# A Bit-Map-Assisted Energy-Efficient MAC Scheme for Wireless Sensor Networks

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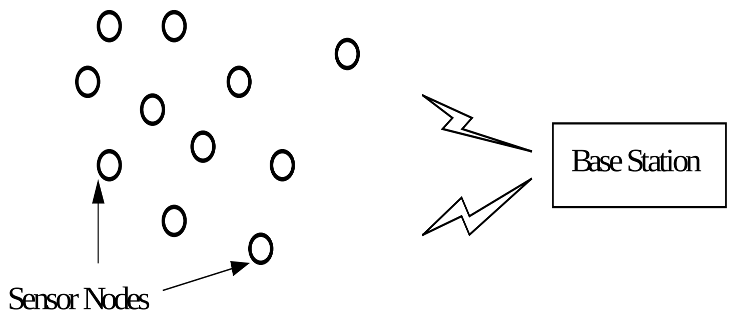
# Outline

- Introduction and Motivation
- Cluster-Based MAC Schemes
- Bit-Map-Assisted (BMA) MAC Scheme
- Energy Model
- Simulation Experiment
- Conclusions and Future Work

# Introduction of WSNs




- Wireless Sensor Network (WSN) — base stations and a number of wireless sensors.

- Sensor node — a unit with wireless networking capability that can collect and process data independently.

- Applications — military, seismic detection, ocean monitoring, and medical application.

- Operation at extremely low power is a critical design constraint.

# What is the Problem?

- Time Division Multiple Access (TDMA)-based MAC — a natural choice for sensor networks.

- Clustering solutions are often combined with TDMA-based schemes to reduce the cost of idle listening.

- TDMA-based solutions perform well under high traffic load conditions.
  - Conventional TDMA: when a node has no data to send, it still has to turn on the radio during its scheduled slots.
  - Energy-efficient TDMA (E-TDMA): the cluster head has to keep on the radio during all the time slots.

- TDMA-based schemes: can not change the time slot allocations and frame lengths dynamically according to the unpredictable variations of sensor networks.

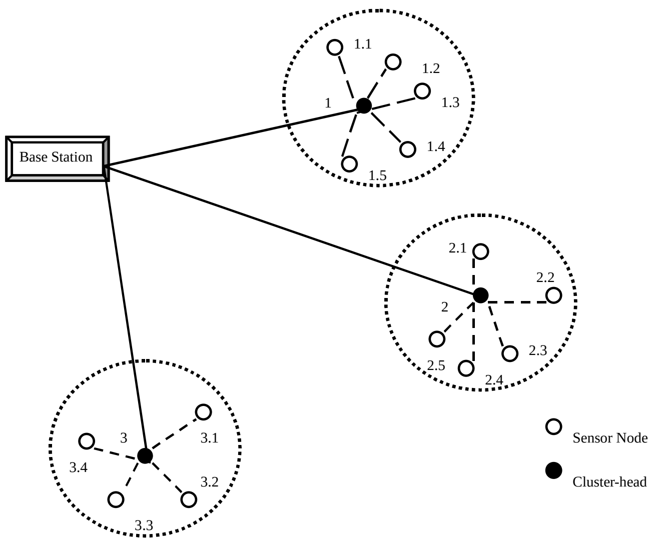
# What is This Research All About?

- **Propose** an intra-cluster communication bit-map-assisted (BMA) MAC protocol for large-scale cluster-based WSNs.
  - Intended for event-driven applications.
  - Reduce energy consumption due to idle listening and collisions.
  - Change dynamically according to the variations of networks.

- **Provide** two different energy models for
  - BMA
  - Conventional TDMA
  - Energy Efficient TDMA (E-TDMA)

- **Construct** simulation models and validate the analytic energy models.

# Clustering WSNs




- Divide the whole network into different clusters.
- A cluster-head among each cluster.
- Each node communicates with the cluster-head directly.
- The cluster-head transmits data to the global base station.

# Medium Access Control (MAC) Schemes

- Medium Access Control (MAC) — avoid collisions by keeping two or more interfering nodes from accessing the medium at the same moment.

- Four of the major performance metrics of MAC layer:
  - power conservation.
  - average end to end delay.
  - throughput.
  - control overhead.

# MAC Schemes (Cont.)

Two categories of MAC schemes for wireless networks

## Contention-based schemes

- Widely applied to ad hoc wireless networks because of simplicity and a lack of synchronization requirements.
- Require sensor nodes to keep their radios on at all times to receive possible incoming messages.
- IEEE 802.11 wireless LAN standard.

## Contention-free schemes ( Reservation-based schemes)

- Detect the neighboring radios before allocating collision-free channel to a link.
- TDMA — a natural choice for sensor networks.

# Cluster-Based MAC Schemes

## Conventional TDMA

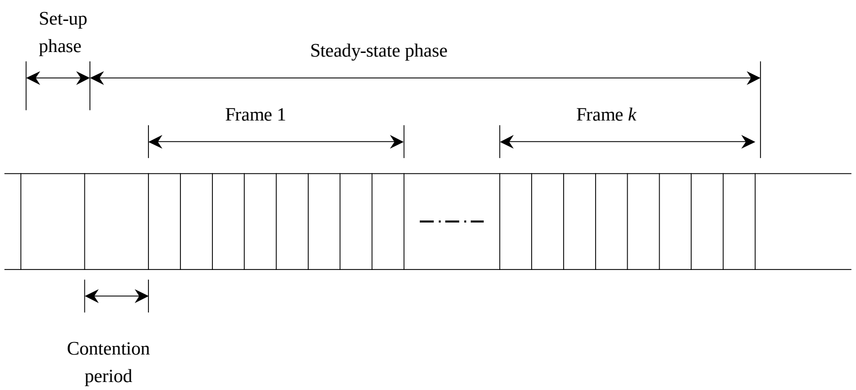



Illustration of a Conventional TDMA

The operation of conventional TDMA is divided into rounds. Each round consists of a *cluster set-up phase* and a *steady-state phase*.

### *A. Cluster Set-Up Phase*

- Node — decide whether it could become a cluster head based on its energy level.
- Cluster-head — broadcast an advertisement message to all other nodes claiming to be the new cluster-head.

# Cluster-Based MAC Schemes (Cont.)

### Conventional TDMA

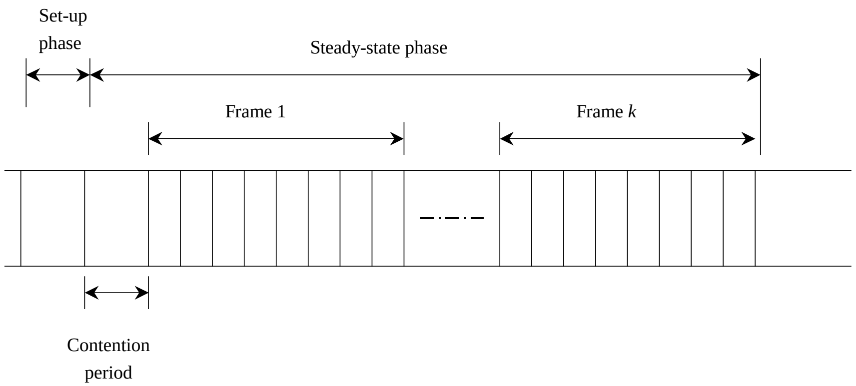



Illustration of a Conventional TDMA

### *B. Steady-State Phase*

- Divided into a contention period and *k* frames.
- Contention period — the cluster-head builds a TDMA schedule and broadcasts it to all nodes.
- Source node — turn on radio and send data over the allocated slot-time.
- Disadvantage: a node always turns on its radio during its assigned time slot regardless whether it has data to transmit or not.

# Cluster-Based MAC Schemes (Cont.)

## Energy-Efficient TDMA (E-TDMA)

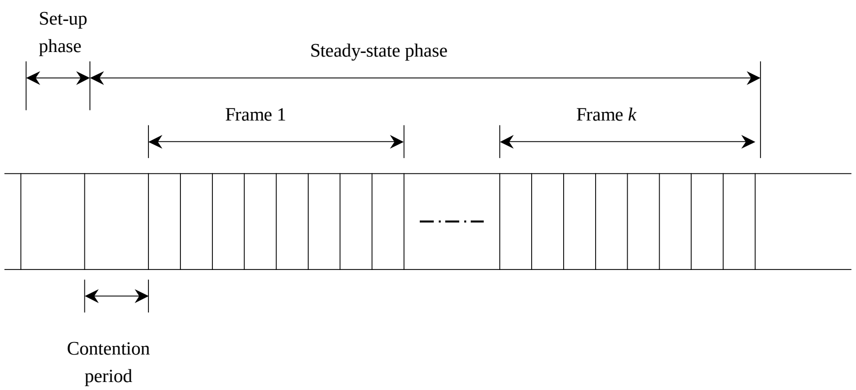



Illustration of a Conventional E-TDMA

- Extend the basic TDMA in order to reduce the energy consumption due to idle listening.
- A node keeps its radio off during its allocated time slots when having no data to transmit.

# Bit-Map-Assisted (BMA) MAC

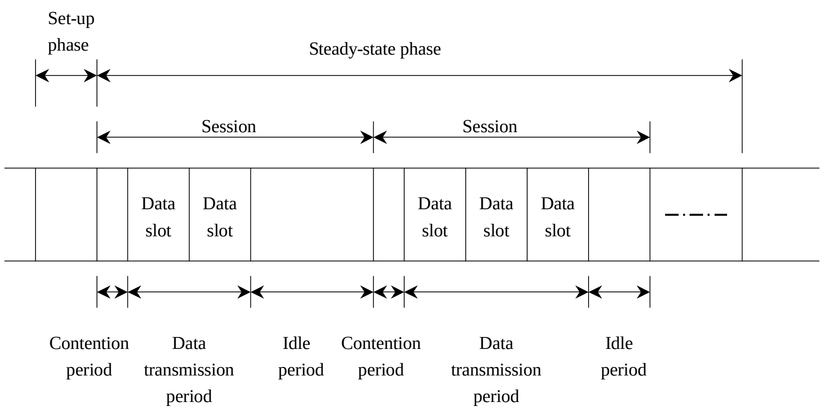



Illustration of a Single Round

The operation of BMA is divided into rounds. Each round consists of a *cluster set-up phase* and a *steady-state phase*.

## *A. Cluster Set-Up Phase*

- Node — decides whether it could become a cluster head based on its energy level.
- Cluster-head — broadcast an advertisement message to all other nodes claiming to be the new cluster-heads.

## *B. Steady-State Phase*

- Divided into *k* sessions.
- Each session consists of a contention period, a data transmission period and an idle period.

# Bit-Map-Assisted (BMA) MAC (Cont.)

**Bit-Map-Assisted (BMA) MAC**

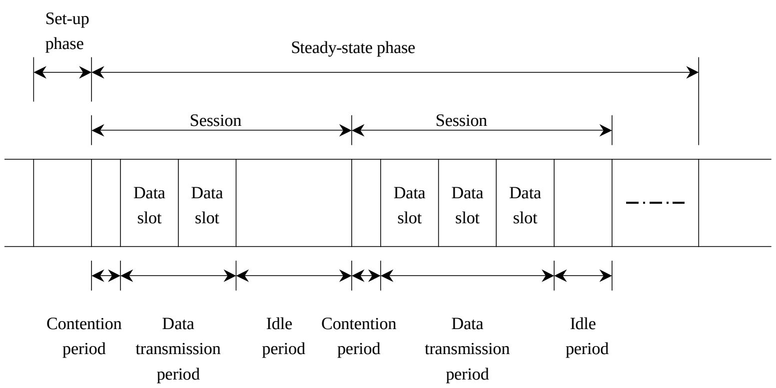



Illustration of a single round

## *B. 1. Contention Period*

- Node — transmit a 1-bit control message during its scheduled slot if it has data to transmit.
- Cluster-head — set up and broadcast a transmission schedule for the source nodes.

## *B. 2. Data Transmission Period*

- Source node — sends its data over its allocated slot-time, and keeps its radio off at all other times.
- Non-source nodes — have their radios off during the data transmission period.

# Energy Model I

- Energy Dissipation in Transmit mode

$$E_{Tx}(T) = P_t \cdot T$$

- Energy Dissipation in Receive mode

$$E_{Rx}(T) = P_r \cdot T$$

- Energy Dissipation in Idle mode

$$E_I(T) = P_i \cdot T$$

$P_t$ — power consumption during the Transmit mode

$P_r$ — power consumption during the Receive mode

$P_i$ — power consumption during the Idle mode

$T$ — transmitting/receiving/idle time

# Energy Model I — Parameters

- ***N*** — the number of non-cluster-head nodes within a cluster.
- ***k*** — the number of sessions/frames within a round.
- ***p*** — The possibility that a node has data to transmit.

- $T_d$ — the time to transmit/receive a data packet.
- $T_c$ — the time to transmit/receive a control packet.
- $T_{ch}$ — the time required for the cluster-head to transmit/receive a control packet (BMA).

# Energy Model I — BMA

Average system energy consumed during each round

$$E = E[E_{round}] = E[\sum_{i=1}^{k} E_{si}] = kE[E_{si}] = k[\sum_{j=1}^{n} E_{sn} + \sum_{j=1}^{N-n} E_{in} + E_{ch}]$$

The energy consumption by the $j^{\text{th}}$ *source node* during a single session

$$E_{sn} = P_t T_c + (N-1) P_i T_c + P_r T_{ch} + P_t T_d$$

The energy consumption by the $j^{\text{th}}$ *idle node* during a single session

$$E_{in} = N P_i T_c + P_r T_{ch}$$

The energy consumption by the *cluster-head node* during a single session

$$E_{ch} = n(P_r T_c + P_r T_d) + (N-n) P_i T_c + P_t T_{ch}$$

# Energy Model I — TDMA

Average system energy consumed during each round

$$E = E[E_{round}] = E_c + kE[E_{fi}] = E_c + k[nE_{sn} + (N-n)E_{in} + E_{ch}]$$

The energy consumption by the $j^{\text{th}}$ *source node* during a single session

$$E_{sn} = P_t T_d$$

The energy consumption by the $j^{\text{th}}$ *idle node* during a single session

$$E_{in} = P_i T_d$$

The energy consumption by the *cluster-head node* during a single session

$$E_{ch} = nP_r T_d + (N-n)P_i T_d$$

The total system contention energy dissipation

$$E_c = N[P_t T_c / \alpha + (N-1)P_i T_c / \alpha + P_r T_c] + NP_r T_c + P_t T_c$$

# Energy Model I — E-TDMA

Average system energy consumed during each round

$$E = E[E_{round}] = E_c + kE[E_{fi}] = E_c + k[nE_{sn} + (N-n)E_{in} + E_{ch}]$$

The energy consumption by the $j^{\text{th}}$ *source node* during a single session

$$E_{sn} = P_t T_d$$

The energy consumption by the $j^{\text{th}}$ *idle node* during a single session

$$E_{in} = 0$$

The energy consumption by the *cluster-head node* during a single session

$$E_{ch} = nP_r T_d + (N-n)P_i T_d$$

The total system contention energy dissipation

$$E_c = N[P_t T_c / \alpha + (N-1)P_i T_c / \alpha + P_r T_c] + NP_r T_c + P_t T_c$$

# Energy Model I — Evaluation Parameters

$$E_{Tx}(T) = P_t \cdot T$$

$$E_{Rx}(T) = P_r \cdot T$$

$$E_I(T) = P_i \cdot T$$

- The data packet size

  $k_d = 250$ *bytes*

  The control packet size

  $k_c = 18$ *bytes*

- The data rate

  $R = 24$ *kbps*

- The power parameter

  $P_t = 462$ *mW*

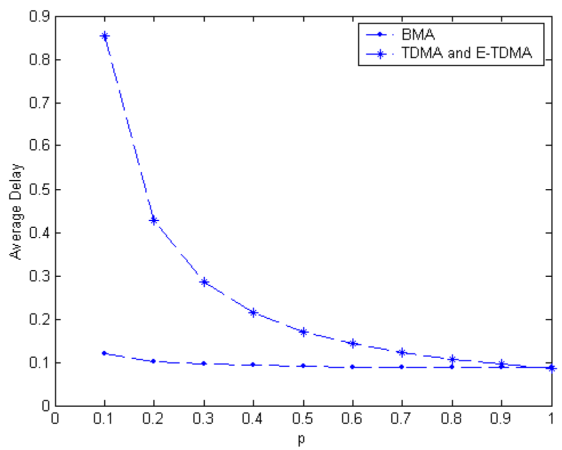
  $P_r = 346$ *mW*

  $P_i = 330$ *mW*

- The throughput of non-persistent CSMA

  $\alpha = 0.815$

# Energy Model I — Evaluation Results



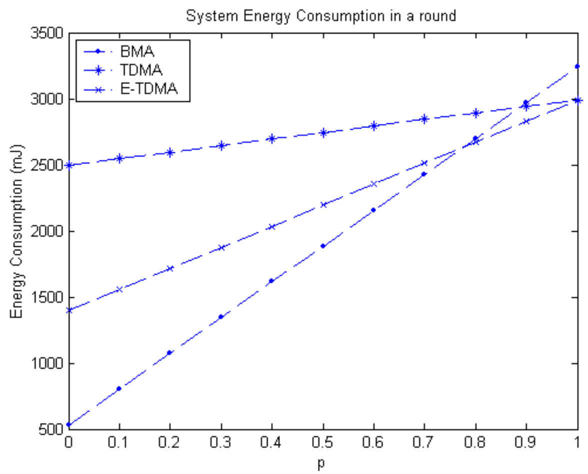

Average packet latency vs. p for the case of N=10 and k=4.

- ***Average Packet Latency*** — the average time required for a packet to be generated by a source node and received by the cluster-head.

- For $p$ high, all three schemes have similar low average packet latencies.

- As $p$ goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially.

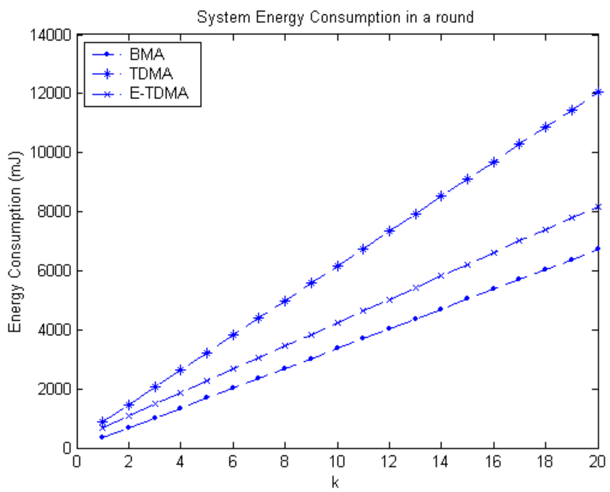
# Energy Model I — Evaluation Results



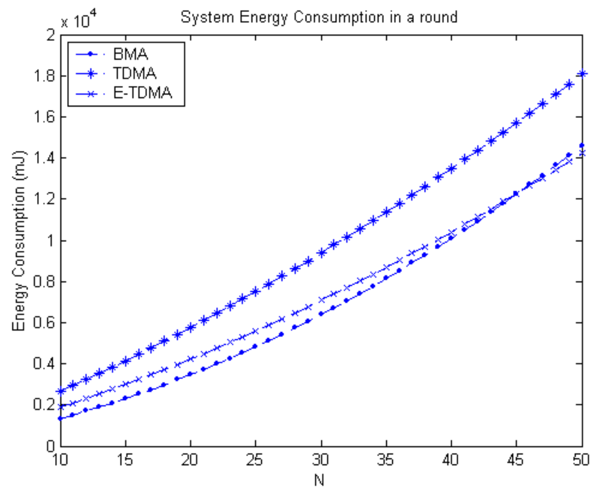

Average total cluster energy consumption vs. p for the case of N=10 and k=4.

- When p is less than 0.75, BMA performs better than both TDMA and E-TDMA.
- For p above 0.75, E-TDMA scheme performs better.
- E-TDMA always outperforms TDMA.

# Energy Model I — Evaluation Results

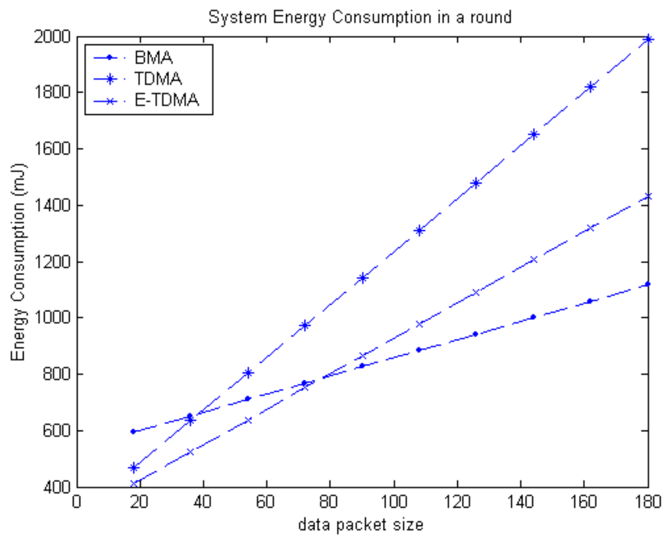



Average total cluster energy consumption vs. k for the case of N=10 and p=0.3.




Average total cluster energy consumption vs. N for the case of k=4 and p=0.3.

# Energy Model I — Evaluation Results




System energy consumption in a round. N=10, p=0.3, and k=4.

# Energy Model II

- Energy Dissipation in Transmit mode

$$E_{Tx}(k,d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2$$

- Energy Dissipation in Receive mode

$$E_{Rx}(k) = E_{elec} \cdot k$$

$E_{elec}$ (J/b) — the energy dissipated to run the transmit or receive electronics

$\varepsilon_{amp}$ (J/b/m$^2$) — the energy dissipated by the transmit power amplifier to achieve an acceptable $E_b/N_0$ at the receiver.

- Energy Dissipation in Idle mode

$$E_I(k) = \beta \cdot E_{rx}(k)$$

$\beta$ — the ratio of the energy dissipated in *idle listening* mode to the energy dissipated in *receiving* mode.

# Energy Model II — Parameters

- $N$ — the number of non-cluster-head nodes within a cluster.
- $k$ — the number of sessions/frames within a round.
- $p$ — The possibility that a node has data to transmit.

- $k_c$ — the normal control packet size.
- $k_d$ — the data packet size.
- $k_{cB}$ — the source to cluster head control packet size (BMA).
- $d_j$ — the distance between node $j$ and the cluster head.
- $d_{max}$ — the maximum distance between nodes and the cluster head.

# Energy Model II — BMA

Average system energy consumed during each round

$$E = E[E_{round}] = E[\sum_{i=1}^{k} E_{si}] = kE[E_{si}] = k[\sum_{j=1}^{n} E_{sn}(j) + \sum_{j=1}^{N-n} E_{in}(j) + E_{ch}]$$

The energy consumption by the $j^{\text{th}}$ *source node* during a single session

$$E_{sn}(j) = E_{Tx}(k_{cB}, d_j) + (N-1)E_I(k_{cB}) + E_{Rx}(k_c) + E_{Tx}(k_d, d_j)$$

The energy consumption by the $j^{\text{th}}$ *idle node* during a single session

$$E_{in}(j) = NE_I(k_{cB}) + E_{Rx}(k_c)$$

The energy consumption by the *cluster-head node* during a single session

$$E_{ch} = nE_{Rx}(k_{cB}) + nE_{Rx}(k_d) + (N-n)E_I(k_{cB}) + E_{Tx}(k_c, d_{\max})$$

# Energy Model II — TDMA

Average system energy consumed during each round

$$E = E[E_{round}]$$
$$= E_c + kE[E_{fi}]$$
$$= E_c + k[\sum_{j=1}^{n} E_{Tx}(k_d, d_j) + 2(N-n)E_I(k_d) + nE_{Rx}(k_d)]$$

The total system contention energy dissipation

$$E_c = \sum_{j=1}^{N} \frac{1}{\alpha} E_{Tx}(k_c, d_j) + E_{Tx}(k_c, d_{\max}) + \frac{N(N-1)}{\alpha} E_I(k_c) + 2NE_{Rx}(k_c)$$

# Energy Model II — E-TDMA

Average system energy consumed during each round

$$E = E[E_{round}]$$
$$= E_c + kE[E_{fi}]$$
$$= E_c + k[\sum_{j=1}^{n} E_{Tx}(k_d, d_j) + (N-n)E_I(k_d) + nE_{Rx}(k_d)]$$

The total system contention energy dissipation

$$E_c = \sum_{j=1}^{N} \frac{1}{\alpha} E_{Tx}(k_c, d_j) + E_{Tx}(k_c, d_{\max}) + \frac{N(N-1)}{\alpha} E_I(k_c) + 2NE_{Rx}(k_c)$$

# Energy Model II — Evaluation Parameters

$$E_{tx}(k,d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2$$

$$E_{rx}(k) = E_{elec} \cdot k$$

$$E_I(k) = \beta \cdot E_{rx}(k)$$

- The data packet size

  $k_d = 500$ *bytes*

  The control packet size

  $k_c = 25$ *bytes*

- The energy dissipated to run the transmit or receive electronics

  $E_{elec} = 50$ *nJ/bit*

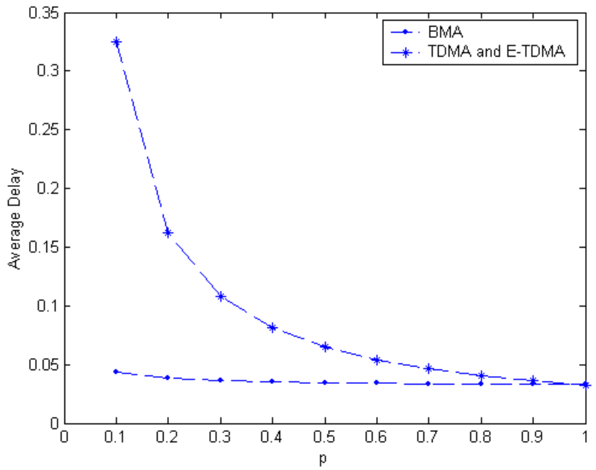
- The energy dissipated by the transmit power amplifier

  $\varepsilon_{amp} = 10$ *pJ/bit/m²*

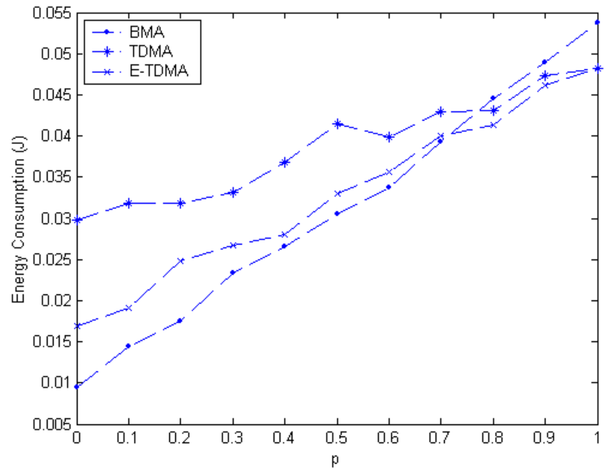
- The ratio of the energy cost in idle listening to the energy dissipation in receiving mode

  $\beta = 0.8$

# Energy Model II — Evaluation Results

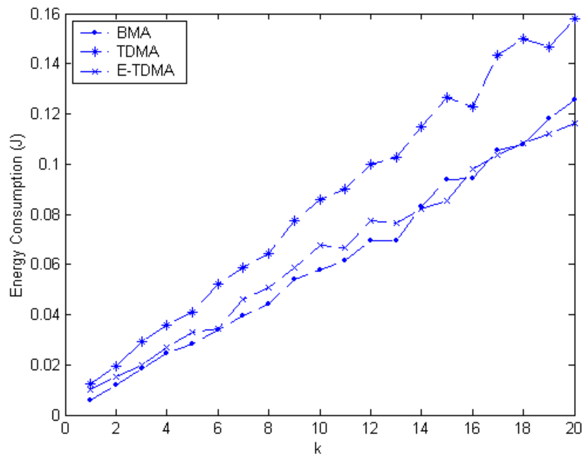



Average packet latency vs. p for the case of N=20 and k=4.

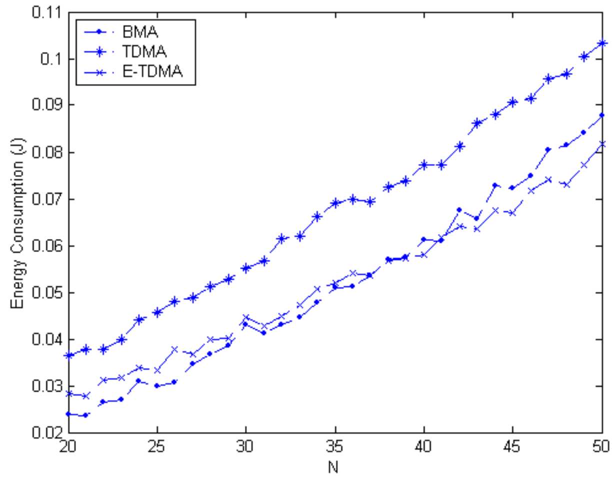



Average total cluster energy consumption vs. p for the case of N=20 and k=4.

# Energy Model II — Evaluation Results

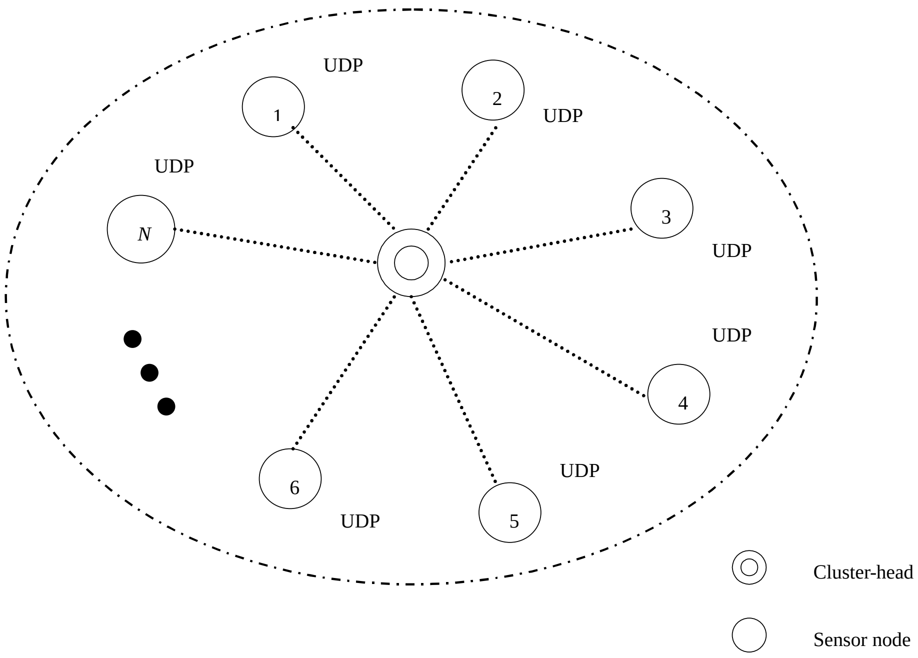



Average total cluster energy consumption vs. k for the case of N=20 and p=0.3.




Average total cluster energy consumption vs. N for the case of k=4 and p=0.3.

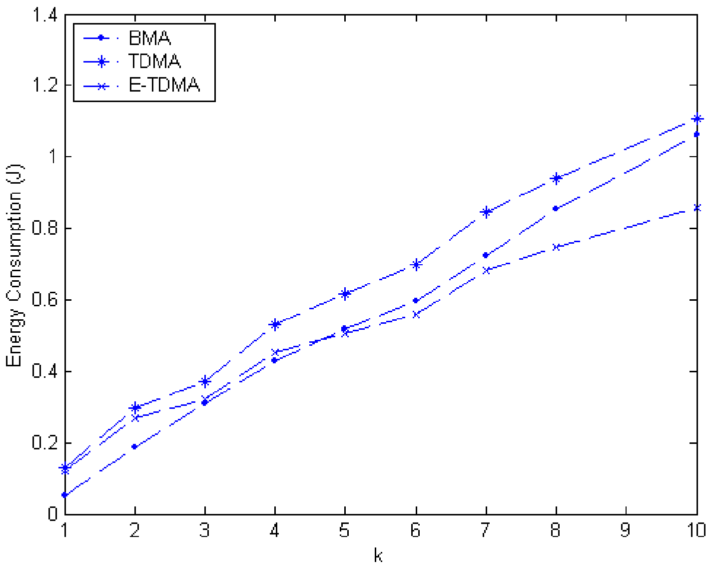
# Simulation



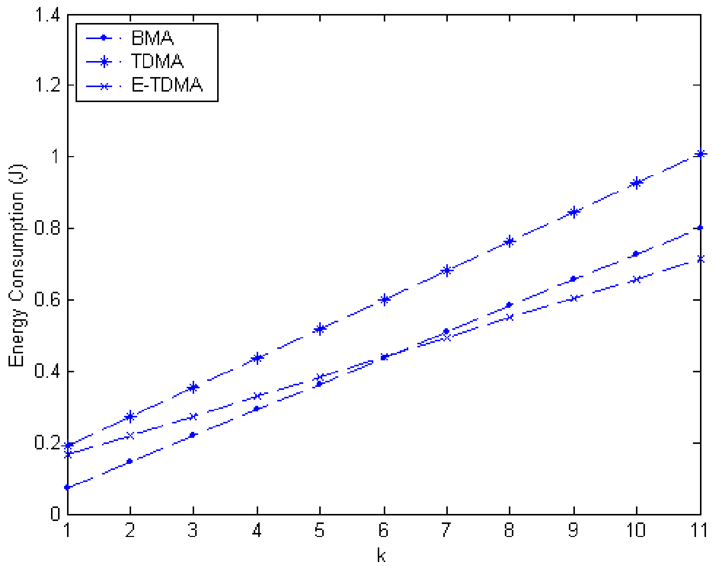

Simulation Topology

- UDP agents.
- The nodes are deployed randomly through the 100m $\times$ 100m area.
- Each node begins with 100 J of energy.
- Power consumption
  - Transmitting power: 462 mW
  - Receiving power: 346 mW
  - Idle listening power: 330 mW
- Bandwidth — 2 Mbps.

# Simulation Results

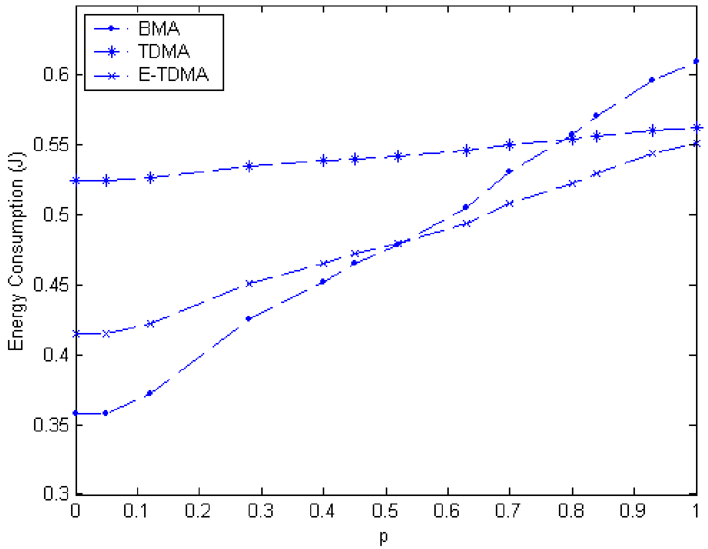



Simulation Result
Average total cluster energy consumption vs. k
( N=20 and p = 0.3 )

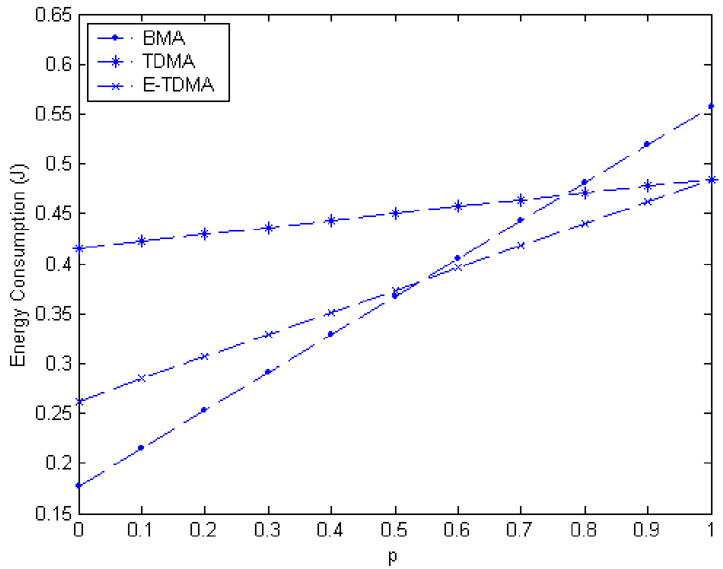



Analytic Result
Average total cluster energy consumption vs. k
( N=20 and p = 0.3 )

# Simulation Results

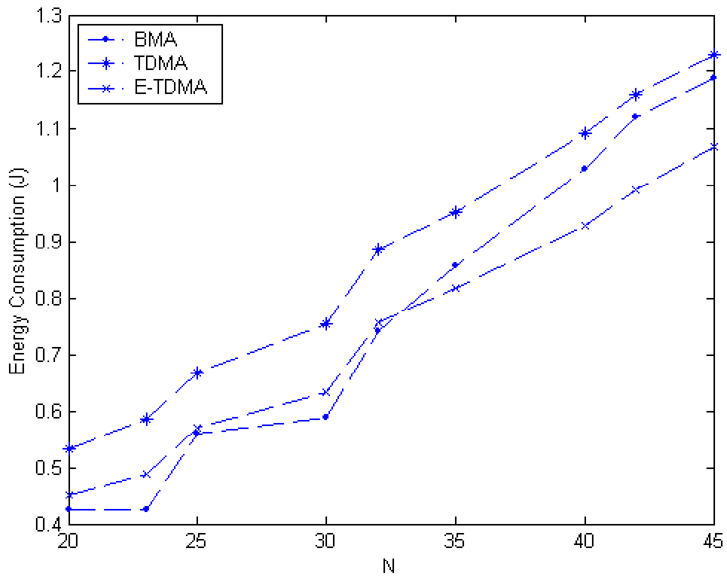



Simulation Result
Average total cluster energy consumption vs. p
( N=20 and k =4 )

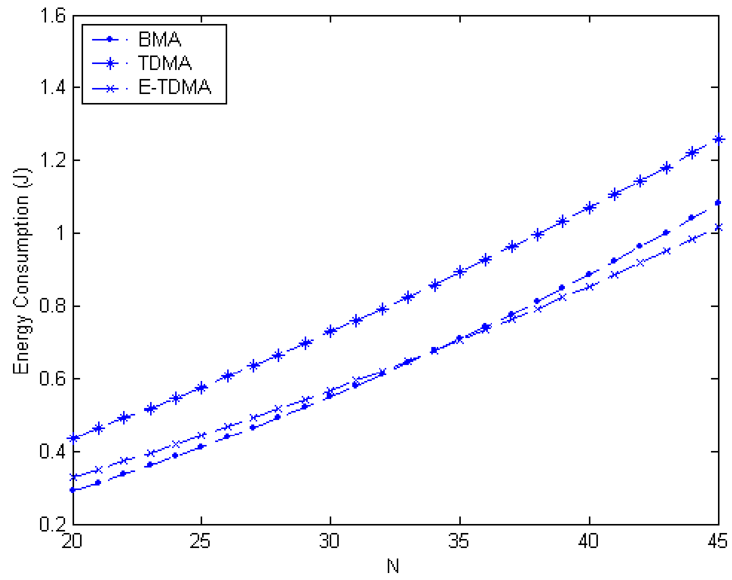



Analytic Result
Average total cluster energy consumption vs. p
( N=20 and k =4 )

# Simulation Results

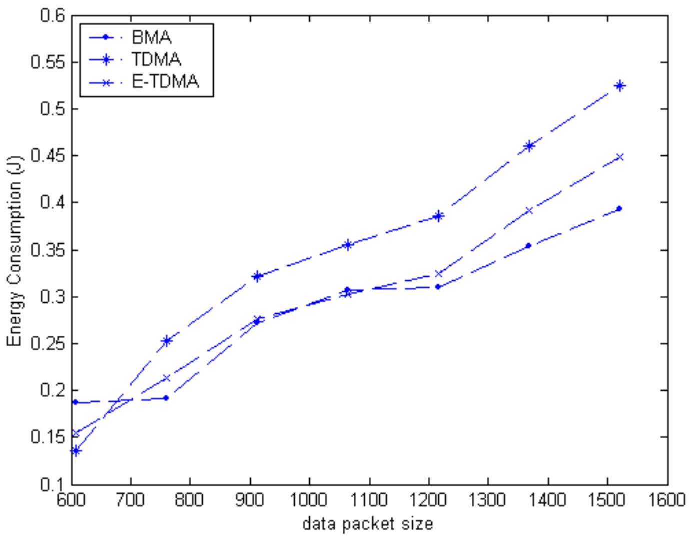



Simulation Result
Average total cluster energy consumption vs. N
( k = 4 and p = 0.3 )

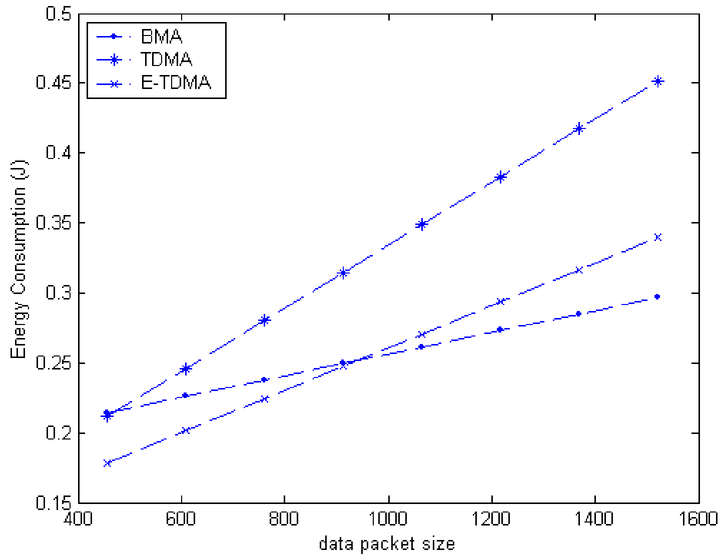



Analytic Result
Average total cluster energy consumption vs. N
( k = 4 and p = 0.3 )

# Simulation Results




Simulation Result
Average total cluster energy consumption vs. data packet size
( N=20, k = 4 and p = 0.3 )




Analytic Result
Average total cluster energy consumption vs. data packet size
( N=20, k = 4 and p = 0.3 )

# Conclusions

- In terms of average packet latency, BMA is superior.

- In terms of energy efficiency, BMA performance heavily depends on
  - The sensor node traffic offer load (parameter p)
  - The number of sensor nodes within a cluster (parameter N)
  - The data packet size
  - The number of sessions per round (parameter k).

- BMA is superior for the cases
  - Low and medium traffic loads
  - Relatively few sensor nodes per cluster
  - Relatively large data packet sizes

- The performance of BMA improves as the data packet size increases.

# Future Work

- Take the possibility of bit-errors in the contention period into consideration.

- Evaluate the whole operation procedure, including cluster set-up phase.

- Only the power conservation and the average end to end delay parameters are used to evaluate the proposed scheme. The other two performance parameters could be considered.

- The optimal values of the parameters *p*, *N*, $k_d$ and *k* are not given. A future research topic could be optimizing the problem

$$0 < \frac{E_{BMA}}{E_{ETDMA}} < 1$$

and finding the optimized relationship between those parameters.