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Asynchronous Power Saving Schemes for Ad Hoc Wireless Networks

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Abstract: In this study, we introduce novel power saving schemes for multihop wireless networks. The proposed schemes achieve high energy efficiency and good network throughput without using any global clock synchronization scheme. The main idea of the proposed power saving schemes is to dynamically adjust the length of the beacon interval based on the communication demand. Due to this dynamic adjustment of the beacon period, mobile nodes can sleep longer if they are not involved in any active communication and achieve both high energy-efficiency and high network throughput. We conduct a comprehensive simulation study to evaluate the efficiency of the proposed protocols in terms of energy consumption, network throughput, latency and packet loss ratio. The results of our simulation study show that the proposed dynamic beacon interval adjustment approach performs very well and energy efficient. Especially, the result of one of the proposed protocol is really promising. This scheme conserve about 40% of battery power without compromising throughput compared to IEEE 802.11 Power Saving Scheme.

Key words: Asynchronous wakeup, power saving, IEEE 802.11 PSM, ad hoc networks

INTRODUCTION

An ad hoc network consists of a number of wireless nodes without any fixed base station or wired backbone infrastructure. Because an ad-hoc network does not rely on existing infrastructure and is a self-configurable network, it can be rapidly deployed in applications such as tactical communication for military, search and rescue mission, disaster recovery, etc. In multihop wireless networks, two hosts can communicate directly with each other if they are located within their radio range. If the destination is located outside of the sender's transmission range, a packet is relayed via intermediate nodes located between the two nodes (Bergamo *et al*., 2004; Xu *et al*., 2001).

Since nodes in an ad hoc network are operated using scarce battery power and since battery life is not expected to increase significantly in the near future, energy efficiency is one of the most important design aspects of mobile networks. As a result of that, there have been a number of research activities in designing energy efficient protocols for mobile ad hoc networks (Gomez *et al*., 2001; Sagduyu and Ephremides, 2003; Zheng and Kravets, 2005).

According to the results of several experimental studies in the literature (Chen *et al*., 2002; Stemm and Katz, 1997), the energy consumption of wireless devices in the idle state is only slightly less than that of the transmitting or receiving state. From these experimental results, we can easily see that data traffic is not a primary source of energy consumption of wireless units. Therefore, a power saving protocol should reduce the idle energy consumption by shutting off the radio device when it is not used (Heinzelman *et al*., 2000; Intanagonwiwat *et al*., 2003).

In this study, we have proposed a novel power saving approach that achieves high energy efficiency without degrading network performance considerably. The proposed schemes are asynchronous and so they do not require synchronization of the local clocks. The main idea of the proposed schemes is the dynamic adjustment of a beacon interval length based on communication requirements in order to reduce the energy consumption of idle listening. When network communication requirements decrease, the length of the beacon period increases and so does the sleeping period. On the other hand, the length of the beacon frame reduces if there are high communication demands. With this dynamic adjustment of the beacon intervals, the proposed schemes achieve both high energy-efficiency and high network performance at the same time.

Since the proposed schemes are based on the IEEE 802.11 Distributed Coordination Function (DCF) power saving methods, we first briefly discuss the 802.11 standard here. In IEEE 802.11 DCF Power Saving Mode (PSM), time is divided into so-called beacon intervals and each beacon interval starts with a fixed time interval called an Ad hoc Traffic Indication Message (ATIM) window.

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All nodes must wake up at the beginning the ATIM window and remain awake until the end of the ATIM window. At the beginning of each ATIM window, the nodes contend to send a beacon message. Any successful beacon message serves as the purpose of synchronizing mobile nodes' clock.

After receiving the beacon, a node with buffered unicast packets can send an ATIM frame to its intended receiver using a contention-based protocol. First, it picks a random back-off interval in the range (0, cw), where cw denotes the size of contention window. The back-off interval decreases by 1 after each clock tick when the channel is idle. Once the back-off interval reaches 0, an ATIM frame is transmitted. When a node receives an ATIM frame, it replies with an ATIM-ACK.

The IEEE 802.11 power saving scheme is capable of reducing the power consumption of each mobile terminal in a single-hop wireless network. However, the IEEE 802.11 Power Saving scheme has some issues yet to be solved for multi-hop wireless ad hoc networks. First, it requires tight clock synchronization which is very hard to achieve in ad hoc networks. Second, the unsynchronized ATIM windows among neighboring nodes can cause network partitioning. If ATIM windows of power saving hosts are not properly synchronized, they may wake up at different times and networks can be divided into several synchronized groups. Furthermore, in IEEE 802.11 PSM, all nodes should periodically wake up and listen to ATIM messages from neighboring nodes. This periodical listening would result in considerable energy wastage for nodes not involved in any active communications.

ASYNCHRONOUS POWER SAVING SCHEMES

Power conserving schemes in wireless communications in one of the most extensively studied research topics and many multiple access protocols have been proposed for wireless network (Monks *et al*., 2001; Raghavendra and Singh, 1998; Ye *et al*., 2000). However, there have been relatively few studies for asynchronous wake-up mechanisms (Feeney, 2002; Zheng *et al*., 2003). Most asynchronous approaches proposed in the literature use a fixed beacon period. However, power conserving schemes with a fixed beacon interval period are not flexible enough to dynamically respond to the network load. For example, in a network with low traffic volumes, a fixed beacon interval scheme unnecessarily wastes battery power due to periodic wake-up tasks. In order to address this issue in fixed-beacon power saving schemes, we design asynchronous power saving schemes with dynamic adjustment of beacon interval. One of the major challenges of asynchronous power saving approaches is ensuring the overlap between a power saving node's wake-up time and that of its neighbors. This is a very important requisite of asynchronous approaches since a node cannot deliver any data packet to a neighboring node if the neighbor is in the sleep mode. Therefore, a sleep/wake-up scheduling scheme must ensure sufficient overlapping of wake-up periods for any pair of power saving nodes to allow message exchange.

The goal of the proposed schemes is to extend network lifetime as much as possible while maintaining acceptable throughput and delay in asynchronous networks. To do this, the proposed schemes conserve battery power by turning radio device off and also attempt to reduce the communication delay by adaptively controlling the length of a beacon interval.

The key differences between the proposed schemes and the IEEE 802.11 PSM are summarized below:

- **Asynchronous:** The proposed protocols do not require global clock synchronization and hence eliminate synchronization overhead.
- **Dynamic adjustment of the length of the beacon interval:** In the IEEE 802.11 PSM protocol, a node wakes up periodically to check for arrival of ATIM frames. This periodical wake-up can be advantageous for a node actively communicating with others. However, some nodes may waste their scarce energy for idle listening without having any data exchanges. The proposed schemes allow such nodes to increase their beacon intervals to reduce energy consumption.
- **Beacon interval announcement:** In the proposed schemes except CIAD, an ATIM frame contains the length of sender's beacon interval. When a node receives an ATIM frame destined to it, it sets its beacon interval to the advertised value in the received ATIM frame. Therefore, after the first handshaking, both the sender and receiver can synchronize their wake-up cycles continuously.

Beacon interval adjustment: The focus of the study is dynamic adjustment of the length of the beacon interval. Before discussing the proposed approach, we first need to introduce a new beacon structure used in the proposed schemes. The structure of a beacon frame is shown in Fig. 1. A beacon interval consists of three parts; a fixed-size ATIM window, a Base Beacon Interval (BBI) and an Extended Beacon Interval (EBI). During the ATIM window, a node must stay awake and listen to the channel. However, during BBI and EBI, a node turns off its radio to preserve energy, if it does not transmit or receive an ATIM message. The length of the ATIM window and BBI is fixed, but the duration of an EBI is dynamically adjustable based on the communication

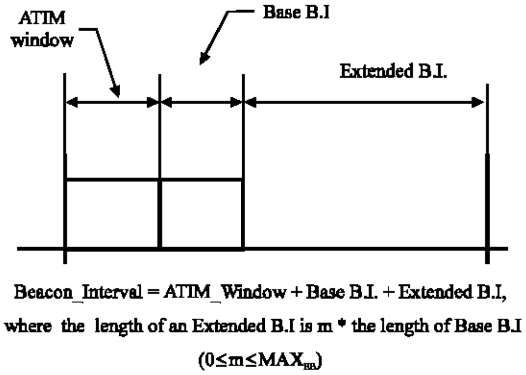

Fig. 1: Proposed Beacon interval structure

requirements of each node. The length of an EBI is m* the length of a base beacon interval, where $0 \leq m \leq MAX_{EB}$. Note that the duration of the ATIM window plus a base beacon interval must be shorter then the duration of beacon interval in IEEE 802.11 PSM. Due to the asynchronous property of the proposed schemes, a node may receive an ATIM frame from a neighboring node during BBI. On reception of an ATIM frame, the node should reply with an ACK and stay awake until it receives data from the ATIM frame sender.

The basic idea is as follows. When a node does not have any active communication with a neighbor, it increases the length of EBI to conserve power. As a result of this EBI incensement, the sleeping period also increases. But, if a node has a packet to transmit or receive an ATIM request from a neighboring node, it shortens its beacon interval by reducing the duration of EBI.

Since the proposed approach is asynchronous, a sender may transmit an ATIM frame while its receiver is in the sleep mode. Then, the sender chooses a random back-off period and resends the ATIM message again after waiting the back-off period. The conventional binary exponential back-off algorithm (Crow *et al.*, 1997) will be used to select the back-off period and this process will be repeated until the end of the ATIM window. The sender may try again at the beginning of its next beacon interval. If it fails more than a maximum retrial limit (ATIM-MaxRetry) which is set to 10 in our experiments, the sender drops the current packet and advances to the next one.

Now we describe algorithms for dynamic adjustment of the extended beacon interval. There are three events that trigger a change in the length of an extended beacon interval:

- **Event PTS (Packet To Send):** If a node has a packet to send, it should transmit an ATIM frame to a neighboring node. Thus, in order to cut down packet delay, the node shortens EBI using one of the proposed beacon-interval adjustment schemes.
- **Event RAM (Receiving an ATIM Message):** Upon the reception of an ATIM frame, a receiving node decreases the length of the extended beacon interval using the adjustment schemes discussed below.
- **Event CIL (Consecutive Idle Listening):** If a node does not receive any ATIM message and if it does not have any pending packet to transmit during the period of the ATIM window and BBI, it increases an idle counter by 1. If the idle counter reaches k $(k > 0)$, then the node sets k to 0 and increases m according to beacon-interval adjustment rules.

From now, we focus on the dynamic beacon interval adjustment schemes proposed in the paper. The proposed power saving protocols increase or decrease m in order to dynamically adjust the length of extended beacon interval. For every scheme, m is set to 0 initially and grows up to MAX_{EB} which is set to 15 for the proposed schemes.

Cyclic Increase Aggressive Decrease (CIAD): This protocol is more focused on latency than on energy efficiency. CIAD increases m by 1 for k consecutive idle listening periods (event CIL) until it reaches MAX_{EB}. Once m reaches MAX_{EB}, it will be back to 0 in the next beacon period. In CIAD, for any active communication event (an event PTS or an event RAM), the size of an extended beacon interval (m) will be set to 0. Figure 2 shows the pseudocode of the CIAD scheme. With this scheme, the network latency will be very short since CIAD aggressively decreases m to 0 when a node needs to communicate with its neighbor. However, due to the aggressive decrease of m, CIAD consumes more power than other proposed schemes in the study.

Cyclic Increase Multiplicative Decrease (CIMD): This protocol is similar to CIAD. To reduce energy consumption, CIMD increases m by 1 for a k consecutive idling event. The differences between CIMD and CIAD are as follows; for a PTS event, CIMD decreases m by half of the current EBI size and for a RAM event, m will be set to the value of the advertised beacon interval in the received ATIM frame. The pseudocode of CIMD is shown in Fig. 3.

Linear Increase Multiplicative Decrease (LIMD): The LIMD scheme is more concerned with energy efficiency than latency. In order to reduce energy consumption,

```
Procedure CIAD( )
Initialization: $MAX_{EB} = 15$
                $m = 0$
while (true) {
   switch (event) {
      case: event CIL
         if ($m == MAX_{EB}$) $m = 0$
            else $m = m + 1$

      case: event PTS or event RAM
         $m = 0$
   }
}
```

Fig. 2: Pseudocode and example of CIAD

```
Procedure CIMD( )
Initialization: $MAX_{EB} = 15$
                $m = 0$
while (true) {
   switch (event) {
      case: event CIL
         if ($m == MAX_{EB}$) $m = 0$
            else $m = m + 1$

      case: event PTS
            $m = \left\lfloor \frac{m}{2} \right\rfloor$

      case: event RAM
      /* the value in the received ATIM message */
      m = advertised EBI in the received ATIM
}
```

Fig. 3: Pseudocode of CIMD

```
Procedure LIMD( )
Initialization: $MAX_{EB} = 15$
                $m = 0$
while (true) {
   switch (event) {
      case: event CIL
         if ($m < MAX_{EB}$) $m = m + 1$

      case: event PTS
            $m = \left\lfloor \frac{m}{2} \right\rfloor$

      case: event RAM
      /* the value in the received ATIM message */
          m = advertised EBI in the received ATIM
   }
}
```

Fig. 4: Pseudocode of LIMD

LIMD also increases m linearly for Event CIL. However, when m reaches MAX_{EB}, m will not be decreased. Instead, LIMD keeps the maximum value (m = 15) until it has a packet to send or receives an ATIM frame. For PTS event, LIMD sets m to the half of the current value; m = m/2. After receiving an ATIM message, a node sets its beacon interval to the advertised beacon interval value in the received message. Figure 4 depicts how LIMD changes the length of the extended beacon interval.

```
Procedure MIMD( )
Initialization: $MAX_{EB} = 15$
                $m = 0$
while (true) {
   switch (event) {
      case: event CIL
         if ( $2 * m < MAX_{EB}$) $m = m * 2$
            else $m = MAX_{EB}$

      case: event PTS
            $m = \left\lfloor \frac{m}{2} \right\rfloor$

      case: event RAM
      /* the value in the received ATIM message */
         m = advertised EBI in the received ATIM
   }
}
```

Fig. 5: Pseudocode of MIMD

Multiplicative Increase Multiplicative Decrease (MIMD): The MIMD scheme aims at maximizing battery life by increasing the sleeping time. Although the MIMD protocol is similar to LIMD, it further conserves energy by doubling the size of the extended beacon interval (m) for the idle listening event (event CIL). The following pseudocode in Fig. 5 describes the MIMD scheme.

SIMULATION STUDY

We have conducted a simulation study to evaluate the performance of the proposed asynchronous power saving schemes. In this section, we first discuss the simulation environment and metrics used in the study and then present the results of our simulations with a brief analysis and discussion.

The proposed power saving protocols are implemented in ns-2 (Fall and Varadhan, 2007) with CMU wireless extensions and all nodes use the IEEE 802.11 radio and MAC model provided by the ns-2 simulator. We simulate a wireless LAN environment with 10 mobile nodes that are distributed in a 1000×1000 m field as shown in Fig. 6. In all considered scenarios, Constant Bit Rate (CBR) traffic is used for evaluation and transmission range is set to 250 m. Each simulation run lasts for 900 seconds of simulated time. A node's transmitting, receiving, idling and sleeping power consumption rates are set to 1.4, 1.0, 0.83 and 0.13 W, respectively. Each

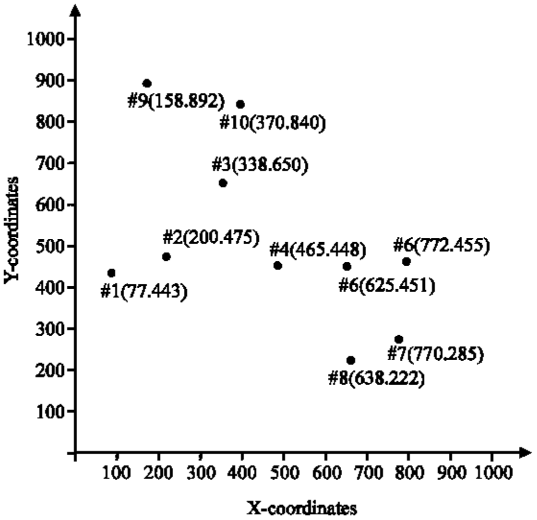

Fig. 6: Node layout

node has an initial energy of 1000J. We set k to 3 in this study; i.e., after 3 consecutive idle listening periods, a node increases m. The number of maximum retransmission before dropping packet (ATIM-MaxRetry) is set to 10 for the proposed protocols and 3 for both 802.11 and PSM.

In this comparison study, we evaluate the following protocols: IEEE 802.11 without power saving mode (802.11), IEEE 802.11 with Power Saving Mode (PSM), Cyclic Increase Aggressive Decrease (CIAD), Cyclic Increase Multiplicative Decrease (CIMD), Linear Increase Multiplicative Decrease (LIMD) and Multiplicative Increase Multiplicative Decrease (MIMD). The performances are measured by the following metrics:

- **Energy consumption:** The energy consumption is defined as the sum of each node's energy consumption in the transmitting, receiving and idling modes.
- **Energy efficiency:** This is defined as the ratio of the total energy consumption over the sum of each node's throughput. We use joule per bytes as a measurement of energy efficiency.
- **Average network throughput:** The average network throughput is defined as the ratio of the total number of received bytes during the simulation over the number of nodes.
- **Average network latency:** This is an average time interval between the packet being ready and the packet arriving at the destination.
- **Average data loss ratio:** This is defined as the ratio of the total number of lost packets over the total number of transmitted packets during the simulation.

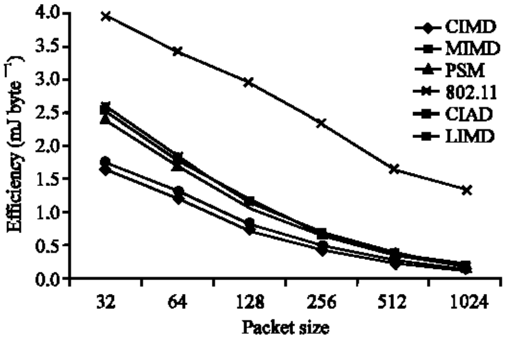

Fig. 7: Energy efficiency vs. packet size

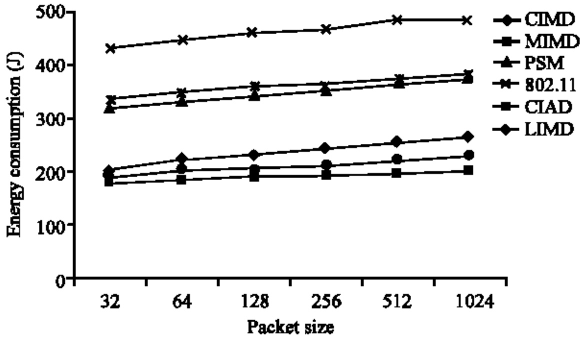

Fig. 8: Energy consumption vs. packet size

Impact of the packet size: We first discuss the impact of packet size on the proposed power saving schemes. In this experimental study, we vary packet size from 32 bytes to 1024 bytes.

Figure 7 shows the energy efficiency of the protocols considered in the study. In terms of energy efficiency, CIMD outperform others in most simulated scenarios. Especially, the differences between CIMD and other schemes are significant in the case of small packets. As the packet size increases, the energy efficiency of other power saving schemes improves consistently and becomes close to that of CIMD. This is because, as the packet size increases, the amount of energy consumption for productive communications increases accordingly.

As we expected, both LIMD and MIMD reduce energy consumption significantly (Fig. 8). However, the latency and throughput of LIMD and MIND are not as good as others. This is due to the fact that, in LIMD and MIND, the nodes stay the maximum extended beacon interval until they receive an ATIM frame from a neighboring node. Because of this long sleeping period, a receiver can be hardly synchronized with an ATIM sender and so the sender holds a packet for a long time. As a result of that, LIMD and MIMD have relatively high data loss rate due to buffer overflow. In many simulated scenarios, CIAD outperforms PSM in terms of throughput, latency and data loss although CIAD shows slightly higher energy consumption than PSM. Overall,

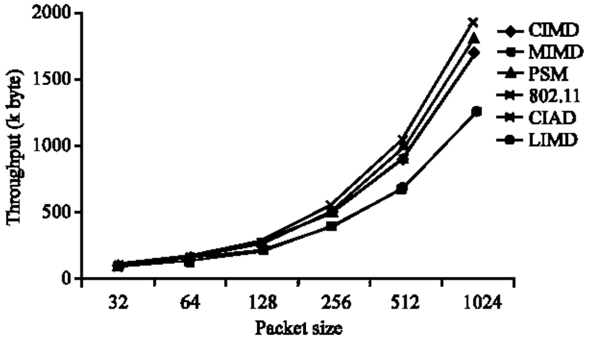

Fig. 9: Network throughput vs. packet size

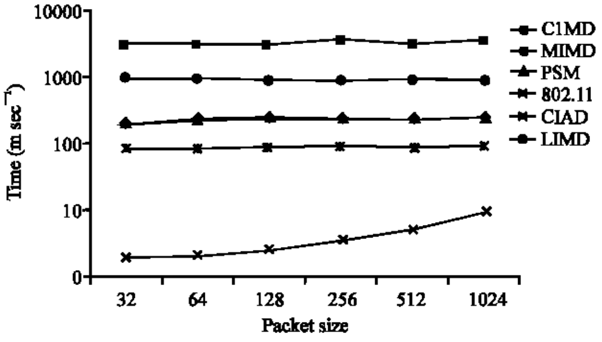

Fig. 10: Network latency vs. packet size

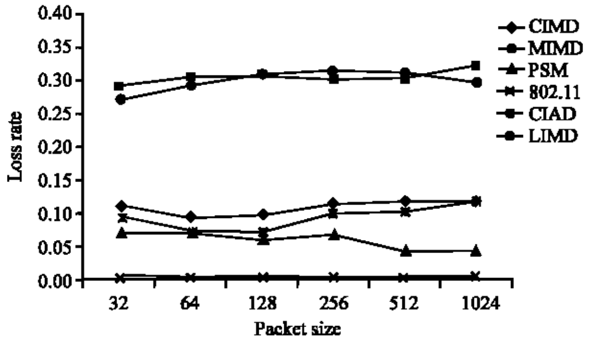

Fig. 11: Data loss rate vs. packet size

CIMD shows very good energy efficiency while maintaining network throughput high: the energy consumption of CIMD is only 60% of that of PSM and the throughput and network latency of CIMD are very similar to those of PSM. PSM just slightly outperforms CIMD in terms of throughput. Both CIMD and PSM have 0.2 seconds average network latency as shown in Fig. 9, 10 and 11 plots the data loss ratio. The average data loss ratio of the CIMD and PSM are around 10 and 5%, respectively.

Impact of node's mobility: In this subsection, we discuss the impact of the node's mobility. Mobile nodes move according to the random way-point model (Fall and Varadhan, 2007) with a speed of 10 meters per second. To study the impact of node's mobility, we consider the following simulation cases:

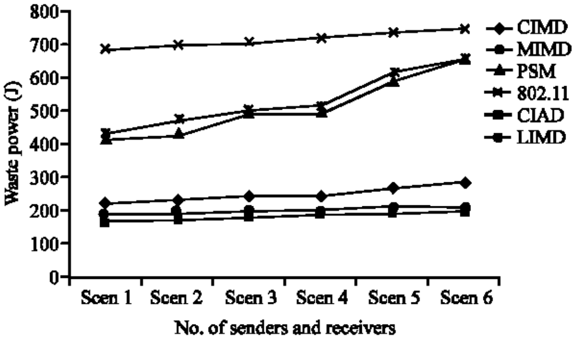

Fig. 12: Energy consumption vs. mobility

- **Scenario 1:** One CBR traffic from a randomly selected mobile source to a random static node is used during 900 sec simulation time. Only the sender is mobile and all other nodes are static.
- **Scenario 2:** There are two CBR connections in the scenario. Two senders are mobile and all others including the receivers are static.
- **Scenario 3:** Three source-destination pairs are randomly chosen to simultaneously transmit CBR data packets. There are 4 mobile nodes which are either the senders or receivers of the CBR connections. All others are static in the scenario.
- **Scenario 4:** There are three CBR connections and 6 mobile nodes. All the senders and receivers of the CBR traffics are mobile in this scenario.
- **Scenario 5:** Eight nodes are randomly selected for four CBR connections and they are mobile. There are only two static nodes in the scenario.
- **Scenario 6:** Each node acts as either a mobile sender or a mobile receiver and five CBR connections run in parallel during whole simulation time.

Figure 12 and 13 show the energy performance of the discussed methods in the study. CIMD, LIMD and MIMD outperform PSM in terms of energy consumption and energy efficiency. However, LIMD and MIND have quite high data loss ratio as shown in Fig. 15 and 16. CIMD also shows higher data loss ratio compare to the result of the static simulation scenarios. Overall, asynchronous schemes do not perform quite well in mobile networks. This is because, in mobile networks, the exchange of ATIM frames is more challenging due to the nodes mobility. We notice that the proposed

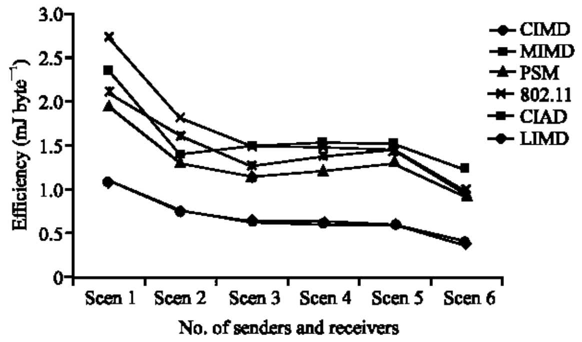

Fig. 13: Energy efficiency vs. mobility

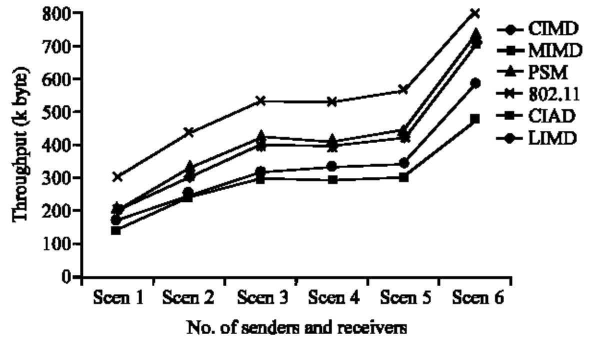

Fig. 14: Network throughput vs. mobility

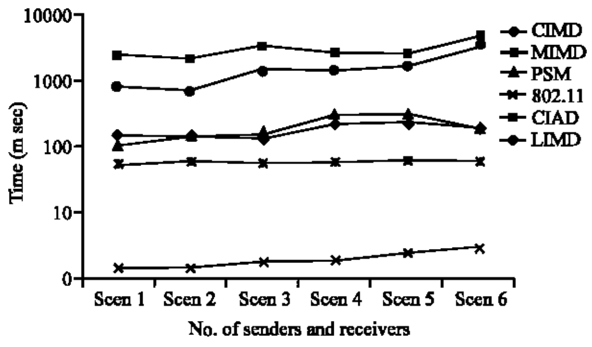

Fig. 15: Network latency vs. mobility

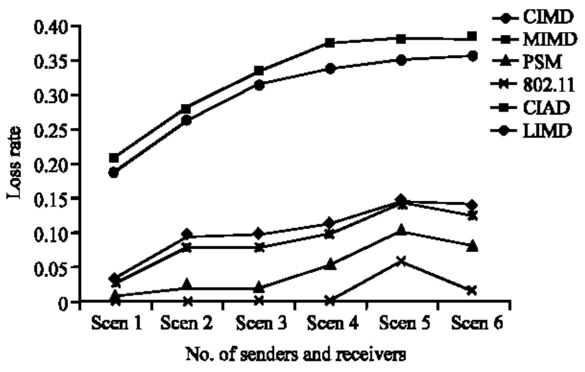

Fig. 16: Data loss rate vs. mobility

asynchronous power saving protocols drop a number of packets because of ATIM frame exchange failures.

CONCLUSION AND FUTURE WORK

This paper presents a new approach to provide an energy-efficient solution for battery-constrained wireless networks. In the proposed schemes, a beacon interval consists of three parts; a fixed-size ATIM window, base beacon interval and extended beacon interval. During the ATIM window and base beacon interval, a node stays awake and monitors the channel. The length of the ATIM window and base beacon interval is fixed, however the duration of an extended beacon interval is dynamically adjustable based on the communication requirements of each node. Due to the dynamic adjustment of the length of the beacon interval, the proposed schemes have higher energy-efficiency while, at the same time, avoiding network performance degradation.

We also present experimental results on simulated wireless networks. The results of this simulations validate the efficiency of the proposed protocol. The proposed power saving schemes can save considerable battery power with reasonable network latency and data delivery rate. As shown in the simulation study, the energy consumption of CIMD is only 60% of that of IEEE 802.11 PSM and the throughput and network latency of CIMD are very similar to those of IEEE 802.11 PSM. In case of low data traffic volume, the proposed schemes show the best improved performance over IEEE 802.11 PSM (Fig. 14). However, in the mobile networks, the asynchronous power saving protocols suffer from high packet loss and latency due to ATIM frame exchange failures. Based on these simulation results, we conclude that the proposed asynchronous schemes are better suited for static ad hoc networks or mobile networks with low node mobility.

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