Adaptive Multi-antenna Power Control in Wireless Networks

Mohammad Z. Siam, Marwan Krunz, Alaa Muqattash, and Shuguang Cui

Department of Electrical and Computer Engineering
The University of Arizona
Tucson, AZ 85721

{siam, krunz, alaa, cui}@ece.arizona.edu

ABSTRACT

Transmission power control has often been used in wireless packet networks to improve the channel reuse and 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, is based on a modification of the classic CSMA/CA access scheme, where we dynamically adjust 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). Our energy model accounts for both the transmission and the circuit powers. While the MIMO mode requires less RF transmission energy than the other three modes, it also incurs the highest circuit energy consumption. 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 ad hoc and infrastructure-based scenarios and compare it with two channel access protocols (802.11 and BASIC) that use a fixed transmission mode (SISO or MIMO) all the time. Our simulations show that E-BASIC often consumes much less total energy than the reference protocols. We further incorporate E-BASIC into the design of a power-aware routing (PAR) scheme that uses a variant of Dijkstra's algorithm to select the most energy-efficient end-to-end path between nodes.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication; C.2.2 [**Network Protocols**]

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.
IWCMC'06, July 3–6, 2006, Vancouver, British Columbia, Canada.
Copyright 2006 ACM 1-59593-306-9/06/0007 ...$5.00.

General Terms

Design, Performance

Keywords

Power control, MIMO, ad hoc networks, infrastructure-based networks, IEEE 802.11, power-aware routing, energy efficiency.

1. INTRODUCTION

Energy is one of the most critical resources of a wireless network. It can be conserved by controlling the transmission power of packets and/or by putting inactive nodes to sleep. In this work, we focus on transmission power control (TPC), which has been extensively researched for both cellular as well as ad hoc networks (see [13] for a survey of this topic). 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 at the link layer [16], whereby multiple transmit and/or receive antennas are exploited to achieve spatial diversity. For example, it was shown in [4] that MIMO-based transmission consumes much less *transmission power* than SISO-based transmission for the same throughput.

When used over a fading channel, MIMO technology offers three types of gains: *array*, *diversity*, and *multiplexing* gains [16]. In our work, we mainly 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 array gain, which only requires channel state information at the receiver. The two gains can be used to achieve higher link reliability (lower BER p_b), longer communication distance, or reduced SNR requirement. We focus on the last benefit, whereby a target p_b is set and the signal transmission power is minimized to achieve a given SNR threshold.

As discussed earlier, for a given average p_b requirement a multi-antenna transmission scheme requires less transmission power than a SISO transmission. However, it also requires more circuit power at both ends of the transmission. As a result, a distance-dependent tradeoff emerges between transmission and circuit powers [5]; for relatively small distances, circuit power is dominant, and hence a

Petitioner Samsung Ex-1006, 0001

SISO mode is more energy-efficient than a multi-antenna transmission mode. As the transmitter-receiver separation increases, the tradeoff shifts in favor of multi-antenna modes (SIMO, MISO, or MIMO). Joint optimization of transmission/circuit powers was considered in several previous studies (e.g., [5]), although the focus has been on SISO systems. The authors in [4] 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 contention-based wireless packet network. We consider both infrastructure based (e.g., 802.11 WLANs with access points) as well as ad hoc networks. We propose a packet-based channel access scheme called Enhanced-BASIC (E-BASIC) that jointly adapts the transmission mode and transmission power on a per-packet basis such that the total energy consumption is minimized. In our setup, each node is equipped with two antennas, allowing a packet to be transmitted over a link using one of four possible transmission modes: 1×1 (SISO), 2×1 (MISO), 1×2 (SIMO), and 2×2 (MIMO). E-BASIC is an extension of BASIC, a power-controlled MAC protocol that was originally developed for SISO-based ad hoc networks [12]. Both BASIC and E-BASIC aim at reducing energy consumption by manipulating the transmission powers of DATA and ACK packets. They both use a variant of CSMA/CA with virtual carrier sensing for channel access. In contrast to BASIC, which uses a fixed transmission mode, E-BASIC allows a pair of nodes to select the optimal transmission mode along with the optimal transmission power on a per-packet basis.

The rest of the paper is organized as follows. In section 2 we briefly overview related work in the area of power control for 802.11-based and general ad hoc networks. The proposed E-BASIC protocol is introduced in section 3. In the same section, we integrate E-BASIC in the design of a PAR protocol for MIMO-capable mobile ad hoc networks (MANETs). In contrast to the standard min-hop routing, PAR attempts to compute *energy-efficient* end-to-end paths. The performance of E-BASIC and PAR/E-BASIC is studied via simulations in section 4. In that section, we also compare E-BASIC with both the 802.11 scheme and BASIC, where the latter two are operated under a fixed transmission mode (either SISO or MIMO). Section 5 summarizes our main findings.

2. POWER CONTROL FOR 802.11-BASED AND GENERAL AD HOC NETWORKS

The vast majority of currently deployed wireless LANs are based on the IEEE 802.11 standard [1], which is also considered the de facto approach for channel access in ad hoc networks [13]. In addition to defining the physical layer, the 802.11 standard defines a channel access (MAC) scheme that is based on a variant of CSMA/CA with optional virtual carrier sensing, i.e., request-to-send/clear-to-send (RTS/CTS) exchange, for transmission of large packets. By default, the 802.11 scheme uses a fixed (maximum) power level for transmission of control (RTS/CTS), DATA, and ACK packets. Several studies have demonstrated the inefficiency of the fixed-transmission-power strategy in terms of energy consumption and spatial channel reuse (e.g., [7]). One remedy is to allow the transmission power to be adjusted on a per-packet basis. Many TPC protocols have been proposed for this purpose. Some of these protocols are aimed at energy conservation (e.g., [12]) while others are throughput oriented (e.g., [14], [15]). For example, in the BASIC protocol [12], RTS and CTS packets are transmitted at a fixed maximum power ($P_{\max}$), while DATA and ACK packets are transmitted at the minimum power level that guarantees the required SNR threshold. 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 [15] addresses the channel reuse issue by redefining the role of the RTS/CTS exchange, making it possible for multiple pairs of neighboring nodes to exchange packets provided that their power levels do not cause the SNR at any receiver to fall below the SNR threshold. Other protocols improve the performance by using busy-tones (e.g., [19]) and prioritized back-off (e.g., [20]). An overview of various TPC mechanisms for MANETs can be found in [13].

All the aforementioned TPC schemes were targeted at SISO-based wireless networks. The authors in [18] presented a new MAC protocol for ad hoc networks with MIMO links. The application of MIMO techniques in MAC and routing design in MANETs was explored in [9]. In [8], the authors highlighted the importance of MIMO as an emerging technology, both in terms of the significant increase in data rate and range that it enables as well as the considerable challenge that it presents for the development of low-power wireless LAN products. The spectral efficiency of a MIMO ad hoc network was studied in [3]. Various architectures of MIMO systems and their features were discussed in [6], including those proposed for the IEEE 802.11n standard. The authors in [17] 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 in [11] based on probabilistic analysis of the achievable capacity of random topologies.

3. E-BASIC PROTOCOL AND POWER-AWARE ROUTING

In this section, we introduce E-BASIC and later incorporate it in the design of an energy-efficient PAR scheme. We start by describing the power consumption model used in the paper.

3.1 Power Consumption Model

We adopt the multi-antenna link layer model of [4], where $M_t = M_r = 1$ for the SISO case, $M_t = 1$ and $M_r = 2$ for the SIMO case, $M_t = 2$ and $M_r = 1$ for the MISO case, and $M_t = M_r = 2$ for the MIMO case. The total power consumption consists of transmission and circuit powers. The transmission power is given by $P_t = (1 + \delta)P_{out}$, where δ is a factor that depends on the *drain efficiency* of the power amplifier and the underlying modulation scheme [5], and P_{out} is the total transmit power at the air interface. This P_{out} can be expressed as

$$P_{out} = \gamma N_o B N_f G_o d^4 M_l \quad (1)$$

where γ is the required SNR at the receiver, N_o is the single-sided thermal noise power spectral density (PSD), B is the passband bandwidth, N_f is the receiver noise figure (defined as $N_f = \frac{N_r}{N_o}$, with N_r being the PSD of the total effective noise at the receiver input), d is the transmitter-receiver distance, G_o is a constant that depends on the transmitter and receiver antenna gains, and M_l is a link margin that

Petitioner Samsung Ex-1006, 0002

compensates for hardware variations and other sources of interference. 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 [4]

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

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 (DAC), the mixer, the low noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter and the receiver sides, the analog-to-digital converter (ADC), and the frequency synthesizer, respectively.

In this paper we assume a fixed-rate BPSK system. The total energy consumption per bit for such a system can be written as [4]

$$E_{bt} = \frac{P_t + P_c}{R_b} \quad (3)$$

where the bit rate $R_b \approx B$ bits/sec for BPSK modulation. Our goal is to design an adaptive MIMO power control protocol that minimizes the value of E_{bt} for any pair of communicating nodes.

3.2 E-BASIC Protocol

Similar to the IEEE 802.11 and BASIC protocols, E-BASIC uses CSMA/CA with virtual carrier sensing (RTS/CTS exchange) to reduce packet collisions. Assume that a node X wants to send a packet to another node Y. Node X first senses the channel to see if it is idle or not. If the channel is detected as being idle, X starts a timer with a randomly chosen period of time. The timer duration is decremented while the channel is idle and is frozen when the channel is busy. Once the timer expires, node X can transmit. If a collision happens, an exponential backoff algorithm is used. If RTS/CTS handshake is used, then according to this handshake procedure, node X sends an RTS packet to Y, checking whether Y is ready to receive a DATA packet or not. Upon receiving the RTS packet, node Y responds by sending a CTS packet, indicating its willingness to receive the DATA packet from X. Following the RTS/CTS exchange, node X sends its DATA packet to Y, which responds back with an ACK packet (if the transmission was successful).

The IEEE 802.11 protocol is based on fixed SISO or MIMO schemes only, which means that there is no ability for this protocol to adaptively choose the multiple antenna scheme, and it uses a fixed (maximum) power level for both RTS/CTS and DATA/ACK packets. Therefore, IEEE 802.11 is quite conservative in power consumption and it may yield to a reduction of network throughput due to the resulting high interference level. Another protocol that we want to compare E-BASIC with is the BASIC protocol [12], which uses similar principles as in IEEE 802.11 protocol with a very important difference, where it uses the minimum allowable power level to send the DATA and ACK packets while keeping the RTS/CTS transmission as it is in IEEE 802.11 protocol. This change results in a reduction of the total power consumption. BASIC protocol, as IEEE 802.11 protocol, uses only fixed SISO or MIMO schemes without the ability to adaptively choose one of the four schemes (SISO, SIMO, MISO, or MIMO).

E-BASIC protocol uses adaptive multi-antenna schemes along with power control to send packets. Specifically, it uses the maximum power level for RTS/CTS handshake with the fixed MIMO scheme, but the minimum allowable power level for DATA/ACT packets with an optimally chosen multi-antenna scheme (among SISO, SIMO, MISO, or MIMO) according to the total power consumption that each scheme results. This protocol saves more power than both the IEEE 802.11 and BASIC protocols, even when the IEEE 802.11 or BASIC protocol is deployed on a fixed MIMO system. This is because that MIMO may not lead to the minimum total power consumption due to the large value of circuit power, which has a varying significance relative to the transmission power in different scenarios. Specifically, at short distances, SISO is more power efficient than MIMO since the circuit power dominates the transmission power [4]. At long distances, MIMO is more power efficient than SISO. For intermediate distances, SIMO or MISO may be more power efficient. In the E-BASIC protocol, we choose one of the four modes (SISO, SIMO, MISO, or MIMO) according to the transmission distance, with the goal of minimizing E_{bt}.

3.3 Power-Aware Routing based on E-BASIC

We now combine E-BASIC with power-aware Routing (PAR/E-BASIC) to further improve the power efficiency, where the routing is implemented with a modified Dijkstra's algorithm. Specifically, this modified algorithm depends on calculating the total end-to-end energy consumption for all possible routes (1-hop routes as well as multi-hop routes) between two nodes that want to communicate. For each link along the route, we have the freedom of choosing one out of four modes (SISO, SIMO, MISO, or MIMO). This is equivalent to the case where we have four possible paths between each pair of connected nodes, as shown on the left side of Figure. 1, where each path weight is defined by the energy per bit required for the particular multi-antenna mode. It is easy to show that the overall optimal routing problem can be decomposed into two steps. Step 1, we choose the most energy efficient multi-antenna mode for each pair of connected nodes and delete the paths resulting from the other three modes such that the overall network is reduced to a single-link network, as shown in Figure. 1 where in this example we assume the optimal modes for $X \rightarrow Y$, $X \rightarrow Z$, and $Y \rightarrow Z$ are SISO, MIMO, and SIMO, respectively. Step 2, we run the modified Dijkstra's algorithm where the path weight is defined as the minimum E_{bt} that is achievable over that path among four different multi-antenna modes. Note that the complexity is only increased by $4M$ compared with a regular Dijkstra's algorithm, where M is the number of links in the network.

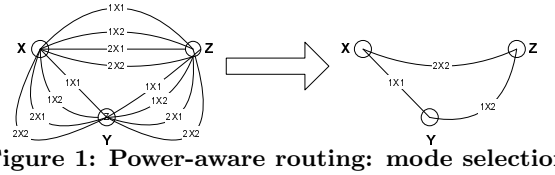

Figure 1: Power-aware routing: mode selection.

4. PERFORMANCE EVALUATION

In this section, we compare the performance of the E-BASIC protocol with IEEE 802.11 and BASIC protocols. We consider four different networking scenarios, which cover both infrastructure-based and infrastructure-less (ad hoc) cases and give us a thorough understanding of their relative performance. For all the three protocols, we use the following setup in our simulations, unless otherwise stated. We

Petitioner Samsung Ex-1006, 0003

consider a square area (500x500 square meters for infrastructure-based cases and 350x350 square meters for infrastructure-less cases). In the infrastructure-based cases, we put one node at the center of the area to act as an access point (AP) and we randomly deploy other 24 nodes in a uniform way. In the infrastructure-less case, all the 25 nodes are randomly distributed. We assume that the 24 non-AP nodes in the infrastructure-based cases and the 25 nodes in the infrastructure-less cases are moving according to the Random Waypoint model [2] with a speed uniformly chosen from the interval [0, 2m/s] and generate packets according to a Poisson process, which leads to a data rate of 1 Mbps with fixed packet size of 2000 bytes. We further assume that the maximum transmission range is 356 meters and the carrier-sense range is 712 meters. The required (pre-determined) average receiver SNR (γ) when $p_b = 0.001$ is given by [4]: 24.4 dB for SISO, 11.0 dB for SIMO, 13.9 dB for MISO, and 6.9 dB for MIMO. Regarding the channel, we assume Rayleigh fading in addition to an average path loss, which has a power falloff of d^4. All other system parameters such as the circuit power consumption values are quoted from [4]. The networking simulation platform is CSIM [10].

4.1 Scenario 1 : Infrastructure-Based Networks (E-BASIC vs. SISO-802.11 vs. SISO-BASIC)

In this scenario, we assume that IEEE 802.11 and BASIC protocols use SISO schemes to send both the control and data packets, while E-BASIC uses MIMO for control packets and one of the four schemes (SISO, SIMO, MISO, or MIMO) for the data transmission. The networks in this scenario are based on the infrastructure mode, which means that there is a centralized AP that can communicate with all other nodes while all other nodes can only communicate with the AP. It is clear that in this case there are no multi-hop transmissions and there are no data collisions possible with an AP in the center whose maximum power transmission can reserve the whole area. The performance of the E-BASIC protocol in this scenario is illustrated in Figures 2, 3, 4, and 5.

Specifically, Figure 2 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 multi-antenna modes is given as: αP_{max} for SISO, $C_1 \alpha P_{max}$ for MISO, $C_2 \alpha P_{max}$ for SIMO, and $C_3 \alpha P_{max}$ for MIMO, where $C_1 > 1$, $C_2 > 1$, and $C_3 > \max\{C_1, C_2\}$ are some system constants, whose values are defined by specific power consumption values of various circuit blocks. The larger the value of α, the larger is the circuit power relative to the transmission power, while MIMO requires the maximum circuit power, SIMO and MISO require less than MIMO, and SISO requires the minimum circuit power.

According to Figure 2, we see that when α is small, transmission power dominates such that E-BASIC protocol is more energy efficient than IEEE 802.11 and BASIC protocols, since E-BASIC can choose to work in the MIMO mode for DATA/ACK packets to minimize the total power consumption. As α increases, E-BASIC uses less number of antennas for the DATA/ACK packets and eventually chooses to work in the SISO mode when circuit power becomes dominant. In this case, BASIC and E-BASIC protocols achieve similar energy efficiency while E-BASIC may become worse since it uses the fixed MIMO mode in the RTS/CTS phase. The cross point between them is shown in Figure 2 around $\alpha = 10$. For extremely large α values, E-BASIC may become worse than IEEE 802.11. This cross point is not shown in the figure due to the range limitation, while 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/ACT packets.

Figure 3 shows that the three protocols have roughly the same average throughput, which is plotted over λ (the generation rate per node of the Poisson process in bits/sec). This is because that the three protocols 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 multi-antenna mode is used, at different α values. We see that for large α values, since circuit energy becomes more significant, the modes involving less antennas are preferred.

We can also compare the performance among the three protocols over different average transmission distances. Indeed, the variation in the transmission distances is the reason that leads to different ratios between the transmission power and the circuit power. Specifically, the transmission power increases over distance while the circuit power remains roughly the same. Since the average transmission distance is proportional to the diameter of the overall network area, we compare the performance over five square areas of different diameters (500x500, 400x400, 300x300, 200x200, 100x100). Note that the maximum transmission power and transmission ranges are scaled down accordingly for all the three protocols. Figure 5 plots the energy consumption over the square edge length d_0 in meters (500, 400, 300, 200, 100). We see from this figure that E-BASIC saves a large amount of energy over both IEEE 802.11 and BASIC protocols for large values of d_0. Note that the performance gain of E-BASIC over IEEE 802.11 and BASIC protocols is enhanced as d_0 increases. The reason is that for large distances, the transmission energy dominates the circuit energy. Since E-BASIC chooses MIMO to minimize the transmission energy for data packets, it outperforms IEEE 802.11 and BASIC that are both based on SISO mode.

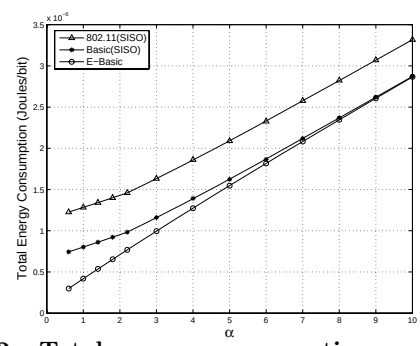

Figure 2: Total energy consumption versus α for scenario 1.

4.2 Scenario 2 : Infrastructure-Based Networks (E-BASIC vs. MIMO-802.11 vs. MIMO-BASIC)

In this scenario both IEEE 802.11 and BASIC protocols use the fixed MIMO scheme for both control and data packets, while E-BASIC operates in the same way as in scenario 1. The energy performance is shown in Figure 6, which shows that the energy savings of E-BASIC over both

Petitioner Samsung Ex-1006, 0004

IEEE 802.11 and BASIC protocols increases over α, since E-BASIC has the freedom to choose modes involving less 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 than 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 are the same for similar reasons as in the scenario 1. Thus it is not plotted here.

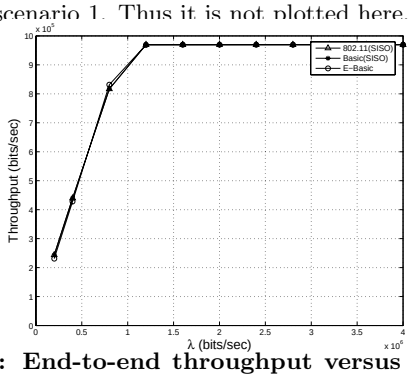

Figure 3: End-to-end throughput versus λ for scenario 1.

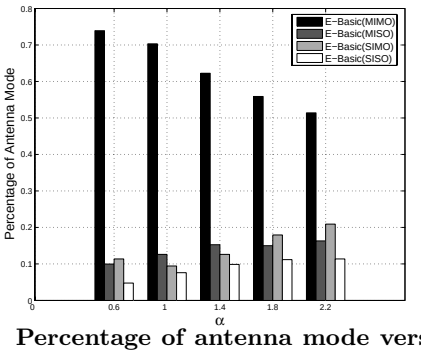

Figure 4: Percentage of antenna mode versus α for scenario 1.

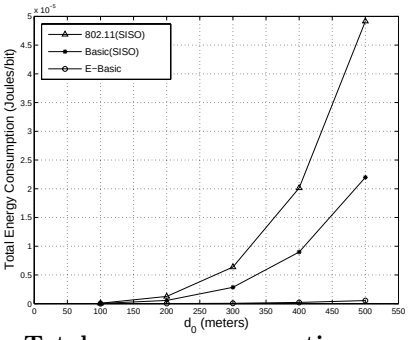

Figure 5: Total energy consumption versus d_0 for scenario 1.

4.3 Scenario 3 : Ad Hoc-Based Networks (E-BASIC vs. MIMO-802.11 vs. MIMO-BASIC)

In this scenario we replace the access point with a regular node (which is also randomly moving) and allow each node to communicate with any other nodes directly, but only single-hop transmissions are allowed. Other setups are the same as in scenario 2. The performance comparisons of energy consumption and throughput are shown in Figures 7 and 8, respectively. The energy performance is similar to that in scenario 2, while we now see a slight throughput degradation of E-BASIC and BASIC compared to IEEE

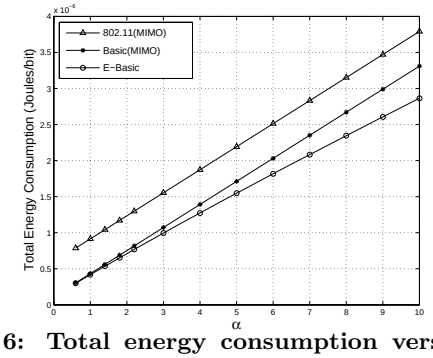

Figure 6: Total energy consumption versus α for scenario 2.

802.11 due to the fact that more collisions may occur when the active nodes are located in the corners.

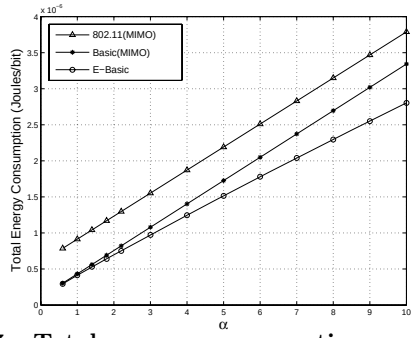

Figure 7: Total energy consumption versus α for scenario 3.

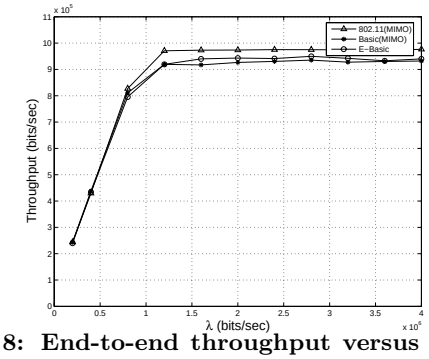

Figure 8: End-to-end throughput versus λ for scenario 3.

4.4 Scenario 4: Ad Hoc-Based Networks with PAR (PAR/E-BASIC vs. E-BASIC without PAR)

In this scenario, we use the same setup as in scenario 3, but allow multi-hop transmissions where the routes are determined by applying the modified Dijkstra's algorithm. Figures 9 and 10 illustrate the performance difference between using E-BASIC without and with PAR. Figure 9 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 10 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 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

Petitioner Samsung Ex-1006, 0005

with PAR is degraded as a price of saving energy. The details is skipped here due to space limitation.

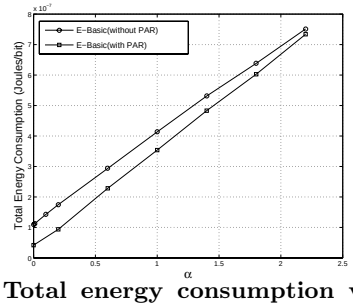

Figure 9: Total energy consumption versus α for scenario 4.

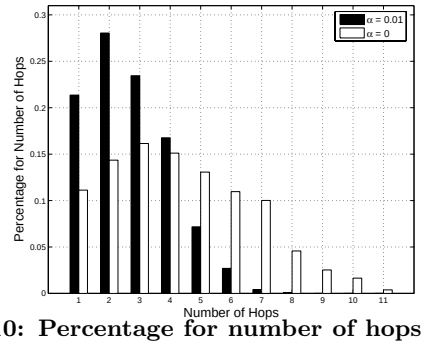

Figure 10: Percentage for number of hops (E-Basic with PAR) with $\alpha = 0$ and $\alpha = 0.01$ for scenario 4.

5. CONCLUSIONS

In this paper, we proposed an adaptive multi-antenna power control protocol for wireless networks, coined as E-BASIC. E-Basic bears the same principles as IEEE 802.11 and BASIC protocols for the RTS/CTS handshake. However, E-BASIC chooses the optimal multi-antenna scheme (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 schemes changes over transmission distance leads to the superior performance of E-BASIC over IEEE 802.11 and BASIC, where the later two are built on fixed multiple antenna schemes. We have also shown that E-BASIC saves more power with no throughput degradation in infrastructure-based networks and with only slight throughput degradation in ad hoc networks. We finally show that using E-BASIC with power-aware routing further improves energy efficiency.

6. REFERENCES

[1] I. S. I. 802.11. *ANSI/IEEE Std 802.11, 1999 Edn. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.*

[2] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the ACM MobiCom Conference*, pages 85–97, Oct. 1998.

[3] B. Chen and M. J. Gans. MIMO communications in ad hoc networks. In *Proceedings of the IEEE Semiannual Vehicular Technology Conference (VTC)*, pages 2434–2438, May 2005.

[4] S. Cui, A. J. Goldsmith, and A. Bahai. Energy-efficiency of MIMO and cooperative MIMO in sensor networks. *IEEE Journal on Selected Areas of Communications*, 22(6):1089–1098, Aug. 2004.

[5] S. Cui, A. J. Goldsmith, and A. Bahai. Energy-constrained modulation optimization. *IEEE Transactions on Wireless Communications*, 4(5):2349–2360, Sept. 2005.

[6] J. M. Gilbert, W.-J. Choi, and Q. Sun. MIMO technology for advanced wireless local area networks. In *Proceedings of the Design Automation Conference (DAC)*, pages 413–415, June 2005.

[7] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Trnansactions on Information Theory*, 46(2):388–404, Mar. 2000.

[8] K. Holt. Wireless LAN: Past, present, and future. In *Proceedings of the Design, Automation and Test in Europe Conference (DATE)*, pages 92–93, Mar. 2005.

[9] M. Hu and J. Zhang. MIMO ad hoc networks: Medium access control, saturation throughput, and optimal hop distance. *Journal of Communications and Networks - Special Issue on Mobile Ad Hoc Networks*, pages 317–330, Dec. 2004.

[10] M. S. Incorporation. *http://www.mesquite.com.*

[11] H. Jafarkhani, H. Yousefi'zadeh, and J. Kazemitabar. Capacity-based connectivity of MIMO fading ad-hoc networks. In *Proceedings of the IEEE GLOBECOM Conference*, pages 2827–2831, Nov. 2005.

[12] E.-S. Jung and N. H. Vaidya. A power control MAC protocol for ad hoc networks. In *Proceedings of the ACM MobiCom Conference*, Sept. 2002.

[13] M. Krunz, A. Muqattash, and S.-J. Lee. Transmission power control in wireless ad hoc networks: Challenges, solutions, and open issues. *IEEE Network Magazine*, 18(5):8–14, Sept. 2004.

[14] A. Muqattash and M. Krunz. A distributed transmission power control protocol for mobile ad hoc networks. *IEEE Transactions on Mobile Computing*, 3(2):113–128, Apr./June 2004.

[15] A. Muqattash and M. Krunz. POWMAC: A single-channel power-control protocol for throughput enhancement in wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications (JSAC) - Special Issue on Advances in Military Wireless Communications*, 23(5):1067–1084, May 2005.

[16] A. Paulraj, R. Nabar, and D. Gore. *Introduction to Space-Time Wireless Communications.* Cambridge University Press, Cambridge, U.K., 2003.

[17] K. Sundaresan and R. Sivakumar. Routing in ad-hoc networks with MIMO links. In *Proceedings of the IEEE International Conference on Network Protocols (ICNP)*, pages 85–98, Nov. 2005.

[18] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang. Medium access control in ad-hoc networks with MIMO links: Optimization considerations and algorithms. *IEEE Transactions on Mobile Computing*, 3(4):350–365, Oct.-Dec. 2004.

[19] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu. Intelligent medium access for mobile ad hoc networks with busy tones and power control. *IEEE Journal on Selected Areas in Communications*, 18(9):1647–1657, Sept. 2000.

[20] Y. Xiao. A simple and effective priority scheme for IEEE 802.11. *IEEE Communications Letters*, 7(2):70–72, Feb. 2003.

Petitioner Samsung Ex-1006, 0006