Exploiting Mobility for Energy Efficient Data Collection in Wireless Sensor Networks (Data Mule)

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Data Collection in Sparse Sensor Networks

• Zebranet
  – Track zebra movement in remote locations
  – Used flooding to get data back to base station

• Other examples
  – Remote weather conditions
  – Habitat monitoring
  – City traffic

• Sensors should last a long time (e.g. months or years) unattended so the principle constraint is energy
Using Data MULEs

• One approach to data collection is to build ad-hoc networks
  – Increased radio power to reach neighboring nodes in sparse network
  – Nodes have to spend energy forwarding other nodes data
  – Network has hop spots near access points

• The data MULE approach exploits mobile actors to carry data to access points
  – Examples of possible MULEs are animals, people, vehicles
  – Low power radios and no routing overhead
  – Tradeoff is high latency (usually acceptable in data collection applications)
Paper Outline

• Contributions
• MULE architecture
• Analytical Model
  – Performance measured in data transfer rate, latency, energy requirements
• Results
  – Order of magnitude energy savings and longevity of sensor nodes over ad-hoc networks
• Conclusion
MULE Architecture

• Lower tier - *sensors*: resource and energy constrained devices

• Middle tier - *MULEs*:
  – Large storage capacity and renewable energy
  – Responsible for discovering sensor nodes and access-points (why?)
  – MULE-to-MULE communication possible enhancement to basic architecture

• Upper tier - *access-points*:
  – Internet connected
  – Enhanced power

• Authors claim tiers can be collapsed into single device (e.g. Zebranet) (is this true?)
Advantages/Disadvantages of MULE Architecture

• Benefits
  – Energy efficient: sensors communicate over short range, no hot spots in network (are you sure about this?)
  – Spatial reuse: short range of communication allows spatial reuse of bandwidth, avoids radio complexities such as collisions (for sensors at least!)
  – No routing overhead
  – Robustness: Performance degrades gracefully as MULEs fail, any single MULE failure does not lead to a disconnected network (makes assumption about mobility!)
  – Scalable: adding new sensors and MULEs requires no network reconfiguration
  – Simplicity: No routing protocol to worry about, sensor’s radio stack can be very lightweight, no need for synchronization or localization
  – Simple security: MULEs authenticate themselves, sensors encrypt data (can be done in advance), and access points decrypt; do not need to worry about buffer overflow?

• Limitations
  – Latency: limits realtime applications
  – Best-effort delivery: what happens when MULE fails, radio communication errors
Performance Metrics

- **Data success ratio (DSR)**: ratio of total amount of data transferred to the access-points to the total amount generated, ideal = 1, < 1 caused by MULE failure, communication errors, or buffer overflow.
- **Latency**: average time for data to reach access-point from time of generation.
- **Communication energy**: both average energy per sensor and worst case (dictates network lifetime).
Parameter Space

• Sensor related:
  – $\lambda := $ average amount of generated be a sensor
  – $SB := $ sensor buffer size

• MULE related:
  – Model assumes knowledge of inter-arrival distribution (MULE arrival is a discrete event)
  – Assume MULE buffers are sufficiently large

• Access point related:
  – Modeled by parameter characterizing distribution of time interval between visits to access-point by a MULE

• Radio related:
  – $r := $ MULEs can communicate within this distance
  – $B := $ rate of data transfer from sensor to MULE
  – $K := $ amount of data transferred between a MULE and a sensor
Model

• Queue of generated (undelivered) data at each sensor
• Queue is served whenever a MULE is in a sensor’s rage (modeled as discrete event)
• Amount of data transferred on a MULE arrival is a random variable that depends on factors such as the time the MULE is in communication rate (for analytical tractability, this is taken as a fixed quantity)
Assumptions

• The MULEs arrival process at a sensor is a renewal process \{S(t), t\geq 0\}, where 
  S(t) is the total number of MULEs that have visited the sensor up until time t. 
  This makes assumption that inter-arrival times of MULEs are independent and 
  identically distributed denoted by random variable X^{S}. With average \( \mu \) and 
  variance \( \sigma_{ms} \)
• At a given time only one MULE interacts with a given sensor, and sensors are 
  not close enough to each other to contend for service
• Sensors are identical and not mobile
• The data generation process at a sensor is a renewal process \{U(t), t \geq 0\}, where 
  U(t) is the total amount of data generated till time t. Average data generation rate 
  is \( \lambda \)
• The queuing discipline is FCFS
• Without loss of generality, SB\geq K. If SB< K then the maximum amount of data 
  that is available at a sensor buffer to transfer is K
• Data transmission does not incur any loss, the only loss is due to sensor buffer 
  overflow
• The queuing system is stable and only the stationary (time independent) 
  probabilities are considered
Results

• Result 1. The system is stable (the queue reaches a unique stationary regime) iff

\[ \frac{\lambda}{K \mu} \leq 1 \]

• Result 2. Data Success Ratio (DSR) is given by:

\[ DSR = \frac{\mu E[\min(K, Q)]}{\lambda} = \frac{\mu \left( \sum_{j=0}^{K} j P_j + \sum_{j=K+1}^{SB} K P_j \right)}{\lambda} \]

• Result 3. Average queuing delay (Wb) is given by:

\[ W_q = \frac{\mu^2 \sigma_{ms} + 1}{2\mu} + \frac{E[B^{no}]}{\mu} \]
Scenarios for distribution analysis

1. The MULE arrival distribution and the data generation process is Poisson
   • In this case, $P_j$ depends only on the ratio of $\mu$ and $\lambda$... thus the specific values are not important

2. $K$ is large ($K \geq SB$)

\[
E[Q] = E[U[E[X^s]]] = \frac{\lambda}{\mu}
\]

Slide 12/20
Determining $K$

Figure 3. Amount of time a sensor is in contact with a MULE.

$$K = \left( \frac{\pi r}{2v} \right) B$$
Impact of sensor duty cycle

- Duty cycle = discovery time / beacon time
- When duty cycle < 100%, performance suffers because:
  - A MULE may not be discovered at all because the sensor was asleep during the time the MULE was in communication range of sensor
    \[
    \mu^* = \frac{\mu(CT - DT)}{BT} \\
    \text{if } CT - DT \geq BT \quad \mu^* = \mu
    \]
  - The amount of data that can be transferred (K) in one contact may decrease if the MULE is discovered in the middle of the duration it is in the communication range of the sensor
    \[
    K^* = \frac{K}{2}(1 + DT/CT)
    \]
Simulation setup

- Two-dimensional grid, sensors and access points randomly placed in grid
- MULEs: described by initial position and mobility pattern (Random waypoint, random walk, deterministic arrivals (fixed route and velocity), and Poisson arrivals)
- Data generation either uniform or Poisson distribution
- Parameters:
  - $K$ is varied by varying radio bandwidth $B$
  - $\mu$ is varied by adding more MULEs
  - 2 km x 2 km grid, 100 sensors and 1 access point at corner
  - MULE buffer was 10 MB, velocity 10 m/s, radio range 25 m
  - $\Lambda$ fixed at 90 KB / hour, sensor duty cycle 1/200
Performance Metrics

- Scaling \( \mu \) and SB

![Graph showing average buffer occupancy vs. \( \mu \) (MULEs per hour). The graph includes simulations and analyses for different SB sizes: 1 MB, 0.1 MB, and 0.05 MB.](image)
Performance Metrics

- Scaling $\mu$ and SB
Performance Metrics

- Scaling $\mu$ and SB

![Graph showing latency vs $\mu$ (MULEs per hour)]
Performance Metrics

• Scaling K

![Graphs showing the effect of scaling K on buffer occupancy and latency.](image)

Figure 5. Effect of scaling $K$. (a) buffer occupancy (b) latency.
## Performance Metrics

**Table 1**

<table>
<thead>
<tr>
<th>Mobility model</th>
<th>CVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson</td>
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<tr>
<td>Deterministic</td>
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</tr>
<tr>
<td>Waypoint</td>
<td>0.75</td>
</tr>
<tr>
<td>Manhattan</td>
<td>2.1</td>
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</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Performance metrics</th>
<th>Buffer Occ</th>
<th>DSR</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^{\uparrow}$</td>
<td></td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$SB^{\uparrow}$</td>
<td></td>
<td>$-$</td>
<td>$\uparrow$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K^{\uparrow}$</td>
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<td>$\downarrow$</td>
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<tr>
<td>$\lambda^{\uparrow}$</td>
<td></td>
<td>$\uparrow$</td>
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<td>$\uparrow$</td>
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</tbody>
</table>

*Note.* $\uparrow$ indicates an increase in the quantity. $\downarrow$ indicates a decrease and $-$ indicates no effect.
Performance Metrics

Figure 6. Effect of different mobility models.
Performance Metrics

Figure 7. Energy comparison of MULE vs Ad-hoc network approach as a function of sensor density.
Conclusions

• Exploiting mobility for energy-efficient data collection in sparse sensor networks vs. forming ad hoc network

• Limited to non real-time communication and only when there are mobile nodes present in the network

• MULE to MULE and sensor to sensor communication could enhance data success ratio