Efficient Medium Access Control and its Effect on Power Consumption in Ad Hoc Networks

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ABSTRACT

To date the most popular techniques for power consumption reduction in ad hoc networks have been: power control, power-aware routing and power efficient medium access control (MAC). We show that the first two achieve suboptimal power efficiency as they promote power consumption reduction solely through control of transmission power. Further more, we prove that optimal power consumption can be achieved only when factors such as energy consumption during idle states, excessive communication overhead and effective channel access arbitration are taken into consideration. Research on TDMA based medium access protocols for ad hoc networks has indicated that they can provide mechanisms for the minimisation and even elimination of some of the above mentioned factors responsible for inefficient power use. To evaluate the effect of efficient medium access control on power consumption in ad hoc networks and to quantify the effect of the above mentioned factors, this paper presents simulation data for a TDMA MAC protocol proposed by the authors. These results are compared to results obtained using the IEEE 802.11 MAC under the same conditions. The scheduled data transmission approach shows significant improvement with respect to medium access control efficiency over the contention based IEEE 802.11 MAC. This is indicated by optimised throughput, reduced communication overhead and improved energy efficiency.

I. INTRODUCTION

For a number of years Mobile Ad Hoc Networks (MANETs) have been receiving significant attention from researchers in the broad field of networking. What makes MANETs attractive is their fully distributed nature, the fact that they do not require a centralised unit (base station) for the coordination of their operation and their ease of deployment.

Early work in the field was focused on MANET routing algorithms [1-3], the greatest challenges being posed by the distributed and mobile nature of the network nodes. The decentralised manner in which packets are routed from source to destination dictates that the routing algorithms themselves have to be decentralised. The first routing algorithms such as DSR[1], DSDV[2], AODV[3] amongst others, were designed to function under these conditions. However, although they provide robust routing they have no inherent power consumption considerations.

The operation of an Ad Hoc Network is dependant on the lifetime of its nodes which is directly related to the nodal power requirements for data processing, transmission and reception and hence, typically, on battery depletion rate.

In the presently perceived applications battery replacement in the field is often highly impractical. This has been the motivation behind research efforts focused on the development of power consumption reduction mechanisms which promote power efficiency through optimisation of the operation of individual OSI layers with respect to energy. The methods that have received most of the research attention include:

- Power control algorithms (Physical layer)
- Power-aware routing protocols (Network Layer)
- Power efficient medium access control (MAC) protocols (MAC Layer)

Performance studies [4, 5] have shown that schemes such as power control algorithms and power-aware routing protocols, which promote efficient power consumption solely through control of the transmission power of a node, are inefficient. This is based on the fact that although the data transmission process requires the largest amount of energy per byte (when compared to data reception and node idle modes), the power expenditure due to data transmission is responsible for only 10-15% of the overall power consumption of a node. The bulk of the energy consumed is due to idle periods of the network interface cards, excessive communication overhead and inefficient channel use.

It is the intent of this paper to show that a solution, affecting all of the above mentioned factors and providing a significant increase in power efficiency, can be achieved at the medium access control level of the network hierarchy. The paper presents a survey of power consumption optimisation techniques that belong to the *network* and *physical* layers of the OSI model. It also analyses the origin of their inefficiency and discusses how that can be offset by an efficient medium access control. The survey is followed by: (i) an evaluation of the ability of an efficient MAC layer to mitigate the adverse power consumption factors and (ii) a quantification of the effects of these factors on the performance of ad hoc networks. To that end, an efficient TDMA MAC protocol is compared through simulations with the popular contention based IEEE 802.11 MAC protocol.

The paper is structured as follows: Sections 2 and 3 provide an overview of power consumption optimisation techniques. Section 4 investigates the factors responsible for excessive energy consumption in ad hoc networks, while Section 5 presents an evaluation of the TDMA MAC approach and quantification through simulations of the power consumption factors.

II. POWER CONTROL ALGORITHMS

Power control in ad hoc networks is the intelligent choice of an adequate transmit-power level by a communicating node. The goal of a power control algorithm is to identify and use the lowest possible transmit power that provides reliable communication between peers. This is achieved with the help of some knowledge about the current status of the communication channel, provided either by a channel model or by information about the attenuation of the received signals.

A number of power control algorithms identify the lowest applicable transmit power level by investigating and maintaining routing tables that correspond to each of the available power levels. COMPOW [6] is such an algorithm. Finding a suitable common power level not only results in power efficiency but also improved network capacity [6].

COMPOW generates a routing table for each available transit power level. Once created, the tables are compared with the table that corresponds to the highest transmission power level. A routing table corresponding to the lowest transmit power level that includes all nodes that appear in the table of the highest transmission power level is chosen as the operating routing table and its corresponding power level is assigned for use.

It is argued in [7] that COMPOW is inefficient in environments with unevenly distributed nodes (eg. clustered ad hoc networks) where it converges to the transmission power level required for reliable communication between the two most remote nodes in the network. This problem is addressed by the CLUSTERPOW[7] algorithm which assigns the transmission power levels in a way that guarantees low power use for communication between nodes close to each other (within a cluster) and higher power only for remotely located nodes (communication between clusters).The algorithm also maintains routing tables for each transmission power level however, instead of identifying the table corresponding to the lowest power level that contains the highest number of neighbouring nodes, it identifies and uses the table corresponding to the lowest possible power level that provides an existing path to the intended destination. This idea is further refined by the Recursive CLUSTERPOW algorithm which attempts to substitute most of the high power hops with a number of low power hops as this increases the power efficiency[7].

Power control through use of embedded signal strength information in the signalling messages (RTS/CTS) of the IEEE 802.11 MAC [8] is the idea behind the scheme proposed in [9]. Such feedback information allows the communicating nodes to adjust their transmission powers to the most suitable level. This procedure starts with the CTS reply to an RTS packet sent by a source node intending to transmit data. The replying node compares the signal strength of the incoming RTS packet with a predetermined receiver sensitivity threshold value and inserts the result in the CTS packet. Using this information, the source node can adjust its transmission power if required, after which it does the same signal strength comparison for the CTS packet and inserts the feedback information in the following data transmission. As a result, the second node is also able to adjust its transmission power.

Often power control algorithms stem from existing power control schemes used in presently deployed cellular networks. Such is the scheme introduced in [10]. Its applicability to ad hoc scenarios is achieved by enabling all of the participating nodes to control the transmit power levels of their neighbours. As a result, the nodes carry out power control functions themselves and the need for a centralised infrastructure such as a base station is eliminated.

III. POWER-AWARE ROUTING

Routing is the process of assigning and maintaining communication links between the nodes of a network

Research has produced an array of routing protocols that provide robust routing with little or no consideration for power consumption efficiency. Some of the techniques result in power expenditure which significantly reduces the life-span of the network.

Woo et al [11] suggest a need for modification of the existing routing protocols for the purpose of power efficiency. According to [11] significant power conservation can be achieved if the route selection process in a routing protocol is based on power conservation criteria. This has since stood as the main driver of power-aware routing.

Routing can be divided into two fields: *unicast routing* and *multicast routing*. The former is associated with data forwarding from a source to a single destination node whereas the latter is used for simultaneous data delivery to many destination nodes.

A. Unicast Routing

Unicast routing further subdivides into three different types: *source initiated*, *table drive* and a *hybrid* of the two.

In the *table-driven* (proactive) approach, each node maintains routing information in the form of routing tables. To keep that information consistent with the network topology, frequent table update processes are triggered either by a timer or by an event such as link error. The disadvantages of the table-driven approach are its poor scalability and high table configuration and maintenance overhead [12]. *Source-initiated* (reactive) routing lessens these disadvantages by significantly reducing the dependence of the routing process on routing tables. Routing protocols of this type discover routes only when they are needed. The newly discovered routes are cached only for the duration of their use.

There are a number of fully established unicast routing protocols [1], [3], [2]. The performance of these protocols has been studied in depth and the results have been presented in a numerous publications, a summary of which can be found in [12]. The general trend is that reactive routing protocols (DSR, AODV) out-perform table-driven protocols (DSDV) in terms of throughput and average end-to-end delay even in cases of high mobility.

Investigation of the energy consumption behaviour of DSR, AODV, DSDV and TORA presented in [5] suggests that

DSR spends 85 % less energy than the second best routing protocol - AODV. This result together with the findings from [12] suggesting that DSR produces the least amount of overhead, underlines the significance of excessive communication overhead as a factor responsible for inefficient power use.

Although DSR has superior power consumption performance, it does not actively employ any power conservation mechanisms. This leaves room for modification which could further improve its power efficiency.

Improved power efficiency is achieved by EADSR[13] through modification of the criteria used by DSR for path selection. In the presence of more than one route between a given source-destination pair, DSR will choose the one that requires the least number of hops, since DSR attempts to optimise the hop-count metric. The operation of EADSR is based on estimation and minimisation of transmit power per source-destination route. It chooses the route that requires the lowest overall transmits power.

Similar modification to AODV is proposed by Senouci et al [14] which increases network survivability with the help of energy-efficient route selection and operation based on residual battery power estimations. There are three modifications of AODV proposed in [14], namely LEAR-AODV, PAR-AODV and LPR-AODV.

LEAR-AODV is intended as a mechanism to balance energy consumption rates network-wide. This is done by allowing the nodes to choose whether they will be part of a route or not. The choice is based on the residual battery power at a node.

PAR-AODV assigns costs to each hop that lies on a source-destination route. The costs are based on the nodal residual battery power. The modified AODV will use route π that minimises the following function:

$$C(\pi,t) = \sum_{i\in\pi} C_i(t) \qquad (1)$$

where

$$C_i(t) = \rho_i \left(\frac{F_i}{E_i(t)}\right)^{\alpha} \qquad (2)$$

and ρ_i is the transmit power of node i, F_i is the full charge battery capacity of the node i, $E_i(t)$ is the remaining battery capacity of node i in time t and α is a positive weighting factor.

The last modification of AODV is LPR-AODV. As in the case of PAR-AODV hops are assigned with costs, however the cost estimation in LPR-AODV is based on battery life time prediction. This is done with the help of past activity records for each node.

B. Multicast Routing

Multicasting communication techniques allow a single source node to simultaneously deliver data to a group of nodes in the network. Most of the research work dedicated to development and optimisation of power efficient broadcast/multicast routing protocols is founded on *source-based* multicast routing. This particular multicast routing approach operates with the help of multicast trees routed at a source node.

Power-efficient multicast routing protocols are subdividable into two categories: *local search algorithms* and *augmentation algorithms*. The difference being that the later type starts with the construction of an energy efficient multicasting tree from an empty entry set, whereas the former types start with an existing tree and transform it to a power efficient multicast tree [15].

Two fundamental augmentation algorithms used in wired networks are also often applied to wireless networks. These are the MST and SPF [16]. However, their *link-base* design (suitable for wired networks) results in suboptimal solutions for wireless *node-based* networks [15].

BIP[17] is a popular augmentation algorithm based on the *minimum incremental cost* heuristic which reflects the increase of transmission power required by an already transmitting node to add a new node to its transmission list. An alternative to the BIP algorithm is the IP3S [18] algorithm. This is a *node-based* broadcast tree construction method that makes use of the *potential power savings* idea proposed by its authors. The difference between IP3S and BIP is in the criteria for the selection of nodes for expansion.

The *potential power savings* idea as defined in [18] is related to the power expansion at each new node. Every time a node increases its power in order to reach new nodes, it checks if it has covered nodes that have already been covered. If it has, then the current power assignment at some other node is redundant. This indicates potential power savings that could be realised if it is possible to eliminate the redundant power assignment.

The Sweep method [17] is a typical local-search algorithm. It is designed to optimise solutions generated by MST or BIP by minimising the overall power consumption of the already created broadcast/multicast tree. This is done by applying the *potential power savings* idea and therefore removing redundant power assignments. The potential power savings idea is taken one step further by EWMA [19] which initially maximises the number of redundant power assignments before they are removed. This maximisation is achieved by increasing the transmission range of a number of appropriately chosen relay nodes. As a *local-search* algorithm, EWMA operates in two phases. Firstly a suboptimal solution is found with the help of MST. This result is then improved during the optimisation phase.

A different approach for total power consumption reduction in a broadcast tree is taken by the S-REMiT [20] algorithm. It achieves power efficiency through reassignment of downstream nodes to new parent nodes that require less energy. The reassignment is based on the energy efficiency gain that would result from the parent exchange.

IV. POWER CONSUMPTION ANALYSIS

All power conservation techniques that have been discussed so far have a common characteristic that renders them somewhat inefficient. Both power control algorithms and power-aware routing protocols promote efficient energy consumption solely through transmission power control. A number of power consumption investigations [5, 21] have shown that although the data transmission mode of operation requires the largest amount of energy (when compared to the data reception and idle mode), it is responsible only for 10-15% of the overall power consumption of the network card. In order to achieve true power efficiency, all of the factors responsible for the other 80-85% of the overall power consumption have to be carefully considered. To do so Feeney et al [4] investigated the dynamics associated with the data transmission process that have significant bearing on power consumption. The investigation incorporates a per-packet energy consumption model represented by the following linear equation:

$$Energy = m \times size + b \qquad (3)$$

The model suggests that from an energy consumption stand point, data transmission can be viewed as a combination of the following two components: a fixed component b which is the energy costs of the MAC/PHY overhead per transmitted packet and an incremental component $m \times size$ that reflects the energy cost for processing a data packet. In the analysis of [4], the value of m represents the energy consumed per byte in the following modes of operation: transmit, receive, idle, disregard, promiscuous and low power. The value of *size* represents the length of the processed packet in bytes.

By subjecting a wireless network interface (WNI) to a number of typical network operation scenarios and performing power consumption measurements for each of them, the authors of [4] have obtained a set of values for m and b. These values are then used to investigate the factors responsible for excessive power consumption. The findings of [4] confirm that power consumption optimisation at the network and physical layers through means of transmit power control is inadequate and thus achieves relatively poor results.

The investigation of the power consumption behaviour of a WNI suggests that, adequate power efficiency can only be achieved if the following issues are addressed jointly at the medium access control layer:

- Elimination of unnecessary energy consumption by making use of the low power mode in all idle periods of the WNI.
- Reduction of the fixed cost of the data transmission process by minimising the control and configuration overhead per data packet sent
- Elimination of packet collisions and packet retransmission through effective channel use

There are two sources of communication overhead in ad hoc networks: routing overhead generated by the network layer and MAC layer signalling and maintenance overhead. Reduction of routing overhead in highly mobile ad hoc networks is not always possible as it would lead to unreliable network operation. Efficient MAC protocols generate only RTS-CTS handshaking overhead to eliminate the *hidden terminal* phenomenon.

Our findings have clearly indicated that the overall amount of communication overhead (both routing and MAC signalling) per bit payload is controllable as it is a function of the ability of the medium access control to use the channel efficiently.

Another adverse effect with respect to power efficiency is presented by packet retransmission which occurs as a result of packet collisions. One of the main tasks of medium access control is to provide effective arbitration of the channel use in order to avoid such collisions.

Significant amounts of research have been dedicated to Time Division Multiple Access (TDMA) MAC protocols [22] as an alternative to IEEE 802.11 MAC. Schemes of this type partition the time axis into slots which are used by the mobile nodes for data transmission. As each node has assigned slots for transmission with a guarantee that no other node will transmit during these slots. TDMA medium access schemes provide fair and efficient channel utilisation and therefore promote mechanisms for the reduction or even elimination of the factors responsible for excessive power consumption. However the advantages of such systems come at a high price associated with the implementation difficulty of a distributed TDMA MAC protocol.

V. QUANTIFICATION OF THE FACTORS RESPONSIBLE FOR EXCESSIVE ENERGY CONSUMPTION

A prototype of a Position Aided Spatial-TDMA MAC protocol proposed by the authors of this paper has been simulated in ns-2 [23]. With the help of the prototype two goals have been achieved: (1) the dependence of the factors responsible for excessive power consumption on fair and efficient channel use has been evaluated and (2) the effect of these factors has been quantified. The evaluations are obtained through performance comparison between the PA-STDMA MAC protocol and the widely used IEEE 802.11 MAC protocol in high load, mobile ad hoc network environment.

The PA-STDMA is a medium access protocol that combines TDMA allocation with contention in a manner similar to ADAPT [22]. The difference being that PA-STDMA relies on real-time slot allocation and thus achieves scalability and improved transmission delays in large networks. As it is topology transparent, the protocol does not require the distribution of any global or local positional or scheduling information for the purpose of time slot scheduling. Instead, an optimised scheduling is achieved through use of positional information which each node obtains from GPS or any other positioning system. The protocol splits the network environment into geographical cells where each cell has a corresponding transmission slot. As in the case of STDMA protocol proposed in [24], the nodes of the network are allowed to transmit in the duration of the slot that corresponds to their cell (position). To improve throughput and efficiency however, PA-STDMA allows the nodes to transmit during a number of slots that belong to neighbouring cells under certain conditions. Co-located nodes acquire the channel through a contention process instead of using costly sequence lists as suggested in [24]. The protocol makes use of the *spatial reuse* phenomenon in order to minimise the occurrence of the *hidden terminal* problem and therefore reduces the RTS-CTS overhead per packet goodput. The existence of the transmission schedules allows use of the low power mode (sleep) without significant disruption of communications in the network. The process of transmission scheduling based on positional information optimises the contention process and therefore the network congestion is reduced.

The simulation scenario includes fifty nodes and thirty data connections. The physical layer data rate is set to 2 Mb/s. The generated traffic is Constant Bit Rate (CBR) data over UDP with data rate of 64Kb/s (suitable for real time voice transmission). The duration of the simulation is 1000 seconds. The movement of the nodes is based on the random waypoint model with maximum velocity of 10m/s and stop time of 5sec.

Figures 1 to 6 present results derived during simulation of the two protocols. Figure 1 offers a comparison of packet delivery ratios.

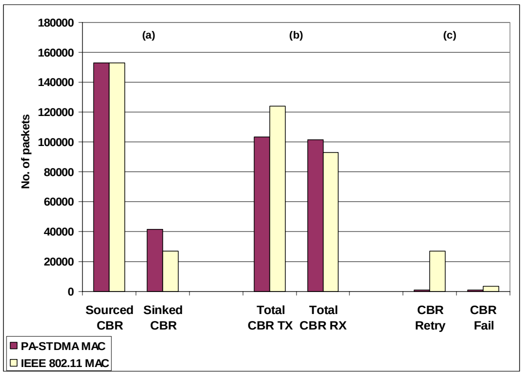

Figure 1: Packet delivery efficiency comparison

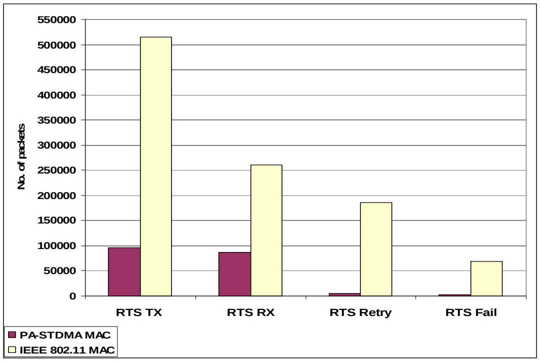

Figure 2: Overhead generation overhead comparison

As shown by graph (a) of Figure 1, the CBR application generates the same number of data packets with both protocols, however a significantly higher proportion of these packets arrive at their final destination node application layer using the PA-STDMA MAC than with the IEEE 802.11 MAC. It is noted that the highly loaded network results in a goodput of between 20 – 30% for both protocols. Graph (b) of Figure 1 shows the transmission success rate of application data packets transmitted by the MAC layer reaching their intended (perhaps intermediate) destination node MAC layers, with graph (c) alluding to a possible reason for the difference.

Figure 2 relates the RTS/CTS overhead associated with each protocol, it is evident that PA-STDMA outperforms IEEE 802.11 in this regard, while still offering equivalent or better delivery ratios. Further analysis has revealed that the IEEE 802.11 MAC under these simulation conditions requires an overhead of 6.3 bits per bit of successfully received payload data, compared to the 1.6 overhead bits per bit under PA-STDMA MAC.

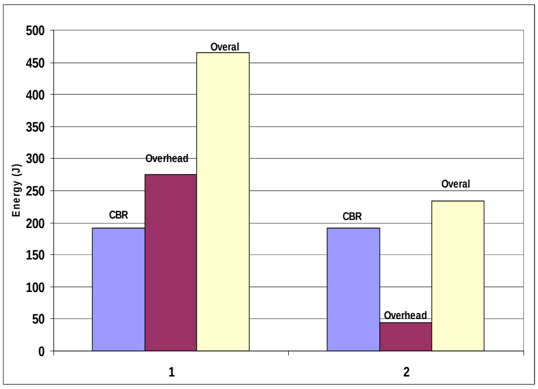

Figure 3: Transmission energy breakdown for IEEE 802.11 MAC (1) and PS-STDMA MAC (2)

Figure 3 presents a breakdown of the consumed energy for transmission of CBR packets, overhead packets (RTS-CTS and routing) and the overall energy consumed for communication. The reduced overhead due to efficient channel use in the case of PA-STDMA MAC results in a 50% overall power saving. Neglecting idle state power consumption, this saving alone results in a doubling of the life time of the network. The difference in power consumption due to the generated overhead per transmitted packet of payload (CBR packets) is depicted in Figure 4.

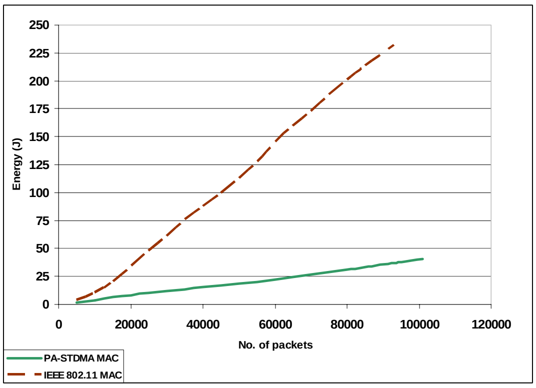

Figure 4: Overhead energy consumption per packet CBR data

Predictions regarding the severe effect of node power consumption during idles states have been confirmed by the simulation results. The initial energy pool of the simulated network amounts to 15000 Joules. Figure 5 shows energy consumption distribution between transmission and idle states.

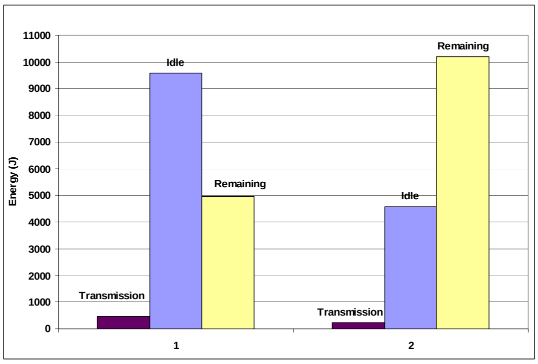

Figure 5: The effect of idle state energy consumption of under IEEE 802.11 MAC (1) and PA-STDMA MAC (2)

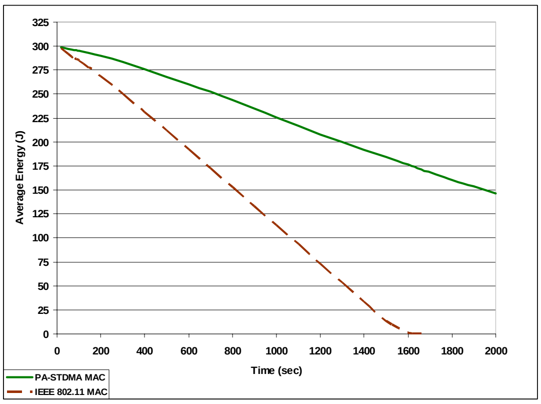

Figure 6: Average remaining battery energy

As a result of the unattended energy waste during the idle state of a node in the case of IEEE 802.11 MAC, the remaining energy of the network at the end of the 1000 second simulation is 52% less than that in the case of PA-STDMA MAC. The negative effect of disregarded energy consumption during idle states is shown in Figure 6. It depicts the average energy consumption in a 2000 seconds simulation run by the two MAC protocols. Due to energy starvation, the network operating under IEEE 802.11 MAC, stops functioning at simulation time 1600sec. Through extrapolation, the life span of the network operated under PA-STDMA MAC is estimated at 4100sec.

VI. CONCLUSION

In this paper some of the popular techniques for power conservation, namely power control, power-aware routing and power efficient medium access control have been summarised. The first two techniques fail to achieve optimum efficiency as they promote power conservation solely through transmission power control. This was confirmed by the simulation results presented in Section 5, which clearly show that the consumed energy due to data transmission is a small fraction in comparison to the energy consumed during the idle operation sate.

The following factors responsible for poor energy efficacy were investigated: excessive overhead per bit goodput, unattended energy waste during idle states and inefficient channel use. To quantify the effects of these factors a comparison between our PA-STDMA MAC protocol, and the popular IEEE 802.11 MAC protocol was made. The superior channel use efficiency of the PA-STDMA MAC protocol was confirmed by improved network congestion, minimised communication overhead and higher throughput. Optimal use of the *spatial reuse* phenomenon by PA-STDMA MAC further optimised the incurred overhead. The efficient channel use alone was responsible for a power efficiency improvement of 50%. The severe effect of power consumption of a node during its idle state of operation was also confirmed. The overall network life extension achieved by PA-STDMA MAC was estimated at 61%.

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