2010 International Conference on Communications and Mobile Computing

Reduced Idle Listening based Medium Access Control Protocol for Wireless Sensor Networks

K. Robert Lai
Dept. of Computer Science
and Engineering
Yuan-Ze University
Taoyuan, 32026, Taiwan, R.O.C.

Prasan Kumar Sahoo
Dept. of Information Management
Vanung University
Chungli, 32061, Taiwan, R.O.C.
Email: pksahoo@mail.vnu.edu.tw

Chih-Yung Chang, Cheng-Chang Chen
Dept. of Computer Science
and Information Engineering,
Tamkang University
Taipei, Taiwan, R.O.C.

***Abstract*—In this paper, an energy efficient MAC protocol based on the finite projective plane (FPP) theory is proposed. Our protocol introduces an adaptive energy-efficient duty cycle for the sensor nodes to reduce the idle listening problem. By assigning each node with an FPP-set, we propose to decrease wake-up time and to determine the sleep or wake-up schedules based on the existing number of neighbors of a network coordinator. We have done rigorous simulation to analyze and compare the performance of our MAC protocol with some important and well known MAC protocols of wireless sensor. The simulation results show that our protocol outperforms over other MAC protocols in terms of energy consumption and end-to-end delay.**

I. INTRODUCTION

Medium access decision in a dense wireless sensor network (WSN) of nodes with low duty-cycles is a challenging problem, which must be solved in an energy-efficient manner. The design of MAC protocols [3] is divided into contention-based and reservation-based. In contention-based methods like IEEE 802.11 protocols, the nodes still waste lots of power being idle for a long time. Previous studies [6], [5] show that the idle listening consumes 50˜100 of the energy required for receiving. In the reservation-based schemes, generally sensor nodes are assigned to fixed channels, such as TDMA-based and LEACH [4] protocols. The authors in [6] propose the Sensor-MAC (S-MAC) based on IEEE 802.11 protocol, in which nodes operate at low duty cycle by putting them into periodic sleep instead of idle listening. Although, S-MAC conserves more energy than IEEE 802.11 MAC, the fixed duty cycle causes more latency and cannot sustain the heavy traffic load.

To conserve more wasted waiting energy of S-MAC duty-cycles, authors in [2] improves the idle listening by using variable length of time, and proposes the Timeout-MAC (T-MAC). Though, the burden of selecting appropriate duty-cycle is reduced, the latency in T-MAC increases, as the data arrived during sleep cycle is queued until the next active cycle is started. An adaptive mechanism that determines the sleep and wake-up schedules for a node based on its own traffic and the traffic patterns of its neighbors is proposed in Pattern-MAC (P-MAC) [7]. However, a large control overhead of packets is involved in P-MAC, which reduces the throughput and cost a lot under high traffic load. Though some MAC protocols propose the sleep and wake-up schedules, we feel that those protocols are not efficient enough to adopt the network traffic and to minimize the energy consumption, end-to-end delay, simultaneously. Hence, in this paper, we present the Finite Projective Plane (FPP) [1] based MAC (FPP-MAC) protocol to reduce the energy consumption and latency of the existing traffic load of the wireless sensor network. In our protocol, it is proposed to reduce the idle listening problem based on the FPP and main contributions of our work are summarized as follows.

- Each node in our protocol is assigned an FPP-set, which minimizes the node wake-up time, and thereby reduces the energy consumption.
- By using a combined scheduling and contention based scheme, FPP-MAC achieves the scalability and collision avoidance.
- Based on current traffic condition of a node, the sleep-wakeup schedules are determined and wake-up time of the nodes is decreased.
- The proposed FPP-MAC protocol maximizes the energy conservation and throughput of the system and minimizes the latency of the network traffic.

The rest of the paper is organized as follows. Section II, describes the FPP theory and our proposed FPP-MAC protocol. In Section III, we analyze and compare the energy consumption, end-to-end delay, throughput and fairness issues of our protocols with existing MAC protocols. Performance evaluation of our protocol is demonstrated in Section IV. Concluding remarks are made in Section V of the paper.

II. DESIGN OVERVIEW

In this section, we describe the finite projective planes (FPP) theory and its mapping to design the traffic adoptive MAC for reducing the idle listening and optimizing the energy consumption of wireless sensor networks.

A. Theory of Finite Projective Planes

The finite projective plane theory arranges elements of the universal set $\{1, ..., N\}$ as vertices of a hypergraph, with N

This work is partly supported by the National Science Council of Taiwan, ROC under the grant NSC 98-2221-E-238-010.

978-0-7695-3989-8/10 $26.00 © 2010 IEEE
DOI 10.1109/CMC.2010.339

number of vertices and edges. The definition of FPP could be given as follows:

Define an index set $P = \{1 \le x \le N\}$. $A_x = \{x \mid x \in P\}$ is a subset of P, which is the collection of N sets for the corresponding FPP of N points, where $m^2 + m + 1 = N$, A_x is a line and x is a point. A finite projective plane of order m, with $m > 0$, is a collection of $\left(m^2 + m + 1\right)$ lines and $\left(m^2 + m + 1\right)$ points. The FPP of order two can be depicted as shown in Fig. **??** and the FPP of order m satisfies the following properties:

1) Each A_x set of the FPP has exactly $(m + 1)$ points, where $m^2 + m + 1 = N$. In terms of the index set, $| A_x |= m+1$ for $1 \le x \le N$ in P, where $| Ax |$ is the number of elements in the set A_x.
2) Two distinct lines intersect at exactly one point, $| A_i \cap A_j |= 1$, where $1 \le i, \;\; j \le N$.

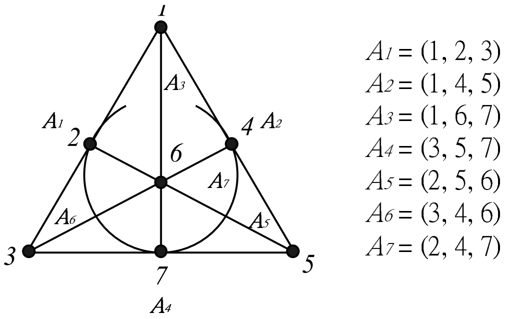
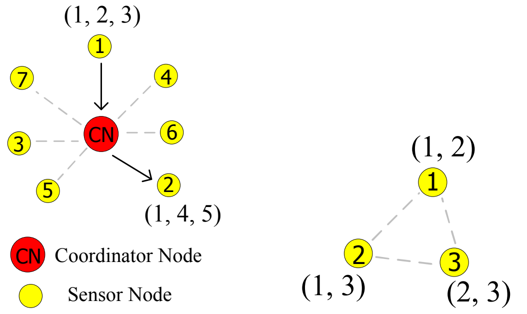


Fig. 1. An example of FPP of order two.

For example, a finite projective plane of seven points has the index set $P = \{1, 2, 3, 4, 5, 6, 7\}$, and collection of sets including $A_1 = (1, 2, 3)$, $A_2 = (1, 4, 5)$, $A_3 = (1, 6, 7)$, $A_4 = (2, 4, 7)$, $A_5 = (3, 4, 6)$, $A_6 = (3, 5, 7)$ and $A_7 = (2, 4, 7)$, as shown in Fig. 1. It is to be noted that the order of the FPP with 7 points is two; i.e. $m = 2$. Similarly, for an FPP with 13 and 21 points, the orders are $(m = 3)$ and $(m = 4)$, respectively. Since, it is difficult to draw the hypergraphs on paper, the nomenclature of set theory is used instead of the pictorial descriptions of the graph theory. However, order 1 to 5 are existing plane for the FPP theory.

B. The FPP-MAC Protocol

Consider a multi-hop wireless sensor network, where the whole network is classified into two types of nodes. They are the coordinator nodes (CN) and sensor nodes (SN). It is assumed that the coordinator nodes are main powered with higher communication range and transmit data from one coordinator to another. Either the coordinator (CN) or sensor (SN) of the WSN follows its own schedules. A CN can be active all the time, which sends or receives packets to or from its neighbors. The SNs are assigned sleep and wake-up slots and each SNs follow those schedules. We assume that each CN has its own neighbor list and number of neighbors associated to it. Our FPP-MAC protocol can be explained in the following subsections.



(a) Connections of SN-CN (b) Connections of SN-SN

Fig. 2. Connections of SN-CN and SN-SN.

TABLE I

NEIGHBOR SELECTION ALGORITHM

```
1. $num\_neighbor$: Number of neighbors of a node;
2. $node\_set$: Assigned set of a node;
3. $m$: Order of FPP, where $m = 1, 2, 3, 4, 5$;
4. $N_m$: Boundary number of neighbors of FPP set,
where $N_m = m^2 + m + 1$;
If ($num\_neighbor < N_1$)
    5. $m \leftarrow l$;
    6. $node\_set$ assigns $(1 + 1)$ points of sets of $N_1$ randomly;
ElseIf ($N_i < num\_neighbor < N_{i+1}$)
    7. $m \leftarrow i$;
    8. $node\_set$ assigns $(m + 1)$ points of sets of $N_i$ randomly;
9. ElseIf ($N_i < num\_neighbor$)
    10. $m \leftarrow 5$
    11. $node\_set$ assigns $(5 + 1)$ points of sets of $N_5$ randomly;
EndIf
```

According to FPP theory, any two different set can intersect with each other exactly at one point, which implies that any two nodes can communicate with each other in the same frame. For example, as shown in Fig. 1, SN1 chooses the set (1, 2, 3) and SN 4 chooses the set (3, 4, 6) of FPP size $N = 7$. If SN1 wants to communicate with SN2, it sends data to CN, which is later transferred to SN2 in time frame 1.

1) FPP based Node Scheduling: Consider a group of SNs that are connected with a CN, as shown in Fig. 2. Initially, all nodes of the network perform the neighbor discovery process. Then, the CN sends a *SYNC* packet to its neighbors, which contains its ID, number of neighbors (*num_neighbor*) attached to it, and the slot scheduling information. Upon receiving this information, each SN chooses its FPP-set based on the $num\_neighbor$. On the other hand, if any SN does not receive the *SYNC* packet, it chooses a num_set of order m from the message broadcast by the CN. The num_set is the selected FPP-set for that group of nodes.

According to finite projective plane theory, an FPP of order m, with $m > 0$ is a collection of $\left(m^2 + m + 1\right)$ points. As shown in Algorithm 1, $num\_neighbor$ is the number of neighbors of a node, N_m is the boundary number of neighbors of FPP set, where $N_m = m^2 + m + 1$. If $num\_neighbor$ is between 3 and 31, it sets different order of N_m. If $num\_neighbor$ is less than 3 or larger than 31, it sets N_1 and N_5, respectively. For example, as shown in Fig. 2, CN has seven SNs and each SN selects a num_set of order

2 randomly. Once the nodes are selected to participate in the FPP based MAC scheduling, they announce it by broadcasting a *SYNC* packet. Upon receiving the *SYNC* packet, other nodes know about the slot scheduling period and goes to the sleep state for that specified period of time.

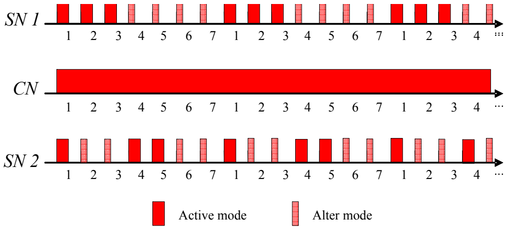


Fig. 3. An example of the proposed protocol.

2) Time Frame Scheduling: After the neighbor nodes of a CN are selected to take part in MAC scheduling, the selected nodes decide their slots based on the FPP theory. Ultimately, each SN has its own sleep and wake-up schedule. Accordingly, they are active at each specified time frames, whereas each CN wakes up all the time. As shown in Fig. 3, there are two types of connection in our protocol, i.e. SN to CN and SN to SN. Each participating SN sends or receives data to or from the CN in its active state and each CN forwards the packets to the destination node, whenever the receiver is awoke. However, if unpredicted channel errors occur during data transmission, the data has to be resent in the next active time frame. Furthermore, if the size of the packet is too big and is not possible to send in the specified time frames, the remaining unsent data is sent to the nodes whenever they wakes up. Besides, we design a short time called *alterTime* to receive the data, which is used to improve the possible end-to-end delay. In the short duration, the node only can be in the receiving mode. An example of the slot scheduling for the control packets and *alterTime* interval in the active mode is shown in Fig. 4. Hence, we propose that the lower limit on the interval *alterTime* = *contenetion windows* + RTS + CTS.

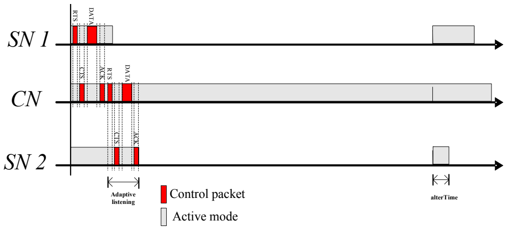


Fig. 4. Slot scheduling for sn to cn.

It is to be noted that any two SNs can communicate with each other in their common time frame, which totally complies with the property of FPP theory. The detail of the time frame scheduling algorithm is given in Table II.

It is to be noted that each node has to estimate the traffic condition and delay for itself after waiting for a random duration. If the traffic load is heavy, the node modifies the number of sets to adapt the current network traffic. The traffic condition that we evaluate is the utilization *U*, which $U = \frac{T_{ts}+T_{rs}}{T_{ts}+T_{rs}+T_{idle}}$. It depends on the ratio of actual communication time over total listen interval. We could modulate the times of wake-up frames in terms of utilization. Then, it has to announce the changing schedule to its neighbors in the next frame.

TABLE II
SLOT SCHEDULING ALGORITHM

```
1. $node\_set$: Assigned set of a node;
2. $frameCounter$ Counter of each frame;
3. $frameCounter \leftarrow 0$
If ($frameCounter$ belongs to $node\_set$)
4. $wakeup()$;
Else
5. $Sleep()$;
EndIf
6. $frameCounter++$;
```

III. ANALYSIS AND COMPARISON

This section analyzes and compares the efficiency of FPP-MAC protocol with several existing schemes as follows.

A. Energy consumption

The energy consumption during idle listening is the primary wastage of energy. Fixed duty-cycle mechanism in S-MAC can avoid nodes of the network being active in all the time. T-MAC uses the adaptive listen interval to strike the unnecessary power loss. However, to wake up every sensor node at each frame is not efficient when the traffic load is light. P-MAC provides a method to modulate the sleep-wakeup schedule dynamically. By exchanging patterns at every wakeup frame, sensor node could decide the actual schedule according to its own traffic condition. As we have mentioned earlier, our FPP-MAC conserves more energy by waking up in fewer time frames, whereas a node has to be active in every time frame in S-MAC. For a period of t units the energy consumption could be estimated as

$$E(t) = N_T(t)E_T + N_R(t)E_R + T_S(t)E_s + T_I(t)E_I \quad (1)$$

where, $N_T(t)$ and $N_R(t)$ denote the number of packets transmitted or received for a period of t units, respectively. E_R and E_T are the amount of energy consumed during the transmission or reception of a packet in period t, respectively. $T_S(t)$ and $T_I(t)$ represent the time in sleep and idle mode, respectively. Furthermore, E_S and E_I stand for the power consumption in sleep and idle mode, respectively. Considering the delays as mentioned in S-MAC for sending or receiving the RTS, CTS, ACK and data packets, energy consumption could be estimated as follows.

$$E_T = P_{tx}(t_{RTS} + t_{data}) + P_{rx}(t_{cs} + t_{CTS} + t_{ACK}) \quad (2)$$

where, P_{tx} and P_{rx} stand for the power consumption in transmission and reception mode of a node. t_{RTS}, t_{CTS},

t_{ACK}, t_{data} are the time spent in sending RTS, CTS, and receiving ACK and data packets, respectively. The energy consumption for receiving a packet can be evaluated as

$$E_R = P_{tx}(t_{CTS} + t_{ACK}) + P_{rx}(t_{RTS} + t_{data}) \quad (3)$$

In FPP-MAC, the frame includes listen frame (T_{Listen}) and alter frame (T_{Alter}). Let p be the probability of a frame being selected in an FPP set, as $\frac{m+1}{m^2+m+1}$. Hence, we can expect the time in idle and sleep mode as follows. As explained here, we can realize that FPP-MAC has longer sleeping period as compared to other MAC protocols.

$$T_I(t) = T_{Listen} \times tp + T_{Alter} \times t(1-p) \quad (4)$$

$$T_S(t) = T_s \times tp + T_{s'} \times t(1-p) \quad (5)$$

where, T_s and $T_{s'}$ are the sleep time of frames with listen and alter apart. The total t frames represent

$$tT_{frame} = T_I(t) + T_S(t) \quad (6)$$

B. Latency

End-to-end delay consists of carrier, backoff, transmission, propagation, processing, queueing and sleep delay. The latency of sleep delay is the unique component in S-MAC, which is incurred due to the periodic sleeping of each sensor. In T-MAC, the latency situation is almost like S-MAC, but the probability of delay is higher, since a node may go to the sleep mode before it receives the data. P-MAC can decide the schedules according to its own and neighbors traffic situation. For FPP-MAC protocol, sender transmits data to the receiver in the preassigned time frames of its neighbors and sleep in other time frames. Therefore, in FPP-MAC, latency is incurred, if a node transmits data when its neighbor is in the sleep mode. However, in order to avoid too much delay, each frame will be active for a short time to receive the possible packets. Thus, there is a tradeoff between energy saving and latency in FPP-MAC.

C. Fairness

S-MAC and T-MAC protocols are slot-based protocols, in which each sensor node has the same schedule. When some large packets have to send, SNs contend free medium at the same time. For P-MAC, sensor nodes follow their own schedule within a STF period and they have to compete the resource, too. But, the competition occurs near the senders only. Sensor nodes do not follow the same schedule. Hence, they have to spend more cost to know other schedules of each other and to calculate what the following schedules are. Based on the cost, sensor nodes in FPP-MAC also follow different schedules, but they do not exchange schedule information all the time. By the property of FPP-MAC, it can reduce the collision probability and most of the time the channel could be error free as the slots are preassigned. Moreover, all the available times frame in FPP-MAC are equally divided among the neighbors of a CN to maintain the fairness. Besides, the neighbors use the channel in a predefined basis and the number of neighbors are selected based on the FPP theory in each round, where fairness is maintained strictly.

IV. PERFORMANCE EVALUATION

Our protocol is simulated using the NS 2.29. We have considered a squared network area of size 100m*100m, where 50 sensor nodes are distributed randomly. The communication range of each node is fixed at 10m. The transmitting power, receiving power, idle power and sleeping power are set to be 2W, 1W, 1W and 0.001W, respectively. It is assumed that each node has initial energy of 1000 Joules. The bandwidth is set to be 20Kbps and each control packet size and data packet size are kept to be 10 bytes and 512 bytes, respectively. The default duty cycle is set to be 10 % same as S-MAC. The transition power is taken 0.2W and transmission time is set to be 0.005 sec. The duty cycle is considered as 10 100 %. The constant bit rate (CBR) type of traffic is considered and $SYNC\_CW$ is taken to be 31 slots. The $DATA\_CW$ is taken to be 63 slots and $SYNC\_PERIOD$ is set to be 10 cycles.

A. With packet inter-arrival rates

As shown in Fig. 5, T-MAC saves more energy than S-MAC as it lets sensors sleep after pre-defined period of idle listening time instead of waiting until the end of listen interval in SMAC. Because of the adjustment of wakeup/sleep schedule according to wakeup/sleep pattern of their neighbors, energy saving in P-MAC is better than T-MAC. However, the schedule adjustment in P-MAC creates the control overhead during active period. Sensor nodes in FPP-MAC can wake up when they have packet to send to their neighbors instead of being active, and thereby saves more energy than others. Hence, energy consumption in FPP-MAC is less than that of P-MAC.

As shown in Fig. 6, the end-to-end delay decreases, when the inter-arrival rate increases. The latency in T-MAC is worse than S-MAC, as the premature elimination of the active time in T-MAC causes longer sleeping interval in S-MAC. On the other hand, P-MAC is better than S-MAC and T-MAC, since it can adjust the wakeup schedule according to their neighbor schedule pattern. Under heavy traffic load, collision will cause packet delay. Therefore, sensor nodes in P-MAC updating their pattern in every wakeup time slot will cause more delay than FPP-MAC. The reason of decreasing differences in P-MAC is the update times minimization when the inter-arrival rate arises.

B. With different duty cycles

Duty cycle means the active ratio of a whole frame time. For example, 10% of duty cycle in a 100-slots frame implies that the active interval will be 10-slots, and sleep interval will be 90-slots. As shown in Fig. 7, if the duty cycle is increased, more energy consumption is wasted. S-MAC and T-MAC have less power saving than P-MAC and FPP-MAC. We can see from the figure that the energy consumption of those methods is very high after about 80% duty cycles, as the active period

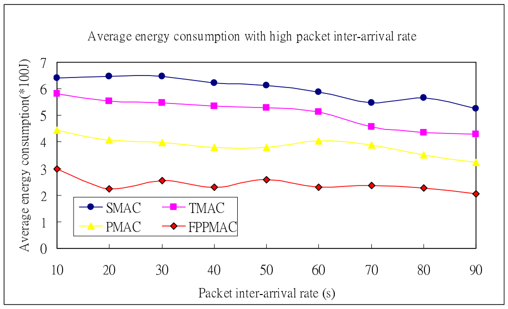


Fig. 5. Average energy consumption with packet inter-arrival rates.

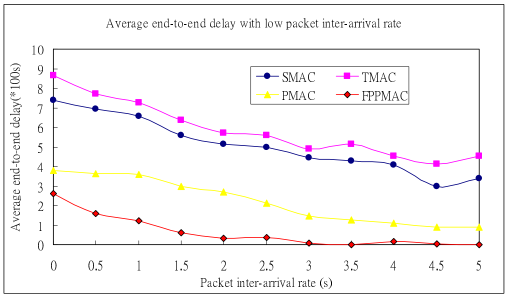


Fig. 6. Average end-to-end delay with packet inter-arrival rates.

is almost same with the wake-up period during the whole frame. It is observed that FPP-MAC outperforms over other protocols as it does not send packets continuously. Besides, energy wastage raises rapidly after the duty cycle achieves to 20% and almost out of power at 80%.

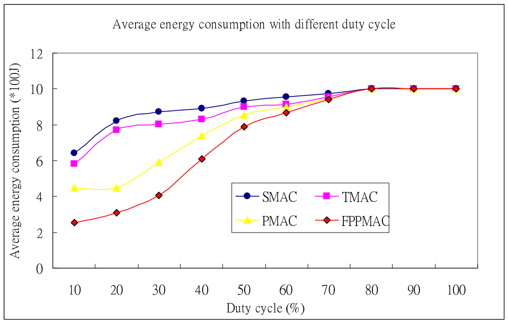


Fig. 7. Average energy consumption with different duty cycle.

C. With different number of neighbors

In our simulation, we vary different topology with different number of neighbors. Neighbor number 5 means the nodes in the network have neighbors not more than five nodes, 10 means each node has neighbor number not more than ten. It is to be noted that the same group of competing nodes for an available time slot may collide over and over when neighbor numbers grow. Nodes have to spend more cost to resend the queued packets. As shown in Fig. 8, if number of neighbors are increased, more amount of energy is consumed. It is observed that P-MAC spends less power than S-MAC and T-MAC. In FPP-MAC, one of the features is the arbitrary pair of sets of points intersects at exactly one point. Hence, any two nodes wake up at one slot frame, which can save more energy. The collision causes more packets delay under heavy traffic loads and more number of neighbors.

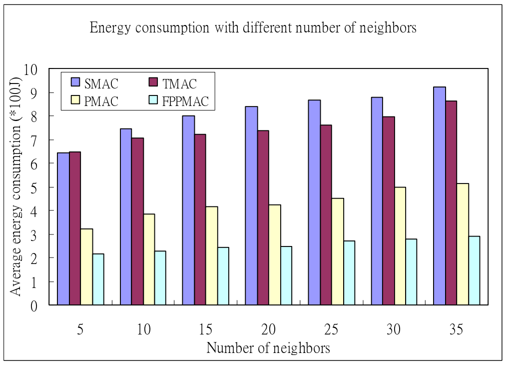


Fig. 8. Average energy consumption with different number of neighbors.

V. CONCLUSIONS

This paper proposes a new MAC protocol, FPP-MAC, which reduces active frames of sensor nodes to conserve energy by using the finite projective plane theory to allocate the wakeup-sleep schedules. The major characteristic of the theory is that any two node can interact with each other at the same frame interval. It can improve the energy wastage and latency due to collision under high-traffic load. Thus, a WSN can have unpredictably various traffic load. Our experimental results show that in comparison with S-MAC, T-MAC and P-MAC, FPP-MAC achieves more power saving under heavy traffic load in WSN.

REFERENCES

[1] A. Albert and R. Sandler, “An Introduction to Finite Projective Planes,” *New York: Holt*, 1968.

[2] Tijs van Dam and Koen Langendoen, “An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks”, *Proceeding of ACM SenSys*, November 2003.

[3] I. Demirkol, C. Ersoy and F. Alagoz, ”MAC protocols for wireless sensor networks: A survey,” *IEEE Communications Magazine*, 44(4), 115-121. 2006.

[4] W. Heinzelman, R. A. Chandrakasan and H. Balakrishnan, ”Energy-efficient communication protocol for wireless microsensor networks,” *IEEE Transactions on Wireless Communications*, 2000.

[5] R. Jurdak, P. Baldiy and C. Videira Lopes, “Adaptive Low Power Listening for Wireless Sensor Networks,” *IEEE Transactions On Mobile Computing*, 2007.

[6] W. Ye, J. Heidemann and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks”, in *IEEE/ACM Transactions on Networking*, Apr. 2004.

[7] T. Zheng, S. Radhakrishnan, and V. Sarangan, ”PMAC: An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks,” *IEEE International Parallel and Distributed Processing Symposium (IDPDS)*, 2005.