A Hybrid MAC with Intelligent Sleep Scheduling for Wireless Sensor Networks

Mohammad Arifuzzaman
Waseda University, Tokyo, Japan
arif@fuji.waseda.jp
Outline of Presentation

- Introduction
- Standardization of MAC protocol for Sensor Network
- Proposed MAC protocol
- Result & Discussion
- Summary
Introduction

- Wireless sensor networks (WSNs) have become very popular in recent years.
- The sensor nodes are typically
  - small,
  - low-cost, and
  - equipped with low-powered battery
- **Prolonging lifetime** of sensor nodes is definitely a critical issue.
- Therefore, in order to design a MAC protocol for WSNs it is important to consider **energy efficiency**. The other important attributes are latency, delivery ratio, fairness etc.
Introduction

- **Idle listening** is the major source of energy wastage for WSNs.
- Therefore, **nodes** do not wake-up all the time to maximize throughput and minimize delay.
- Rather, nodes **prefer energy preservation by going to sleep from time to time**.
- So, a straightforward approach can be to **assign each communication link a time slot**.
- But this scheme requires much **more time slots** than necessary.
Introduction

- Minimizing the number of slots assignment for an interference free link scheduling is a NP complete problem.
- Broadcast scheduling is less energy efficient.
- Henceforth, we propose a new hybrid MAC protocol for wireless sensor network, called IH-MAC (Intelligent Hybrid MAC), which combines –
  - the strength of CSMA,
  - pair wise TDMA (link scheduling)
  - broadcast TDMA.
The first step of standardization for low rate wireless personal area networks was taken in 2003 when IEEE 802.15.4 was approved. IEEE 802.15.4 standard specifies only the lowest part of OSI communication model: PHY layer and MAC sub-layer. But unlike 802.11 WLAN cards where MAC is usually included as part of the chipset, in WSNs the MAC designer has absolute control on the design of MAC layer.
Standardization of MAC protocol of WSNs considering Proposed IH-MAC and other existing S-MAC, T-MAC etc

**Fig 1.** Structure of IEEE 802.15.4 protocol stack and the area of our proposed work
Proposed MAC Protocol

- Each slot in IH-MAC is a periodic interval which consists of:
  - fixed length SYNC period,
  - fixed length Listen period (For RTS/CTS)
  - sleep period.
- Nodes are allowed to transmit in any slot, but **owner** of the slot will get the **priority**.
- **Contention window size** ensures priority.
- Each node can make some of its owned slot as a **rendezvous slot**.
- A **rendezvous slot** is a slot explicitly dedicated to a pair of nodes to communicate.
Proposed MAC Protocol

- **Owner calculation** is performed by each sensor node **locally** by **clock arithmetic**.
- Let there are 8 neighbor nodes (every node is 1 or 2-hop neighbor to each other),
- T1, T2...represent the slot sequences and S1, S2...represent the sensor nodes.
- According to clock arithmetic (mod 8) sensor node **S1** will be the **owner** of slot T1 & T9.

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>T2</td>
<td>T3</td>
<td>T4</td>
<td>T5</td>
<td>T6</td>
<td>T7</td>
<td>T8</td>
<td>T9</td>
<td>T10</td>
</tr>
</tbody>
</table>

Fig.2 Owner selection of each slot for 8 sensor nodes
Proposed MAC Protocol

- The rendezvous slots can also be calculated by clock arithmetic,
- Let node **S1 wants** to create a rendezvous.
- By using **modulo 16**, the rendezvous slots of node S1 will be a subset of [1, 17...].
- **S1** can make **T17** as its rendezvous slot.
- Though **S1 is owner** of both **T9 and T17** but S1 cannot make T9 as its rendezvous slot. It is because 9 is not a subset of [1, 17 ....].

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T9</td>
<td>T10</td>
<td>T11</td>
<td>T12</td>
<td>T13</td>
<td>T14</td>
<td>T15</td>
<td>T16</td>
<td>T17</td>
<td>T18</td>
</tr>
</tbody>
</table>

**Fig.3 Rendezvous slot selection for 8 sensor nodes (T17 is rendezvous slot for S1 but T9 is not rendezvous slot)**
Consider a simple case of four sensor nodes A, B, C, & D. And there are four consecutive slots.

During Slot i, let data transmission occur between node B and C.

But A and D also
- need to wake up
- Subsequently they go to sleep

---

**Proposed MAC Protocol**

**Fig. 4.** Network of 4 Sensor Nodes connected to each other

<table>
<thead>
<tr>
<th>Node A</th>
<th>Listen</th>
<th>Sleep</th>
<th>Listen</th>
<th>Sleep</th>
<th>Listen</th>
<th>DATA</th>
<th>Listen</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node B</td>
<td>Listen</td>
<td>DATA</td>
<td>Listen</td>
<td>DATA</td>
<td>Sleep</td>
<td></td>
<td>Listen</td>
<td>Sleep</td>
</tr>
<tr>
<td>Node C</td>
<td>Listen</td>
<td>DATA</td>
<td>Listen</td>
<td>Sleep</td>
<td>Listen</td>
<td>DATA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Node D</td>
<td>Listen</td>
<td>Sleep</td>
<td>Listen</td>
<td>DATA</td>
<td>Sleep</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.** Timing Diagram of sensor nodes working in IH-MAC
(The blue portion of figure is rendezvous slot of IH-MAC and the remaining slots are like S-MAC, T-MAC etc.)
In slot $i+2$, node A and C created rendezvous between them.

On that slot node B and D will not wake up.

Thus, B and D save energy by lingering sleep time and avoiding transition.

Fig. 5. Timing Diagram of sensor nodes working in IH-MAC (The blue portion of figure is rendezvous slot of IH-MAC and the remaining slots are like S-MAC, T-MAC etc.)
Proposed MAC Protocol

- Node A & C save energy by avoiding RTS, CTS
- Contention for getting the slot.
- Thus, creation of rendezvous slot enhance energy efficiency for all nodes in two hop neighbor whether they participate in transmission or not.

<table>
<thead>
<tr>
<th>Node A</th>
<th>Listen</th>
<th>Sleep</th>
<th>Listen</th>
<th>Sleep</th>
<th>Listen</th>
<th>DATA</th>
<th>Listen</th>
<th>Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node B</td>
<td>Listen</td>
<td>DATA</td>
<td>Listen</td>
<td>DATA</td>
<td>Sleep</td>
<td></td>
<td>Listen</td>
<td>Sleep</td>
</tr>
<tr>
<td>Node C</td>
<td>Listen</td>
<td>DATA</td>
<td>Listen</td>
<td>Sleep</td>
<td>Listen</td>
<td>DATA</td>
<td>Listen</td>
<td>Sleep</td>
</tr>
<tr>
<td>Node D</td>
<td>Listen</td>
<td>Sleep</td>
<td>Listen</td>
<td>DATA</td>
<td>Sleep</td>
<td></td>
<td>Listen</td>
<td>Sleep</td>
</tr>
</tbody>
</table>

Slot i Slot i+1 Slot i+2 Slot i+3

Fig.5. Timing Diagram of sensor nodes working in IH-MAC (The blue portion of figure is rendezvous slot of IH-MAC and the remaining slots are like S-MAC, T-MAC etc.)
The power adjustment features of IH-MAC allow the sensor nodes to suitably vary the transmission power to reduce energy consumption.

\[ P_{\text{desired}} \approx \frac{P_{\text{max}}}{P_r} \times R_{\text{thres}} \times c \]

Here, \( R_{\text{thres}} \) is the minimum necessary signal strength, \( P_r \) is the received power level and \( c \) is a constant. And sensor node transmits the RTS and CTS packets with maximum power \( P_{\text{max}} \).

The source node uses power level \( P_{\text{desired}} \) to transmit data packet.
Proposed MAC Protocol

- We also develop an **analytical model** for the energy consumption of nodes for IH-MAC. For time constraints we will omit the detail.

- **Simulation time**,

\[ t_{SIM} \approx t_{TX} + t_{RX} + t_{OH} + t_{IDLE} + t_{SLEEP} + t_{TRANS} \]

- \( t_{TX}, t_{RX}, t_{OH}, t_{IDLE}, t_{SLEEP}, t_{TRANS}, \) are denoted as the time spent for transmitting, receiving, overhearing, idle listening, sleep, and radio transitions during sleep to wakeup state of a sensor node, respectively.
Proposed MAC Protocol

- **Energy consumption during** $t_{SIM}$

\[
e \approx n_{TX(w)} \times e_{TX(w)} + n_{TX(R)} \times e_{TX(R)} + n_{RX(w)} \times e_{RX(w)} \\
+ n_{RX(R)} \times e_{RX(R)} + t_{OH} \times e_{OH} + t_{IDLE} \times e_{IDLE} \\
+ t_{SLEEP} \times e_{SLEEP} + t_{TRANS} \times e_{TRANS}
\]

- $n_{TX(w)}, n_{TX(R)}, n_{RX(w)}, n_{RX(R)}$ represents the total number of times that a node transmits or receives with or without rendezvous during $t_{SIM}$

- And $e_x$ represents the required energy for the operation $x$
The parameter we use in performance evaluation:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth</td>
<td>20 kbps</td>
</tr>
<tr>
<td>Data Packet length</td>
<td>20 bytes</td>
</tr>
<tr>
<td>Transmission power</td>
<td>36 mW</td>
</tr>
<tr>
<td>Receive power</td>
<td>14.4 mW</td>
</tr>
<tr>
<td>Idle power</td>
<td>14.4 mW</td>
</tr>
<tr>
<td>Sleep state</td>
<td>15 μW</td>
</tr>
<tr>
<td>Frame Length</td>
<td>1 sec</td>
</tr>
<tr>
<td>Threshold value for the buffer size (for IH-MAC)</td>
<td>3 packet</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>15 %</td>
</tr>
</tbody>
</table>
Result & Discussion

- We took existing S-MAC (Sensor MAC) and T-MAC (Time out MAC) protocol for comparison.
- Performance metrics used in evaluation of IH-MAC protocol are
  - Energy consumption,
  - Delivery ratio and
  - Average Packet Latency.

- **Energy Consumption:** During heavy traffic IH-MAC outperforms S-MAC and performs like T-MAC. It is because **during heavy traffic IH-MAC makes rendezvous slots.**
Result & Discussion

- But as traffic declines, energy efficiency of IH-MAC deteriorates.
- T-MAC perform better during low traffic. But, T-MAC trades off latency for energy savings.
- It is evident from that If we can implement power adjustment feature of IH-MAC it will be more energy efficient.

Fig. 6(a) Average energy consumption per bit under different traffic load
Result & Discussion

- **Average packet latency:**
  - The IH-MAC protocol achieves better delay performance.
  - It is because during heavy traffic load IH-MAC use the **link scheduling** where it minimizes
    - control signal
    - contention phase.

![Graph showing packet latency under different traffic load](image)

Fig. 6(b) Packet latency under different traffic load
Result & Discussion

- **Average Packet Delivery Ratio:**
- The average packet delivery ratio is the number of packet received to the number of packets sent over all the nodes.
- **Delivery ratio of IH-MAC is higher** due to use of link scheduling which is like TDMA.

![Fig. 6(c) Packet delivery ratio under different traffic load](image-url)

Summary

The contribution of the paper are:

- **Identification of need for standardization work in the area of MAC protocol of WSNs.**
- **Proposal of a novel MAC protocol** which can be considered as a candidate for standardization.
- **Introducing the concept of link scheduling and broadcast scheduling together.**
- **Introducing power adjustment feature** for the sensor nodes during transmission.
- As a future work, we intend to implement the power adjustment feature of IH-MAC and also we have a plan to implement our protocol on the Mote hardware.
Thank You