-1} && (14) \end{aligned}$$

$$\begin{aligned} \frac{1}{b_{(0,0)e}} &= (1-q) + \frac{q^2W(W+1)}{2(1-(1-q)^W)} + \frac{q(W+1)}{2(1-q)}\left(\frac{q^2W}{1-(1-q)^W} + p(1-q) - q(1-p)^2\right) \\ &+ \frac{pq^2}{2(1-q)(1-p)}\left(\frac{W}{1-(1-q)^W} - (1-p)^2\right)\left(2W\frac{1-p-p(2p)^{m-1}}{1-2p} + 1\right) \end{aligned} \tag{15}$$

where q is the probability of packet generation at a station. By taking $q = 1$, the above equations reduce to those of the saturation case.

Note that the effect of the constellation size b on the average packet delay appears through T_P, which means that (5) will be reduced (after substituting the previous equations and their values into (5)) to an equation with a single variable b. Therefore, the optimization is done here with respect to the constellation size to have higher values of b than in the non-constrained case, which results in smaller packet transmission time, and hence a higher throughput. This satisfies our goal behind this optimization, where this optimization aims at accounting for the energy-throughput tradeoff by imposing a constraint on the average packet delivery time.

We emphasize here that although Bianchi's and Malone et. al's analysis was conducted for a fully connected (one-hop) topology, this does not preclude its application in our multi-hop scenario. The reason is that we translate the end-to-end delay constraint into a per-hop constraint, which we use when optimizing the constellation order for that particular hop.

It should be noted that our delay analysis starts with the goal of imposing a constraint on the end-to-end delay. To do that, we translate the end-to-end delay bound into a per-hop delay constraint, as it is intractable to analytically deal with multi-hop delay in the presence of hidden terminals. Because we assume a fixed number of hops (known) for the given route, we could as well have started the treatment with the goal of constraining the single-hop delay directly (i.e., we could state our goal as imposing a bound on the single-hop delay and proceed based on Bianchi's work).

The additional presence of hidden terminals (for a single hop) has a somewhat little impact on Bianchi's analysis. The reason is that in Bianchi's analysis, if two nodes start simultaneously, they will collide, and back off. This happens with a certain probability. The colliding terminals will wait for an ACK, time out, and then decide that a collision took place. In the case of hidden terminals, the probability of a collision is still the same (this probability depends on the traffic loads at various nodes), and the procedure for detecting the collision is the same as in the absence of hidden terminals. The main difference between the two cases comes from determining what nodes contribute to a collision; in Bianchi's work (and its extensions to the non-saturated case), all the nodes are within each others' range, so any two that transmit simultaneously cause a collision. In the case of hidden terminals, only the nodes that are within the transmission range of the given receiver can cause a collision to that receiver (i.e., the neighborhood of the receiver). In other words, the parameter n in Bianchi's analysis, which refers to the size of the network, now refers to the size of the neighborhood of a given receiver. For a given field of a given density and transmission range, $E[n]$ is readily available.

III. PERFORMANCE EVALUATION

In this section, we study the performance of our MIMO-adaptive approaches. We compare the performance of E-BASIC with the IEEE 802.11 and BASIC protocols. We consider five sets of simulations: (1) AP topologies with fixed-rate modulation, (2) ad hoc topologies with fixed-rate modulation, (3) AP topologies with adaptive modulation, (4) ad hoc topologies with adaptive modulation, and (5) ad hoc topologies subject to a delay constraint. Unless stated otherwise, we assume the following setup. We consider a square area of 500×500 meters^2 for AP topologies and 350×350 meters^2 for ad hoc topologies. In the AP topologies, we put one node at the center of the area to act as AP, and we randomly deploy the remaining 24 nodes. In the ad hoc topologies, all the 25 nodes are randomly distributed. We assume that the 24 non-AP nodes in the AP topologies and the 25 nodes in the ad hoc topologies are moving according to the random waypoint model (Broch et. al [35]) with a speed that is uniformly distributed in the interval [0,2] meters/second. Note that with this model, the speed should be bounded away from zero (Yoon et. al [37]). However, the likelihood of choosing zero speed in the uniform interval [0,2] is negligibly small.

Each node generates packets according to a Poisson process with rate λ in bits/sec (same for all nodes), with a data rate of 1 Mbps and a fixed packet size of 2000 bytes. For the AP topologies, packets generated by non-AP nodes are destined to the AP, whereas packets generated by the AP are destined to a randomly chosen non-AP node. In the ad hoc topologies, packets generated by a given node are destined to a randomly chosen node out of the other 24 nodes. For all figures, we set the maximum transmission range to 356 meters and the carrier-sense range to 712 meters. These values ensure no hidden-terminal problems for the AP scenario, but hidden-terminal collisions can occur in the ad hoc scenario (despite the fact that all nodes are within the carrier-sensing range of each other). As Cui et. al [14], we take the required SNR (γ) under fixed-rate modulation (BPSK) with $p_b = 0.001$ to be equal to: 24.4 dB for SISO, 11.0 dB for SIMO, 13.9 dB for MISO, and 6.9 dB for MIMO. We assume a Rayleigh fading channel with an average path loss that falls off with the distance d as d^4. We ran our experiments for 10 simulation seconds. The actual transmission time is 16 milliseconds, which is the ratio between the data packet size (2000 bytes) and the data rate (1 Mbps). We repeated each experiment 4 times with different seed numbers and averaged the results. The confidence intervals were sufficiently tight, and are not shown to prevent cluttering the plots. Other system parameters are tabulated in Table I, as given by Cui et. al [14]. The simulation platform is CSIM [36].

In our simulations, the reported energy consumption includes all sources of energy dissipation, such as retransmissions,

TABLE I
SYSTEM PARAMETERS

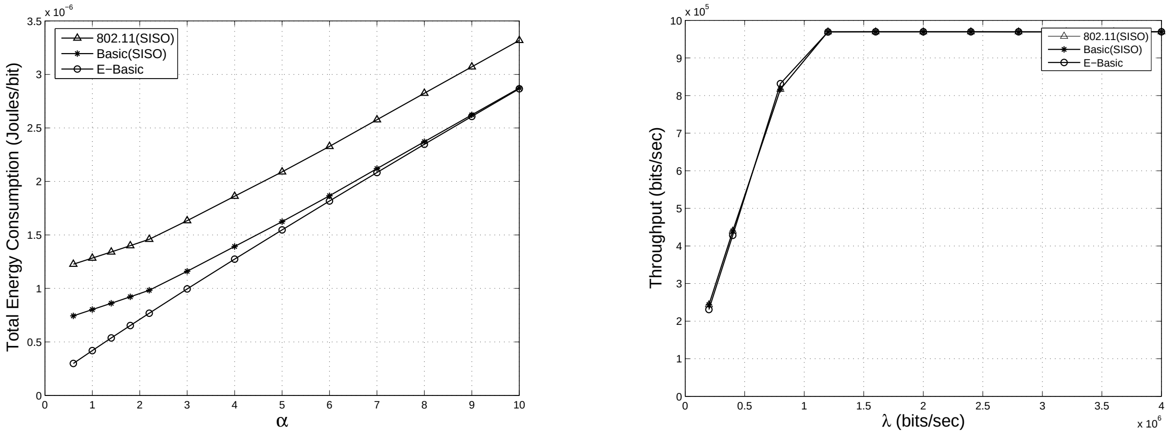
B	10 KHz
P_{mix}	30.3 mW
p_b	0.001
P_{filt}	2.5 mW
P_{filr}	2.5 mW
N_f	10 dB
P_{syn}	50.0 mW
P_{LNA}	20 mW
M_l	10 dB
G_o	1 m^{-4}

control packets, collisions, hidden terminals, etc.

A. AP Topologies with Fixed-Rate Modulation

1) E-BASIC vs. SISO-only protocols: In this case, we contrast the IEEE 802.11 and BASIC protocols operating under the SISO mode with E-BASIC, which uses MIMO for control packets and one of the four modes (SISO, SIMO, MISO, or MIMO) for data transmission. Figure 3(a) shows the total energy consumption per bit (averaged across the network) versus α, where α is the ratio of the circuit power of the SISO mode and the maximum transmission power $P_{\max}$. For each value of α, the circuit power of the four antenna modes is given as: $\alpha P_{\max}$ for SISO, $G_1 \alpha P_{\max}$ for MISO, $G_2 \alpha P_{\max}$ for SIMO, and $G_3 \alpha P_{\max}$ for MIMO, where $G_1 > 1$, $G_2 > 1$, and $G_3 > \max\{G_1, G_2\}$ are constants whose values depend on the power consumption of various circuit components. The larger the value of α, the larger is the circuit power relative to the transmission power. Recall that MIMO requires the maximum circuit power compared with the other three modes, SIMO and MISO require less than MIMO, and SISO requires the minimum circuit power.

According to Figure 3(a), when α is small, the transmission power dominates, so E-BASIC is more energy efficient than the IEEE 802.11 and BASIC protocols. As α increases, E-BASIC uses fewer transmit/receive antennas for the data/ACK packets, and eventually chooses to operate in the SISO mode. When the SISO mode becomes preferable, both BASIC and E-BASIC achieve comparable energy efficiencies (in fact, E-BASIC has a slightly higher energy consumption since it uses the fixed MIMO mode in the RTS/CTS phase). The cross point between BASIC and E-BASIC is around $\alpha = 10$. In the range of α below this point, both BASIC and E-BASIC are more energy efficient than IEEE 802.11, since they transmit at the minimum required power for the data/ACK packets, while IEEE 802.11 still uses the maximum power for data/ACK packets.



(a) Total energy consumption versus α.

(b) End-to-end throughput versus traffic load (λ).

Fig. 3. Energy and throughput performance for AP topologies with fixed-rate modulation.

Figure 3(b) depicts the throughput performance for the three protocols. It shows that they have roughly the same average throughput. This is because they reserve the same transmission region for each active node by using the same maximum power during the RTS/CTS phase. Figure 4 shows the fraction of time that each mode is used in E-BASIC at different α values. For large α values, modes involving fewer antennas are preferred, since circuit energy becomes more significant.

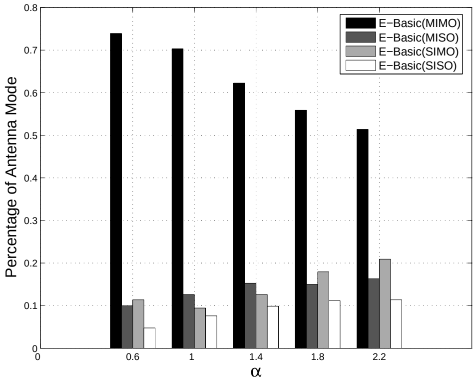


Fig. 4. Percentage of antenna mode versus α for AP topologies with fixed-rate modulation.

2) E-BASIC vs. MIMO-only protocols: In this case, both IEEE 802.11 and BASIC protocols use fixed MIMO mode for both control and data packets, while E-BASIC operates in the same way as described in subsection III-A.1. The energy performance is shown in Figure 5, which shows that the energy savings of E-BASIC over both IEEE 802.11 and BASIC protocols increase over α, since E-BASIC has the freedom to choose modes involving fewer antennas when α gets large, i.e., when circuit energy becomes significant. For extremely small α values (when transmission energy consumption dominates), E-BASIC and BASIC achieve the same performance, which is superior to IEEE 802.11 due to the fact that IEEE 802.11 always transmits at the maximum power level for both control and data packets. Note that the relative end-to-end throughput performance among the three protocols is the same for similar reasons as described in subsection III-A.1. Therefore, it is not plotted here.

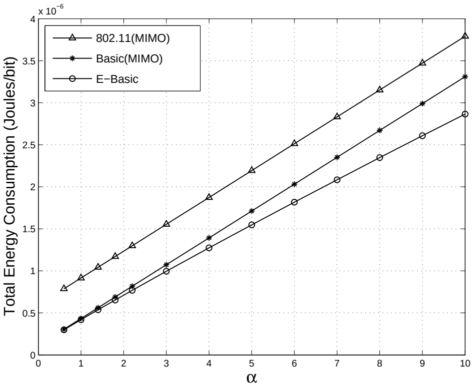
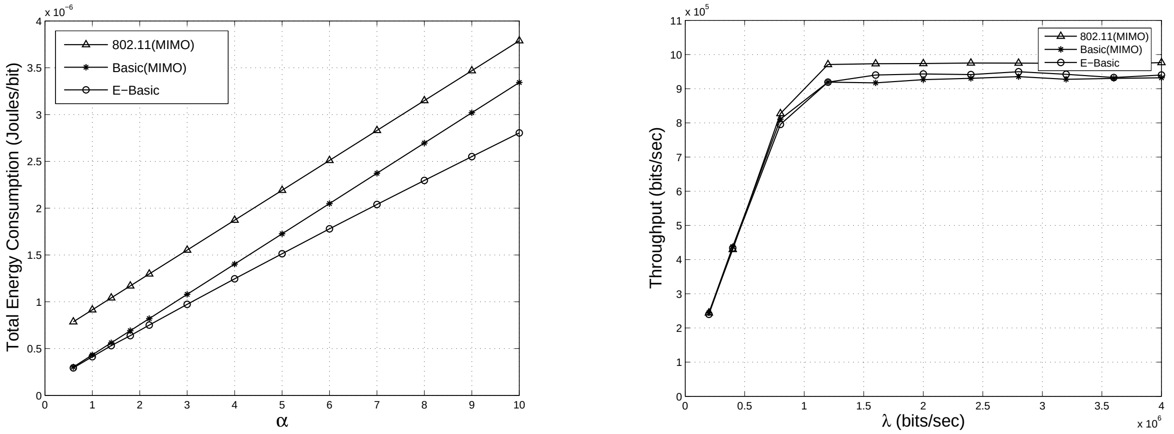


Fig. 5. Energy performance for AP topologies with fixed-rate modulation.

B. Ad Hoc Topologies with Fixed-Rate Modulation

1) E-BASIC vs. MIMO-only protocols: In this case, we replace the access point with a regular node (which is also randomly moving) and allow each node to communicate with any other node directly, but only single-hop transmissions are allowed. Other setups are the same as described in subsection III-A.2. The performance comparisons of energy consumption and throughput are shown in Figures 6(a) and 6(b), respectively. The energy performance is similar to that in AP topologies when IEEE 802.11 and BASIC protocols are operating under MIMO mode, while we now see a slight throughput degradation of E-BASIC and BASIC compared to IEEE 802.11 due to the fact that more collisions may occur when the active nodes are located in the corners.

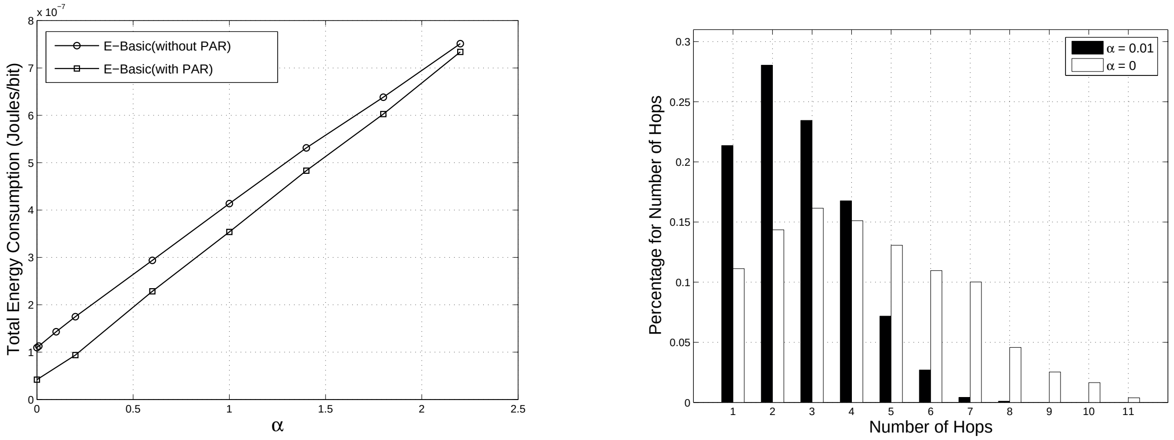
2) PAR/E-BASIC vs. E-BASIC without PAR: In this case, we use the same setup as described in subsection III-B.1, but allow multi-hop transmissions where the routes are determined by applying the modified Dijkstra's algorithm. Figures 7(a) and 7(b) illustrate the performance difference between E-BASIC without and with PAR. Figure 7(a) shows that for small values of α, E-BASIC with PAR saves up to 61% energy over E-BASIC without PAR, since multi-hop transmissions save energy when transmission power dominates. Figure 7(b) shows the fraction of time that different numbers of hops are used in the routing. When the circuit power is assumed to be zero ($\alpha = 0$), routes with large number of hops exist. When we



(a) Total energy consumption versus α.

(b) End-to-end throughput versus traffic load (λ).

Fig. 6. Energy and throughput performance for ad hoc topologies with fixed-rate modulation.



(a) Total energy consumption versus α.

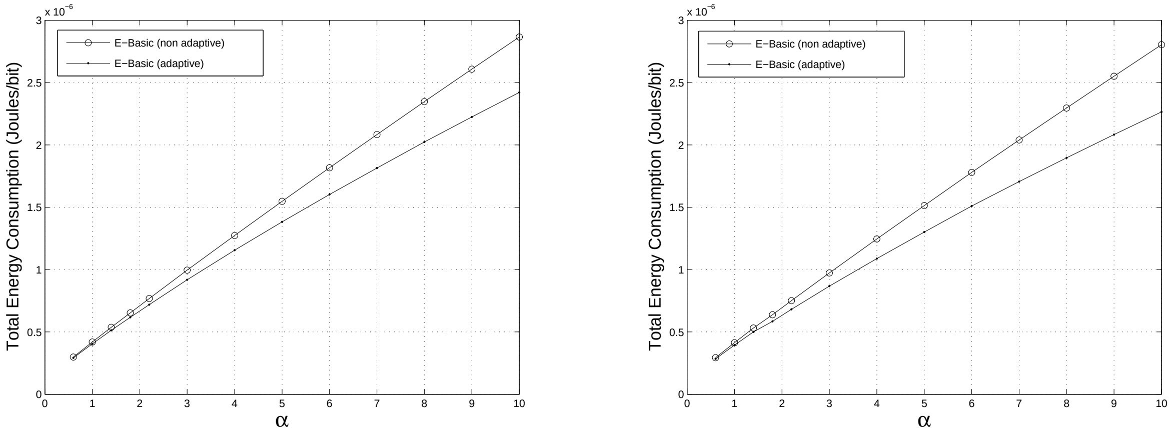
(b) Percentage for number of hops with $\alpha = 0$ and $\alpha = 0.01$.

Fig. 7. PAR/E-BASIC performance with fixed-rate modulation.

have non-zero circuit power ($\alpha = 0.01$), the average number of hops across all routes is reduced to balance the extra circuit power in the relay nodes. Note that the throughput performance of E-BASIC with PAR is degraded as a price of saving energy.

C. AP and Ad Hoc Topologies with Adaptive Modulation

In this section, we study the performance of AP and ad hoc topologies under adaptive modulation. Figure 8(a) shows the behavior of the total energy consumption for E-BASIC protocol with a fixed-rate modulation and E-BASIC with adaptive modulation. This figure is plotted versus α considering AP topologies. It shows that for small values of α, the transmission



(a) Total energy consumption versus α for AP topologies.

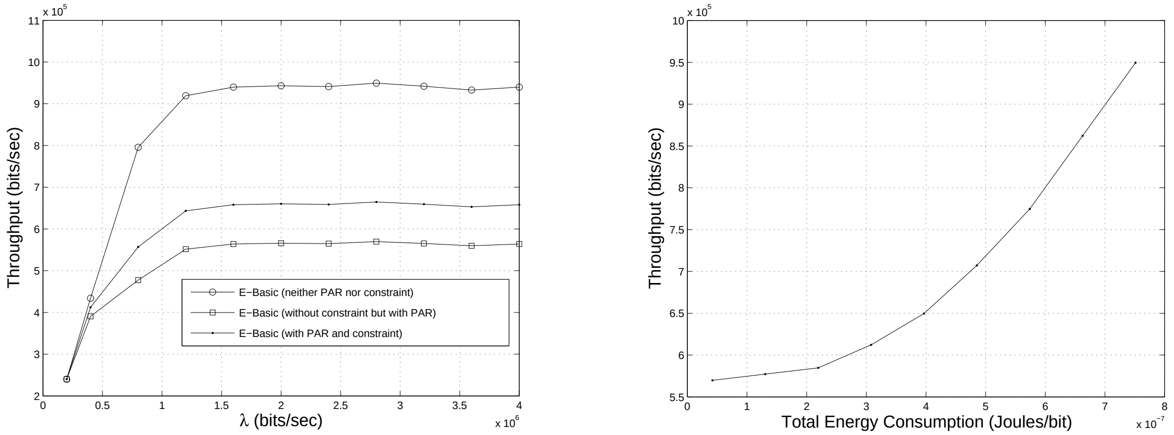
(b) Total energy consumption versus α for ad hoc topologies.

Fig. 8. Energy performance under adaptive modulation.

power dominates over the circuit power, making MIMO the preferable mode. Therefore, the smallest value of b, i.e., $b = 1$, provides the minimum total energy consumption. Note that the transmission energy is somewhat directly proportional to b, which means that $b = 1$ is the best choice for the modulation order. However, as α increases, the circuit power dominates the transmission power, making SISO more preferable. In this case, larger values of b are chosen to obtain the minimum total energy consumption. Figure 8(b) compares the total energy consumption for E-BASIC with a fixed-rate modulation and E-BASIC with adaptive modulation. This figure is plotted versus α for ad hoc topologies. The performance of the total energy consumption in this figure is similar to that in Figure 8(a) with more energy saving for large values of α.

D. Ad Hoc Topologies Under a Delay Constraint

In this section, we study the performance of ad hoc topologies with a delay constraint. Note that our simulations account for the queueing delay at the transmitter and assume a non-saturated scenario. Figure 9(a) compares the throughput performance for three curves: the first curve is for E-BASIC without PAR (i.e., only one hop transmissions are allowed) and without a delay constraint for a fixed-rate modulation, which is the same as Figure 6(b). The second curve is for PAR/E-BASIC protocol with a fixed-rate modulation, but without a delay constraint. The throughput performance in this case is poor since multi-hop transmissions provide fewer number of successfully delivered packets compared with the one-hop transmissions during the same period of time. On the other hand, the total energy consumption is improved in this case, as shown in Figure 7(a). The third curve is for PAR/E-BASIC with both adaptive modulation and delay constraint, i.e., we have an upper



(a) End-to-end throughput versus traffic load (λ) for ad hoc topologies.

(b) End-to-end throughput versus total energy consumption for ad hoc topologies.

Fig. 9. Performance of E-BASIC with delay constraint.

bound on the average delay that a packet needs to be considered successfully delivered. We can see from this figure that the throughput has been improved compared to the unconstrained case. This improvement depends on the delay bound that we apply. Note that throughput performance can be improved further by changing the bound, but this will affect the total energy consumption that we achieve as shown in Figure 9(b), which shows the throughput versus the total energy consumption for the PAR/E-BASIC with both adaptive modulation and delay constraint. This figure ensures that there is a tradeoff between the throughput and the total energy consumption, which means that the total energy consumption can be improved, but with a throughput price, and visa versa.

It should be noted that given the short simulation time, any node can move within a small portion of its neighbor's range. We study the impact of the simulation time on the throughput performance of PAR/E-BASIC via Figure 10. This figure reveals that when longer simulation time is used, more link breakages occur. This results in a reduction in the throughput performance. Note that mobility does not have much of an impact on the one-hop performance (E-BASIC). As for the routing performance, an energy-efficient route will often have more hops than the min-hop route. The likelihood of route breakage is obviously higher for a path that contains more hops. However, such an effect is mostly visible when one accounts for the delay incurred in discovering the path (e.g., the time needed for the route-request (RREQ) packets to retrieve a valid route) in reactive routing or, in the case of proactive routing, the time between two flooding epochs. In our work, the interest in routing is mainly related to the path selection algorithm, rather on the discovery process (be it reactive or proactive). Hence, we do not account for the nonzero time needed to discover the route. Instead, we assume that the "state information" is instantaneously available to the source node that runs the energy-oriented route selection algorithm. Because of this, the impact of mobility in our results will primarily be seen in terms of disconnecting the topology and/or changing the optimal routes (i.e., according to our simulations, the source node will always find the "optimal" route, but because of mobility, this optimal route keeps changing).

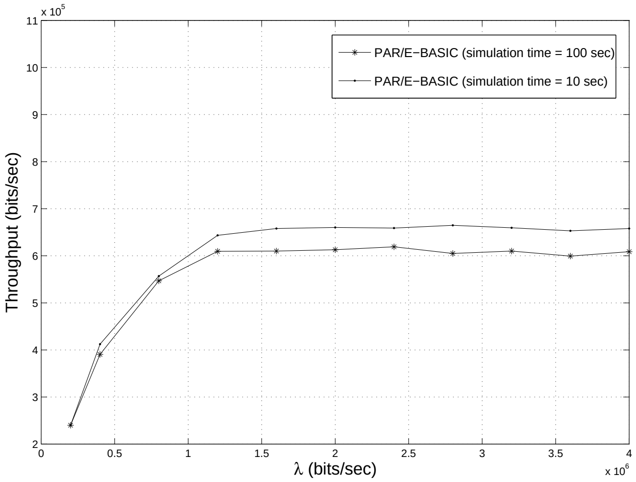


Fig. 10. Impact of simulation time on PAR/E-BASIC.

IV. CONCLUSIONS

In this paper, we proposed an adaptive multi-antenna power-controlled protocol for wireless networks, coined E-BASIC. E-BASIC upholds the same principles as the IEEE 802.11 and BASIC protocols for the RTS/CTS handshake. However, E-BASIC chooses the optimal multi-antenna modes (SISO, SIMO, MISO, or MIMO) along with minimum transmit power for data/ACK packets to minimize the total power consumption of the network. The fact that the relative energy efficiency among different multi-antenna modes changes over transmission distance leads to the superior performance of E-BASIC over the IEEE 802.11 and BASIC protocols, where the later two are built on fixed antenna modes. As a result, E-BASIC saves more power with no throughput degradation in AP networks and with only slight throughput degradation in ad hoc networks. We have shown that E-BASIC with power-aware routing further improves energy efficiency. Our adaptive designs were first conducted assuming fixed-rate transmission, but later extended to multi-rate systems by additionally optimizing the modulation order. Finally, a constraint on the average packet delivery time was imposed to account for the energy-throughput tradeoff in our designs. Simulations showed that our proposed adaptations achieve a significant reduction in the overall energy consumption relative to the non-adaptive MIMO systems.

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