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Improving the ultra-low-power performance of IEEE 802.15.6 by adaptive synchronisation

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Abstract: In ultra-low data rate wireless sensor networks (WSNs) waking up just to listen to a beacon every superframe can be a major waste of energy. This study introduces MedMAC, a medium access protocol for ultra-low data rate WSNs that achieves significant energy efficiency through a novel synchronisation mechanism. The new draft IEEE 802.15.6 standard for body area networks includes a sub-class of applications such as medical implantable devices and long-term micro miniature sensors with ultra-low power requirements. It will be desirable for these devices to have 10 years or more of operation between battery changes, or to have average current requirements matched to energy harvesting technology. Simulation results are presented to show that the MedMAC allows nodes to maintain synchronisation to the network while sleeping through many beacons with a significant increase in energy efficiency during periods of particularly low data transfer. Results from a comparative analysis of MedMAC and IEEE 802.15.6 MAC show that MedMAC has superior efficiency with energy savings of between 25 and 87% for the presented scenarios.

1 Introduction

The rapid expansion of wireless technology has the potential to lead to widespread un-tethered medical surveillance and health monitoring. Health monitoring systems that use cable as a medium can now be replaced with wireless connections. Point to point wireless links such as with the Medical Implant Communication Service, MedRadio [1] and single sensor biotelemetry [2] have been deployed over the last few years. However, thinking has moved on to the benefits of body-centric communication networks with potentially a multitude of ultra-low body area network (BAN) applications with data rates ranging from 0.01 b/s to 10's Mb/s. Medical BAN applications have the potential to be ubiquitous, supporting both in-patient and out-patient care and offsetting the rising cost of healthcare caused by an increasing older population and the growth of chronic illness. Currently, that potential has been unrealised due to the limitations of existing wireless sensor standards such as Bluetooth and IEEE 802.15.4 [3], which includes the lack of ultra-low-power adaptivity demanded by BAN applications. One of the main challenges in BANs is to balance the demands of the hard energy constraint associated with battery powered or energy harvesting low-power wireless sensor nodes, with the quality of service (QoS) demands of the wide range of sensing and control applications. Recently, Bluetooth Low Energy [4] has been developed as a low power solution for wireless sensor networks (WSNs); however, it is aimed at applications up to 1 Mb/s unlike this work which is targeted at ultra-low power and data rate applications. In recognition of the lack of standards for wireless BANs, the IEEE 802.15.6 working group was commissioned to develop standards for the physical (PHY) and medium access control (MAC) layers for BANs in both medical and non-medical applications. At the time of writing development of a MAC and PHY protocol has resulted in a draft standard [5]. Consideration has been given to a wide spectrum of data rates from a few bits per second up to 10 Mb/s covering applications such as very low grade temperature monitoring up to transmission of video imaging, for example, ingestible cameras. The fundamental MAC protocol proposed in IEEE 802.15.6 follows a widely accepted compromise between contention and contention free portions of a beacon-delimited superframe, in a basic star and/or restricted tree topology. One of the chief aims of IEEE 802.15.6 is to provide for energy-efficient operation. However, as will be shown, 802.15.6 does not specifically cater for the ultra-low power scenario where extremely low data rates are the norm and where node lifetimes of 10 years or more will be required, for example, in a battery-powered implanted medical device. Unlike other wireless networks, it is generally impractical to charge or replace exhausted batteries, and therefore battery lifetime defines node lifetime. Since the transceiver communication operations consume much more energy than the processing operations, it is a primary objective to minimise transmit and receive operations to maximise node lifetime. Therefore the MAC protocol in a BAN must be highly energy efficient, adaptive and flexible. The main energy saving features that must be exhibited by a well-designed MAC protocol are: collision avoidance, overhearing, control packet overhead, receiver idle listening and transmitter over-emitting. For ultra-low power and data rate nodes in beacon driven networks there are two further dominant causes of energy usage (as will be shown)

- the rated sleep current of the node,
- waking to receive a beacon every superframe.

The former will rely on developments in IC technology and the subsequent commercial availability of ultra-low power microcontrollers and transceivers. The latter is the focus of this paper and as such is within the control of the MAC designers. Waking up and listening for regular beacons can be the dominant factor in battery consumption with ultra-low power nodes [3]. Consider nodes where the data rate is so low that for many beacon periods (BPs) the only exchange of data occurs when the node wakes up to receive a beacon packet. Nonetheless, waking up to receive a beacon is an accepted method for a node to realign to network time as de-synchronisation can occur owing to the relative drift of uncompensated crystal-based time bases between a node and a hub.

Periodic data are characteristic of many medical services, such as monitoring temperature, glucose levels, heart rate and other physiological parameters. Therefore an adaptive time division multiple access (TDMA)-based MAC protocol is most applicable to a medical BAN [6]. The MedMAC protocol was first introduced in [6] and preliminary results showed that it outperformed IEEE 802.15.4, a contention-based protocol, for two scenarios: a higher rated medical application, EEG with 24 nodes; and a lower rated health monitoring application, pulse, temperature and respiration with a three-node BAN. These results demonstrated how a time scheduling MAC produced a significant advantage over contention access MACs for both a simple and complex medical application. It is possible to maintain synchronisation of TDMA nodes while sleeping through beacons using timestamp scavenging, that is, using routine packets such as data, control and acknowledgement to pass on timestamps from the hub to the node. The energy cost of regular beacon reception is insignificant when the node and the hub are exchanging packets every superframe. However, if there is an interruption in the regular delivery of packets from the hub, or simply that an application requires a very low throughput, then the node cannot rely on scavenging packets to maintain its timing and will have to revert to listening to regular beacons from the hub. The novelty of the MedMAC synchronisation algorithm presented here is that it can significantly reduce the energy cost of waking up the transceiver of an ultra-low power node for a regular beacon without compromise in terms of node synchronisation.

Clock synchronisation of WSNs has been the focus of much research [7–9], particularly in the context of the timing accuracy demanded by TDMA-based MACs and sleep/wake scheduling. In general, time corrections are carried out by regular packets sent with timing information or timestamps to ensure that all nodes are referencing a global network time. However, it is accepted in WSNs that in between updates, synchronisation errors will occur between nodes owing to the relative drift of their timebases. As time progresses between synchronisations the clock errors become more and more significant. Frequent re-synchronisation to avoid errors can consume a significant amount of energy. The use of guard times to offset errors and decrease the rate of re-synchronisation is proposed in many wireless sensor MACs [10, 11], including the IEEE 802.15.6 draft standard [5]. The non-deterministic nature of the errors means that common practice is to use an upper-bound on the clock drift as guard time (GT) which can be wasteful in energy [12]. For example, in [10] the GT for each timeslot is based on the superframe time and the maximum tolerance of the crystal regardless of the time elapsed from the previous synchronisation. In the IEEE 802.15.6 draft [5] it is proposed that the GT is fixed at a nominal value. However, in contrast, the MedMAC synchronisation algorithm creates and refreshes fine-grained guard bands (GBs) which can track the drift between devices which is significantly much more energy efficient.

In this paper, we present detailed simulation results and performance analysis of the MedMAC synchronisation algorithm Adaptive Guard Band Algorithm (AGBA) with drift adjustment factor (DAF). We also demonstrate how in ultra-low power scenarios the MedMAC will outperform the proposed IEEE 802.15.6 MAC. The remaining sections of the paper are presented as follows: Section 2 describes the MedMAC architecture, beginning with a theoretical analysis of potential energy savings, and then followed by the development of the algorithms and their operation; Section 3 presents the simulation model and results followed by the conclusions in Section 4.

2 MedMAC algorithm development

2.1 Theoretical analysis

As an initial step a theoretical analysis was performed to quantify the energy savings that could be made by sleeping through beacons in an ultra-low data rate star-based TDMA wireless network. The analysis was based upon a simple communication scenario typical of a low power WSN, in that a node will wake up to transmit a data packet to the hub and receive an immediate acknowledgement in its timeslot and will sleep for the remainder of the BP. To simplify the analysis it was considered reasonable to assume one packet transmitted per timeslot per BP; however, in real applications lower data rates will actually provide greater savings. If (m) is the number of BPs through which the node sleeps during beacons, then $(m+1)$ is the total number of beacons bounding the BPs in that period and $(m-1)$ is the actual number of beacons through which the node sleeps. The node only wakes up to receive a beacon every (m) BPs. The following equation was developed to quantify the energy saved in this scenario:

$$\text{Energy Saved}(\%) = \frac{100(m-1)E_{\text{beac}}}{m(E_{\text{beac}}+E_{\text{data}}+E_{\text{ack}}+E_{\text{sleep}})+E_{\text{beac}}+E_{\text{BGB}}} \quad (1)$$

where E_{beac} is the energy required to receive a beacon; E_{data} is the energy to transmit a data packet; E_{ack} is the energy required to receive an acknowledgement packet; E_{sleep} the energy required to sleep through the remainder of the BP; E_{BGB} is the energy required for the beacon GB depending on the value of (m) and the timebase crystal tolerances. A spreadsheet based on this equation was devised which allowed the evaluation of energy saved by skipping beacons while varying a number of parameters such as data rate, packet size, BP duration, sleep time in a BP and number of beacons to be skipped $(m-1)$. The following assumptions

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are considered valid for this analysis as they are based upon the only low power wireless sensor standard currently available, IEEE 802.15.4 [3]: energy calculations are based on typical current and voltage values for a low power wireless transceiver of 20 mA for transmit and receive operations and 1 μA for sleep mode, with a 3 V battery power supply; a bit rate of 250 kbps; and a time base crystal tolerance, ±40 ppm. For this scenario Fig. 1 displays the percentage energy saved against the number of beacons skipped for a BP of 1 s duration, and with representative packet sizes of: 200 bits for the beacon packet; an acknowledgement packet of 100 bits; while the data packet is varied from 200 to 1000 bits.

2.2 MedMAC overview

The novel feature of the MedMAC protocol is the adaptive and low-overhead TDMA synchronisation mechanism: the AGBA with DAF. This algorithm will allow the nodes with ultra-low data rates to save power by sleeping through beacons they would normally receive to synchronise to network time. The AGBA introduces two GBs for each slot which are dynamically increased as time advances based on the maximum combined drift specification of the crystal referenced time bases of the hub and the node. Two GBs per slot prevent the two possible timing drift discrepancies of the worst case slow or fast node overlapping and interfering with adjacent timeslots. Fig. 2 shows a worst-case scenario of nodes in adjacent timeslots, one fast and the other slow with respect to the hub, in both transmit and receive modes. The key advantage over other MACs which use guard times is that the GBs are not fixed at some arbitrary or maximum level which results in unnecessary power waste; in fact AGBA generates GBs proportional to the time elapsed from the previous synchronisation point. A further refinement to the algorithm is introduced by using the DAF, which allows GBs to be based on actual drift (AD) of the respective time bases. This ensures even less waste by keeping GBs as close to the required minimum as possible.

Other features of the MedMAC include a contention free channel access over a variable number of TDMA channels; energy efficient and dynamically adjustable timeslots; a novel adaptive and low-overhead TDMA synchronisation mechanism; and optional contention period used for low grade data, emergency operation, and network initialisation

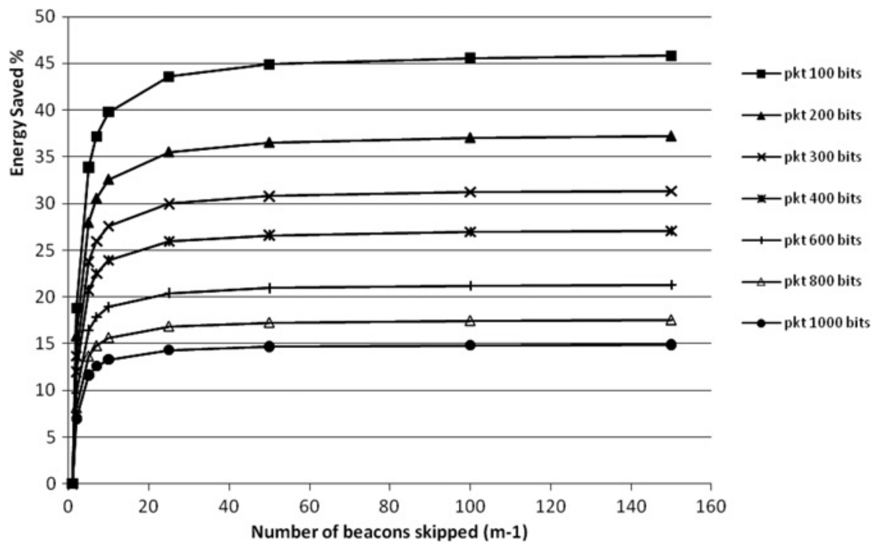

Fig. 1 *Theoretical analysis showing energy saved by a node against beacons skipped in a TDMA scenario with BP of 1 s*

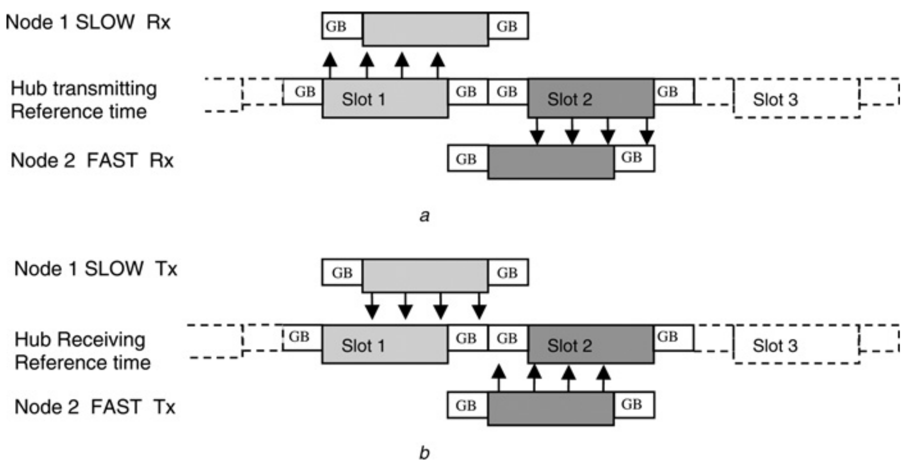

Fig. 2 *Slow and fast nodes in adjacent timeslots*

a Hub transmitting
b Nodes transmitting

procedures. All devices will sleep to save energy when not transmitting or receiving. The network is assumed to be configured in a star topology with the central hub worn outside the body or fixed in a bedside position. The subsequent sections describe the MedMAC superframe architecture and the derivation of the AGBA and DAF algorithm leading to the key design equations for the model.

2.3 Med MAC architecture: superframe and MSF

MedMAC incorporates a multi-superframe (MSF) structure made up from a variable number of superframes (Fig. 3); the MSF indicates the number of beacons through which a node can sleep, except for those bounding the MSF. The superframe is the basic unit of the structure and is a dynamic and programmable period bounded by a beacon frame sent at regular intervals by the hub. The superframe duration is determined by the number of nodes, associated throughput, slot size and latency requirements. It will have an optional contention access period and a contention free period made up of between 1 and 256 timeslots. The superframe structure will be adaptable and responsive to the number of nodes, their applications and respective traffic demands. Each node in a BAN will work within a common MSF structure defined and controlled by the hub through the beacons.

Depending on the application, a node may completely sleep through the MSF but uniquely if it needs to communicate with a hub (uplink or downlink) it can do so at any point in the MSF in its allocated timeslot, as MedMAC ensures synchronisation is maintained with the hub for the duration of the MSF.

2.4 Adaptive GB algorithm

The motivation for the development of AGBA is to reduce the power wastage in ultra-low data rate BANs caused by the receiver waking up for regular beacons. However, in TDMA MACs regular beacons are required to ensure synchronisation of the BAN and the timeslot allocation for each node. By determining GBs that are a function of the elapsed time and crystal tolerances AGBA allows TDMA nodes to sleep through many more beacons while maintaining synchronisation with the network. Upon initialisation of the BAN all nodes are synchronised by a beacon from the hub. The beacon packet will inform the nodes of slot allocation, number of slots (n) in a BP and the number of BPs (m) in the MSF; there are many factors that will influence these decisions including node applications, number of nodes in the BAN, QoS demands such as latency and throughput requirements; however, for the

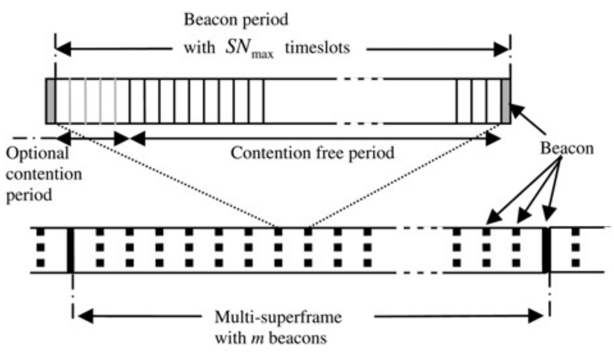

Fig. 3 *MSF structure for the MedMAC protocol*

experiments reported here arbitrary values have been assumed. Fundamentally, the greater the maximum GB value which is selected the greater the MSF duration, and hence a greater number of beacons can be skipped. However, apart from the impracticality of over-large GBs there is a trade-off between energy used by listening to beacons against energy used by extending the GB for every subsequent missed beacon. Our experiments will show that it is possible to determine the optimal number of BPs per MSF for a given GB.

In each node the algorithm will be invoked to calculate the default GBs for all node timeslots across the full MSF and these will be stored as an array. Note that the GB increases with time from the start of the MSF until a timestamp is received from the beacon at the end of the MSF. The GB is based on the maximum drift specification of the crystals and the time elapsed from start of the MSF to the end of the timeslot (2).

$$\mathrm{GB} = (\text{time\_elapsed}) \times (\text{crys\_tol\_TX}) \times (\text{crys\_tol\_RX}) \quad (2)$$

where crys_tol_TX and crys_tol_RX are the timebase crystal tolerances of the node and hub, respectively. These results are known as the default GB values and are stored in each node including the hub during network initialisation. The individual default GB duration for each slot is calculated using the following equations. The GB for the first slot in the first BP will only have a single GB given by

$$\mathrm{GB}_{1,1} = (\mathrm{SD}) \cdot (X\text{\_tol}) \quad (3)$$

where SD is the slot duration measured in seconds and X_tol is the combined tolerances (ppm), of the hub and the node time base crystals. For the remaining slots in the first BP, (4) determines the GB for each slot. This equation is iterative and incorporates the GBs of previous slots into the time elapsed

$$\mathrm{GB}_{n,m} = \frac{X\text{\_tol}(n.\mathrm{SD} + \mathrm{GB}_1 + \mathrm{GB}_2 + \cdots + 2\,\mathrm{GB}_{n-1})}{1 - X\text{\_tol}} \quad (4)$$

where n indicates a slot number in a BP and its range is $1 \le n \le \mathrm{SN}_{\max}$ where $\mathrm{SN}_{\max}$ is the maximum number of slots; m is the BP (superframe) number in a MSF and its range is $1 \le m \le \mathrm{BPN}_{\max}$ where $\mathrm{BP}_{\max}$ is the maximum number of BPs in the MSF. Now to calculate the GBs in the subsequent BPs of the MSF the following generic equation can be used:

$$\mathrm{GB}_{n,m} = \frac{X\text{\_tol}(n.\mathrm{SD} + (m-1).\mathrm{BP} + \mathrm{GB}_1 + 2\,\mathrm{GB}_2 + \cdots + 2\,\mathrm{GB}_{n-1})}{1 - X\text{\_tol}} \quad (5)$$

Alternatively, GB values can also be calculated by using

$$\mathrm{GB}_{n,m} = \mathrm{GB}_{n,m-1} + \mathrm{BP} \cdot (X\text{\_tol}) \quad (6)$$

From the default GB values the new slot start times (SSTs), both for receiving and transmitting, can be determined for

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each node. The SST for waking up to receive a packet

$$SST_{n,m}(rx) = SST_{1,m} + (n-1).SD + 2\,GB_{1,m} + 2\,GB_{2,m} + \cdots + 2\,GB_{n-1,m} \quad (7)$$

where

$$SST_{1,m} = SST_{1,1} + (m-1).BP + GB_{1,m} \quad (8)$$

and BP is the BP measured in seconds and $SST_{1,1}$ is the beacon start time.

The SST for waking up to send a packet is

$$SST_{n,m}(tx) = SST_{1,m} + (n-1).SD + 2\,GB_{1,m} + 2\,GB_{2,m} + \cdots + 2\,GB_{n-1,m} + GB_{n,m} \quad (9)$$

where

$$SST_{1,m} = SST_{1,1} + (m-1).BP \quad (10)$$

Fig. 4 illustrates how the GBs increase with time to accommodate drift. As GBs grow with time, SSTs in successive BPs will change therefore (7) and (9) are invoked in the nodes to determine the new SSTs in each subsequent BP of the MSF.

2.5 Drift adjustment factor

In practical cases the actual crystal drift between a hub and a node will often be a lot less than the default GB derived from the maximum crystal tolerances. For increased energy saving the AGBA incorporates a novel feature called the DAF, which minimises the waste of bandwidth and energy when using GBs with fine grained tracking of the actual relative drift of device time bases. The DAF is determined, from the relative drift, the default GB and the AD and an adjustment is made to the current GB. If the drift does not grow at the maximum rate as determined by the AGBA then the actual GB can be reduced. The DAF is calculated at the end of each MSF by the hub based on timing information received from the nodes during the MSF. Each time a packet arrives at the hub from a node it delivers the actual (node) time SST. Comparing the node time with the global network time the hub can determine the AD between the devices. The hub will only store the worst-case AD, of all the nodes in a BAN, together with the slot identity (n) and BP number (m). The node with the worst case AD will be the reference for the DAF (AD_{ref}). The DAF is then calculated in the hub by comparing the AD_{ref} with its corresponding GB derived for the previous MSF with equivalent slot number and beacon number.

If the drift (positive or negative) is greater than some threshold say 5% (an arbitrary value chosen for simulation purposes) of the timeslot duration then the DAF is sent via the beacon to the nodes; if less than the threshold then the node knows to revert back to default AGBA values for the next MSF. For example, if (11) is true then the DAF should be invoked.

$$\frac{GB_{n,p} - AD_{n,p}}{SD} > 5\% \quad (11)$$

The DAF value will be sent to all the nodes in the BAN which will allow each one to update the GB values closer to the actual relative drift. In each node two arrays of GB values will be maintained. One array stores all the AGBA default values created when the node is initialised into the network; the other will be updated regularly with the DAF derived values based on actual drifts between the hub and a node. The AD and the corresponding GB are compared to determine whether the DAF algorithm is invoked or if the node should revert to the default AGBA values. So if (11) is true and if $AD_{ref,m,p} < GB_{ref,m,p}$ then (12) is applied to reset the GB for the corresponding timeslot in the first BP of the next MSF

$$GB_{ref,m,p+1} = GB_{ref,m,p} - \left(\frac{GB_{ref,m,p} - AD_{ref,n,p}}{2}\right) \quad (12)$$

where $p+1$ is the new MSF and ref is the timeslot number of the reference slot.

Equation (12) ensures a gradual adjustment to the actual drifts over several MSFs, avoiding over-correction. This effectively allows the GB excess to be reduced by a factor of two in consecutive MSFs until the percentage difference between previous GB and current AD is equal to or less than the appropriate threshold (5% in this current work). If it becomes less than the threshold then DAF will increase the GB using (13).

$$GB_{ref,m,p+1} = GB_{ref,m,p} + \left(\frac{GB_{ref,m,p} - AD_{ref,n,p}}{2}\right) \quad (13)$$

The new GB can be determined for the corresponding time slot in the corresponding BP of the next MSF. The difference between the old GB and the new GB is used to derive the DAF value.

$$DAF = \frac{GB_{ref,m,p} - GB_{ref,m,p+1}}{GB_{ref,m,p}} \quad (14)$$

The GBs for all the nodes for each BP of the new MSF are then adjusted by this factor

$$GB_{n,m,p+1} = (GB_{n,m,p} \times DAF) + GB_{n,m,p} \quad (15)$$

If AD_{ref} is larger than the corresponding GB in the MSF by

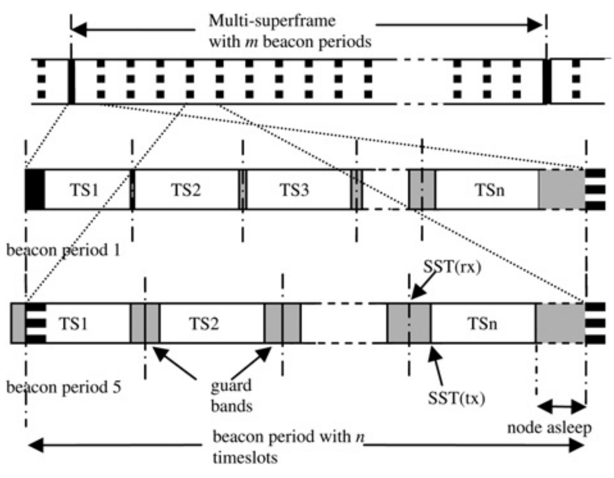

Fig. 4 *MSF showing beacon frame, timeslots and GBs*

more than the selected threshold then the node is commanded to invoke the default AGBA values for GBs, therefore if $AD_{ref,m,p} > GB_{ref,m,p}$ then invoke the default AGBA algorithm.

The final condition to be considered is when the AD is equivalent to the GB. If this is true then the current GB values are maintained whether they are AGBA default or DAF values. If $AD_{ref,m,p} = GB_{ref,m,p}$, then current GB values are maintained in the node for the next MSF. A flag is set in the beacon to let the node know whether the DAF_array is to be used. Table 1 shows the two flags in the beacon which control the node GBs for the next MSF for all the conditions described. The flowcharts in Figs. 5*a* and *b* summarise AGBA and DAF process in the node and hub, respectively.

Table 1 Beacon flags controlling node GB values

DAF_flag	DAF_array	Node command
0	0	revert to default AGBA GB values
0	1	current DAF array invoked
1	1	iterate DAF array
1	0	create new DAF array

3 Simulations and results

A discrete event simulation model was designed in OPNET to analyse the performance of MedMAC in a star network model and also to compare its performance with IEEE 802.15.6. Typical current consumption values were used, derived from the well-known Micaz 2420 low power transceiver

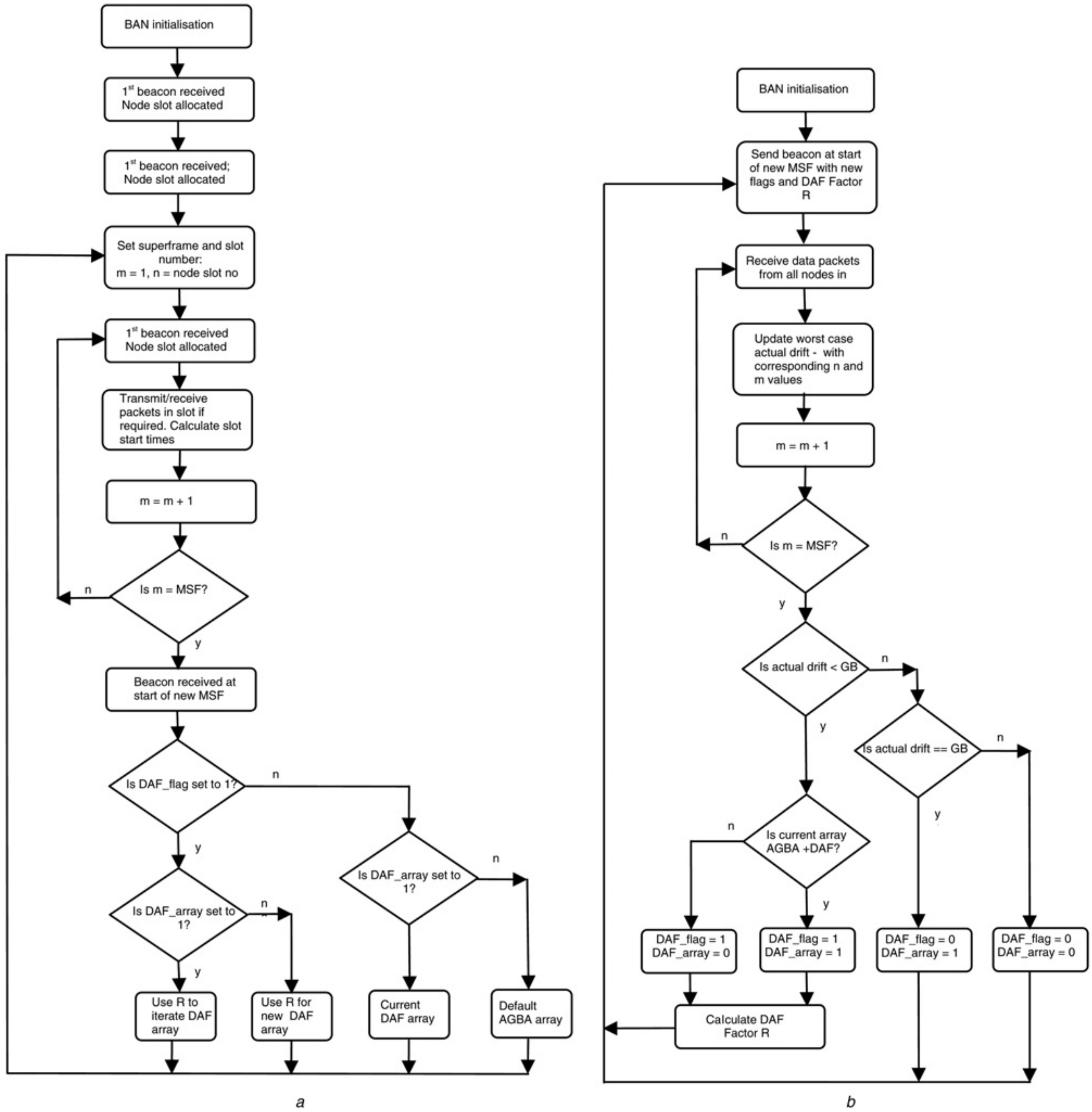

Fig. 5 *Flowchart for the AGBA/DAF process in node device and hub*

a Node AGBA/DAF process
b Hub AGBA/DAF process

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specification [13, 14]. The powered states and associated current draws for the transceiver are: 17.4 mA for transmit, 19.7 mA for receive, 426 μA for idle (crystal and voltage regulator both on) and 1 μA for sleep. Transmitting and receiving operations are responsible for the largest drain on node energy levels and the simulation model includes energy analysis which permits measurement of node transceiver energy savings for the new protocol.

3.1 Operation of AGBA with DAF

To illustrate the operation of AGBA and DAF and how it controls the GB durations to maintain synchronisation the simulation model was run under each scenario and the slot size recorded across the MSF. For both simulations the following controlled conditions were implemented: a timeslot of 2 ms duration, a BP of 0.1 s, maximum GB duration 2 ms with resulting maximum slot size (including GBs) of 0.6 ms. The combined crystal tolerance of two communicating devices was ±80 ppm, that is, ±40 ppm for each device [3], and from (1) these values limit the MSF to 250 BPs or 25 s. The simulation was run for 400 s which ensured enough time for the DAF operation to settle to a steady state.

Fig. 6 demonstrates the functioning of the AGBA algorithm with slot duration against time. Through one full MSF the slot duration increases from 2 to 6 ms over the 25 s period due to increasing GBs indicating that the node sleeps through all beacons except the beacons bounding the MSF. Receipt of the beacon allows the node to correct its time to network time and the slot is returned to its default duration of 2 ms and the process repeated for the next MSF.

The same scenario was repeated with DAF enabled and the slot duration increasing to 6 ms in the first MSF. Fig. 6 shows how the hub monitors the AD simulated at +10 ppm and reduces the GBs for subsequent MSFs until the slot duration including GBs reaches a steady-state value of approximately 2.5 ms, which reflects the slot size required for the actual drift. As seen from Fig. 6 the DAF algorithm allows the overall GBs to track the AD fluctuations, both positive and negative, every MSF, resulting in the energy savings which are demonstrated in the following experiments.

3.2 Energy performance of MedMAC

The following simulations quantify the energy savings that can be achieved by a node using the MedMAC with AGBA and DAF against waking up for a beacon every single superframe. The results of the simulations are plotted as energy consumed per node against the number of BPs per MSF for a range of low data packet rates. The results are also summarised in Table 4 at the end of this section. Two general scenarios are simulated to demonstrate the protocol performance: the first is where the node sleeps in the slot except during packet transmission and acknowledgment; in the second the node listens in the slot except during packet transmission. The parameters used for the simulation are given in Table 2.

3.2.1 AGBA mode – sleep-in-slot, three packet rates: The AGBA simulations were run for three packet rates while varying the MSF duration from 1 BP, up to the maximum MSF duration of 250 BPs. The node is in sleep mode between slots and only wakes up in the slot to transmit a packet and receive an acknowledgment. In this 'transmit-only' mode the nominal start of the slot (SST_{tx} in Fig. 4) is at the end of the first GB which means that GBs of the node should have little effect on the energy consumed by the node. Any drift between the node and the hub will impact on the hub GBs. However, the hub will often be a device with a rechargeable or mains power supply and therefore this effect has less impact on the overall system performance. Nonetheless, GBs are still required by the node for it to function in a BAN with neighbouring timeslots allocated to other nodes. It can be seen from Fig. 7 that there is a significant reduction in energy consumed as the MSF grows from 1 BP, illustrating the benefit of sleeping through beacons. This reduction tails off quite rapidly and there is little significant reduction when the MSF is greater than 30 BPs.

This scenario was repeated with DAF enabled with no difference to the results of Fig. 7 because the GBs do not impact on the energy consumed by the node in this 'transmit-only' scenario.

Table 2 Simulation parameters and assumptions

Simulation parameters	Values
crystal tolerance of device	±40 ppm [3]
timeslot duration	2 ms
superframe duration	0.1 s
data packet size	168 bits
beacon packet size	136 bits
Ack packet size	88 bits
transceiver wake up time	0 s
simulation time	600 s
MSF variation	1–250 BP
max guard band	0.002 s

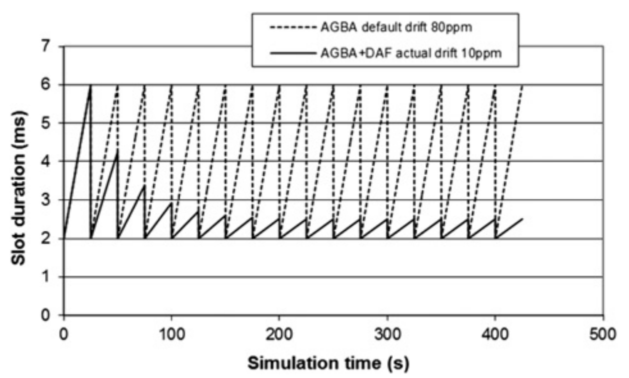

Fig. 6 *Slot size variance for AGBA and AGBA plus DAF MSF cycles*

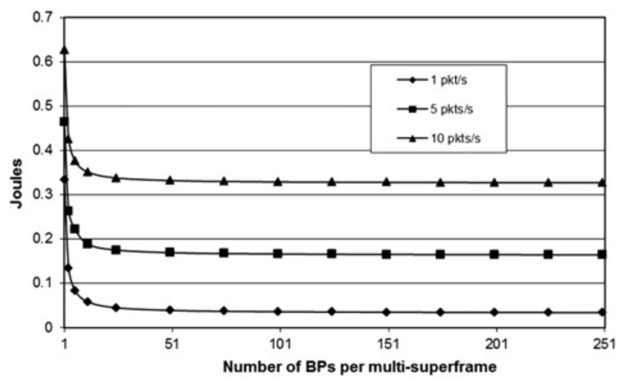

Fig. 7 *Energy consumed against number of beacons skipped for AGBA default – node sleeps in timeslot*

3.2.2 AGBA mode, receiver-on-in-slot, three packet rates: In this simulation AGBA mode was selected and energy consumed was measured against increasing MSF size, however, in this case the node is always awake and listening in its timeslot unless it is transmitting data packets. In Fig. 8 it can be seen that there is a significant drop in consumed energy as we increase the number of beacons skipped. However, energy consumption begins to rise again as the MSF increases in duration; this indicates a clear trade-off between the energy saving achieved by sleeping through beacons and the increased energy consumption caused by the receiver remaining on in a slot with growing GBs. This model permits the detection of optimal GB duration for maximum energy saving for any given scenario, that is, the minimum point on the graph in Fig. 8.

3.2.3 Comparison of AGBA and DAF modes – receiver-on-in-slot: The 'receiver-on-in-slot' case was re-simulated with DAF operational and with the assumption of an actual relative drift between the hub and the node of +10 ppm, in contrast with the worst case relative drift of ±80 ppm used for AGBA default simulations. A packet rate of 1 pkt/s was used to compare the two. Fig. 9 shows the DAF mode adds a further improvement in energy consumption by tracking the AD between the devices and reducing the GB required for each slot.

3.3 Energy efficiency comparison of MedMAC and IEEE 802.15.6 for ultra-low data rates

Simulations were undertaken to quantitatively compare energy consumption of nodes when operating in ultra-low data rate in star topology BAN for the IEEE 802.5.6 and

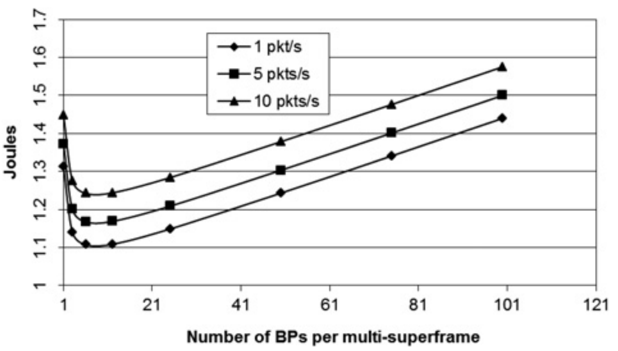

Fig. 8 *Energy against number of beacons skipped for AGBA default – node receiver-on-in-slot*

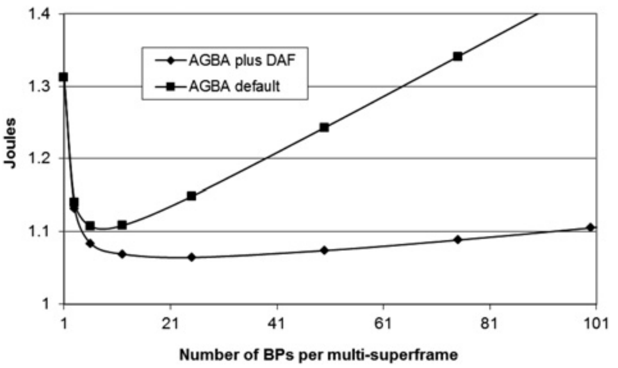

Fig. 9 *Comparison of AGBA and DAF energy consumption – node receiver on timeslot, packet rate 1 pkt/s*

the MedMAC MAC protocols. The draft IEEE 802.15.6 standard [5] defines narrowband (NB), ultra-wide band and human body communications physical layers and a common frame structure. The standard specifies three access modes, the first of which is used for our analysis

- Beacon mode with BP superframe boundaries.
- Non-beacon mode with superframe boundaries.
- Non-beacon mode without superframe boundaries.

The timebase is divided into equal length superframes bounded by a beacon and each superframe is divided into allocation slots. In the first access mode synchronisation of the BAN and the superframe structure is maintained by the beacons and T-poll frames sent by the hub. The draft IEEE 802.15.6 superframe structure allows three types of access, the third of which is used for the analysis

- Random access (contention based) CSMA/CA for NB.
- Improvised, unscheduled access with posts and polls from hub; devices must be awake.
- Scheduled access (contention free), frames exchanged in reserved allocation slots.

The draft defines four acknowledgement policies: not-acknowledged (N-ACK); immediately acknowledged (I-ACK); block-acknowledged later (L-ACK); and block acknowledged (B-ACK). For our comparative analyses the IEEE 802.15.6 mode required is NB, beacon mode, with scheduled access, and immediate acknowledgments.

In terms of energy saving, the IEEE 802.15.6 optionally allows a node to completely sleep through m beacons, (m-periodic allocations) and which may have to re-synchronise upon waking up. In contrast, the MedMAC AGBA plus DAF mechanism allows the node to sleep through many BPs but with the advantage of being able to wake-up and transmit or receive in an allocated timeslot at any time in the MSF without having to re-synchronise. Synchronisation in the IEEE 802.15.6 between the node and hub will be maintained using clocks with a specified accuracy of ±20 ppm, combined with a nominal guard time (GT_n) fixed at value proportional to a nominal synchronisation interval (SI_n) equivalent to $8 \times \mathrm{BP}$. If the elapsed time since the last synchronisation timestamp is less than or equal to SI_n then the guard time is GT_n. If the elapsed time is greater than SI_n then an additional guard time GT_a is factored in, based on the additional time, that is, synchronisation interval (SI_a).

3.3.1 Simulation conditions: To ensure the node is awake in every superframe available for data transfer as per the MedMAC it is assumed that the IEEE 802.15.6 BAN is operating in 1-periodic mode. For typical current consumption values we referenced the Micaz incorporating Texas CC2420 [13, 14] with conditions as stated in Section 3. As we are comparing the draft IEEE 802.15.6 standard to MedMAC we also include the wake up conditions for this device in the following simulations for more authentic results (Table 3).

As these scenarios are focussed on ultra-low power and data rate conditions, the slot size was chosen to be 2 ms duration. The IEEE 802.15.6 standard [5] offers seven frequency bands with a range of modulation schemes, code rates, spreading factors, together with information data rates ranging from 57.5 to 971.4 kbps. For these simulations a representative scenario was selected from the 868/915 MHz

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Table 3 Micaz wake up conditions

State	Current
sleep (volt reg off)	1 μA
volt reg start-up (0.3 ms)	20 μA
crystal start up (1 ms)	426 μA (assumed same as idle)
RX/TX turnaround (192 μs)	426 μA (assumed same as idle)

bands, with modulation $\pi/4$-DQPSK, symbol rate 250 ksps and information data rate 404.8 kbps. Minimum 802.15.6 packet lengths were selected: beacon 407 bits; acknowledgement 295 bits and data $295 + n$ octets. In all simulations each MAC packet is immediately acknowledged. For MedMAC devices the assumed crystal tolerance is ± 20 ppm as per IEEE 802.15.6 specification (with this tolerance, slot size, and MSF of duration 250 BP, the maximum GB is limited to 1 ms); for the DAF condition we assumed an AD equivalent to $+5$ ppm which is proportional to the ratio of AD to overall crystal tolerance of the previous simulations in Section 3.2.3 ensuring a meaningful comparison. A bit rate of 250 kbps is assumed for MedMAC.

3.3.2 Comparison of IEEE 802.15.6 and MedMAC – sleep-in-slot: In this simulation we compare the energy consumed by the IEEE 802.15.6 and MedMAC in a scenario where the node sleeps in the MSF and its timeslot except when transmitting a packet or receiving an acknowledgment. The 802.15.6 nodes cannot sleep through any BPs because they need to be awake to send data and receive acknowledgments, while the MedMAC node will sleep through beacons while maintaining synchronisation permitting data packet and acknowledgement transfer. The results are from a MedMAC node with MSF of 250 BPs. As with the results of Section 3.2.1 there is very little difference between the AGBA and DAF because GBs do not significantly affect node energy consumption in a transmit-only scenario. Fig. 10 shows that MedMAC has an energy saving over IEEE 802.15.6 that ranges from 43 to 87% across a packet rate from 10 to 1 pkt/s, respectively, for a minimal data packet length of 300 bits. It also illustrates the change in energy consumption as data packet length is increased from 300 to 500 bits – the maximum that can be transmitted in the given slot (Table 4).

3.3.3 Comparison of IEEE 802.15.6 and MedMAC – receiver-on-in-slot: In this simulation the node listens in the slot for packets from the hub (radio receiver ON), except when it is transmitting data. The IEEE 802.15.6 node requires the GT to be invoked, and from [5] is calculated for a BP of 0.1 s. In this scenario the AGBA with DAF achieves optimal energy performance for all packet rates when the MSF duration is set to 42 BPs. An arbitrary low data IEEE 802.15.6 packet length of 295 + 4 octets payload was chosen. The results of this simulation are shown in Fig. 11, where the energy consumed is plotted across a range of packet transmission rates. AGBA shows a minimum energy saving ranging from 25.9% at 10 pkt/s to

Table 4 Summary of results showing energy savings of MedMAC

MAC packet tx rate		One packet/s, %	Five packet/s, %	Ten packet/s, %
Energy saved by MedMAC by sleeping through beacons (pkt = 168 bits)				
AGBA – sleep-in-slot		90.0	64.6	48.0
AGBA – rx-ON-in-slot		15.7	15.0	14.4
DAF – rx-ON-in-slot		19.0	–	–
Energy saving of MedMAC over IEEE 802.15.6				
sleep-in-slot with variable tx packet size	300 bits	86.9	60.2	43.4
	400 bits	85.5	56.8	40.0
	500 bits	84.0	53.8	37.1
DAF rx-ON-in-slot	327 bits	33.2	30.5	27.7
AGBA rx-ON-in-slot	327 bits	30.8	28.3	25.6

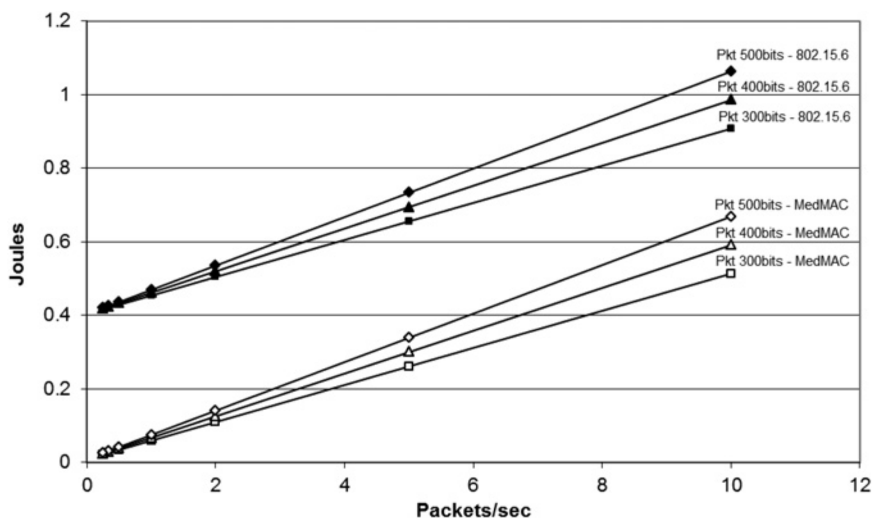

Fig. 10 *Energy consumed against packet rate for IEEE 802.15.6 and MedMAC modes – sleep-in-slot*

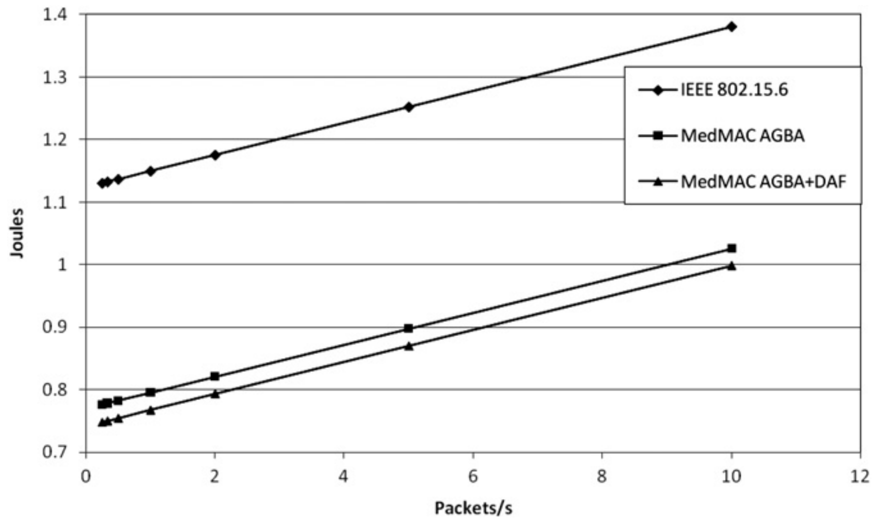

Fig. 11 *Energy consumed against packet rate for IEEE 802.15.6 and MedMAC modes – receiver-on-in slot*

31.0% at 1 pkt/s, and for DAF with AD of +5 ppm, an improved saving of 27.7% at 10 pkt/s to 33.2% at 1 pkt/s is achieved.

4 Conclusions

We have presented the MedMAC protocol with the AGBA and DAF synchronisation mechanism and demonstrated the significant energy savings that could be achieved in ultra-low power BANs. Two simulation sets were performed: the first compared the energy performance of MedMAC using AGBA and DAF, with a standard TDMA MAC which wakes up for every beacon; the second compared the energy consumption of MedMAC with the emerging draft IEEE 802.15.6 standard for BANs. The results are summarised in Table 4.

In the first scenario of transmit-only mode with sleep-in-slot, we see that AGBA can deliver an energy saving of 90 to 48% for the packet rates 1 to 10 pkt/s, respectively. With the receiver ON for the duration of the timeslot, AGBA provided energy savings of 15.7 to 14.4% for the packet rates 1 to 10 pkt/s, respectively; with DAF invoked, improved energy savings of 19% were demonstrated at 1 pkt/s with AD set to +10 ppm.

When comparing IEEE 802.15.6 with MedMAC in transmit-only mode, the results show that MedMAC can deliver an energy saving of 86.9 to 43.4% for the packet rates 1 to 10 pkt/s, respectively, for a minimal IEEE 802.15.6 data packet length. We also examined the effect of increasing the data packet length from 300 to 500 bits which as expected demonstrated larger energy savings for lower data rates and packet lengths; however, MedMAC still produced a saving of 37.1% for a packet of 500 bits at 10 pkts/s. With the receiver ON for the duration of the timeslot, MedMAC displayed a marked improvement in energy consumption over the 802.15.6 with an energy saving of 30.8 to 25.6% for AGBA and 33.2 to 27.7% for AGBA + DAF (AD +5 ppm), for the packet rates 1 to 10 pkt/s, respectively. The lower the AD, the greater the energy savings of MedMAC.

Although the IEEE 802.15.6 incorporates a nominal GT to compensate for drift in synchronisation, it is a blunt tool being fixed in value for a given BP regardless of time elapsed from the last synchronisation or the actual drift. It has been shown that the synchronisation algorithm of MedMAC with adaptive GBs can provide significant energy savings in ultra-low power mode. Our future work will develop the MedMAC to incorporate variable timeslot lengths and two-hop topology.

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