LE-WiMARK: An intelligent power-efficient Ad Hoc MAC protocol with Busy Tone and Power Control

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***Abstract*— Ad hoc networks have been known to be extremely vulnerable to the hidden and exposed terminal problems. To effectively address this problem a power-save MAC layer protocol, Low Energy Wireless Medium Access through Record Keeping(LE-WiMARK), is being proposed, combining the busy tone, the table-driven, power-control and power-save protocols.**

***Keywords*—Ad hoc, MANET, Busy Tone, Power Control, MAC, power save.**

I. INTRODUCTION

The scientific area of ad hoc networking has become a popular subject for research since it provides simple, cost effective and robust solutions to problematic applica-tions of wireless communications. Basic configuration and rapid deployment made ad hoc networks convenient for emergency situations like natural disasters, military conflicts, critical medical situations etc. However, nowadays the role of ad hoc networking has expanded from emergency only situations to essential parts of every day routine. Typical examples are the use of Bluetooth™ enabled phones to exchange Personal Information Manager(PIM) cards or data files; also the MIT media lab 100$ laptop project, which aims to produce inexpensive laptops for developing countries which use ad-hoc wireless mesh networking to connect to the Internet; and finally the use of Vehicular ad-hoc networks or VANETs for communication among vehicles and between vehicles and roadside equipment for safety reasons.

In ad hoc networks, the arbitrary topology that is formed and the absence of a central administrating station increase the number of hidden and exposed terminals and thus contribute greatly to the degeneracy of performance. A hidden-terminal situation occurs, as shown in Fig.1, when node H tries to transmit, while node R receives from node S. As we can see H is unaware of S's transmission because it is outside of its range. Therefore, it cannot detect it and consequently destroys both transmissions.

On the contrary an exposed terminal is a terminal that can detect an ongoing transmission and mistakenly defers from transmitting itself to a node outside the receiver's range. In Fig.2 node E is exposed to node S's transmission and does not transmit to node A although such a transmission could be

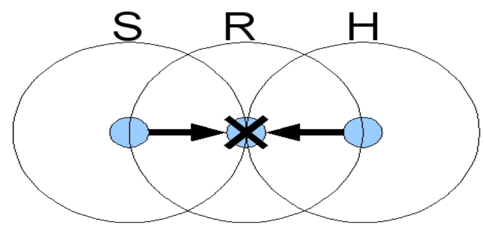

Figure 1. Hidden Terminal Problem.

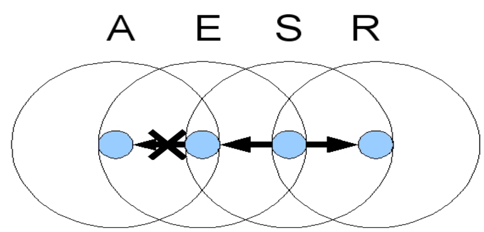

Figure 2. Exposed Terminal Problem.

successfully received without interrupting node R's reception. From the above discussion it is clear that an effective MAC protocol would be one solving both of the problems mentioned above. In other words, a protocol that prohibits hidden terminals from transmitting while permitting exposed terminals to transmit. The Power Control scheme inserts a third parameter in the above definition. A hidden node should be allowed to transmit on the condition that its intended receiver is closer than the current receiving neighbouring node and that it transmits at a power level that will not disrupt such ongoing receptions.

In this paper we suggest the Low Energy Wireless Medium Access through Record Keeping (LE-WiMARK) protocol. In LE-WiMARK nodes periodically transmit a Status Message (SM) containing information about their current status, indicating whether a node is idle, transmitting or receiving and to/from whom. Nodes that receive an SM store the containing information into a local matrix. The received power of the SM is also stored and it is used as an indication of the power level that is required in order for a transmission to successfully reach the corresponding station. Based on the knowledge of the surrounding area derived from the matrix, nodes are able to take the best possible decision on initiating a connection with a neighbouring node, whether that is to transmit or to receive. A Status Message is considered to be critical if it broadcasts a change from IDLE to RECEIVING_DATA state. Critical SMs are protected by a busy tone, since it is obvious that a failure to pass on this information to the neighbouring nodes will definitely result in a plethora of collisions. The peers that participate in the network try to broadcast their DATA packets with the minimum possible power needed to be correctly received and thus acquiring the smallest possible area. The desired power level is calculated based on the received power of the latest transmitted SM of the target node, if the later was transmitted in maximum power.

The rest of the paper is organized as follows: In sections II, III and IV we present the operational rules of the LE-WiMARK protocol. Section V provides the simulation results, illustrating the performance of LE-WiMARK. Finally the concluding remarks are presented in section VI.

II. THE LE-WIMARK PROTOCOL

The key feature in LE-WiMARK is the use of an internal matrix in order to "map" the surrounding area and obtain and maintain a 1-hop neighbourhood knowledge. To the best of our knowledge, this concept has never been used in ad-hoc networking, primarily due to the lack of a central access point (which is often the most suitable place to store a database) and also due to the large overhead that the exchange of DB's tables would create. In LE-WiMARK we use a combination of simple control messages and a busy tone to achieve maximum exploitation of the provided bandwidth with the minimum possible overhead. Each node in LE-WiMARK utilises a periodically updated internal matrix that stores the current status of all the neighbouring nodes (i.e. nodes that are in range). This internal matrix, which from now on we will refer to it as Table, is used in order to decide whether it should pursue or agree with the establishment of a connection with another node. Having full knowledge of its vicinity, a node can take the best possible decision regarding the current topology of the network, a task that is generally very challenging in ad-hoc networks. Each node in LE-WiMARK transmits a special control message called *Status Message* (SM). A typical SM consists of the following information:

- A preamble stating whether this SM is critical or not.
- The MAC address of the transmitting node.
- The MAC address of the node that the current node transmits to (if any).
- The MAC address of the node that current node receives from (if any).
- A flag indicating whether this SM was transmitted in full power or not.

If a node does not transmit or receive, it broadcasts a null SM, meaning an SM containing only its MAC address. A record that derives from receiving a null SM is called a Neighbour Record (NR) because it is used only to notify of a node's existence, whereas a record created by the reception of a normal SM is called a Status Record (SR), because it also notifies of the current status of node (idle, transmitting, receiving etc.). When a node receives an SM it stores the containing information in its Table along with the signal strength that it was received at. The signal strength allows a node to determine the minimum power level that an imminent future transmission must have in order to successfully reach this node and it plays an important role in the decision making process, as explained in the next section. It must be noted here that if the flag of the SM states that it was not transmitted in full power, the power level that it was received at is not stored, because it is not indicative of the relative distance.

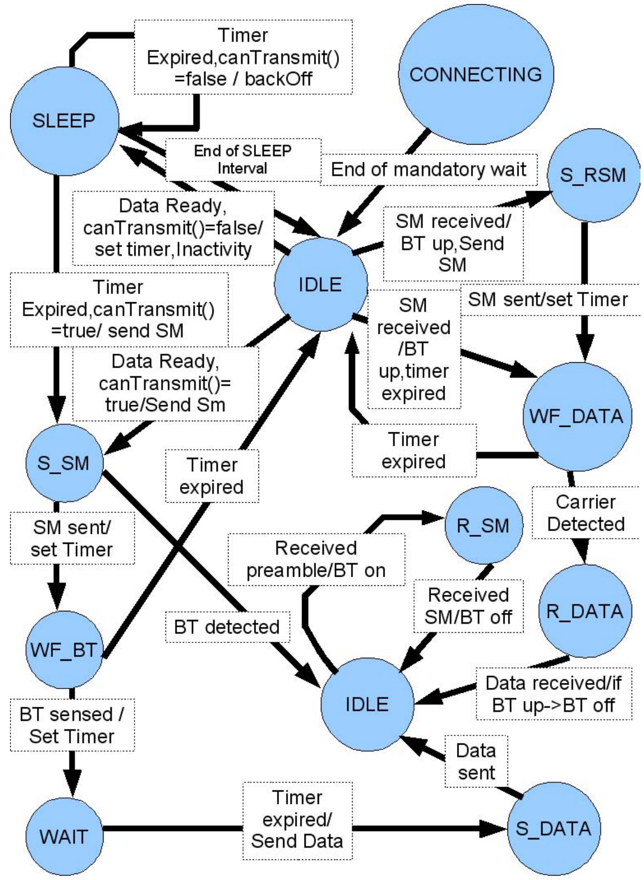

Figure 3. Finite State Machine of LE-WiMARK.

A node implementing the LE-WiMARK protocol can be in one of the following eleven states: CONNECTING, IDLE, CONTEND, S_SM, S_RSM, S_DATA, R_SM, R_DATA, WF_BT, WF_DATA, and WAIT. Fig.5 depicts the Finite State Machine (FSM) of the LE-WiMARK scheme. When a node is activated, it enters the CONNECTING state, during which it is forced to abstain from transmitting for a specific amount of time and to listen for incoming SMs; thus it familiarises itself with its neighbours and their signal strengths. Later on, the node transmits its own SM notifying all peers within range, of its existence. Every record in a node's Table is valid for a specific time interval after which it either resets (explained later) or is deleted. If a node does not transmit an SM for a relatively long period of time (Time for Neighbour Record Expiration – T_{NRE}) its record is deleted from the Table and the node is considered to be no longer present in the network. This is a way to save valuable space in a node's Table by storing only the active nodes. A node in the IDLE state waits for the arrival of a packet in its buffer while an internal counter counts the time since the last SM transmission. There are two conditions under which a node leaves the IDLE state. The first occurs when a packet arrives at the MAC layer for transmission. The second takes place when $T_{LSM} = T_{NRE}/2$, where T_{LSM} is the time that has passed since the last SM transmission. At that point the node tries to transmit a null SM (according to a specific Decision Making Algorithm – DMA, explained in detail in section IV) in order not to be deleted from its neighbouring Tables. If it succeeds, it enters the Sending SM or S_SM state, otherwise it enters the CONTEND state and sets a timer (equal to SM transmission duration - Δ_{SM}). T_{LSM} value has been chosen to be a lot smaller than T_{NRE}, because a node must be given enough time to transmit a null SM, taking into consideration that the aggregate network load could be high. For enhanced comprehension the rest functionality of the LE-WiMARK protocol is examined under the scope of a transmitting, a receiving and neighbouring node's point of view.

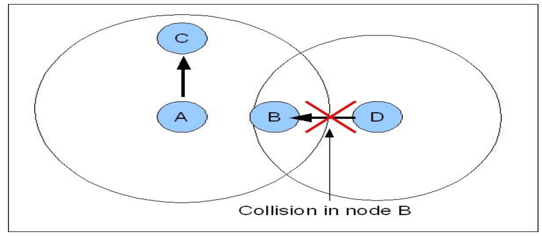

Figure 4a

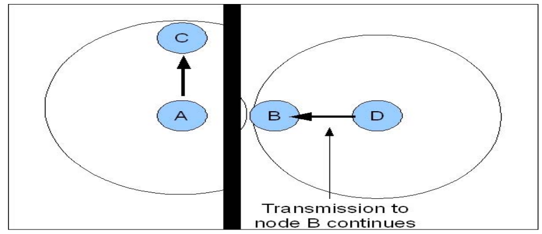

Figure 4b

A. Transmitting Node:

A node initiates the transmission process when a packet arrives at the MAC sublayer. If the sending node is permitted to transmit (according to DMA) it enters the S_SM state, otherwise it enters the CONTEND state and sets a timer (equal to Δ_{SM}). Upon time-out in the CONTEND phase the sender runs the DMA algorithm again. If the outcome is positive the sender enters the S_SM state, otherwise it sets up a timer according to a certain back off algorithm and tries again when the timer expires. When the sender finishes the transmission of the SM it sets up a timer (equal to $r + t_d$, where r equals the maximum one-way propagation delay and t_d is the busy tone detection time) and goes into the Wait For Busy Tone state or WF_BT. If it detects a BT before the timer expiration the node goes into the WAIT state and stays there for time equal to $\Delta_{SM} + r + t_d$ before it goes into the Sending Data state or S_DATA. Otherwise, it withdraws and returns to the IDLE state. The power level of the transmission is calculated according to the power that, the last SM from the destination node, was received at. If during the WAIT period the sender received a responding SM then it is certain that the receiver will definitely receive the data packet. That is due to the mechanism used by a receiving station as to force all its neighbouring nodes to receive a replying SM (explained in detail in *B* and *C*). Hence the response SM plays the part of an ACK message on behalf of the receiving node thus letting the sender remove the acknowledged data packet from its buffer, when it has finished transmitting it. If the receiver responds only with a BT and doesn't send a responding SM, a different strategy is used in order to acknowledge the packet. Upon completion of data transmission the sender keeps monitoring the BT pulse. If BT stays alive for at least a time interval equal to data acknowledgement duration (Δ_{ACK}) then the packet is acknowledged. If not, the packet stays in buffer for a future retransmission.

B. Receiving Node:

On the receiver's side, when a node receives an SM destined for it, it checks with the DMA if it should proceed or not with the connection. If the node is permitted to receive, it responds to the sender and enters the Sending Reply SM state or S_RSM. If not, it stays in IDLE state and resets the record, meaning that it keeps the NR of the sender but nullifies the rest of the record as if the node that it refers to was idle. There are two ways to respond to an invitation to receive a data packet. Either by turning on a BT and transmitting an SM or by just turning on a BT. The latter would happen if, for example, a nearby node is currently receiving and its reception should not be interrupted by the reply SM. After having sent the reply SM or after Δ_{SM} (in the second scenario), the receiver enters the Waiting For Data or WF_DATA state. If it had previously replied with an SM it turns its BT off. Otherwise it keeps on transmitting its BT until the end of the reception plus Δ_{ACK} if the packet was received correctly, thus constantly protecting and acknowledging the incoming data packet.

C. Neighbouring Node:

When a BT's sensed nodes are prohibited to transmit an SM, or when they should already be in the S_SM state, they must abort transmission immediately and enter the IDLE state. After (and if) the preamble of a reply SM has been successfully received, the node automatically goes into Receive SM or R_SM state and turns on its BT for time equal to Δ_{SM} before it returns back to the IDLE state. Reasons for activating the BT are obvious. It is extremely important for all the nodes in the receiver's vicinity to receive the reply SM, because if a node fails to receive it, its Table would not be accurate, thus resulting in data collisions. By forcing all neighbouring nodes to turn on their BT we ensure that all nodes within a two hop range from the receiving station will not interfere with the reception of the reply SM. It must also be noted here that in the latter case the BT stays on for a very small amount of time (roughly Δ_{SM}), which produces minimum impact to the network performance in comparison with the gain that derives from it. When a node receives an SM it inserts the record into its Table and sets a Time To Live (TTL) value referring to that record. For an SM stating the beginning of a transmission (one that was received by a sender) the TTL is equal to $\Delta_{SM} + \Delta_{DATA} + t_d + 2r$, whereas for a reply SM, TTL is equal to $\Delta_{DATA} + r$,

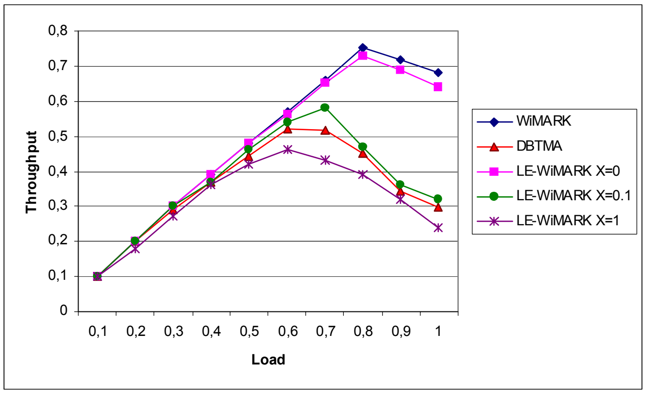

Figure 5. The throughput versus offered load simulation results for LE-WiMARK, WiMARK and DBTMA.

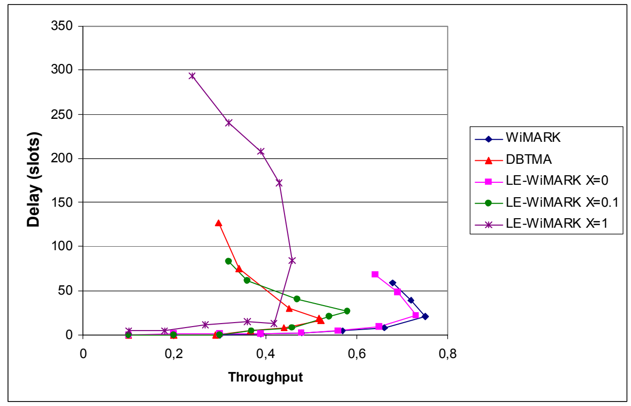

Figure 6. The delay versus throughput simulation results for LE-WiMARK, WiMARK and DBTMA.

where Δ_{DATA} equals data packet transmission time. After a record has expired, the node resets it. Setting a valid period for every record of the Table helps reduce, by a considerable amount, the number of SMs that the nodes need to exchange in order to keep their records up-to-date, thus lifting the main disadvantage of maintaining an accurate internal matrix.

III. Power Conservation

A lot of research nowadays addresses energy preservation issues. According to [5] and [7] essential reduction in dissipated energy is achieved only by entering a SLEEP mode of operation, and not by maximizing a node's stay in the IDLE mode, as power consumption in IDLE mode is reduced by less than a factor of two, in comparison to Transmitting and Receiving modes. In LE-WiMARK power conservation is a three-fold process. Firstly, nodes use power control in every data packet transmission, thus reducing by a significant factor the amount of energy consumed. Secondly, a mechanism similar to [3] is being used, meaning a node in LE-WiMARK turns itself off if a neighbour is transmitting and it has no packets waiting for transmission, or if it has a packet to transmit, but a receiving neighbour is inside the imminent transmission's interference range (i.e. a node goes to SLEEP instead of contending). Finally, a special mode of operation exists in LE-WiMARK, called Very Conservative Mode (VCM). A node operating under VCM, broadcasts critical SMs denoting that it will enter the SLEEP mode for X seconds, after a period of inactivity(typically between 1 to 5 Δ_{DATA} intervals). When a node wakes up, all currently receiving neighbouring nodes(that now know that the node has awaken) will turn their BTs on, in order to warn for a possible interference. X depends on application specific demands, and its optimum value is discussed in the next section. The first two approaches result in energy preservation with negligible or no performance degradation, and are most effective in networks with high density and traffic load. The third approach is a trade-off between performance and energy-efficiency and is better utilized in low traffic applications, as proved in V.

IV. The Decision Making Algorithm

All nodes in LE-WiMARK perform certain checks to evaluate whether the current condition of the network allows them to initiate a transmission or agree to an incoming one.

When a node has a packet to transmit it commits a series of checks. To initiate a transmission a node needs to examine the consistency of its map. In order to do that the node listens for a busy tone for duration equal to t_d. If none is detected then it knows that no neighbour is initiating a reception and so its Table is up-to-date. If it detects one it abstains from transmission for Δ_{SM}. To check the status of the destination, the node consults its Table. If the target-node is not idle, the node waits for time equal to the record's TTL before it tries again. If it is idle, the node proceeds to scanning its Table to see if a node in its vicinity is receiving. If none is receiving, it goes immediately into S_SM state. Otherwise it performs a calculation to check whether a transmission can take place without interrupting that node's reception. This is accomplished by comparing the power level of the last received SM from both stations. In LE-WiMARK the power level is not used to indicate the relative distance between two nodes, since this would directly imply the adoption of the free space propagation, but whether an imminent transmission will interfere with a third node's reception or not. The stronger the power level, the shorter or less obstructed is the way towards a node, thus needing a smaller power output to reach it and interfere with its reception. For example let us assume that nodes A, B and C are in the same area and each one is visible to the other. If P_{RX_B} is the power level of B's last SM reception, P_{RX_C} is the power level of C's last SM reception (both at node A), and $P_{RX\_C}>P_{RX\_B}$ then node A is able to transmit to C by adjusting its transmission power level to an appropriate value, regardless of node B's status(IDLE or RECEIVING).

Data Channel Rate	1 Mbps
SM/RTS Packet size	200 bits
Data Packet size	4096
Maximum Range	35m
Area size	$50x50m^2$
Number of Nodes	20
Max one way Propagation Delay	0,12μs
Busy Tone Detection Delay	10^{-4}s
Duration(real time)	100s

TABLE I. Simulation Parameters

To analyse this further, consider the paradigm depicted in Fig.4a (Note: all the following units are expressed in decibel-Watts-dBW). In this example node B is closer to node A than C

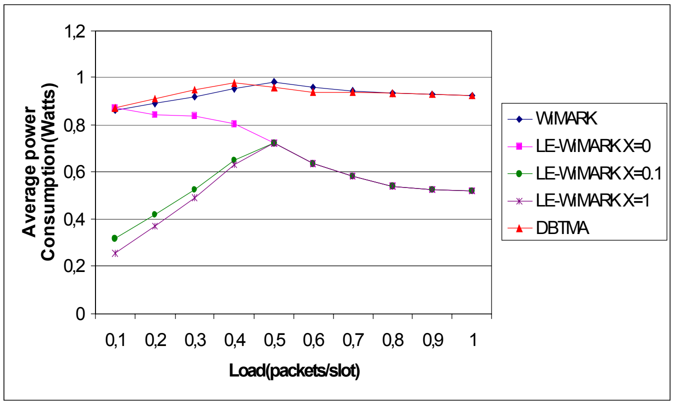

Figure 7. Average mobile power consumption for LE-WiMARK.WiMARK and DBTMA.

and no obstacles exist between any of the nodes. This results in node A receiving B's SM at a higher power level than C's ($P_{RX\_B}>P_{RX\_C}$). If node B is receiving, then node A cannot, under any circumstances, transmit to node C, even with the use of power control, because A's transmission signal is bound to reach, and destroy B's reception. In Fig.4b node B is again closer to node A than node C but the received signal strength of B's SM is dramatically reduced by an obstacle illustrated as a black rectangle, whereas C's is not, and therefore, C's SM reaches A at a much higher power level($P_{RX\_C}>P_{RX\_B}$). In the latter case, even if B is receiving, it is possible for node A to transmit a data packet to node C by adjusting its transmission to an appropriate power level. Suppose that P_{RX_B} is the power level of B's last SM reception, and P_{RX_C} is the power level of C's last SM reception, both at node A. From the above it is clear that $P_{RX\_C}>P_{RX\_B}$. If $P_{THRESHOLD}$ is the minimum power level that is needed to correctly receive a packet and P_{MAX} is the maximum reception power (i.e. when distance is zero) then $P_{TX\_N} = P_{THRESHOLD} + (P_{MAX}-P_{RX\_N})$ where P_{TX_N} is the power that will be used to transmit to a node N. Since $P_{RX\_C}>P_{RX\_B}$ then from the previous equation we have $P_{TX\_C} < P_{TX\_B}$, and therefore a transmission aimed to node C will not disrupt a possible reception by node B. From the above it is clear that, by storing valuable information for each neighbouring node, LE-WiMARK takes full use of the power control scheme, an ability that significantly increases the overall throughput of the network. A node that wishes to receive a packet must examine whether it can reply to the sender with an SM or just with a BT. In order to do this it listens firstly for a BT. If a BT is indeed detected, the node replies only by turning its BT on, because either a node is transmitting a reply SM or a reception is in progress. By doing so, the node is able to commence a packet reception, even though an SM cannot be sent, since control and data packets share the same channel.

V. SIMULATION RESULTS

In order to measure the performance of LE-WiMARK we coded our own simulator in Java. For comparative reasons, the tests were held against the DBTMA[2] and the WiMARK[1] scheme. WiMARK is the non energy-efficient version of LE-WiMARK, and is oriented in high performance, rather than power saving. DBTMA and LE-WiMARK resemble in the fact that they both broadcast the current condition of the nodes; DBTMA continuously with BTs and LE-WiMARK once with the use of short SMs. For this simulation, which is depicted in Figures 5, 6 and 7, the number of nodes was kept stable while the offered load of the network was gradually increased (for a full list of the simulation's parameters consult Table 1). In order to determine the most suitable SLEEP interval duration, three different X values where tested: 0(no SLEEP intervals), 100ms and 1 second. Throughput was measured as the packets that were correctly delivered per time slot, where time slot equals Δ_{DATA}. In terms of performance, Figures 5 and 6 show clearly that LE-WiMARK maintains a high throughput/load ratio, while delay/load ratio is kept in very low numbers for a power-saving protocol. When utilising the VCM, we observe that although performance drops, for small X values throughput/load ratio is kept in very acceptable values, while, as X grows performance drops significantly. In terms of power conservation LE-WiMARK manages a high reduction in its average power consumption, which can be as high as 60%, compared to WiMARK or DBTMA, as depicted in Fig.7.

VI. CONCLUSIONS

LE-WiMARK offers a hybrid and novel approach, by combining a busy tone, power control, and power efficiency techniques with an internal matrix that keeps records of all the transactions that take place in a station's vicinity. This feature results in a significant increase of channel utilization, because knowledge obtained through their Tables in conjunction with power control and the Decision Making Algorithm, allows nodes to take advantage of even the smallest available Moreover the use of a three-fold power saving mechanism results in great power gains, in both heavy traffic and quiescent networks. This is a unique characteristic of LE-WiMARK, as most power efficient protocols perform well in one situation or another but not in both.

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