# A receiver initiated power control multi-access protocol in wireless ad hoc networks

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***Abstract*— In this paper, we address the issue of transmission power control (TPC) in wireless ad hoc networks. Power control plays an important role in energy saving and network performance enhancement. However, the existing TPC schemes either face the problem of hidden and exposed terminal or have additional hardware requirements. We propose a novel distributed power control protocol, called Receiver Initiated power control Multi-Access (RIMA) that ideally eliminates the hidden terminal problem and at the same time enjoys the same single-channel, single-transceiver design of nodes in IEEE 802.11 and 802.15 MAC standards. An enhanced version of RIMA is also proposed where reduced power RTS transmission is allowed to improve spatial reuse of the wireless channel. Simulations are performed to demonstrate the enhanced frame loss rate and network delay performance of the proposed approach with respect to a competitive approach, called transmitter initiated power control MAC protocol.**

## I. Introduction

Wireless distributed MAC protocols (e.g., 802.11 DCF [1] and 802.15.4 contention mode [2] standards) with single channel are inherently associated with the hidden terminal and exposed terminal problem. Due to the hidden terminals, frame collision probability increases, which eventually reduces the network throughput. The terminals exposed to the on-going transmissions, on the other hand, sometimes wait unnecessarily for their transmission activity, and it eventually increases the network delay. The combined effect has been reduction in channel utilization efficiency and energy efficiency in resource-constrained ad hoc networks.

To address the power consumption issue in ad hoc networks, several power control schemes have been proposed. Simply transmitting data at lowest allowable power does not work well, especially at high network density or at high traffic load. An Improved power control MAC protocol (PCM) in the context of 802.11 was proposed in [7] to achieve power saving and overcome the shortcomings of previous power control protocols. The PCM protocol still does not solve the problem of collisions, thus leading to degraded network throughput and delay at higher network load.

In order to resolve the hidden terminal problem and reduce the exposed terminals, we present a new power control protocol, called Receiver Initiated power control Multi-Access (RIMA). This protocol has two novelties:

1) Periodic transmission of pulsed busy tones at maximum power by the receiver (during which the transmitter does not send data to the receiver) to eradicate the hidden terminal problem. We call this approach as basic RIMA (or b-RIMA).
2) Reduced power RTS transmissions to minimize the exposed terminals problem and hence increase spatial reuse. We call this approach as enhanced RIMA (or e-RIMA).

Simulation results show overall improved performance of RIMA over the PCM in terms of frame loss rate and average waiting time per successful transmission. The significance or reduced power RTS is also clearly observed. The performance enhancement is more prominent as the network load increases.

The rest of the paper is organized as follows. Section II reviews the related works. The RIMA protocol operation is presented in Section III. Simulation based performance results are provided in Section IV. Section V concludes the paper.

## II. Related Work

A class of proposals to solve the hidden/exposed terminal problem has been using busy tone signal from the receiver using a separate channel, with or without power control [14], [15], [16], [6], [5], [9]. Although the dual channel approach improves the network utilization, it entails additional hardware cost (due to multiple transceivers), and is not be applicable to already-deployed devices (e.g., via reprogramming the driver software).

A few single-channel power control approaches have been proposed in recent literature, that address network and energy performance. In order to increase spatial reuse of communication channel and at the same time save energy, single-channel power control schemes have been proposed in [12], [4], [3], [11]. But in high density/ high load networks, these schemes fail to achieve their goal due to excessive collision.

The authors in [7] proposed a power control MAC (PCM) protocol, where RTS/CTS (request to send/ clear to send) signals are sent at full power, and the data frames are transmitted at lowest possible power that allows the receiver just to be able to correctly receive the data. The transmit signal power is periodically increased to the full level, and the periodicity of these high power pulses are chosen optimally to virtually create the same interference environment as in 802.11 DCF* without power control. The PCM protocol achieves power saving without deteriorating the network performance compared to the basic 802.11 standard without power control, however the hidden/exposed terminal problem of the basic 802.11 DCF remains unresolved. Interference in the PCM (and 802.11 DCF) protocol at a receiver under consideration from a potential transmitter in the interference zone is depicted in Fig. 1.

Another single-channel ad hoc MAC protocol proposed in [10] allows more than one power controlled transmission within the transmission vicinity of a node by staggered handshake approach. After a transmit-receive pair decides on data transmission, the transmitter waits for a certain duration to allow a nearby transmitter to do the handshake for a parallel transmission. This approach helps increase network throughput and possibly reduce per-bit energy consumption with respect to 802.11 DCF without power control. However this protocol does not eliminate the hidden terminal problem completely, because a node in the interference vicinity (but outside the transmission/reception vicinity) of an active receiver may corrupt the reception process by initiating a transmission.

In [13], low power protocols at the physical and MAC layers were studied and optimum number of channels in multi-channel regular access schemes (TDMA, FDMA) were investigated.

The proposed power control protocol in this paper is close to the works in [7], [10], as all three schemes operate on a single channel. However, unlike in [7], [10], we aim at eliminating the hidden terminals by transmitting the periodic high power pulsed in-band busy signal from the receiver. Also, reduced power RTS/CTS in our approach helps reduce the exposed terminals, which can be improved further by the location awareness of nodes.

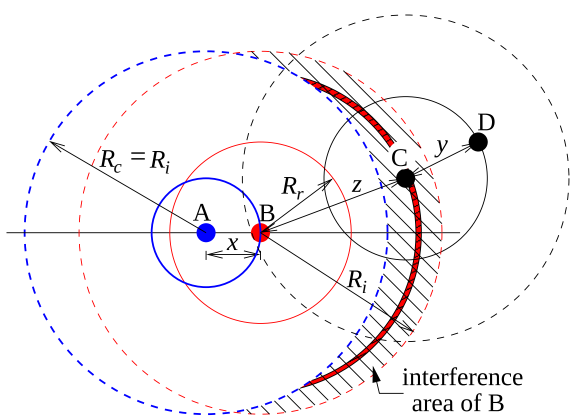


Fig. 1. Example of interference caused by hidden terminals in 802.11 DCF [1] and in PCM [7]. A transmitting node in the shaded region may cause interference to the on-going reception at node B.

## III. Overview of RIMA protocol

We first define the coverage concepts that are used in our subsequent discussion in the paper. The nodes are assumed equipped with isotropic antenna and the coverage range is considered circular. *Receive range* $R_r$ is the maximum allowable distance between a transmitter and its corresponding receiver, i.e., the radius of the circle around a receiver from where a transmission can be perfectly received. $R_r$ is also called the transmission coverage when a transmitter transmits at full power $P_{max}$. *Interference range* $R_i$ is the maximum distance of a transmitter from where it can cause interference to a receiver. If an interfering transmitter's distance $z$ from a receiver is such that $R_r < z \leq R_i$, the receiver cannot decipher the exact content of transmission, but the signal can corrupt the ongoing reception from a desired transmitter, subject to the interfering transmitter's power level. *Carrier sense range* $R_c$ is the maximum distance around a transmitter within which a node is considered to be exposed. Following the observation in [8], we have considered $R_i \approx 2R_r$. With no power control, i.e., when a transmitter transmits at full power $P_{max}$, $R_c = R_i$. If power control is employed such that a transmitter transmits at a minimum possible power $P_{min}$ to an $x$ distance away receiver, then $R_c \approx 2x \leq R_i$.

### A. The basic RIMA protocol

The proposed b-RIMA protocol works as follows:

- The transmitter and the receiver transmit the RTS and CTS at $P_{max}$. If a node in the carrier sensing zone receives but fails to decode a signal, it sets its NAV (network allocation vector) to an EIFS duration. For calculations, we take the EIFS duration to be 190 $\mu$s (according to [1], assuming 2 Mbps transfer rate).
- The transmitter transmits the data at $P_{min}$, the minimum power required to carry out successful communication, which can be decided based upon the receiver's receive threshold, transmitter-to-receiver distance, and the existing signal-to-interference-and-noise (SINR) level.
- The data frame is formatted such that after every EIFS period there is a bit stuffing period during which the transmitter does not transmit valid data to the receiver, and the receiver switches to transmit mode to send out an in-band busy tone at full power $P_{max}$ to its potential interferers. The bit stuffing duration is chosen 20 $\mu$s following the observation in [7], where 15 $\mu$s is the duration of the busy tone and 5 $\mu$s is for receive-to-transmit and transmit-to-receive changeover delay and re-synchronization with the transmitter.
- Since the data frame is transmitted at $P_{min}$, the transmitter is susceptible to interference at the time of receiving the frame acknowledgement (ACK). However, ACK frame being very short, its error probability would be low. To minimize further this error, an ACK is transmitted by the receiver at maximum power level $P_{max}$.

Periodic busy tone from the receiver in the b-RIMA protocol eliminates the hidden terminal problem, as shown in Fig. 2 (compare with the shaded interference zone of node B in Fig. 1). A frame transmission operation in b-RIMA protocol can be shown similarly as in Fig. 4, with the exception that the RTS is transmitted at $P_{max}$.

*Henceforth, by 802.11 DCF we will refer to the distributed wireless MAC standards, e.g., IEEE 802.11 DCF and 802.15.4 contention mode.

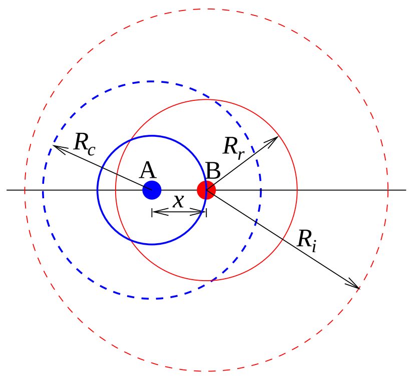


Fig. 2. Elimination of hidden terminal problem in b-RIMA protocol, which is achieved by periodic high power in-band busy tone signal from the receiver. As in [7], repetition duty cycle is chosen for data transmission at a rate 2 Mbps.

The basic difference between PCM and b-RIMA is that in PCM the transmitter sends out periodic full power transmit signal pulses, whereas in the case of b-RIMA, the receiver sends out periodic in-band busy tone pulses. Hence, the b-RIMA protocol works on the single channel, single transceiver design. During a data frame reception process, the periodic receiver-originated in-band busy tones prohibit the potential interferers of receiver from initiating a transmit-receive activity. Thus, collision of a data frame is prevented, leading to reduced frame loss rate and hence increased energy efficiency. Note that, besides eliminating the hidden terminals, bit stuffing period can be used judiciously by the transmitter as well as the receiver to enable location awareness as well as for other telemetric data exchange.

Another difference of b-RIMA with respect to PCM is that, in PCM the ACK frames are transmitted at $P_{min}$. However the performance difference is possibly insignificant because of very small ACK frame size.

Ideally, though b-RIMA zeroes down the probability of data frame collisions from hidden terminals and reduces the need of retransmissions; it consumes little more energy with respect to the PCM to carry out a transmission. The extra energy is consumed due to the additional periodic bit stuffing and synchronization. Furthermore, the data frame in b-RIMA being a little stretched, it will cause some additional delay (approximately 10%) in successfully transmitting a data frame.

### B. The enhanced RIMA protocol

Referring to Fig. 2, in the b-RIMA protocol, if a node is within the range $R_c$ around the transmitter A or within the range $R_i$ around the receiver B, that is an exposed terminal and has to postpone its activity throughout the data frame transmission period. We observe that this unnecessary delay can be reduced, and thereby spatial channel reuse can be increased, to some extent by allowing reduced power RTS transmission. We call this enhanced approach, enhanced RIMA (e-RIMA) protocol. A key assumption in this enhanced approach is that an exposed node is able to estimate its distance from a receiving node either reading the location information from the busy tone or by periodic peak-to-average difference signal strength measurement (similar to physical carrier sensing). Specifically, the proposed e-RIMA protocol works as follows:

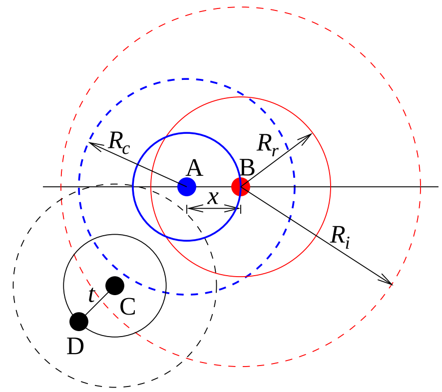


Fig. 3. An example of additional reduction of exposed terminal problem in e-RIMA protocol. A transmitter, which would have been otherwise exposed in PCM [7] or in basic 802.11 [1], is allowed to initiate a transmission process as long as its receiver is outside the carrier sense zone of receiver B.

- As shown in Fig. 3, if a transmitter C within the exposed zone can decode the location of the currently active receiver B, e.g., via busy tones from B or via the signal from A during the bit stuffing duration, it determines its distance from B. C then selects its receiver D from its local neighbors' location information such that C-to-D transmission at $P_{min}$ does not interfere B (or does not decrease the SINR level at B below an acceptable threshold). If such a node D can be found, C-to-D RTS is transmitted at $P_{min}$, while D-to-C CTS is transmitted at $P_{max}$, and the data frame transmission follows as in b-RIMA.
- On the other hand, when a transmitter C is within the exposed zone but it cannot decode the location of B, only receive periodic busy signals from B, it estimates its distance from B by measuring received peak-to-average carrier sensed signal. Based on a conservative estimate of C-to-B distance, C may be able to choose its potential receiver D so that C-to-D communication is not expected to interfere A-to-B communication.

An example of reduced exposed terminals in e-RIMA protocol is also depicted in Fig. 3. It may be noted that, reduced power RTS transmission allows some exposed nodes to act as transmitters, however none of the exposed nodes can be a receiver.

The operation of e-RIMA protocol is schematically shown via a timing diagram in Fig. 4. Low-power RTS and full power CTS ensures necessary synchronization between the transmitter and the receiver. Full power CTS also ensures that the prospective interferes of the receiver will stay idle at least for an EIFS period. Afterward, as in b-RIMA, at every end of EIFS interval, full power busy tone from the receiver will ensure that the potential interferers (especially in its carrier sensing zone but outside the receiving zone) do not cause a collision.

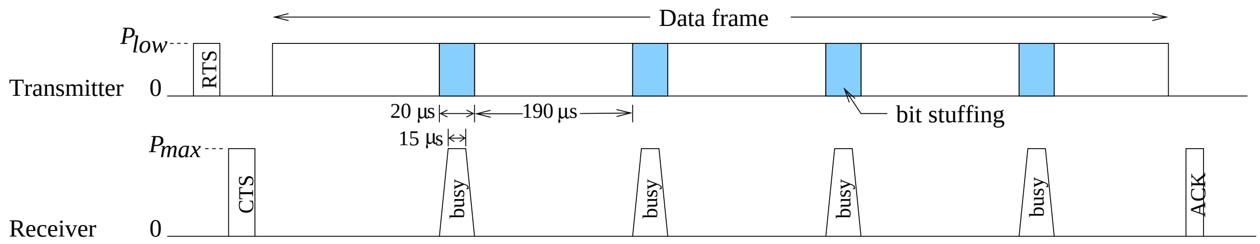


Fig. 4. Operation of e-RIMA protocol. For simplicity, only transmit power levels at the transmitter and the receiver are shown. Besides ensuring continued synchronization in the data reception process, the bit stuffing period can be used intelligently, e.g., for disseminating location information of the transmitter.

## IV. Simulation Studies and Results

### A. Simulation environment

We have conducted preliminary evaluation of the proposed RIMA protocol performance via network simulations using MATLAB. The network consists of 800 nodes, each with unit disc coverage range $R_r = 40$ meter, uniformly random distributed in a location space of size 500 meter square. Frame arrival process in the network is considered Poisson distributed, and the per node arrival rate is varied between 3 frames/s and 7 frames/s to achieve different network traffic load. Frames are of constant size 2kb, and transmission speed of a node is considered 2 Mbps. This environment effectively simulates CSMA (carrier sensing multiple access) Aloha system with an appropriate power control mechanism (PCM, b-RIMA, or e-RIMA). The effect of power control is simulated by considering carrier sensing range $R_c$ that is twice the transmitter-receiver distance. The effect of full power transmission is simulated by considering interference range $R_i = 2R_r$.

When a frame arrives at a transmitter node, it determines if there are ongoing communications in its neighborhood by physical carrier sensing (CS). If the physical CS finds the surrounding idle, depending on the power control protocol, the transmitter exchanges suitable power RTS and CTS messages, i.e., determines its receiver's surrounding. If successful, the appropriate carrier sensing range $R_c$ around the transmitter and the interference range $R_i$ around the receiver is considered busy. In e-RIMA simulation, a potential transmitter in the exposed zone is assumed to know the exact location of the active receiver, based on which it tries find its suitable receiver. In PCM protocol simulation, if a new frame transmission is initiated from the hidden terminals zone, the ongoing as well as new frames collide, and both are considered lost. If at any time a frame is collided or if the channel is found busy during a transmission attempt (i.e., the transmitter is an exposed terminal, and cannot initiate transmission immediately), the frame is backlogged following binary exponential backoff with initial backoff period twice the frame transmission time, i.e., 2 ms. After 4 tries on a frame transmission, it is declared lost. In RIMA, frame delay and loss can happen if the channel is found occasionally busy, and some additional delay can happen due to the added bit stuffing period in a frame. On the other hand, in PCM, frame loss and delay can happen due to hidden terminals as well as if the channel is found occasionally busy.

For a transmitter, a receiver is selected randomly from among its local neighbors. One-hop frame loss rate and average delay per successful frame are considered as performance parameters, where average delay includes the waiting time in queue plus the frame transmission time. Since in e-RIMA an exposed transmitter node attempts to find a suitable closeby receiver to achieve a higher spatial reuse, we anticipate a little shorter distance between a transmitter-receiver pair on average. So, this is considered as a performance tradeoff measure of e-RIMA protocol.

### B. Results and discussion

In Fig. 5 the average frame loss rate is plotted against different network traffic load. The RIMA protocol has clearly

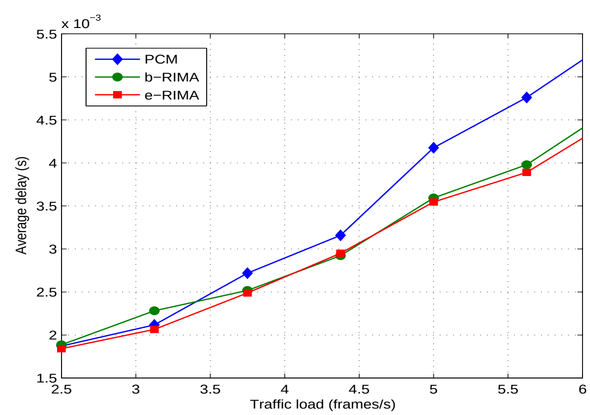


Fig. 5. Frame loss rate performance versus network load.

lower frame loss rate, which is attributed by the existing hidden terminals in PCM, and this problem is aggrevated at higher network load. The effect of reduced exposed terminals is also observed in e-RIMA performance, which is more prominent at higher network traffic. This is because at higher traffic load, probability of finding a potential transmitter within an exposed zone of an ongoing transmission is higher. In b-RIMA (as well as in PCM), such a transmitter has to wait and eventually the frame may be lost after a repeated such waits. On the other hand, in e-RIMA, an exposed terminal transmitter may be able to find a suitable receiver, and thus the frame success rate is expected to to be low.

The average delay before a frame is successfully transmitted is plotted with varying network load in Fig. 6. The PCM performance is the poorest, which is again attributed to the fact that due to hidden terminals frame collitions may happen, and they are backlogged for longer time before some of

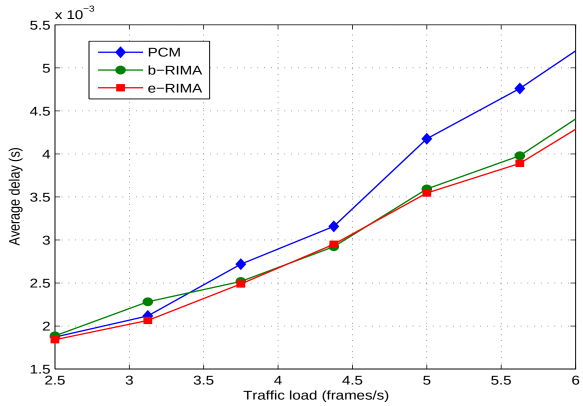


Fig. 6. Average delay of a successfulframe versus network load.

them are successfully transmitted. The e-RIMA performance improvement over b-RIMA is also clearer as the network load increases.

In Fig. 7, the average distance between a transmitter-receiver pair is captired at different traffic load. It may be noted that a reduced distance between a transmitter-receiver pair would have implied that more hops (and hence more energy consumption) would be required to cover a geographic distance. We do not observe any significant reduction in

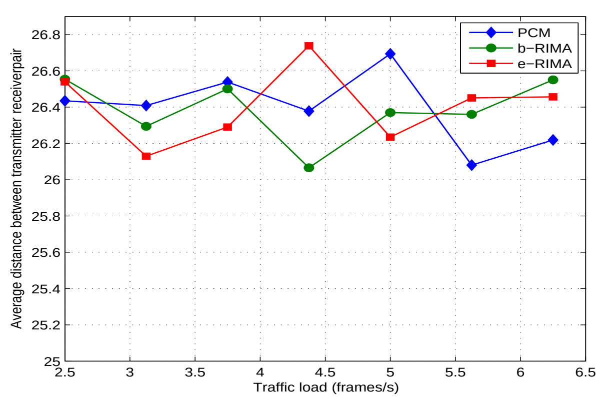


Fig. 7. Average transmitter-receiver geographic distance at different traffic load.

transmitter-receiver distance in e-RIMA, which indicates that the gain in performance in e-RIMA is not at a tangible cost of reduced one-hop distance. Since we have considered random forwarding, varying traffic load does not have any effect on the transmitter-receiver distance.

Overall, although the RIMA protocol needs to stretch the data frame length approximately by 10%, the total average waiting delay of RIMA is quite small and compensates a little longer frame transmission delay.

## V. Conclusion

In this paper, a new receiver initiated distributed power control multi-access (RIMA) protocol has been proposed that works based on conventional single-channel single-transceiver design of ad hoc network nodes. The basic protocol eliminates the exposed terminal problem by stretching a data frame transmission period approximately by 10% and incorporating periodic in-band busy tones from the receiver. An enhanced version of the protocol (e-RIMA) works by reduced power RTS transmission thereby increasing spatial reuse of the wireless channel, and hence reducing the exposed terminal problem. The proposed protocol performance has been compared with a competitive transmitter initiated power control MAC (PCM) protocol. Simulation based performance evaluation has shown that although the RIMA protocol requires a little extra frame transmission time, overall frame loss ratio and average delay per successful frame transmission is significantly better with respect to the PCM protocol.

As a future work, we will conduct theoretical analysis and more rigorous simulations to compute the relative benefits of collision performance, on the degree of reduction in exposed terminals in e-RIMA protocol, as well as on possible reduction in average distance between two communicating nodes in e-RIMA protocol. Also, overall benefit in terms of energy savings needs to be quantified in the proposed approaches.

## References


[1] "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications, IEEE Std 802.11," 1999 Ed. (R2003).

[2] "Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs), IEEE Std 802.15.4," 2003.

[3] S. Agarwal, S. Krishnamurthy, R. H. Katz, and S. K. Dao, "Distributed power control in ad hoc wireless networks," in *Proc. PIMRC*, 2001.

[4] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving transmission power in wireless ad hoc networks," in *Proc. ICNP*, Nov. 2001.

[5] Z. J. Hass and J. Deng, "Dual busy tone multiple access (DBTMA) – a multiple access control scheme for ad hoc networks," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 975–985, Jun 2002.

[6] V. B. J.P. Monks and W.-M. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, Apr. 2001, pp. 219–228.

[7] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," in *Proc. ACM MOBICOM*, Atlanta, GA, Sept. 2002, pp. 36–47.

[8] A. Kamerman and L. Monteban, "WaveLAN-II: A high-performance wireless LAN for the unlicensed band," *Bell Labs Tech. Journal*, vol. 2, pp. 118–133, Summer 1997.

[9] A. Muqattash and M. Krunz, "Power control dual channel (pcdc) medium access protocol for wireless ad hoc networks," in *Proc. IEEE INFOCOM*, San Fransisco, CA, April 2003.

[10] ——, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proc. ACM MOBIHOC*, Roppongi, Japan, May 2004, pp. 210–221.

[11] S.-J. Park and R. Sivakumar, "Load-sensitive transmission power control in wireless ad hoc networks," in *Proc. IEEE GLOBECOM*, Taipei, Taiwan, ROC, Nov. 2002.

[12] M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient transmission and routing protocols for wireless multi-hop networks and spread-spectrum radios," in *Proc. EUROCOMM*, 2000.

[13] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *Proc. ACM MOBICOM*, Rome, Italy, July 2001, pp. 272–286.

[14] F. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part II – The hidden terminal problem in carrier sense multiple-access and the busy-tone solution," *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1417–1433, Dec. 1975.

[15] C. Wu and V. Li, "Receiver-initiated busy-tone multiple access in packet radio networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 17, no. 5, pp. 336–342, Oct./Nov. 1987.

[16] 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 J. Sel. Areas Commun.*, vol. 18, no. 9, pp. 1647–1657, Sept. 2000.