Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks

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Presented by Rabin Karki

Outline

- Introduction
- Background
- Overview of TRAMA
- Neighbor Protocol
- Schedule Exchange Protocol
- Adaptive Election Algorithm
- Experimental Setup
- Simulation Results
- Conclusions

Introduction

- Sensor networks
  - Consist of a set of interconnected sensor nodes
  - Each node is equipped with one or more sensors and is normally battery operated
  - Nodes communicate with each other via wireless connection

Introduction

- The deployment of sensor network usually done in ad-hoc manner
  - Self-organize into a multi-hop wireless network
- Nodes may be difficult to recharge
- Nodes recharging may not be cost effective
- Major challenge
  - Self adaptive to changes in traffic, node state
  - Prolong the battery life

Some Applications

Great duck island, Maine

Habitat Monitoring

Some Applications

Habitat Monitoring

Great duck island,

Environment Observation and Forecasting System

Floating Weather Station, Alaska

Some Applications

Habitat Monitoring

Great duck island,

Environment Observation and Forecasting System

ather Station, Alaska

Automated Local Evaluation in Real Time (ALERT)

Weather Station, Pima, AZ

Some Applications

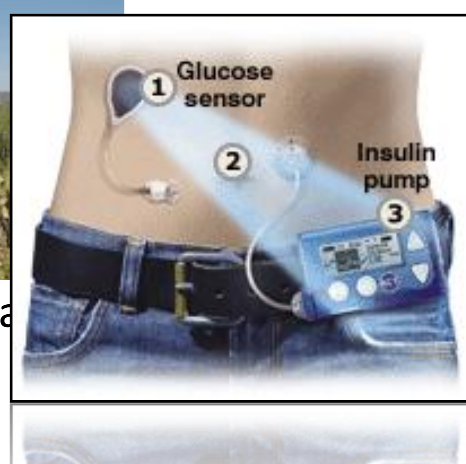
Habitat Monitoring

Great duck island,

Environment Observation and Forecasting System

ather Station, Alaska

Weather Station, Pima



ocal Evaluation (ALERT)

Glucose Level Monitoring

Some Applications

Habitat Monitoring

Great duck island,

Environment Observation

stem

ather Station

Smart Energy Meters

Weather Station, Pima

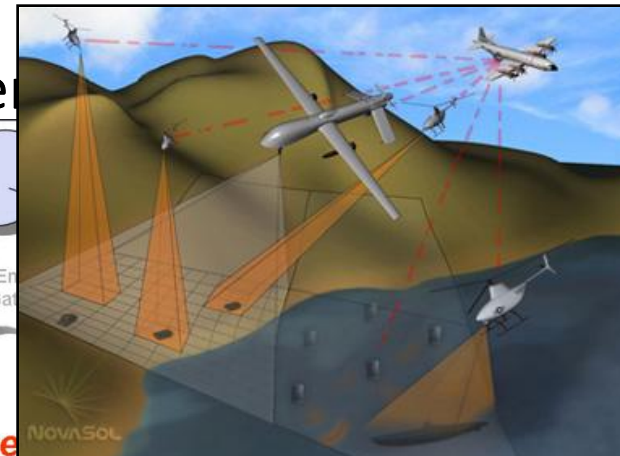
Glucose Level Monitoring

Some Applications

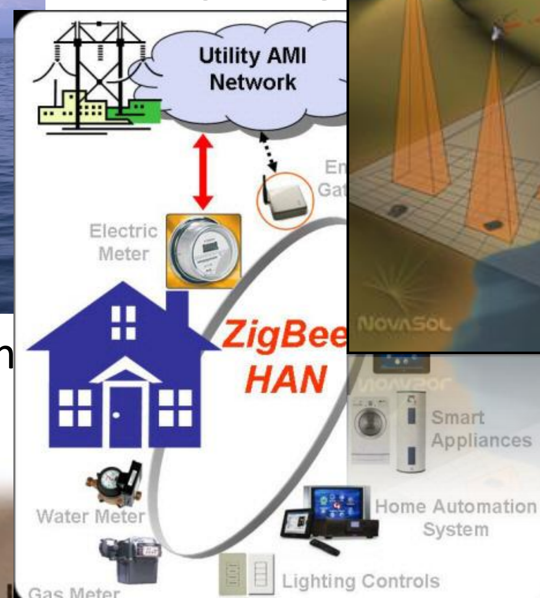
Habitat Monitoring

Great duck island,

Military



Environmen



ather Station

Weather Station, Pima

Glucose Level Monitoring

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Background

Categorization of MAC Protocols

- One approach (be nice – *share*)
  - Avoid interference by scheduling nodes on sub-channels
  - **TDMA** (Time-Division Multiple Access)
  - **FDMA** (Frequency-Division Multiple Access)
  - **CDMA** (Code-Division Multiple Access
- Another approach (Compete/contend)
  - Don't pre-allocate transmissions, compete
  - ALOHA (Transmit, collision? Yes => retransmit later)
  - Carrier Sense (802.11)

Background: Power aware contention-based protocols

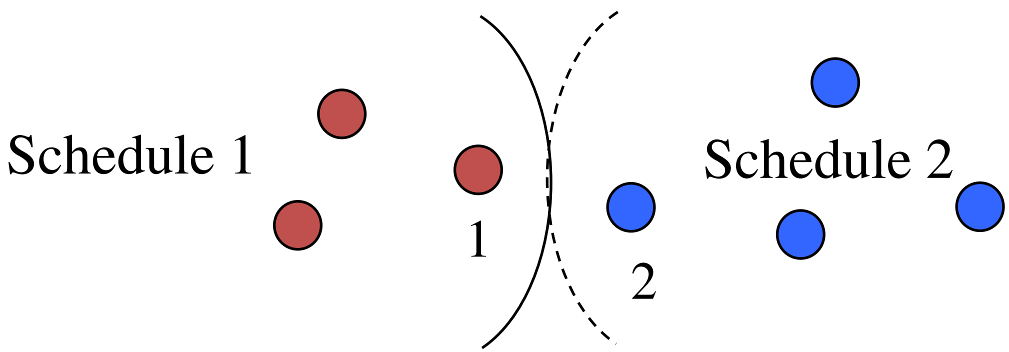
PAMAS (Power aware multi-access protocol)

- Designed for multi-hop wireless networks
- Saves energy by avoiding overhearing
- Uses out-of-band signaling i.e. RTS-CTS message exchange takes place over a signaling channel that is separate from the channel used for packet transmissions.
- Every node in the system makes the decision to power off independently.
- A node knows if a neighbor is transmitting because it can hear the transmission (over the data channel).
- Likewise, a node (with a non-empty transmit queue) knows if one or more of its neighbors are receiving because the receivers transmit a busy tone when they begin receiving a packet (and in response to RTS transmissions).

Background: Power aware contention-based protocols

Sensor-MAC

- Like PAMAS, S-MAC also avoids overhearing
- But uses in-channel signaling
- Neighbors synchronize sleep schedules
  - Nodes periodically broadcast schedules
  - New node tries to follow an existing schedule



  - Nodes on border of two schedules follow both

Background: Collision free protocols

- But increased load increases the probability of collisions of control and data packets in any contention-based schemes
- Resulting in degraded channel utilization and reduced battery life
- This motivates towards the development of schedule based transmission schemes

NAMA (Node Activation Multiple Access)

- For each time slot, only one transmitter per two-hop neighborhood is selected
- But does not address energy conservation (non-transmitting nodes switch to receiver mode)

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TRAMA: Overview

- Energy efficient, collision free transmission attained by
  - Transmission schedules that avoid collision of data packets
  - Having nodes switch to low power mode when there is no data packet destined to those nodes
- Adequate throughput & fairness achieved by
  - Transmitter election algorithm that is inherently fair and promotes channel reuse
- Supports for unicast, broadcast and multicast traffic

TRAMA: Overview

- Nodes exchange
  - Their two-hop neighborhood information
  - The transmission schedule specifying the intended receivers in chronological order
- Nodes that should transmit and receive during each time slot are then selected according to that information

TRAMA: Overview

Consists of three components

- Neighbor Protocol (NP): to transmit two-hop neighbor information
- Schedule Exchange Protocol (SEP) : to exchange schedules
- Adaptive Election Algorithm (AEA) : to select the transmitters and receivers using neighborhood and schedule information. All other nodes can then sleep.

TRAMA: Overview

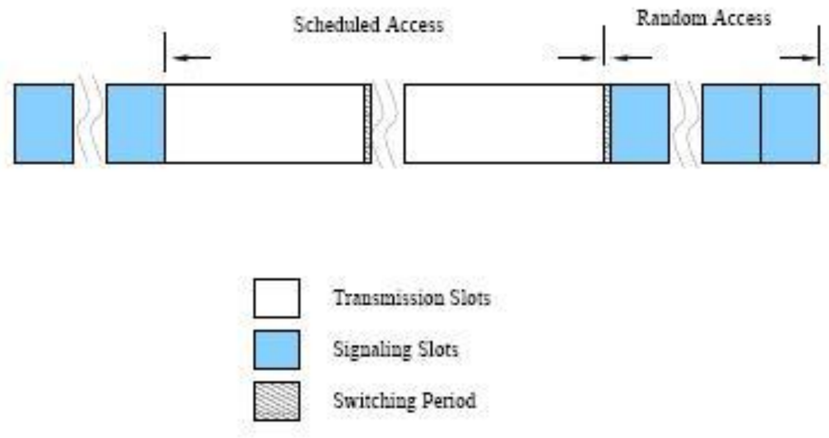

Figure 1: Time slot organization

- Uses single, time-slotted channel for both data and signaling transmissions.

TRAMA: Overview

- Time slot duration is larger than typical clock drifts
- Time slots of approx. 46ms are used in the paper, so drifts in the order of ms can be tolerated although they are typically in the order of µs
- So very simple and cheap-to-implement timestamp mechanisms can be used for node synchronization (*post-facto synchronization,* for example)
- In the paper, transmission slots are 7x longer than signaling slots

TRAMA: Neighbor Protocol

- NP propagates one-hop neighbor info during the *random access* period
- TRAMA starts in random access mode
  - Each node transmits by selecting a slot randomly
  - More dynamic networks require more frequent random access periods
  - All nodes have to be in Tx or Rx mode during this period
  - Node addition or deletion is done during this period

TRAMA: Neighbor Protocol

Type	SourceAddr	DestAddr	DeleteNum	AddNum	Deleted NodeID's	Added NodeID's

(a) Signal Header

- Packets carry incremental neighborhood updates
- If there have been no changes since the last update, signaling packets are sent as mere “keep-alive” beacons
- If the node doesn’t hear back for a certain period of time, it times out and retransmits
- By the end of random access period, all nodes will have the information about two-hop neighbors with 0.99 probability

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TRAMA: Schedule Exchange Protocol

- *Transmission slots* are used for collision free data transmission and schedule propagation
- A node has to announce its schedule using SEP before starting actual transmissions
- SEP maintains consistent schedule information across neighbors and periodically updates it

TRAMA: Schedule Exchange Protocol

Schedule Generation

- Each node computes *SCHEDULE_INTERVAL* based on the rate at which packets are produced by the higher layer
- The node then pre-computes the number of slots in the interval *[t, t + SCHEDULE_INTERVAL]* for which it has the highest priority among its two-hop neighbors
- The priority of node u at time slot t is

$$prio(u,t) = hash(u \oplus t)$$

TRAMA: Schedule Exchange Protocol

- Slots thus obtained are called "*winning slots*"
- The node then announces the intended receivers for those slots
- If it doesn't have enough data to fill up all the "*winning slots*", it announces that it has "*given up*" those slots (referred to as "*vacant slots*" later)
- Last winning slot is reserved for broadcasting node's schedule for next interval

TRAMA: Schedule Exchange Protocol

- Nodes announce their schedule via *schedule packets*
- Receiver address is not required. Bitmap of length equal to the number of one-hop neighbors is used instead
- The neighbors are ordered by their identities in the bitmap
- This decreases the payload and makes multicast/broadcast easier

TRAMA: Schedule Exchange Protocol

- For *vacant slots*, the node announces zero bitmap
- These slots with zero bitmap can be used by other nodes in the two-hop neighborhood
- The slot after which all the *winning slots* go unused is called *ChangeOver* slot.
- All nodes have to listen during the *ChangeOver* slot to synchronize their schedule

TRAMA: Schedule Exchange Protocol

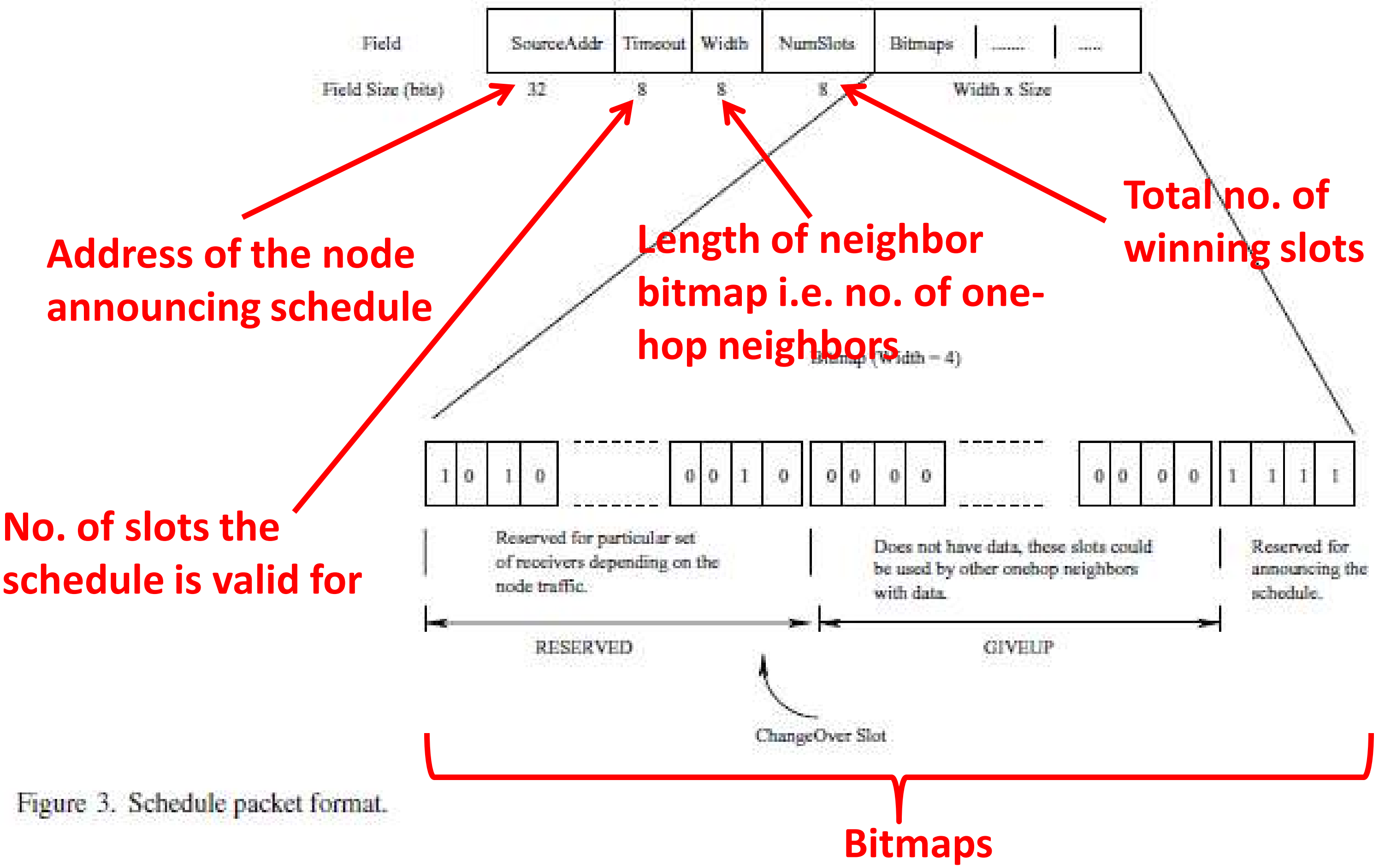


Figure 3. Schedule packet format.

TRAMA: Adaptive Election Algorithm

- At any given time slot t, the state of a given node u is determined by u's two-hop neighborhood information and the schedules announced by u's one hop neighbors
- At any given slot t, a node can be in one of three states *i)* transmit (TX) *ii)*receive (RX) or *iii)* sleep (SL)
  - A node u at t is in TX if i) u has the highest priority and ii) u has data to send
  - It is in RX if it is the intended receiver of the node which is in TX in the current slot.
  - Otherwise it can switch itself off to SL state

TRAMA: Adaptive Election Algorithm

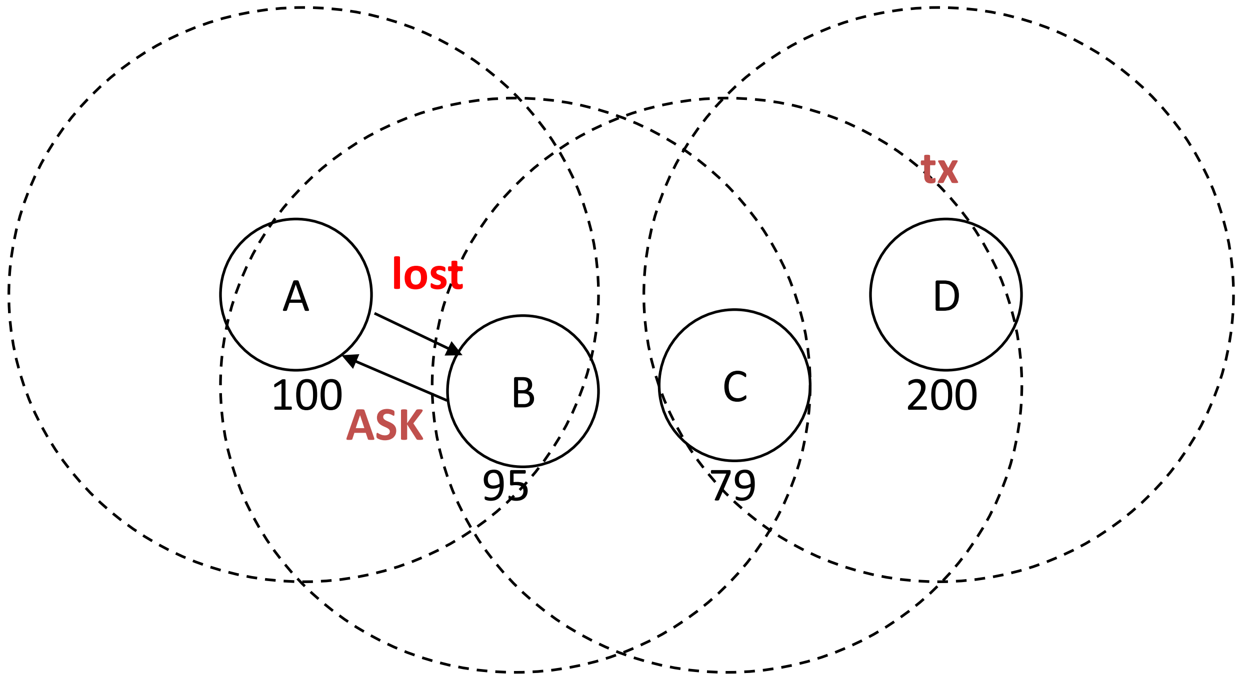
Table 1
Notations and terminologies.

N2(u)	Set of neighbors of node u which are two-hops away.
N1(u)	Set of neighbors of node u which are one-hop away.
CS(u)	u's *Contending Set* is the set of nodes in u's two-hop neighborhood such that $\{u \cup \mathbf{N1}(u) \cup \mathbf{N2}(u)\}$.
$tx(u)$	*Absolute Winner* is the node with the highest priority in **CS**(u).
$atx(u)$	*Alternate Winner* is the node which has the highest priority among u's one-hop neighbors, i.e., over the set $\{u \cup \mathbf{N1}(u)\}$.
PTX(u)	*Possible Transmitter Set* is the set of all nodes in $\{u \cup \mathbf{N1}(u) - atx(u)\}$ that satisfy the condition given in equation (2).
NEED(u)	*Need Contender Set* is the set of nodes in $\{\mathbf{PTX}(u) \cup u\}$ that are in need of additional transmission slots.
$ntx(u)$	*Need Transmitter* is the node with the highest priority among the set of nodes **NEED**(u) containing valid synchronized schedule.

TRAMA: Adaptive Election Algorithm

- Whenever a node becomes *Absolute Winner* for a particular time slot, and has announced non-zero bitmap, no other node in its two-hop neighborhood will transmit in this slot – **for sure.**
- If it is not the *Absolute Winner,* it won't know who the actual transmitter for that particular slot is. This can lead to inconsistency.
- Let's look at an example:

TRAMA: Adaptive Election Algorithm



Inconsistency problem

Happens only when *Alternate Winner* is hidden from the *Absolute Winner* i.e., they are three hops away.

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Experimental Setup

- Simulation platform
  - Qualnet
- Physical layer model
  - Based on TR1000
- 50 nodes are uniformly distributed over a 500m x 500m area
- 6 one-hop neighbors on average
- 17 two-hop neighbors on average
- 2 different types of traffic load
  - Synthetic data generation
  - Data gathering application

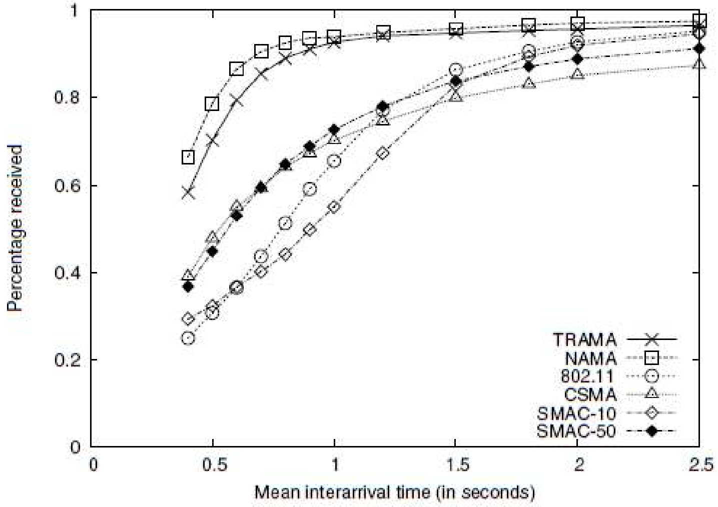
Performance Metrics

- Average Packet Delivery Ratio: ratio of number of packets received to the number of packets sent, averaged over all the nodes
- Percentage Sleep Time: ratio of number of sleeping slots to the total slots averaged over the entire network
- Average Queuing Delay: average delay for the packet to be delivered to the receiver
- Average Sleep Interval: average length of sleeping interval. Measure of no. of radio mode switchings.

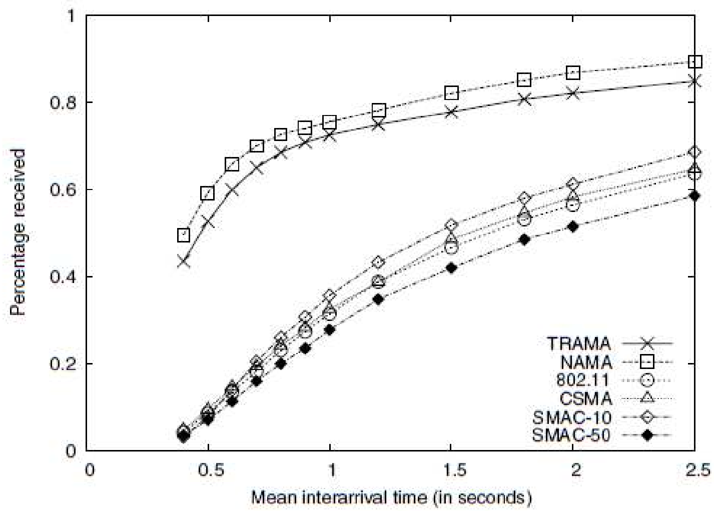
Synthetic Data Generation

- Data generated using exponential inter-arrival time varying rate from 0.5 to 2.5 secs
- All nodes in the network generate traffic based on that distribution
- A neighbor is randomly selected as the next hop
- Tested for unicast and broadcast traffic

Simulation Results: Synthetic Traffic (Packet delivery ratio)



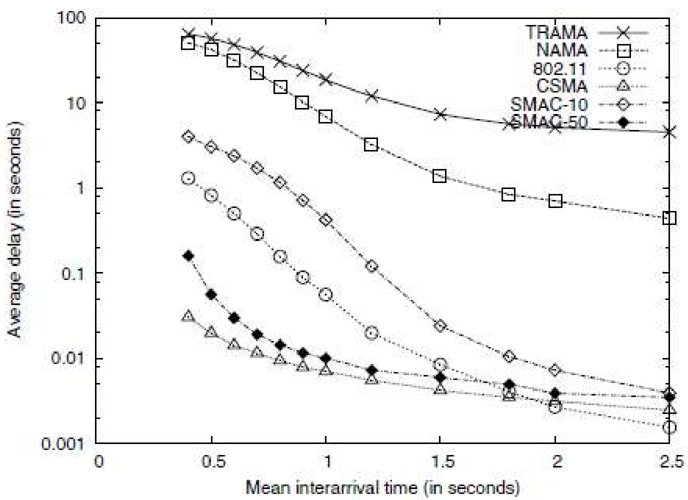
(a) UnicastTraffic



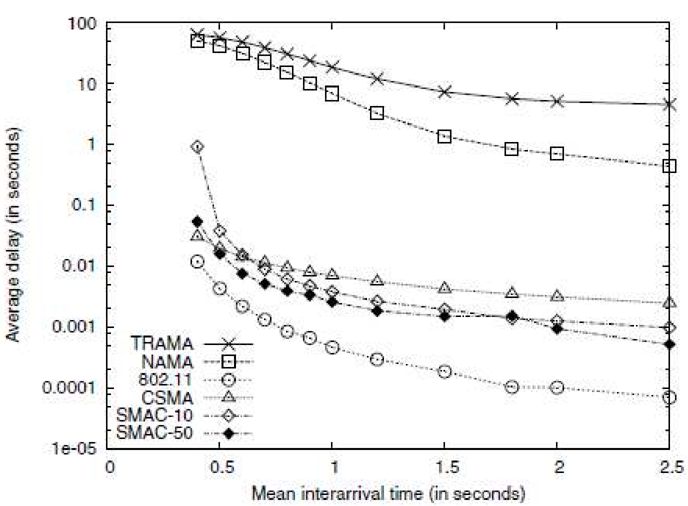
(b) Broadcast Traffic

- Schedule based MACs achieve better delivery
- Broadcasting decreases the delivery ratio significantly in collision-based protocols *(kind-of obvious).*

Simulation Results: Synthetic Traffic (Average queuing delay)



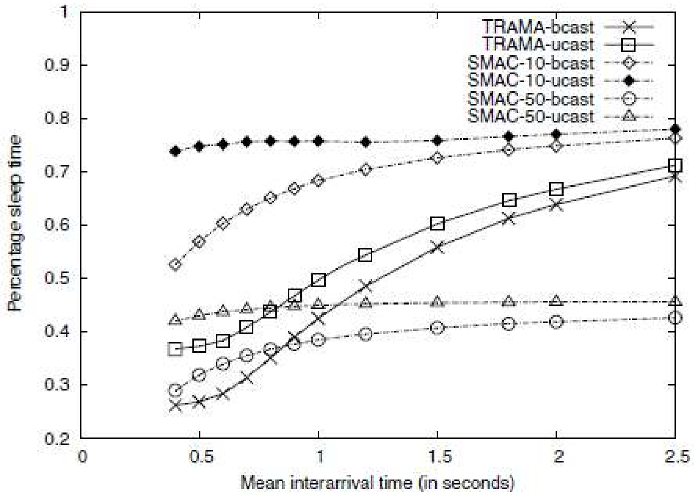
(a) Unicast Traffic



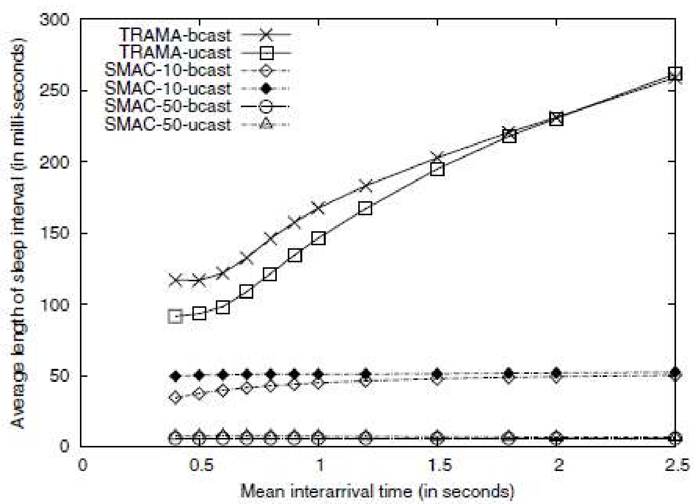
(b) Broadcast Traffic

- Schedule based MACs incur higher queuing delay
- TRAMA has more queuing delay than NAMA because of the schedule info propagation overhead

Simulation Results: Synthetic Traffic (Energy savings & avg. sleep interval)



(a) Percentage Energy Savings



(b) Average Sleep Interval

- S-MAC with 10% duty cycle has higher percentage sleep time, but average length of sleep interval is much lower.
- So the overhead for mode switching is higher in S-MAC

Data Gathering Application

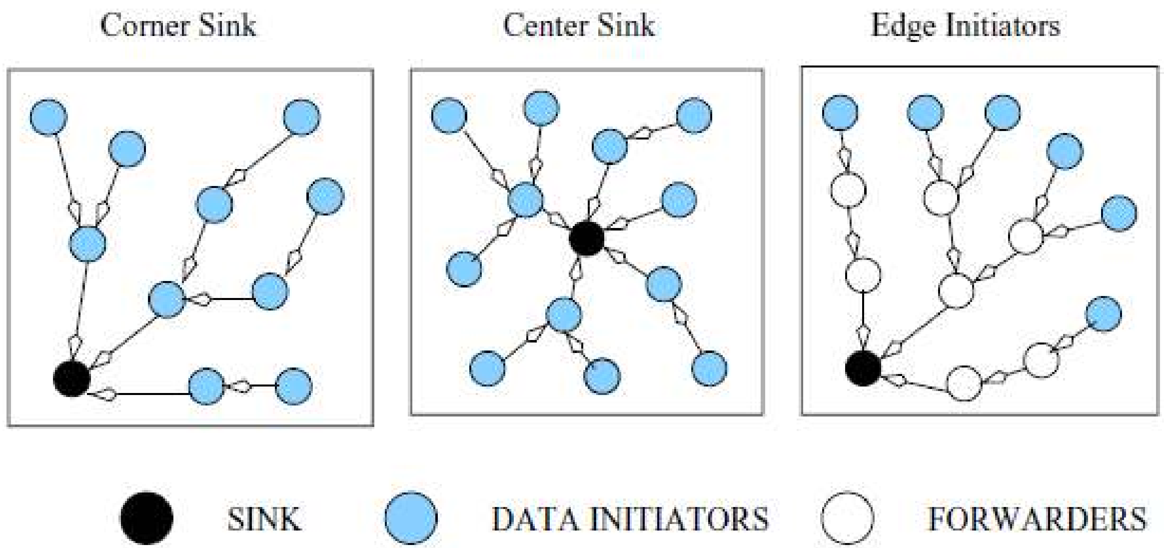
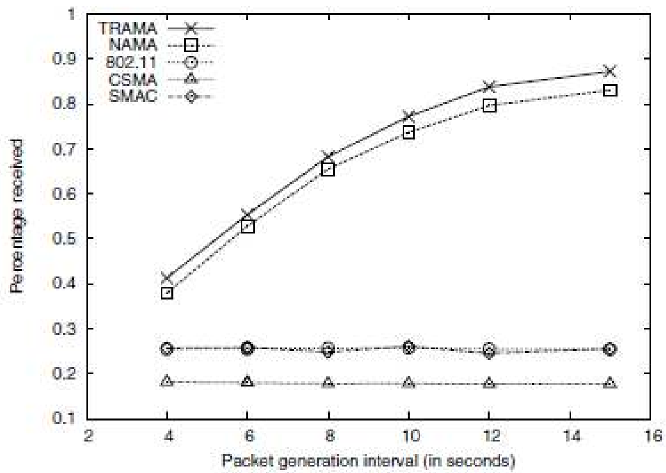


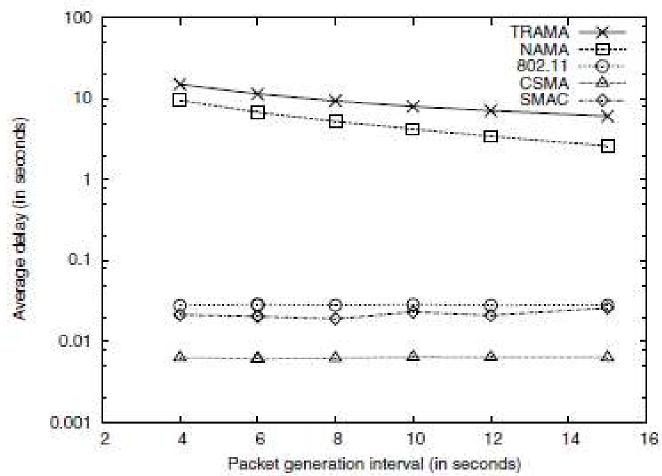
Figure 7. Data gathering application.

- Sink sends out a broadcast query requesting data from the sensors
- Sensors respond back with the data
- Simple reverse-path routing used to forward data from sensors to the sink

Simulation Results: Data Gathering Application



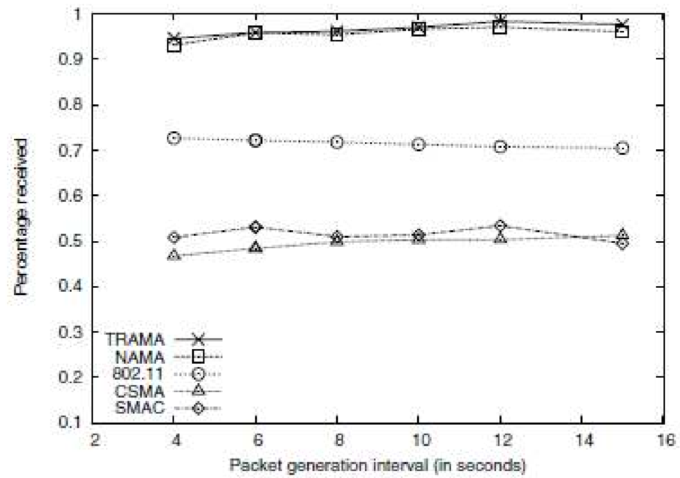
(a) Average delivery ratio



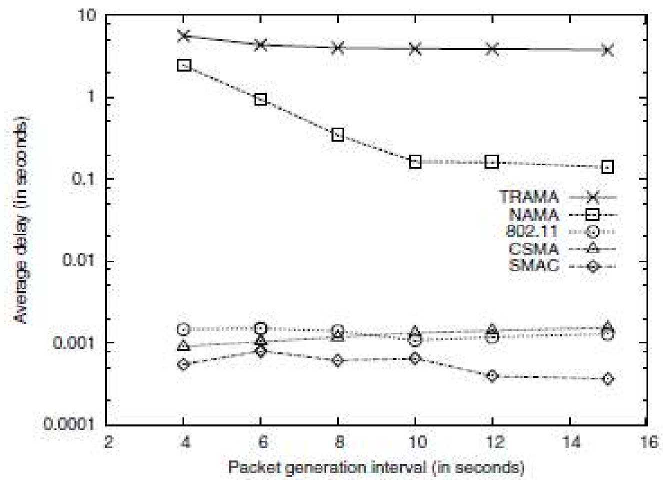
(b) Average queuing delay

Figure 11. Corner sink.

Simulation Results: Data Gathering Application



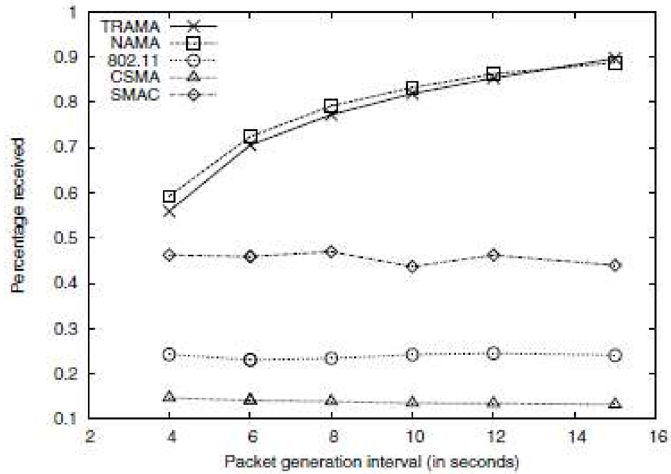
(a) Average delivery ratio



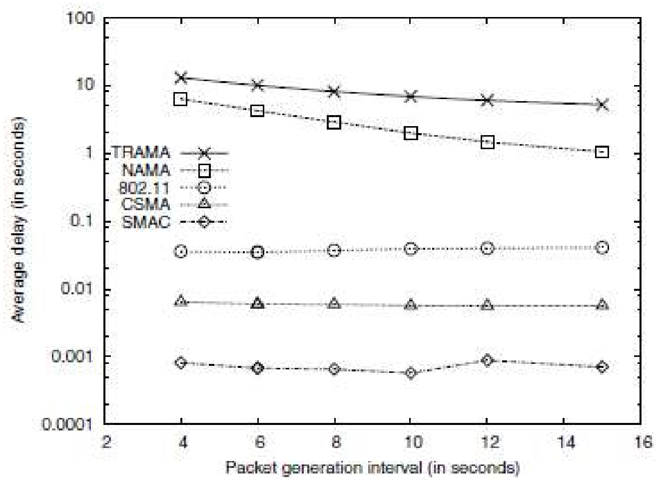
(b) Average queuing delay

Figure 13. Edge sink.

Simulation Results: Data Gathering Application



(a) Average delivery ratio



(b) Average queuing delay

Figure 12. Center sink.

Simulation Results: Data Gathering Application

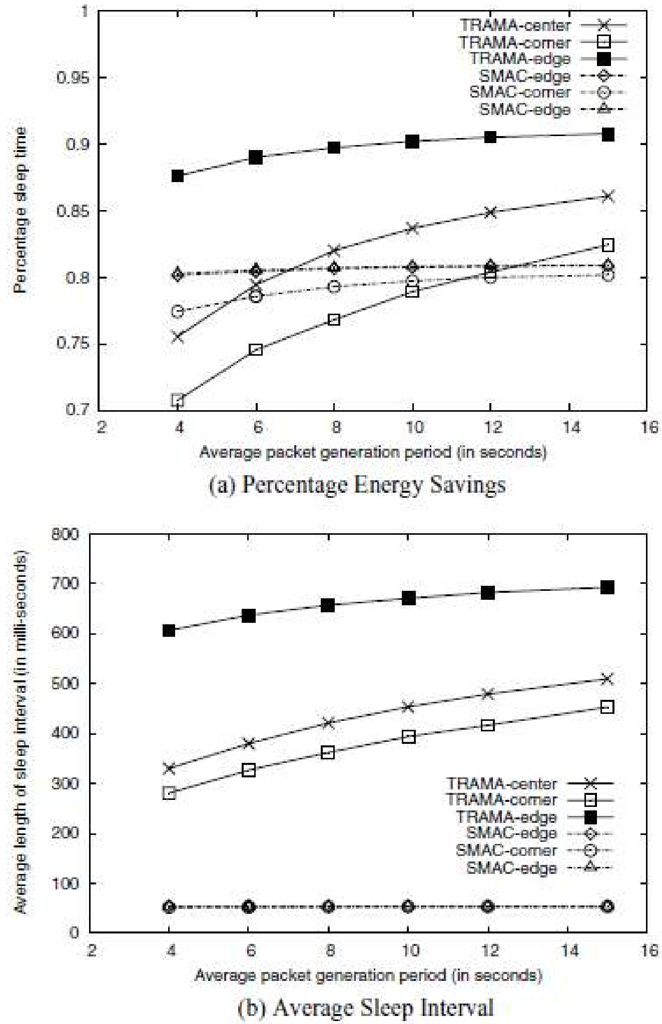


Figure 14. Energy savings and average sleep interval for sensor scenarios.

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Conclusion

- Traffic-based scheduling to avoid wasting the empty slots
- And to switch nodes to a low-power standby mode when they are neither transmitter nor receivers
- Significant energy savings (sleep % upto 87%)
- Higher throughput (40% over S-MAC and 20% over 802.11)
- Higher delay – in general
- Well suited for application not-so-delay-sensitive

Acknowledgements

Some slides, texts or images taken from

- Lecture slides by *A. Krugar, University of Michigan*
- Presentation on TRAMA by *Yung-Lin Yu*
- Presentation on MACs by *Huaming Li*

AEA Pseudocode (*for your viewing pleasure*)

```
Compute tx(u), atx(u) and ntx(u)
if (u = tx(u)) then
  if (u.isScheduleAnnouncedForTx = TRUE) then
    let u.state = TX
    let u.receiver = u.reported.rxId
    Transmit the packet and update the announced schedule
  else if (u.giveup = TRUE) then
    call HandleNeedTransmissions
  endif
else if (tx(u) ∈ N1(u)) then
  if (tx(u).announcedScheduleIsValid = TRUE AND tx(u).announcedGiveup = TRUE) then
    call HandleNeedTransmissions
  else if (tx(u).announcedScheduleIsValid = FALSE OR tx(u).announcedReceiver = u) then
    let u.mode = RX
  else
    let u.mode = SL
    Update schedule for tx(u)
  endif
else
  if (atx(u) hidden from tx(u) AND atx(u) ∈ PTX(u)) then
    if (atx(u).announcedScheduleIsValid = TRUE AND atx(u).announcedGiveup = TRUE) then
        call HandleNeedTransmissions
    else if (atx(u).announcedScheduleIsValid = FALSE OR atx(u).announcedReceiver = u) then
        let u.mode = RX
    else
        let u.mode = SL
        Update schedule for atx(u)
    endif
  else
    call HandleNeedTransmissions
endif
procedure HandleNeedTransmissions
if (ntx(u) = u) then
  let u.state = TX
  let u.receiver = u.reported.rxId
    Transmit the packet and update the announced schedule
else if (ntx(u).announcedScheduleIsValid = FALSE || ntx(u).announcedReceiver = u) then
  let u.mode = RX
else
  let u.mode = SL
  Update the schedule for ntx(u)
endif
```

¿Questions?