The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)

HYMAC: HYBRID TDMA/FDMA MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS SENSOR NETWORKS

Mastooreh Salajegheh, Hamed Soroush, and Antonis Kalis
Athens Information Technology

ABSTRACT

We describe HyMAC, a new hybrid MAC layer protocol for wireless sensor networks that is, to the best of our knowledge, the first effort to combine the strengths of both TDMA and FDMA schemes in these constrained networks. While allowing the network to operate in an energy-efficient collision-free manner, HyMAC takes advantage of the multiple frequencies provided in the radio component of recent sensor node hardware platforms such as MICAZ, TELOS and FireFly. We show how HyMAC outperforms protocols such as B-MAC, RT-Link and MMSN achieving high throughput and small bounded end-to-end delay suitable for newer types of sensor network applications such as real-time voice streaming.

I. INTRODUCTION

A wireless sensor network is a network made of tiny embedded systems each of which composed of sensors (for light, temperature, etc.), a low-power communication device (radio transceiver), small amount of memory and processing capability as well as limited battery power supply. Traditional WSN applications such as [1] [2] [3] have mostly focused on passive low-duty cycle sensing and monitoring, in-network data reduction and asynchronous operation designed to extend the sensor-net lifetime. However, recently proposed applications of sensor networks in both mission-critical operations and wide-area surveillance like real-time streaming for voice and low-rate video delivery [4] require relatively high bandwidth utilization and throughput as well as bounded end-to-end delay of a few milliseconds. Therefore, design of effective WSN medium access control (MAC) protocols has become a more challenging task given the unique set of resource constraints in these networks which result in very different design trade-offs than those in wireless ad hoc networks.

An important fact to be observed in WSN MAC layer protocol design is that current WSN hardware such as MICAZ [6], Telos [7] and CMU FireFly [5] use CC2420 radio [8] which provides multiple channels. Given the limited radio bandwidth available for sensor nodes (19.2Kbps in MICA2 [9] and 250Kbps in MICAZ and Telos), designing MAC protocols which can exploit the available frequencies to improve parallel transmission and increase the network throughput seems to be an imperative task. The significance of such a design becomes even more clear when we notice that almost all of the purposed solutions for WSN MAC layer such as [10] [11] [12] [13] [14] [15] [16] assume the availability of only one single physical frequency.

Although multi-Frequency MAC protocols have been a topic of intense research in general wireless networks, the purposed protocols are a poor fit for wireless sensor networks due to the restricted sensor-net hardware, its limited bandwidth and the small WSN MAC layer packet size. The single low-power transceiver on the WSN node (mote) is not capable of simultaneous packet transmission and reception or simultaneous operation on different frequencies. Consequently, the protocols [17] [18] [19] [20] which assume a hardware capable of listening to multiple frequencies at the same time or protocols designed for frequency hopping spread spectrum wireless cards such as [21] [22] are not suitable to be used in sensor networks. Furthermore, protocols based on IEEE 802.11 [23] like [24] [25] [26] [27] [28] as well as those that employ RTS/CTS control packets for frequency negotiation such as [29] [30] [31] [21] do not prove efficient in sensor networks due to the noticeable overhead imposed by RTS/CTS packets in these networks which have a small MAC layer and data packet size (about 30 to 50 bytes) comparing to much larger packets in general wireless networks (e.g. 512+ byte MAC layer packet).

In this paper, we introduce HyMAC, abbreviation for Hybrid TDMA/FDMA MAC layer protocol for wireless sensor networks. HyMAC provides high throughput, bounded end-to-end delay across multiple hops, collision free operation and predictable lifetime. Furthermore, our protocol, takes advantage of multiple frequencies provided in recent WSN hardware platforms. The rest of the paper is organized as follows: We briefly discuss several key WSN MAC protocols in section II. The details of our proposed protocol is presented in section III. We provide the performance evaluation of HyMAC in section IV. We conclude with a summery of our findings in Section V.

II. RELATED WORK

In this section we briefly overview the key MAC layer protocols that have been proposed for wireless sensor networks.

S-MAC [11] and T-MAC [13] are hybrid CSMA and TDMA approaches that employ local sleep-wake schedules to coordinate packet exchanges and reduce idle listening. The use of RTS/CTS control packets makes up for the possible failures of the loose synchronization of the schemes. However, these schemes suffer from the high overhead of using the RTS and CTS due to the small size of WSN packets. Furthermore, as the size of the network increases, either increasing number of schedules has to be maintained by each node or additional overhead of repeated resynchronization rounds is imposed to the network. B-MAC [10], the default MAC protocol in TinyOs [9] achieves Low Power Listening (LPL) by having each node periodically wake up after a sample interval and check whether the channel is active for a short duration of time (2.5 ms). In the case of detecting the channel to be active, the node stays awake to receive the payload following an extended preamble. In this scheme, the responsibility of ensuring that the receiver receives

1-4244-0330-8/06/$20.00

the packet is delegated to the transmitter, in that it has to transmit a preamble that is long enough to be sensed by the receiver which only wakes up for a very brief moment and sleeps most of the time. Consequently, use of RTS/CTS packets in this scheme - which are required to avoid collisions due to the hidden terminal problem - is not efficient since the RTS has to use the long preamble. In addition, since the transmitter has to remain active during the receiver's channel check interval, receivers are forced to check the channel very often. As a result, operation of B-MAC in dense networks faces severe difficulties such as scalability issues [5]. LMAC [16] and TRAMA [12] which are TDMA based schemes, assume the availability of global time synchronization considering it an orthogonal problem. LMAC introduces a light-weight schedule reservation scheme used to establish collision-free operation by negotiating non-overlapping slot across all nodes within 2-hop radius. TRAMA provides alternating slots of CSMA-based contention (used for network management and node admission) and scheduled access. Note that while TDMA schemes are known to provide excellent energy-efficiency due to minimization of idle listening, elimination of overhearing and collision-free operation, they have not been considered as practical solutions for sensor networks because of the complications of providing WSN time synchronization and difficulties to address scalability challenges. The authors of RT-Link [5], however, have shown that provision of out-of-band hardware-based global time synchronization for multi-hop wireless sensor networks is economical, convenient and less vulnerable than in-band software-based synchronization schemes such as TPSN [32], RBS [33] and FTSP [34]. Consequently, they have proposed a TDMA MAC scheme for WSN operating on FireFly -a hardware platform which provides such synchronization service. RT-Link assigns the time slots centrally at the base station and similar to TRAMA it supports contention slots employing Slotted-ALOHA rather than CSMA. However, in spite of using CC2420 radio [8] provided in FireFly, RT-Link does not take any advantage of the multiple frequencies provided which could noticeably increase the network throughput and reduce the delay. In fact, to the best of our knowledge, MMSN [36] is the only multi-frequency MAC protocol for sensor networks devised prior to HyMAC. MMSN authors propose four frequency assignment schemes for WSN. The first scheme called *exclusive frequency assignment* guarantees that nodes within two hops are assigned different frequencies but only functions when the number of available frequencies is at least as large as the number of such nodes. Furthermore, the communication overhead in this scheme is relatively high due to several broadcasts. The second scheme, *implicit-consensus* provides the mentioned guarantee with smaller overhead but it assumes that physical frequencies are abundant which is not the case in current real-world WSN platforms. The two other schemes, *even-selection* and *eavesdropping* do not guarantee the assignment of different frequencies to two-hop neighbors and therefore, do not avoid potential conflicts. It is important to note that although MMSN requires time synchronization during media access in order to provide efficient broadcast support, it does not take advantage of the synchronization service to resolve the conflicts and/or improve its scheme.

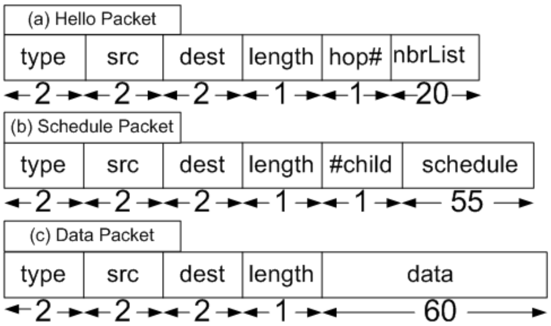


Figure 1: HyMAC Packet Format

III. HyMAC Protocol Design

HyMAC is a hybrid TDMA/FDMA MAC protocol suitable for WSN applications in which data gathered by sensor nodes has to be delivered to at least one base station in a timely manner. HyMAC is designed to provide high throughput and small bounded end-to-end delay for the packets exchanged between each node and the base station. The functionality of HyMAC is independent of its underlying synchronization protocol, however, we believe that it performs best in WSN platforms which employ out-of-band hardware synchronization such as FireFly [5]. While the software-based synchronization protocols such as TPSN, RBS and FTSP provide good accuracy, the diffusion of in-band time sync updates are severely limited due to the usually high link error rate which, according to [35] is over 50% for more than one-third of the population of immobile nodes in an indoor environment; even when the receive signal strength is above the sensitivity threshold. As a result, network performance is reduced when applying these schemes.

In the following, we describe HyMAC packet types as well as its basic operation and scheduling scheme.

A. *HyMAC Operation*

The communication period in HyMAC is a fixed-length TDMA cycle composed of a number of frames. Each frame is equivalently divided into several fixed time slots where a slot duration is the time required to transmit a maximum sized packet. In addition, a fixed number of consecutive slots in each cycle -starting from its beginning- form the *scheduled slots* while the remaining slots of that cycle are its *contention slots*. The base station is responsible to assign an appropriate frequency as well as specific time slot(s) to each node by running an algorithm which will be described later. Such *scheduled node* will be able to communicate in an energy-efficient collision-free manner turning off its radio when it is not necessary. All scheduled nodes employ LPL on contention slots during which they randomly select one slot to send a HELLO message to the base station (using flooding if specific routes are not present). On the other hand, all of the *unscheduled nodes* like the ones which have just joined the network, only operate in contention slots sending the HELLO message in a similar way[1]. If a node hears a HELLO message from any other node in its one-hop distance, it adds the sender to its neighbor list. The updated neighbor list will be included in the next HELLO messages sent by that node. Having received the HELLO messages sent by the nodes, the base station is able to construct the schedule and send it to each node in a SCHEDULE message. Consequently, every node will be able to send DATA messages to its parent using its assigned slot and frequency in a way that maximizes the network throughput and minimizes the overall uplink delay. Figure 1 presents the supported packet types and their format in HyMAC.

B. *Scheduling Algorithm*

As mentioned in the previous section the neighbor lists sent by the nodes is aggregated at the base station allowing it to construct the network connectivity graph. Construction of minimum delay schedules can be reduced to the NP-complete distance-two graph coloring problem and therefore, practical heuristics should be applied [37]. In the following, we describe our heuristic which aims at providing a minimum delay schedule for the network by assigning appropriate time slot(s) and frequencies to the nodes.

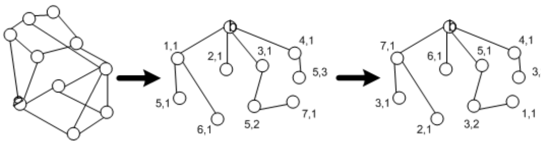


Figure 2: Operation of Scheduling Algorithm. The Numbers Are the Assigned Time Slot and Frequency Respectively.

The algorithm performs a Breath First Search (BFS) constructing a tree having the base node as its root. As each node N_i is traversed by BFS, it is assigned a default time slot and a frequency. Then the possibility of having an interference[2] with any of its same-height previously-visited one-hop AND two-hop neighbors is checked. If a conflicting neighbor N_j is found for N_i, the algorithm checks whether N_i and N_j are siblings. If so, N_i will be assigned a different time slot than that of N_j. If they are not siblings then N_i will be assigned a different frequency than that of N_j, allowing both N_i and N_j to send messages to their parents at the same time slot but in different channels. When BFS is about to start a new level (height) of nodes the default time slot number will be increased by one.

Once all nodes are processed according to the above heuristic, all of the time slot assignments will be inverted such that the slot number assigned to every node is smaller than that of its parent. This inversion is done as following:

$$t_{new} = t_{max} - t_{current} + 1$$

where t_{new} is the new inverted assigned slot, $t_{current}$ is the current slot number assigned to the node and t_{max} is the total number of assigned slots. Note that such an assignment allows the data packets to be aggregated and propagated in a cascading manner to the base station in a single TDMA cycle. The complete steps of the overall process is presented in algorithm 1. Figure 2 shows a sample run of the scheduling on a graph of sensor networks.

Algorithm 1 HyMAC Scheduling Algorithm

```
Require: A Graph of Sensor Network Topology
Ensure: An scheduled Tree of the Given Network
ENQUEUE (Q, S)
while Q is not empty do
  $v \leftarrow$ DEQUEUE(Q)
  $timeSlot[v] \leftarrow currentTimeSlot$
  $channel[v] \leftarrow 1$
  for all Visited same-height 1-2-hop nbr $n$ of $v$ do
    if $parent[n] == parent[v]$ or $\#Channel >= available\_chnls$ then
      if $timeSlot[v] = timeSlot[n]$ then
        $timeSlot[v] \leftarrow timeSlot[n] + 1$
      end if
    else
      if timeSlot[v]=timeSlot[n] and channel[v]=channel[n] then
        $channel[v] \leftarrow channel[n] + 1$
      end if
    end if
  end for
  for all unexplored edge $e$ of v do
    let $w$ be the other unvisited endpoint of edge $e$
    $parent[w] \leftarrow v$
    $height[v] \leftarrow height[w] + 1$
  end for
end while
```

IV. PERFORMANCE EVALUATION

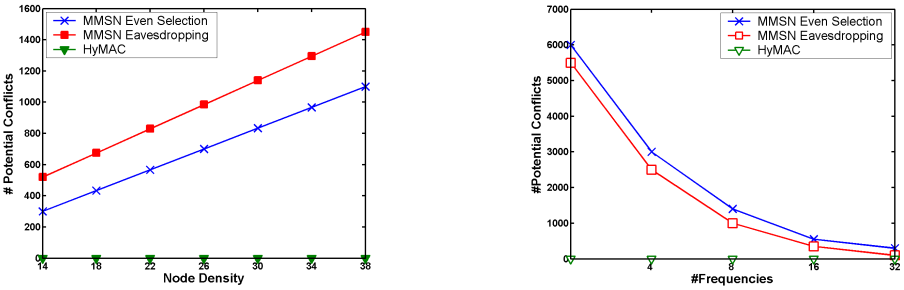
In this section we provide an evaluation of the performance of HyMAC and give a comparison of it with the performance of already proposed MAC protocols for sensor networks.

We use the number of potential conflicts as a performance metric. This number is defined to be the total number of node pairs in the network which satisfy the following condition: if the two nodes are within each other's two communication hops and are assigned the same time slots, they share the same frequency (see MMSN [36] for a similar definition). Since HyMAC operation does not only depend on the number of available frequencies, its performance remains unaffected by a varying number of them. Figures 3(a) and 3(b) show the perfect performance of HyMAC which is interference-free even when there are only 2 frequencies available while MMSN suffers from the communication interference. The cost of this high performance, however, is the increase in the number of required time slots. This is because when a new frequency is needed to

---

[1] The nodes should know the start time of each cycle. Therefore, when using out-of-band hardware time sync, the newly joined node should keep its receiver on until a sync pulse is received. It can then operate in LPL as described.

[2] Obviously, two neighbor nodes cannot communicate at the same time slot and frequency due to interference. Furthermore, if two nodes send messages to the same destination using different frequencies but at the same time slot, the interference still happens.



(a) Number of Potential Conflicts VS. Node Density While the the Number of Frequencies is Fixed at 5

(b) Number of Potential Conflicts VS. Number of Available Frequencies

Figure 3: Comparing HyMAC and MMSN Schemes in Terms of Potential Conflicts

be assigned to a node while the maximum number of available frequencies is already reached, the node is assigned a new time slot instead in order to avoid the potential interferences. Consequently, fewer number of available frequencies results in a larger number of time slots. Figure 4(a) shows the variation of the number of required time slots based on the number of available frequencies for three different node densities. It is important to observe that by employing a higher number of frequencies, a denser network can operate interference-freely without any dramatic increase in the total number of required time slots. In spite of the fact that the increase in the number of needed time slots results in a larger TDMA cycle and therefore a longer end-to-end delay, the worst case performance of HyMAC (where only a single frequency is available) will be the same as that of RT-Link which is shown to be high-quality enough to support real-time streaming for voice over sensor networks [4]. Furthermore, given a fixed cycle length, HyMAC supports denser networks with higher number of nodes -and thus a higher throughput- than RT-Link is potentially able to; thanks to its use of multiple available frequencies. Figure 4(b) compares the total number of assigned time slots by HyMAC and RT-Link protocols when they both operate on FireFly platform which uses CC2420 radio. This radio component provides up to 16 different channels within the 2.4 GHz band in 5MHz steps according to IEEE 802.15.4 specifications.

We have also measured the maximum number of required frequencies for operation in dense networks in order to study the feasibility of HyMAC in practice. Figure 4(c) shows the variations of the number of assigned frequencies based on the changes in the number of nodes of a dense network where each node has 7 neighbors. As it can be observed, the number of needed frequencies is well below the number of provided channels in practical WSN radio components such as CC2420. Even in an extreme case where 900 nodes are presented in the network each of which having 90 neighbors, our simulation results showed that the total number of required frequencies will not be more than 14. In addition, it is important to note that HyMAC is practically adjustable according to the exact number of frequencies that user specifies employing suitable number of time slots.

V. CONCLUSION

In this paper, we propose and study HyMAC, our hybrid TDMA/FDMA MAC protocol for wireless sensor networks. To the best of our knowledge, HyMAC is the first sensor-net MAC protocol that schedules the network nodes in a way that eliminates collisions and provides small bounded end-to-end delay and high throughput while taking advantage of multiple frequencies available in current sensor node hardware platforms such as MICAZ, TELOS and FireFly. Although the functionality of HyMAC does not depend on the type of its underlying synchronization service, we believe that it best performs in presence of a hardware-based out-of-band time synchronization such as FireFly's. The small bounded end-to-end delay and high throughput achieved by HyMAC as well as its energy efficiency due to minimization of idle listening, elimination of overhearing and its collision-free operation make it a more appropriate candidate for the newly emerging sensor network applications such as real-time voice streaming comparing to the previously proposed MAC schemes such as B-MAC, MMSN and RT-Link.

ACKNOWLEDGMENT

The authors would like to thank Professor Raj Rajkumar and Rahul Mangharam of Carnegie Mellon University for lending us CMU FireFly platform and allowing us to use RT-Link in our experiments.

REFERENCES

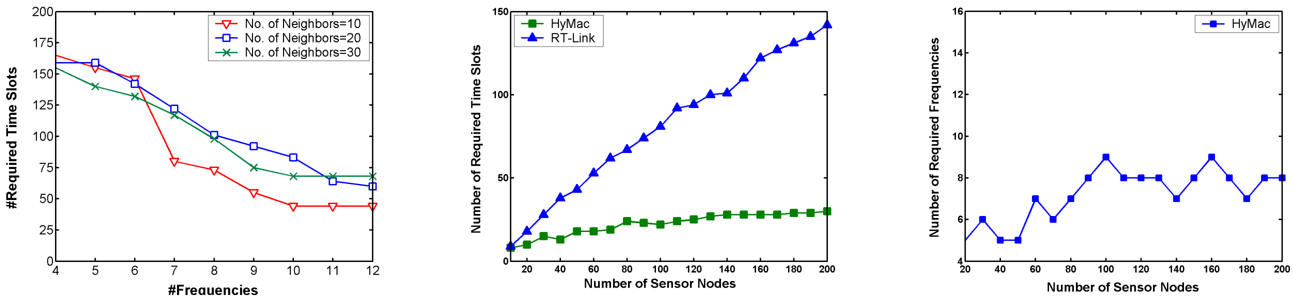
[1] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, "An analysis of a large scale habitat monitoring application," in *ACM SenSys 2004*, November 2004.

[2] N. Xu et. al. "A wireless sensor network for structural monitoring" in *ACMSenSys,* November 2004.

[3] D. Malan, T. Jones, M. Welsh, and S. Moulton, "Codeblue: An ad hoc sensor network infrastructure for emergency medical care," in *ACM MobiSys,* June 2004.

[4] R. Mangharam, A. Rowe and R. Rajkumar, "Voice over Sensor Networks," in *IEEE RTSS*, 2006

[5] A. Rowe, R. Mangharam and R. Rajkumar, "RT-Link: A Time Synchronized Link Protocol for Energy Constrained Multi-hop Wireless Networks,"



(a) Effect of Number of Available Frequencies on the Number of Required Time Slots When the Average Number of Neighbors of each Sensor Node is Fixed.

(b) Comparison of RT-Link and HyMAC Performance in Terms of Required Time Slots. In this experiment, HyMAC Used 11 Different Frequencies.

(c) Required Number of Frequencies VS. Number of Sensor Nodes

Figure 4: HyMAC Performance

[6] "XBOW MICA2 Mote Specifications," http://www.xbow.com.

[7] J. Polastre, R. Szewczyk, and D. Culler, "Telos: Enabling Ultra-Low Power Wireless Research," in *ACM/IEEE IPSN/SPOTS 2005,* April 2005.

[8] "CC2420 2.4 GHz IEEE 802.15.4 / ZigBee - ready RF Transceiver," http://www.chipcon.com.

[9] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, "System Architecture Directions for Networked Sensors," in *The Nineth International Conference on Architectural Support for Programming Languages and Operating Systems,* November 2000, pp. 93104.

[10] J. Polastre, J. Hill, and D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks," in *ACM SenSys 2004,* November 2004.

[11] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," in *IEEE INFOCOM 2002,* June 2002, pp. 1567-1576.

[12] V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks," in *ACM SenSys 2003,* November 2003.

[13] T. Dam and k. Langendoen, "An Adaptive Evergy-Sufficient MAC Protocol for Wireless Sensor Networks," in *ACM SenSys 2003,* November 2003.

[14] A. Woo and D. Culler, "A Transmission Control Scheme for Media Access in Sensor Networks," in *ACM MobiCom 2001,* July 2001.

[15] A. El-Hoiyi, J.-D. Decotignie, and J. Hernandez, "Low Power MAC Protocols for Infrastructure Wireless Sensor Networks," in *The Fifth European Wireless Conference,* February 2004.

[16] L.F.W. van Hoesel and P.J.M. Havinga, "A Lightweight Medium Access Protocol for Wireless Sensor Networks," in *INSS*, 2004

[17] A. Nasipuri, J. Zhuang, and S. R. Das, "A Multichannel CSMA MAC Protocol for Multihop Wireless Networks," in *IEEE WCNC*, September 1999.

[18] S.-L. Wu, C.-Y. Liu, Y.-C. Tseng, and J.-P. Shen, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," in *I-SPAN*, 2000.

[19] A. Nasipuri and S. R. Das, "Multichannel CSMA with Signal Power-based Channel Selection for Multihop Wireless Networks," in *IEEE Vehicular Technology Conference,* September 2000.

[20] M. Caccaco, L. Y. Zhang, L. Sha, and G. Buttazzo, "An Implicit Prioritized Access Protocol for Wireless Sensor Networks," in *IEEE RTSS 2002,* December 2002.

[21] Z. Tang and J.J. Garcia-Luna-Aceves, "Hop-Reservation Multiple Access (HRMA) for Ad-Hoc Networks," in *IEEE INFOCOM 1999,* March 1999.

[22] A. Tyamaloukas and J. J. Garcia-Luna-Aceves, "Channel-Hopping Multiple Access," in *IEEE ICC 2000,* 2000.

[23] "IEEE 802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," 1999, ANSI/IEEE Std. 802.11, 1999.

[24] P. Bahl, R. Chancre, and J. Dungeon, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks," in *ACM MobiCom 2004,* September 2004.

[25] A. Raniwala and T. Chiueh, "Architecture and Algorithm for an IEEE 802.11-Based Multi-Channel Wireless Mesh Network," in *IEEE INFOCOM 2005,* March 2005.

[26] A. Adya, P. Bahl, J. Padhye, A.Wolman, and L. Zhou, "A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks," in *IEEE Broadnets 2004,* 2004.

[27] F. Fitzek, D. Angelini, G. Mazzini, , and M. Zorzi, "Design and Performance of an Enhanced IEEE 802.11 MAC Protocol for Multihop Coverage Extension," in *IEEE Wireless Communications,* 2003.

[28] J. Li, Z. J. Haas, M. Sheng, , and Y. Chen, "Performance Evaluation of Modified IEEE 802.11 MAC for Multi-Channel Multi-Hop Ad Hoc Network," in *IEEE AINA 2003,* 2003.

[29] J. So and N. Vaidya, "Multi-Channel MAC for Ad-Hoc Networks: Handling Multi-Channel Hidden Terminal Using A Single Transceiver," in *ACM MobiHoc 2004,* May 2004.

[30] N. Jain and S. R. Das, "A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks," in *IEEE IC3N,* October 2001.

[31] A. Tzamaloukas and J.J. Garcia-Luna-Aceves, "A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks," in *IEEE INFOCOM 2001,* April 2001.

[32] S. Ganeriwal, R. Kumar, and M. B. Srivastava, "Timing-sync Protocol for Sensor Networks," in *ACM Sensys*, 2003

[33] J. Elson, L. Girod, and D. Estrin, "Fine-grained Networked Time Synchronization Using Reference Broadcast," in *USENIX OSDI*, 2002

[34] M. Maroti, B. Kusy, G. Simon, and A. Ledeczi, "The Flooding Time Synchronization Protocol," in *ACM SenSys*, 2004

[35] J. Zhao, and R. Govindan, "Understanding packet Delivery Performance in Dense Wireless Sensor Networks," in *ACM SenSys*, 2003

[36] G. Zhou, C. Huang, T. Yan, T. He, J.A. Stankovic and T.F. Abdelzaher, "MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks," in *IEEE INFOCOM2006,* 2006.

[37] Hari Balakrishnan et al, "The distance-2 matching problem and its relationship to the mac-layer capacity of ad hoc wireless networks," in *IEEE Journal on Selected Areas in Comm., 22(6):10691079,* August 2004.