A LOW POWER ADAPTIVE MAC PROTOCOL FOR INFRASTRUCTURE WIRELESS LANS

Petros Nicopolitidis, Georgios I.Papadimitriou, T.D.Lagkas and Andreas S.Pomportsis

Department of Informatics, Aristotle University of Thessaloniki
Thessaloniki, Greece, Box 888 54124
e-mail: petros@csd.auth.gr

ABSTRACT: This paper proposes a Low Power Adaptive Polling (LPOAP) MAC protocol for infrastructure Wireless LANs (WLANs) which is capable of operating efficiently under bursty traffic conditions. The protocol utilizes a Learning Automaton at the Access Point of the WLAN. The Automaton utilizes network feedback to select the mobile station that will be granted permission to transmit. We implement a low-power option via specifically utilizing a control packet of the proposed protocol to reduce its energy consumption in medium-to high network loads.

1. INTRODUCTION

Modern WLAN MAC protocols should efficiently handle the bursty traffic that is expected to be generated by WLAN applications (such as client/server and file transfer applications). This paper proposes the LPOAP MAC protocol for infrastructure Wireless LANs. LPOAP, which is based on the LEAP protocol introduced in [1] is capable of operating efficiently under bursty traffic conditions. According to LPOAP, the mobile station that grants permission to transmit is selected by the Access Point (AP) by means of a Learning Automaton. The Learning Automaton takes into account the network feedback information in order to update the choice probability of each mobile station. The network feedback conveys information both on the network traffic pattern and the base-mobile station condition of the wireless links. The learning algorithm asymptotically tends to assign to each station a portion of the bandwidth proportional to the station's needs [1]. Furthermore, the protocol can be used in a low-power mode. Simulation results reveal satisfactory performance for the proposed protocol, as its performance is superior to that of more complex at the hardware level polling MAC protocols for WLANs. Furthermore, the low power mode of LPOAP reduces significantly its energy consumption with reductions up to 60% at high offered loads when compared with LEAP.

2. THE LPOAP PROTOCOL

2.1 Choice probabilities, packet types and power states

According to LPOAP, the Access Point is equipped with a learning automaton which contains the choice probability $P_k(j)$ for each mobile station k under its coordination. Before polling at polling cycle j those probabilities are normalized in the following way:

$$\prod_k (j) = \frac{P_k(j)}{\sum_{i=1}^{N} P_i(j)} \qquad (1)$$

Clearly, $\sum_{i=1}^{N} \prod_i (j) = 1$, where N is the number of mobile stations under the coverage of the Access Point. At the beginning of each polling cycle j, the Access Point polls according to the normalized probabilities $\prod_i (j)$. Each polling cycle consists of a sequence of packet exchanges between the Access Point, the selected mobile and a destination mobile station if a packet is to be transmitted by the selected mobile. The protocol uses four control packets, POLL, NO_DATA, BUFF_DATA and ACK whose duration is t_{POLL}, t_{NO_DATA}, t_{BUFF_DATA} and t_{ACK} respectively.

As far as power consumption at the radio level is concerned, we consider that each station can be at one of the following power states: a) Transmit (TRM) state: A mobile station is in this state if it actively transmits a packet, b) Receive (REC) state: A mobile station is in this state if it received a packet, either with or without bit errors, c) Idle (IDLE) state: A mobile station is in this state if it does not transmit or receive but keeps its transceiver switched on, d) Doze (DOZE) state: A mobile station is in this state when it turns of the electrical circuit of its transceiver.

2.2 Protocol operation

Initially, all mobile stations are in the IDLE state. Assuming that the Access Point polls mobile station k at time position t which marks the beginning of polling cycle j, the propagation delay is t_{PROP_DELAY}, and a

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station's DATA transmission takes t_{DATA} time to complete, the following events are possible:

1. The poll is received at station k at time $t+t_{POLL}+t_{PROP\_DELAY}$. Then:

- If station k does not have a buffered packet, it immediately responds to the Access Point with a NO_DATA packet. If the Access Point correctly receives the NO_DATA packet, it lowers the choice probability of station k and immediately proceeds to poll the next station. This poll is initiated at time $t + t_{POLL} + 2t_{PROP\_DELAY} + t_{NO\_DATA}$. In case of no reception at the Access Point, the choice probability of station k is lowered and the next poll begins at time $t + t_{POLL} + 4t_{PROP\_DELAY} + t_{BUFF\_DATA} + t_{DATA} + t_{ACK}$.
- If station k has a buffered DATA packet, it responds to the Access Point with a BUFF_DATA packet with the address *addr* of the receiver of its DATA packet piggybacked on BUFF_DATA. Every mobile station with address other than *addr* that receive BUFF_DATA will know that there is no reason to retain its radio transceiver on, so it goes to the DOZE state and will return to the IDLE state after the time interval that is needed for the DATA packet to be successfully delivered (a time interval of $t_{DATA} + t_{ACK} + 2t_{PROP\_DELAY}$). Station k transmits the DATA packet to its destination (mobile station with address *addr*) and waits for an acknowledgment (ACK) packet. After the poll, the Access Point monitors the wireless medium for a time interval equal to $t_{BUFF\_DATA} + t_{DATA} + t_{ACK} + 3t_{PROP\_DELAY}$. If it correctly receives one or more of the three packets, it concludes that station k received the poll and has one or more buffered data packets. Thus, it raises station's k choice probability. On the other hand, if the Access Point does not receive feedback, it concludes that it cannot communicate with station k, lowers the choice probability of k and proceeds with the next poll at time $t + t_{POLL} + 4t_{PROP\_DELAY} + t_{BUFF\_DATA} + t_{DATA} + t_{ACK}$.

2. The poll is not received at station k, k does not respond to the Access Point and the choice probability of k is decreased. Then the Access Point proceeds to poll the next station at time $t + t_{POLL} + 4t_{PROP\_DELAY} + t_{BUFF\_DATA} + t_{DATA} + t_{ACK}$.

From the above discussion, it is obvious that the learning algorithm takes into account both the bursty nature of the traffic and the bursty appearance of errors over the wireless medium. Upon conclusion of a polling cycle j, the Access Point uses the following scheme in order to update the selected station's k choice probability:

$$P_k(j+1)=P_k(j)+ L_{LPOAP}\,(1-P_k(j)), \text{ if } FEEDBACK_k(j)=TRANSMIT$$

$$P_k(j+1)=P_k(j)-L_{LPOAP}(P_k(j)-a), \text{ if } FEEDBACK_k(j)=IDLE \text{ or } FEEDBACK_k(j)=FAIL \tag{2}$$

where:

- $FEEDBACK_k(j)=TRANSMIT$ indicates that the Access Point received feedback indicating that station k, upon polled at polling cycle j, transmitted a DATA packet. Thus the Access Point correctly received one or more of the BUFF_DATA, DATA, and possibly ACK, packets exchanged due to k's transmission.
- $FEEDBACK_k(j)=IDLE$ indicates that the Access Point received feedback indicating that station k, upon polled at polling cycle j, did not transmit a DATA packet. This means that the Access Point correctly received the NO_DATA packet transmitted by k.
- $FEEDBACK_k(j)=FAIL$ indicates that the Access Point failed to receive feedback about k's transmission state at cycle j. This is equivalent either to erroneous reception, or to the reception of no packets at all, at the Access Point for polling cycle j.

For all j, it holds that L_{LPOAP}, $a \in (0,1)$ and $P_k(j) \in (a,1)$. Since the offered traffic is of bursty nature, when the Access Point realizes that the selected station had a packet to transmit, it is probable that the selected station will also have packets to transmit in the near future. Thus, its choice probability is increased. On the other hand, if the selected station notifies that it does not have buffered packets, its choice probability is decreased, since it is likely to remain in this state in the near future. In general, the background noise and interference at the Access Point will be the same, if not lower, than that at a mobile station. When the Access Point fails to receive feedback about the selected mobile's state, the latter is probably experiencing a relatively high level of background noise. In other words, it is "hearing" the Access Point over a link with a high BER. Since in wireless communications errors appear in bursts, the link is likely to remain in this state for the near future. Thus the choice probability of the selected station is lowered in order to reduce the chance of futile polls to this station in the near future.

When the choice probability of a station approaches zero, this station is not selected for a long period of time. During this period, it is probable that the station transits from idle to busy state. The same holds for the status of a high-BER link between the mobile station and the Access Point. After a period of time, it is probable that the link's state changes to a low BER one. However, since the

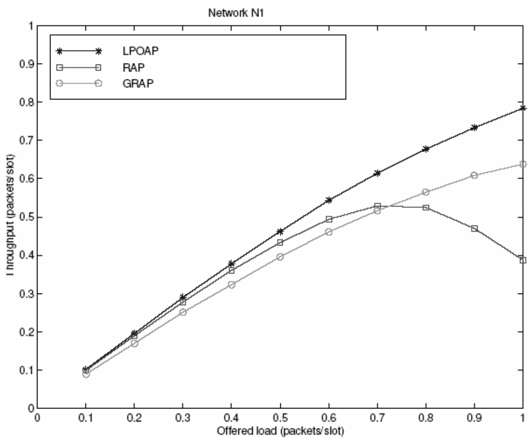

Figure 1. The Throughput versus Offered Load characteristics of LPOAP, RAP and GRAP when applied to network N1.

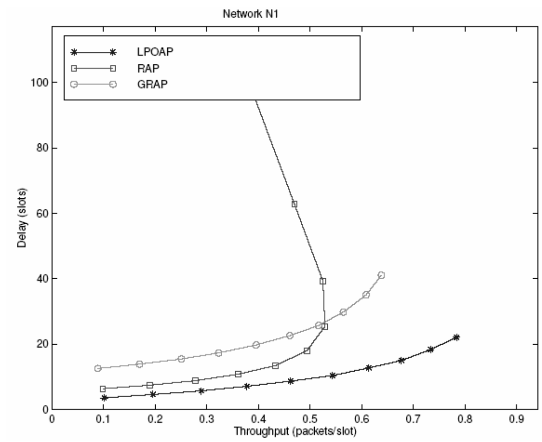

Figure 2. The Delay versus Throughput characteristics of LPOAP, RAP and GRAP when applied to network N1.

mobile station does not grant permission to transmit, the automaton is not capable of "sensing" those transitions. The role of parameter *a*, is to prevent the choice probabilities of stations from taking values in the neighborhood of zero in order to increase the adaptivity of the protocol.

LPOAP updates the choice probabilities of mobile stations according to the network feedback information. The choice probability of each mobile station converges to the probability that this station is ready to transmit, meaning that it has a non-empty queue and it is capable of communicating successfully with the Access Point. For the sake of brevity the proof is omitted.

3. SIMULATION RESULTS

Using simulation, we compared LPOAP against the RAP and GRAP [3, 4, 5] polling protocols for Wireless LANs. Comparison is done under bursty traffic conditions. The bursty traffic was modeled in the following way: We define "time slot" as the time duration required for a DATA packet to be transmitted over the wireless link. Each source station can be in one of two states, S_0 and S_1. When a source station is in state S_0 then it has no packet arrivals. When a source station is in state S_1 then, at each time slot, it has a packet arrival with probability Z. Given a station is in state S_0 at time slot t, the probability that this station will transit to state S_1 at the next time slot is P_{01}. The transition probability from state S_1 to state S_0 is P_{10}. It can be shown that, when the load offered to the network is R packets/slot and the mean burst length is B slots, then the transition probabilities are: $P_{01}=R/(B(NZ-R))$ and $P_{10}=1/B$. Each station uses a buffer to store the arriving packets. The buffer length is assumed to be equal to Q packets. Any packets arriving to find the buffer full are dropped.

In our simulation model, the condition of the wireless link between any two stations (including the base one) was modeled using a finite state machine with two states [2]. Stage G, denotes that the wireless link is in a relatively "clean" condition and is characterized by a small BER, which is given by the parameter *GOOD_BER*. Stage B, denotes that the wireless link is in a condition characterized by a high BER, which is given by the parameter *BAD_BER*. Therefore, for any two stations *A* and *B*, the BER of the link from *A* to *B* and the BER of the link from B to A are the same. The time periods spent by a link in states G and B are exponentially distributed, but with different average values, given by the parameters *TIME_GOOD* and *TIME_BAD* respectively. The status of a link probabilistically changes between the three states. When a link has spent its time in state G and its status is about to change, the link transits to stage B. When a link has spent its time in state B and its status is about to change, the link transits to stage G. Finally, as already mentioned we consider the four power states TRM, REC, IDLE, DOZE with power consumption at each stage being given by parameters POWER_TRM, POWER_REC, POWER_IDLE, POWER_DOZE respectively.

To evaluate the performance of LPOAP against RAP and GRAP [3, 4, 5] we used the delay versus throughput characteristic. Furthermore we made the following assumptions in our simulations:
1. Upon polled, a mobile station can initiate a data packet transmission with any other mobile as its destination. This limits the role of the Access Point to be only the means of executing the polling algorithms and was made to achieve a more generic and fair comparison between LPOAP and RAP, GRAP. 2. We did not account for the effect of a Physical layer preamble. This is a conservative choice for LPOAP as it would slightly increase its

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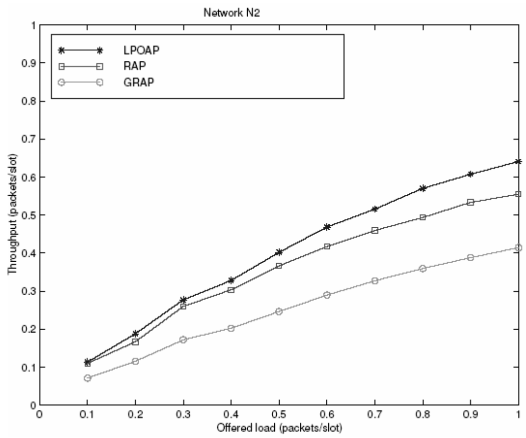

Figure 3. The Throughput versus Offered Load characteristics of LPOAP, RAP and GRAP when applied to network N2.

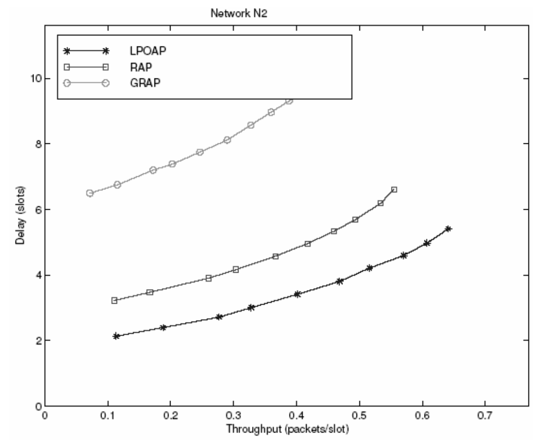

Figure 4. The Delay versus Throughput characteristics of LPOAP, RAP and GRAP when applied to network N2.

superiority over RAP and GRAP due to the higher overhead per DATA packet transmission for RAP-GRAP, as will be explained later.

3. No error correction is used and we did not take into account the packet-capturing phenomenon for RAP and lost. Capturing does not affect LPOAP, since it is collision-free.

4. We did not simulate the power consumption of the RAP and GRAP protocols due to the facts that a) these do not have satisfactory performance for medium to high loads and b) every mobile station must be "awake" in RAP and GRAP as it has no way to know in advance whether it will be or not the intended receiver of the packet transmitted by the polled mobile station. Thus, RAP and GRAP cannot support a DOZE state and therefore cannot provide for power-saving.

We simulated the following network configurations:

- Network N1: N=10, Q=10, B=10, Z=1.0
- Network N2: N=10, Q=3, B=200, Z=0.7

These configurations were simulated for a value of $GOOD\_BER=10^{-10}$ and BAD_BER equal to 10^{-6}. We also set L_{RAP}=2, P_{RAP}=5 [4], *RETRY_LIMIT*=6. The latter sets the maximum number of retransmission attempts per packet. The size of all control packets for the three protocols at the MAC layer is set to 160 bits, the DATA packet size is set to 6400 bits and the overhead for the orthogonal transmission of the random addresses in RAP and GRAP is set to five times the size of the poll packet, as in [4]. The wireless medium bit rate was set to 1Mbps. The propagation delay between any two stations was set to 0.05 msec. Moreover as done in other research in low-power MAC protocols [6], POWER_TRM=1.65W, POWER_REC=1.4W, POWER_IDLE=1.15W, POWER_DOZE=0.045W. As far as the link conditions are concerned, we used *TIME_GOOD*=30 sec and *TIME_BAD*=10 sec.

Figures 1-6 present the simulation results we have obtained. The main conclusions that can be drawn form these Figures are the following:

1. **RAP and GRAP relative performance.** At a first glance it may be surprising that in some cases RAP outperforms GRAP, which is supposed to be more efficient [3]. This can be attributed to the following fact: When the station buffer size Q is close to the mean burst length B, the station is capable of storing in its buffer a large part of the generated burst. Since, due to the protocol's overhead and occurring collisions the time required for the departure of a packet is more than the rate at which packets arrive, the station is likely to remain with a significant number of packets (compared to the mean burst length) in its buffer when it transits from the busy S_1 state to idle S_0. Thus, although in the idle state the station will still compete for medium access with stations entering the busy state for a significant period of time. At high loads, this leads to an increased number of competing stations per polling cycle, and thus collisions, which explains the high- load knee for RAP in Figure 1 and the corresponding excessive delay for RAP in Figure 2. The superframe structure of GRAP divides the competing station into groups, which reduces the collisions at high loads, thus outperforming RAP in these cases. On the other hand, when the buffer size is small compared to the mean burst length, the number of packets that remain in the buffer of a station that transits from busy to idle, is very small compared to the burst that will be generated from stations going to the busy state. Thus, the occurring collisions will be few, a fact that explains the lack of the high-load knee for RAP in Figure 3. In those Figures, RAP outperforms GRAP, since the reduced number of competing stations per

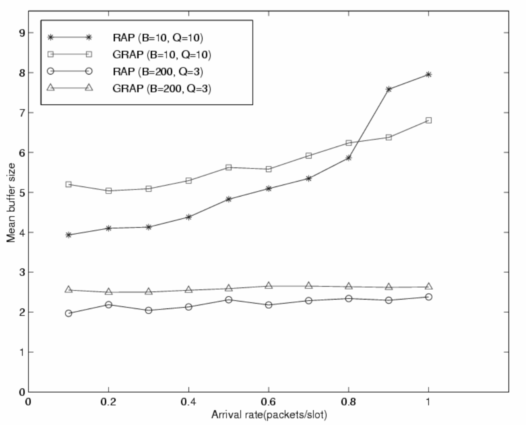

Figure 5. Mean buffer size of stations in transit from busy to idle state

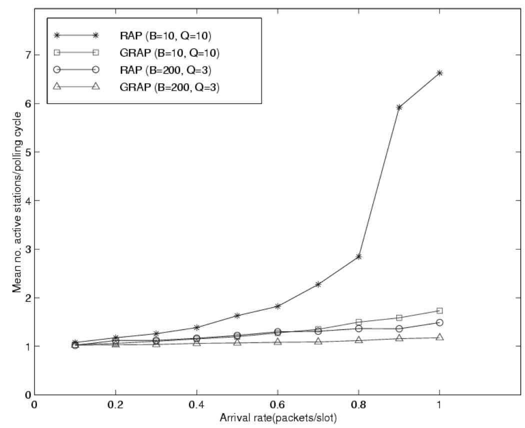

Figure 6. Mean number of competing stations per polling cycle.

polling cycle allows them to be serviced adequately without use of the superframe. The lack of many collisions in RAP in these cases makes the use of the superframe structure in GRAP inefficient due to its additional overhead. This is the reason that the throughput-delay performance of RAP is better than that of GRAP in Figure 4.

These arguments are verified by our simulation results. In Figure 5, we see the mean size of the buffer of a station transiting from the busy state to idle. For the case of B=10, Q=10, this number is comparable to the mean burst length B, whereas for the case of B=200, Q=3, it is insignificant. The respective curves in Figure 6 for RAP show that a buffer size close to the mean burst length leads to an increase in the average number of competing stations per polling cycle at high loads. As this number approaches or exceeds the number of random addresses P, contention increases which results to an increased number of collisions. On the contrary, a buffer size much smaller than the mean burst length leads to an average number of competing stations significantly less than P. In that case, RAP is capable of delivering the offered traffic without many collisions and without the overhead incurred by the superframe in GRAP.

2. **Superiority of LPOAP against RAP and GRAP.** LPOAP outperforms RAP and GRAP in all cases, since it is collision-free and the per-DATA packet transmission overhead of the protocol is less. LPOAP requires an overhead of three control packets per DATA packet (POLL, BUFF_DATA, ACK). RAP and GRAP on the other hand can transmit at most five DATA packets per polling cycle for P=5, assuming no collisions occur, with an overhead of sixteen control packets, for L=1, (READY, orthogonal transmission of random addresses which is equal to five times the duration of a control packet, five POLL packets, five ACK packets) yielding an overhead of 3.2 control packets per DATA packet. However, this scenario seldomly occurs in practice due to the increased number of occurring collisions and the resulting instability of RAP when the number of active station per polling cycle approaches the number of random addresses, P. Moreover, as mentioned before, under heavy bursty traffic conditions the number of active stations per polling cycle is significantly less than P (see Figure 6, for the case of B=200, Q=3), resulting in increased per-DATA packet overhead for RAP and GRAP. The exclusion of the effect of Physical layer preamble in our simulations can be easily seen to favour (although very little) RAP and GRAP. The impact of including its effect in our simulation would be a slightly lower load-throughput characteristic and a slightly higher throughput-delay characteristic. This is due to the fact that the increase in overhead for a data packet transmission would be slightly higher for RAP and GRAP than for LPOAP.

3. **Increased power efficiency of LPOAP.** When LPOAP utilizes the BUFF_DATA control packet to inform mobile stations to go to the DOZE power state its energy efficiency is significantly increased. This can be seen from Figures 7, 8, which plot the average mobile power consumption in Networks N1 and N2 respectively for LPOAP in the normal and low-power modes. It can be seen that the average power consumption is significantly decreased with reductions up to 60% at high offered loads for the low-power version of LPOAP when compared to the normal power mode of LPOAP, which is essentially the LEAP protocol [1]. The power savings of the low-power mode of LPOAP increase for an increasing offered load due to the fact that in such conditions,

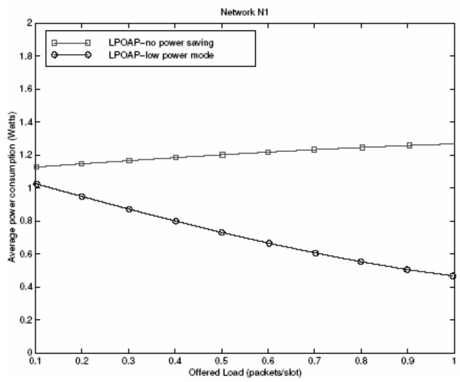

Figure 7. Average mobile power consumption for LPOAP in Network N1.

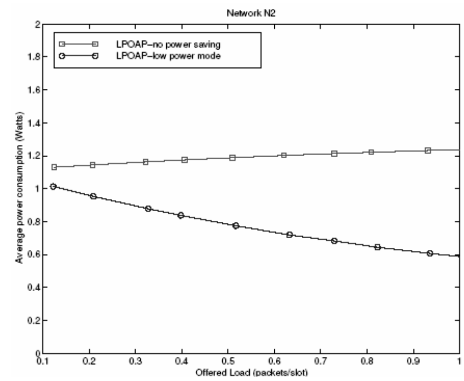

Figure 8. Average mobile power consumption for LPOAP in Network N2.

the learning mechanism almost always polls mobile stations that have buffered DATA packets, a fact that leads the other mobile stations to go to the DOZE state, as explained earlier. On the other hand, in low offered loads polled stations are most of the time idle and thus the other mobile stations do not go to the DOZE state as frequently as they go in high offered loads. Finally, the low-power operation does not impact the performance of LPOAP at all. The results in Figures 1-4 were obtained for the low-power mode of LPOAP and are identical to those that we have obtained for LEAP.

4. CONCLUSION

This paper proposed a Low Power Adaptive Polling (LPOAP) MAC protocol for infrastructure Wireless LANs that is capable of operating efficiently under bursty traffic conditions. The protocol utilizes a Learning Automaton at the Access Point of the WLAN. The Automaton utilizes network feedback to select the mobile station that will be granted permission to transmit. We implement a low-power option via specifically utilizing a control packet of the proposed protocol to reduce its energy consumption in medium-to high network loads. Simulation results reveal satisfactory performance for the proposed protocol, as its performance is superior to that of the more complex at the hardware level RAP and GRAP polling MAC protocols for WLANs. The hardware complexity of these protocols is due to the fact that they require special hardware at the mobile stations and the Access Point for CDMA transmission and reception of the random addresses. On the other hand, LPOAP only requires implementation of the simple learning algorithm at the Access Point. Finally, the low power mode of LPOAP reduces its energy consumption at the mobile stations by as much as 60%.

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