Reliable and Energy-Efficient Data Delivery in Sparse WSNs with Multiple Mobile Sinks

Giuseppe Anastasi

Pervasive Computing & Networking Lab (PerLab)

Dept. of Information Engineering, University of Pisa

E-mail: giuseppe.anastasi@iet.unipi.it

Website: www.iet.unipi.it/~anastasi/

Università di Pisa

PerLab

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Reliable and Energy-Efficient Data Delivery in Sparse WSNs with Multiple Mobile Sinks

Based on joint work with

Eleonora Borgia, Marco Conti and Enrico Gregori
IIT-CNR, Italy

ART DECO
adaptive infrastructures for decentralised organisations

BioNets
Bio-inspired Service Evolution for the Pervasive Age

Overview

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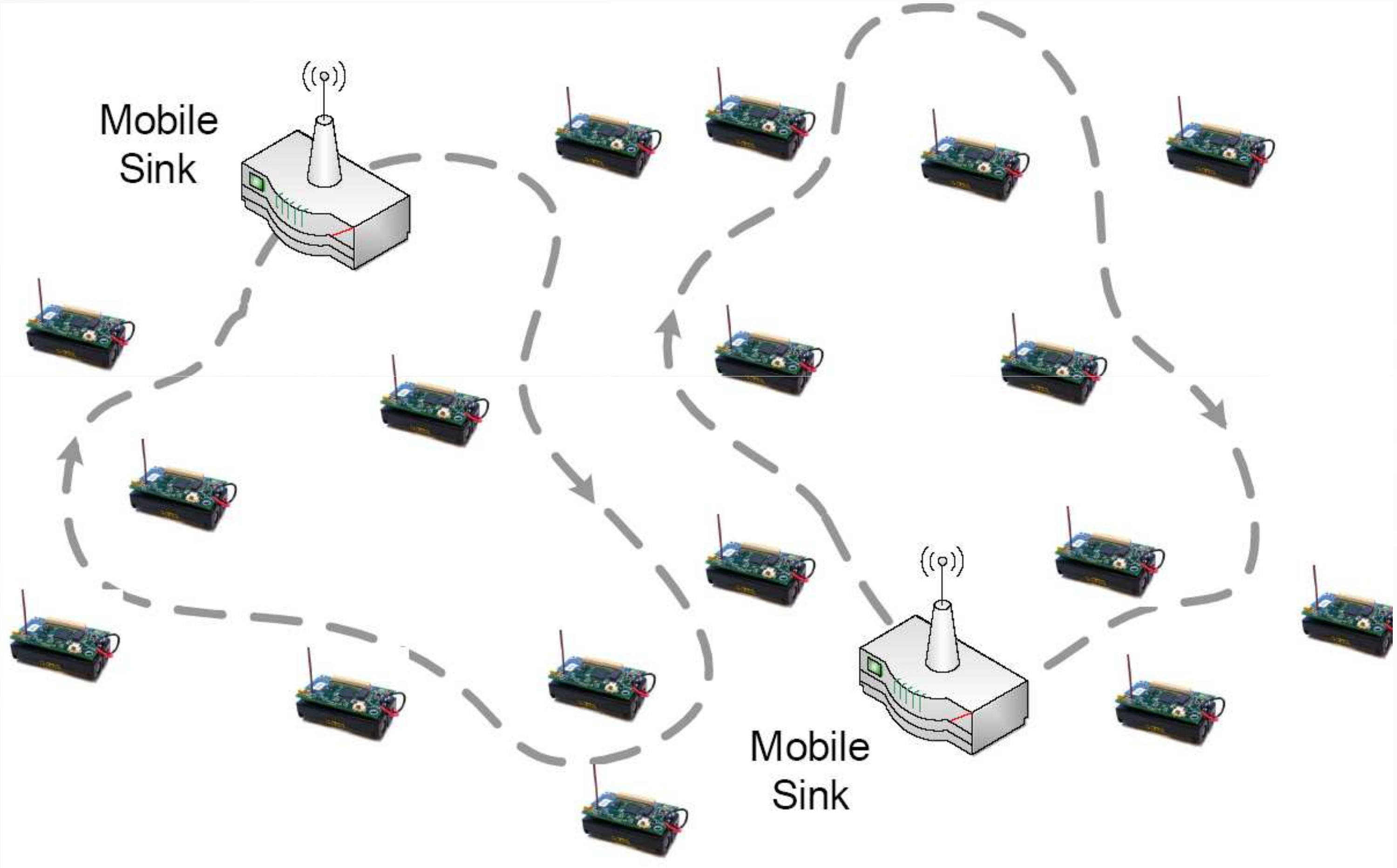
- WSNs with Mobile Sinks
  - Advantages and Challenges
- Reliable & Energy Efficient Data Delivery to MSs
  - Adaptive Hybrid Protocol
- Simulation Results
- Experimental Measurements
- Conclusions

WSNs with Mobile Sinks



WSNs with Mobile Sinks

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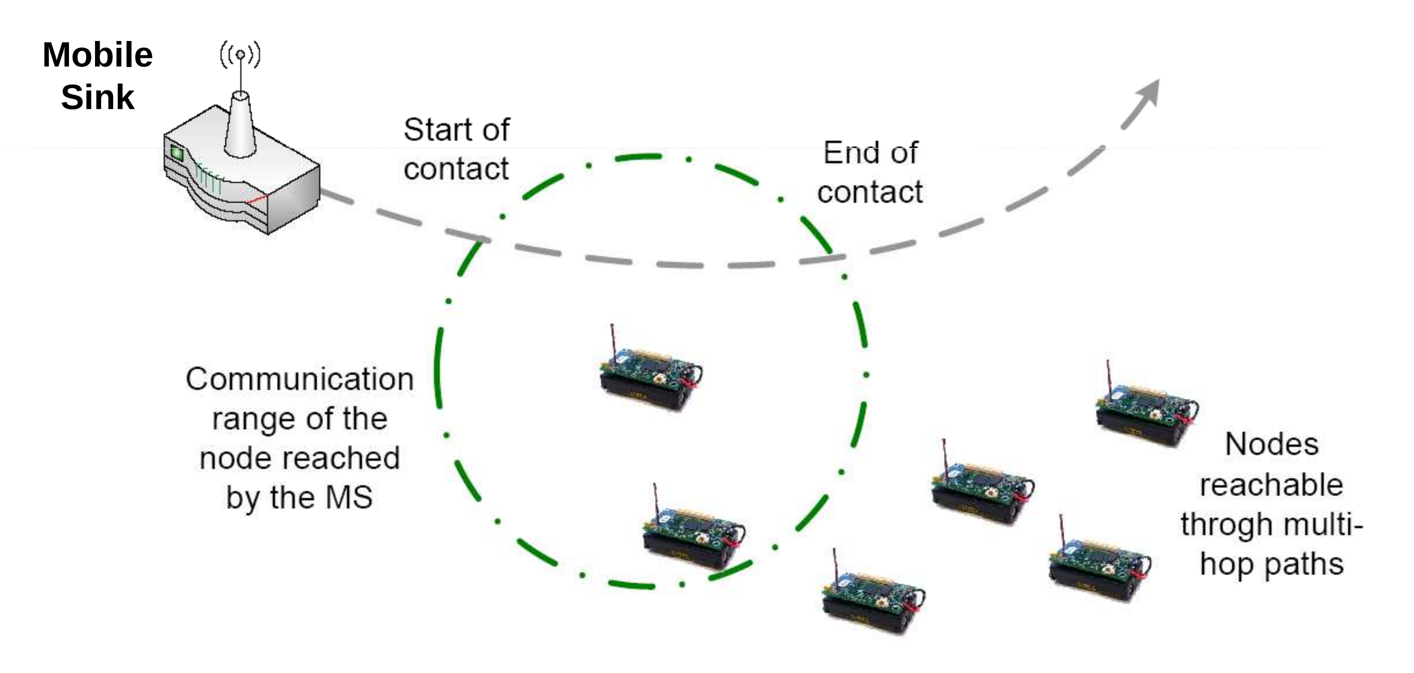
Advantages

- Connectivity
  - A sparse sensor network may be a feasible solution for a large number of applications.
- Cost
  - Reduced number of sensor nodes → reduced costs
- Reliability
  - Single-hop communication instead of multi-hop communication
  - Reduced contentions/collisions and message losses
- Energy Efficiency
  - Mobile Sinks can help reducing the *funneling effect*

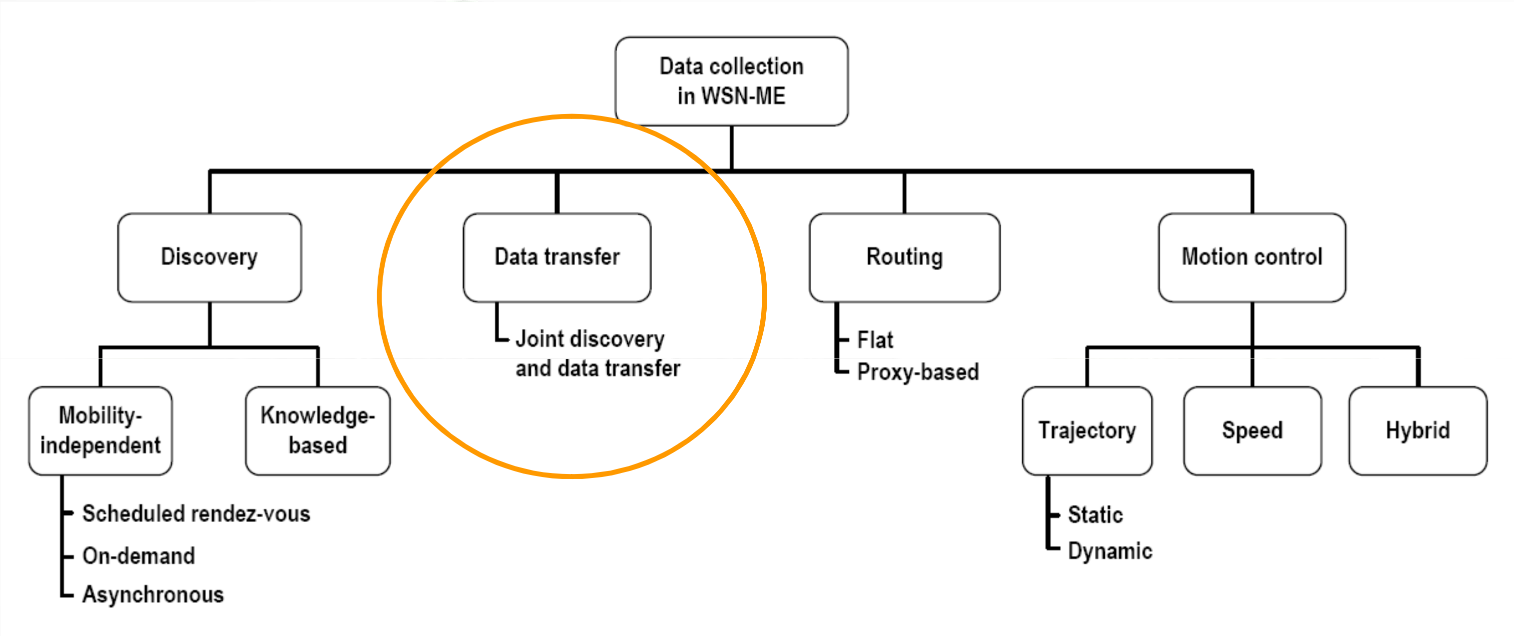
WSNs with Mobile Sinks

Challenges

- Contact Detection
- Reliable Data Transfer
- Data Forwarding
- Mobility Control



Approaches to Data Collection



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Reliable and Energy-efficient Data Delivery to Mobile Sinks

Which is the best way to transfer *all* the data available at the sensor node to the Mobile Sink(s) with the minimum energy expenditure?

Reference Scenario

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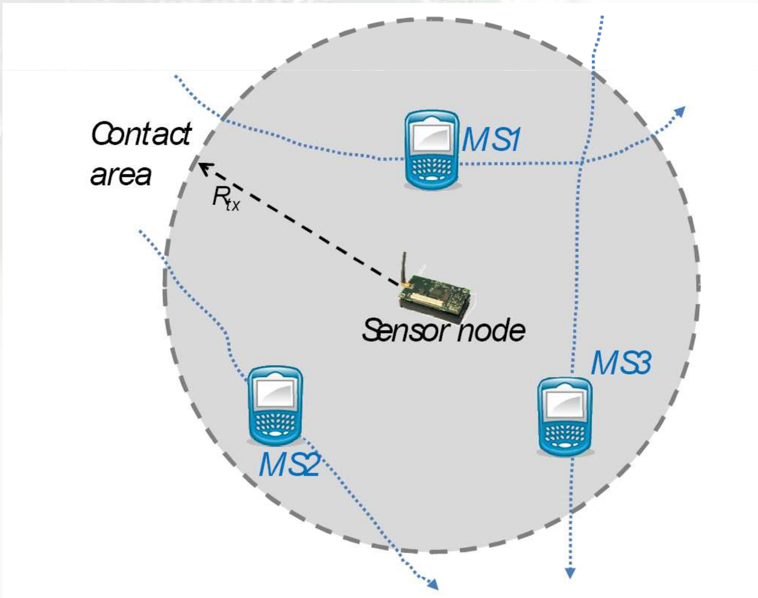
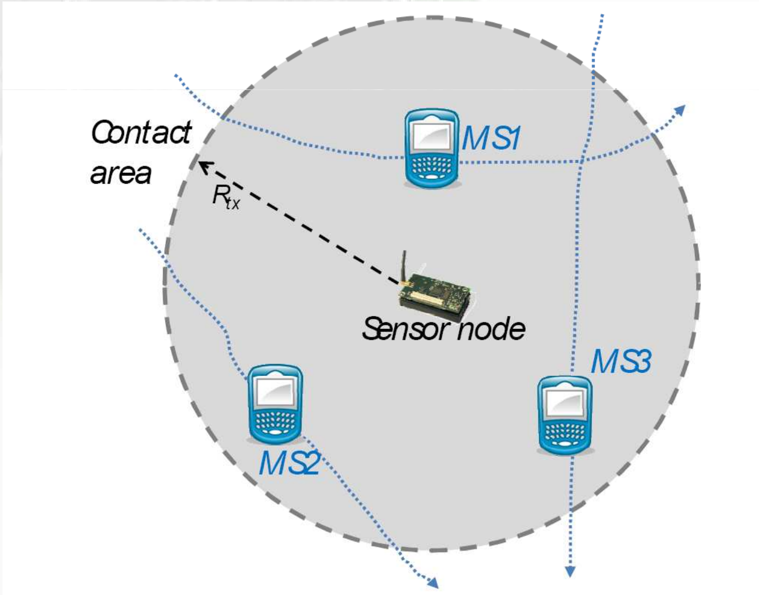
- Urban Sensing Scenario
  - Sparse WSN with multiple mobile users
  - Each user consumes data for its own purposes (MS)
  - Bundle-oriented communication



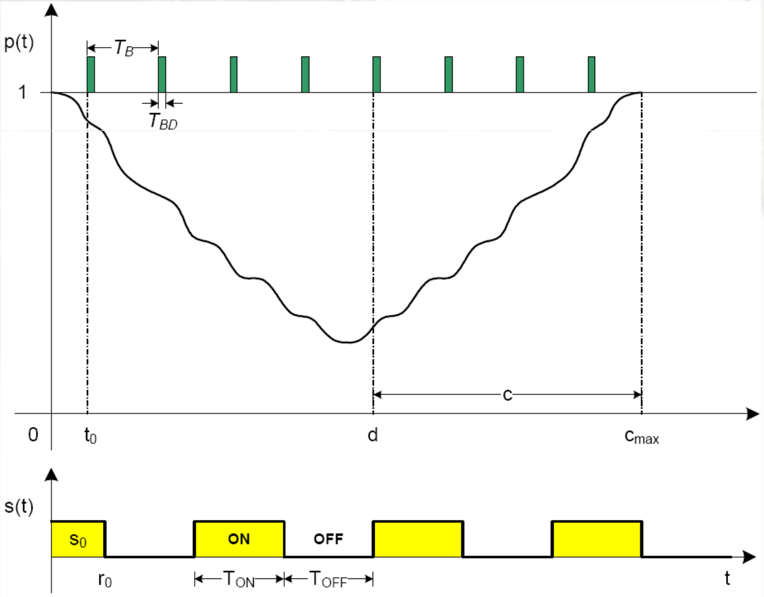
Data Transfer

- Challenges
  - Contacts are sporadic and short
    - ⇨ Contact duration depends on MS path, speed, …
  - Some contacts may be missed due to duty cycle



Data Transfer

- Challenges
  - The discovery phase further reduces the residual contact time



Data Transfer

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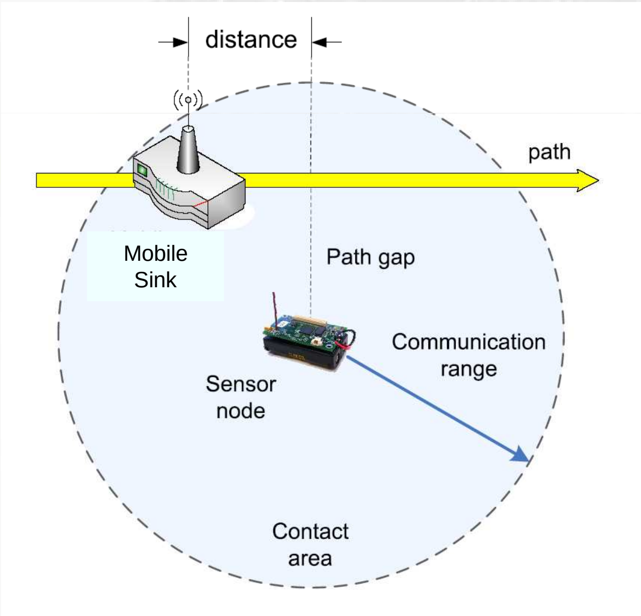
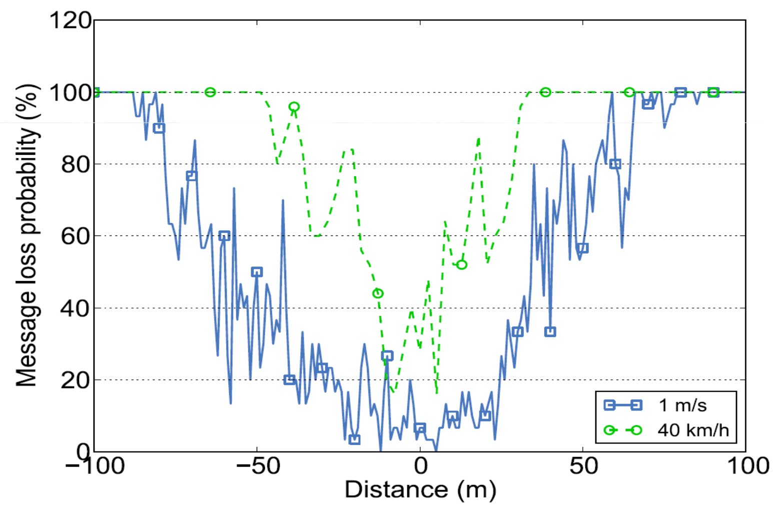
- Challenges
  - Communication is impaired by message losses
  - This reduces the available bandwidth





G. Anastasi, M. Conti, E. Gregori, C. Spagoni, G. Valente, Motes Sensor Networks in Dynamic Scenarios: a Performance Study for Pervasive Applications in Urban Environments, *International Journal of Ubiquitous Computing and Intelligence,* Vol. 1, N.1, April 2007.

Data Transfer

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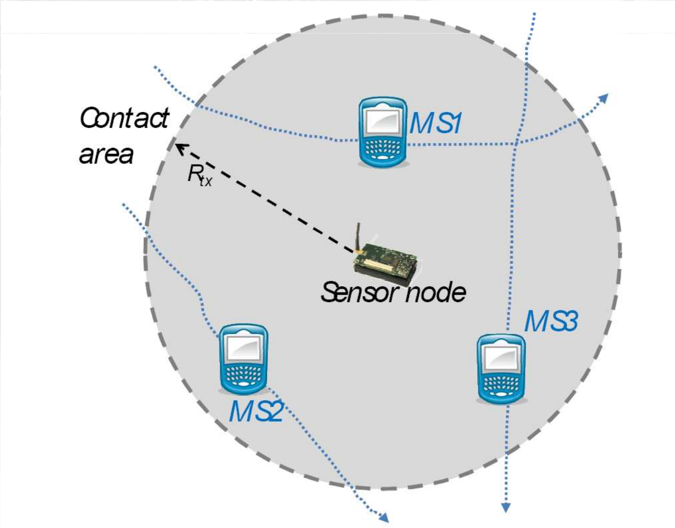
- Challenges
  - Multiple MSs simultaneously in contact
    - ⇨ They typically enter the contact area at different times
    - ⇨ They have different contact durations
    - ⇨ They experience different conditions (e.g., message loss)



Data Transfer Protocol

- Design Principles
  - Reliable communication despite of message losses
  - Efficient exploitation of limited resources
    - ⇨ Verbose protocols should be avoided
  - Adaptation to channel conditions
    - ⇨ Non accurate information
    - ⇨ Time-varying channel conditions
    - ⇨ Multiple MSs
  - Beaconing is required also during communication
    - ⇨ This can be achieved through ACKs

Common Approach

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- **ARQ Scheme**
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Selective Repeat

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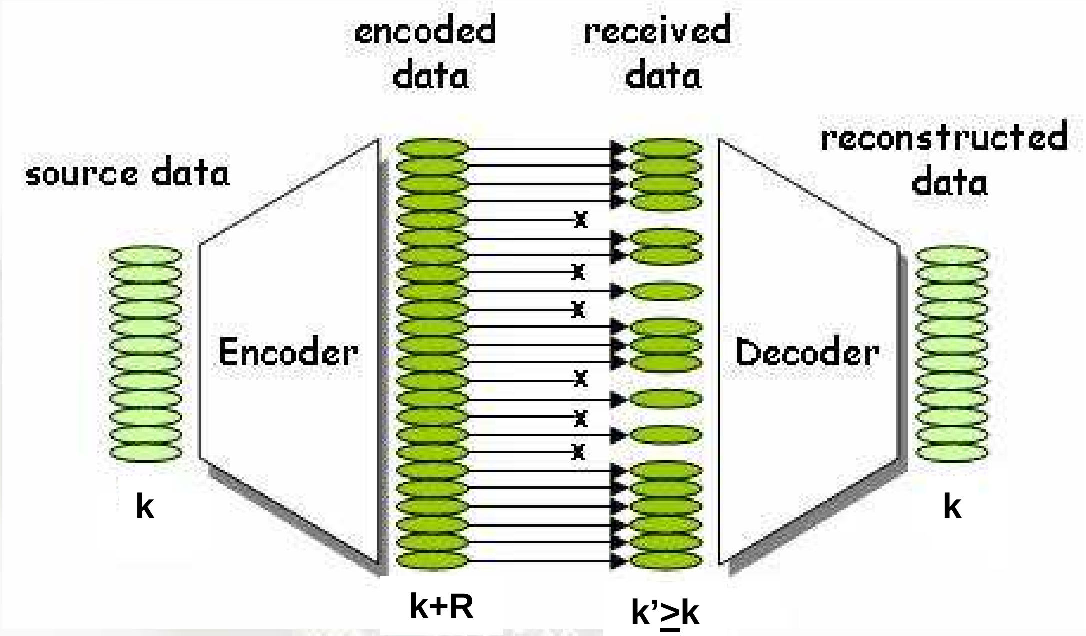
- Simple ARQ Scheme
  - The sender transmits data messages
  - The receiver replies with ACKs including an indication of data messages correctly received
  - Selective retransmission of missed/corrupted messages
- Robust against message losses
  - Corrupted or missed messages are retransmitted
  - No assumption about the MS's location
- Suitable for unicast communication
  - Data are to be transferred to a single MS at a time

Erasure coding



Any subset of *k* encoded blocks allows the receiver to reconstruct the source data

Which is the optimal redundancy?

The source node sends (k + R) codes.

Which is the probability to receive correctly at least k codes at the destination?

$$P_{succ} = \Pr ob\{k' \geq k\} = \sum_{i=k}^{k+R} \binom{k+R}{i} \cdot p^i \cdot (1-p)^{k+r-i}$$

where:

- k': number of codes correctly received by the destination
- p: packet loss (constant)

Energy Efficiency

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$$\eta = \frac{k \cdot S_{MSG}}{(k+R) \cdot \delta_{MSG} \cdot P_{tx}} \cdot P_{succ}$$

where:

- P_{succ} probability to receive at least k codes
- k original number of messages
- S_{MSG} message size (in bytes)
- $k + R$ total number of coded messages sent
- δ_{MSG} time taken to send a single coded message
- P_{tx} transmit power

Optimal Redundancy (k=4)

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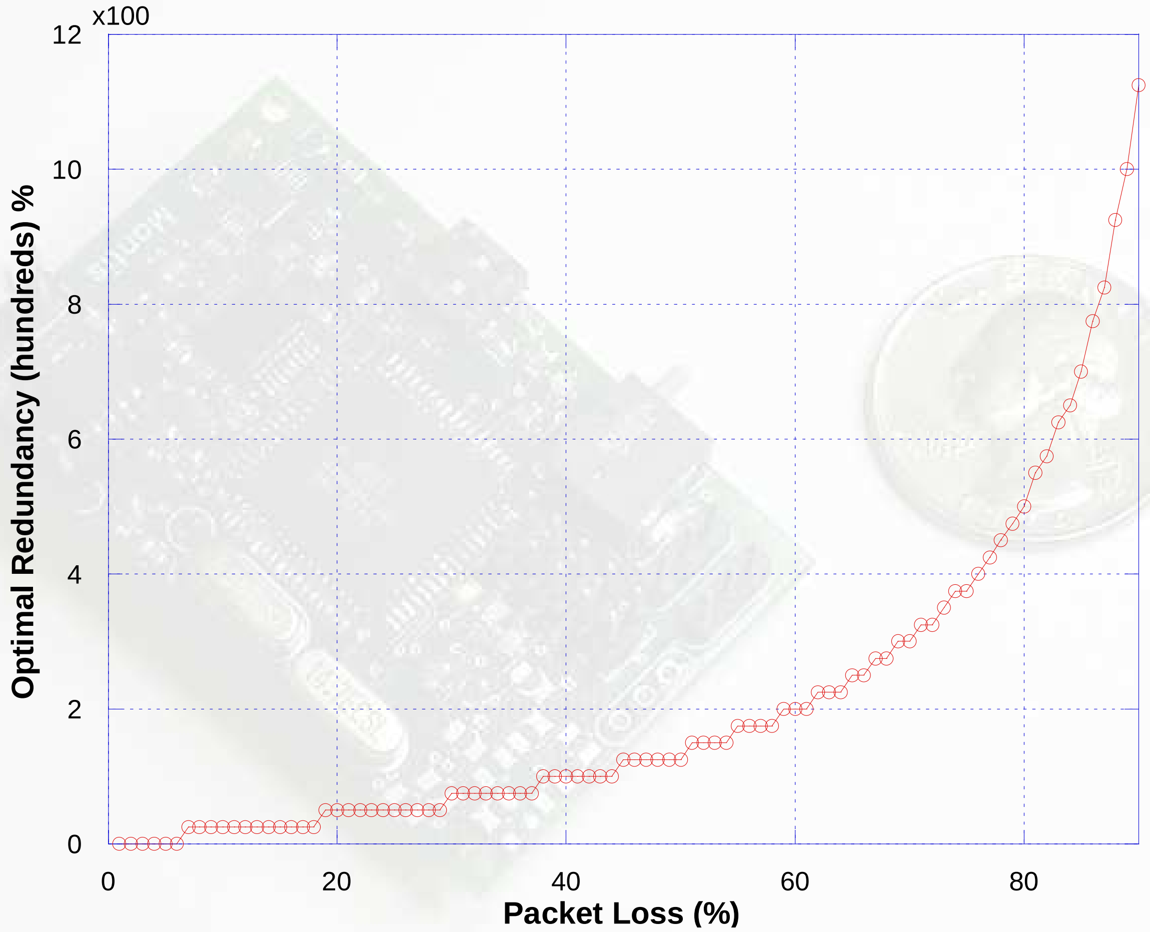
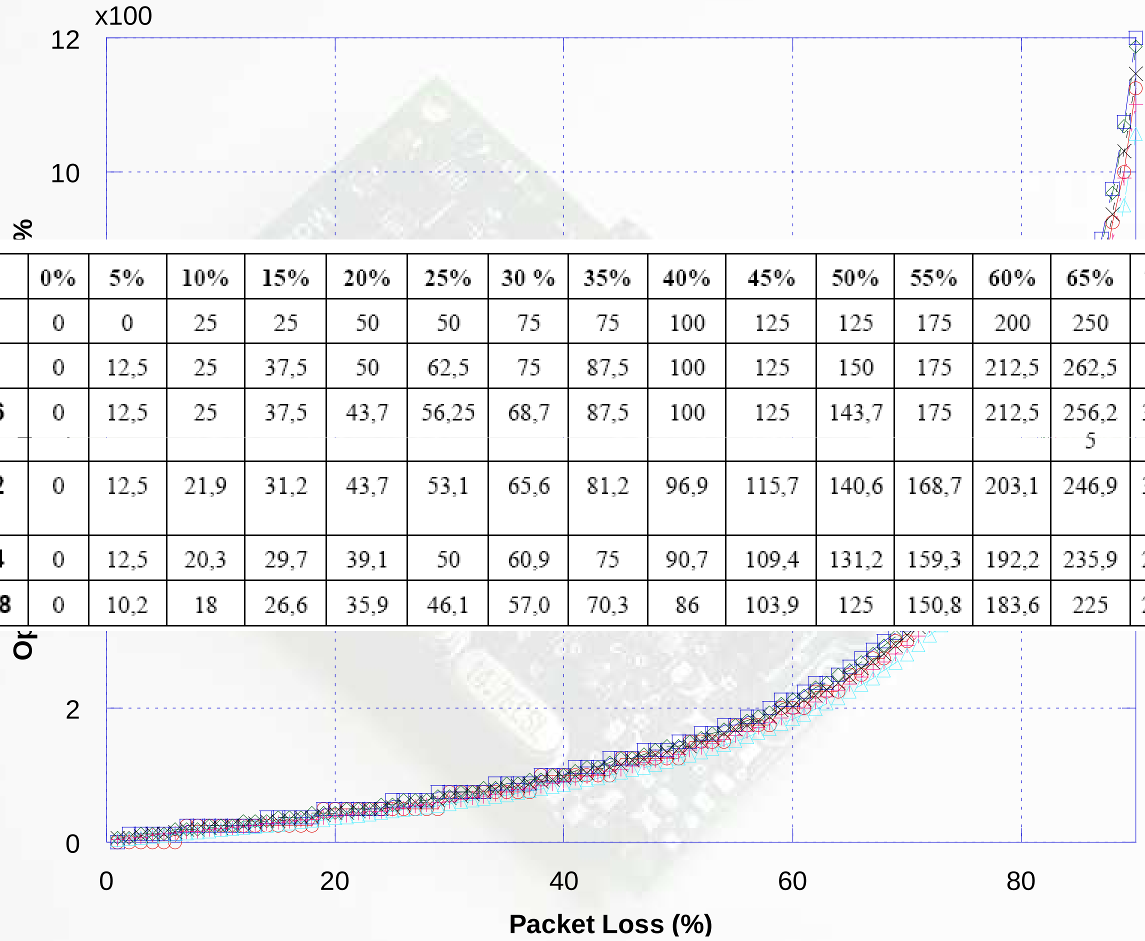


Optimal Redundancy



	0%	5%	10%	15%	20%	25%	30 %	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
4	0	0	25	25	50	50	75	75	100	125	125	175	200	250	300	375	500	700	1125
8	0	12,5	25	37,5	50	62,5	75	87,5	100	125	150	175	212,5	262,5	325	412,5	537,5	762,5	1200
16	0	12,5	25	37,5	43,7	56,25	68,7	87,5	100	125	143,7	175	212,5	256,25	318,7	406,2	537,5	756,2	1187,5
32	0	12,5	21,9	31,2	43,7	53,1	65,6	81,2	96,9	115,7	140,6	168,7	203,1	246,9	309,3	393,7	518,7	728,1	1146,9
64	0	12,5	20,3	29,7	39,1	50	60,9	75	90,7	109,4	131,2	159,3	192,2	235,9	293,7	375	495,3	696,9	1100
128	0	10,2	18	26,6	35,9	46,1	57,0	70,3	86	103,9	125	150,8	183,6	225	280,5	358,6	475	668,8	1057

Erasure coding in our scenario

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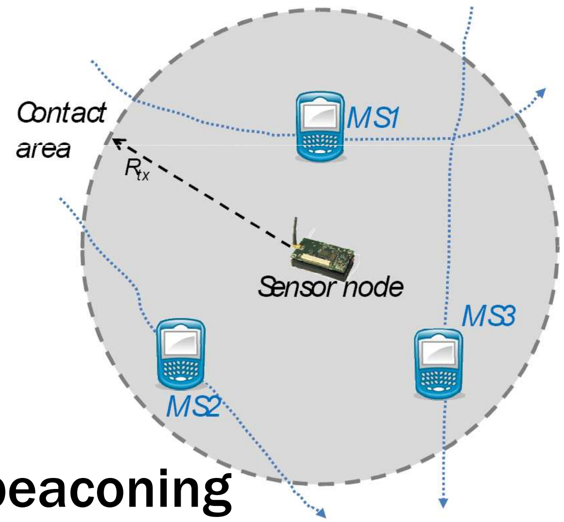
- Multiple MS scenario
  - The required redundancy is different for different MSs
  - For a given MS, the required redundancy varies over time

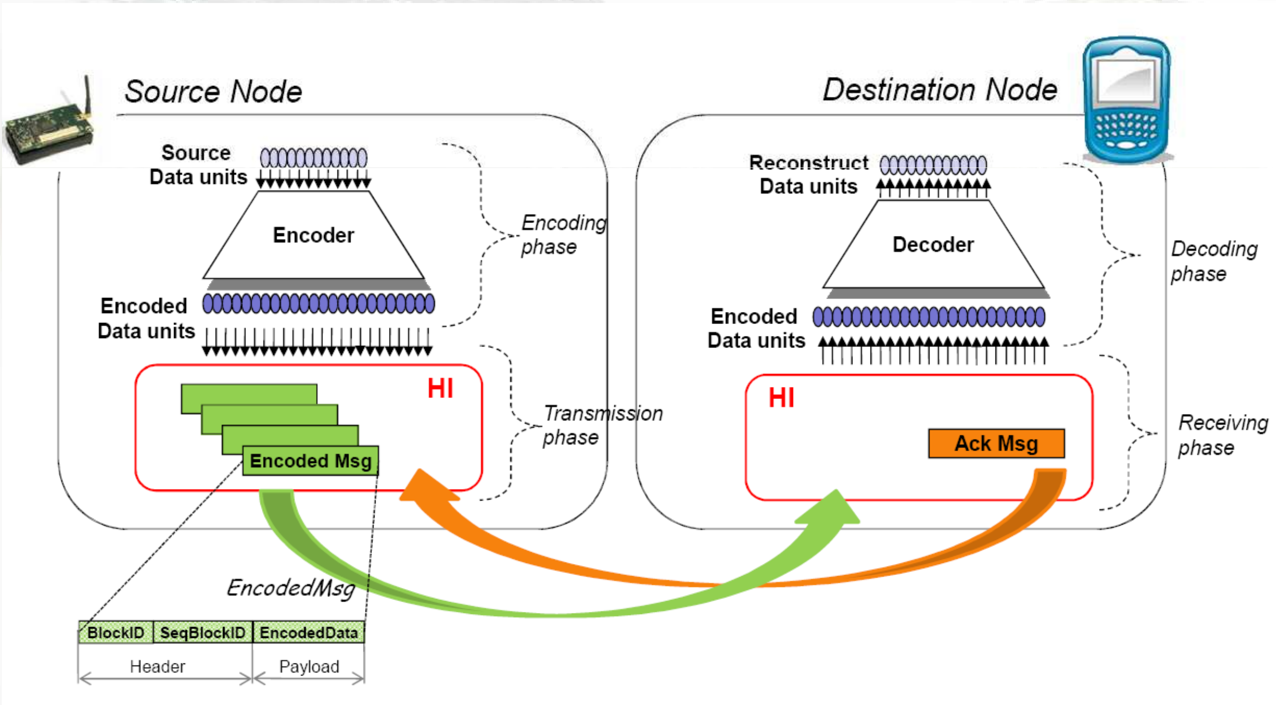
    ⇨ Redundancy should be adaptive



  - ACKs are required for implicit beaconing

Hybrid Approach

- **HI: Hybrid Interleaved Data Delivery**
  - Adaptive Erasure Coding + ACKs
  - Reed-Solomon codes are considered

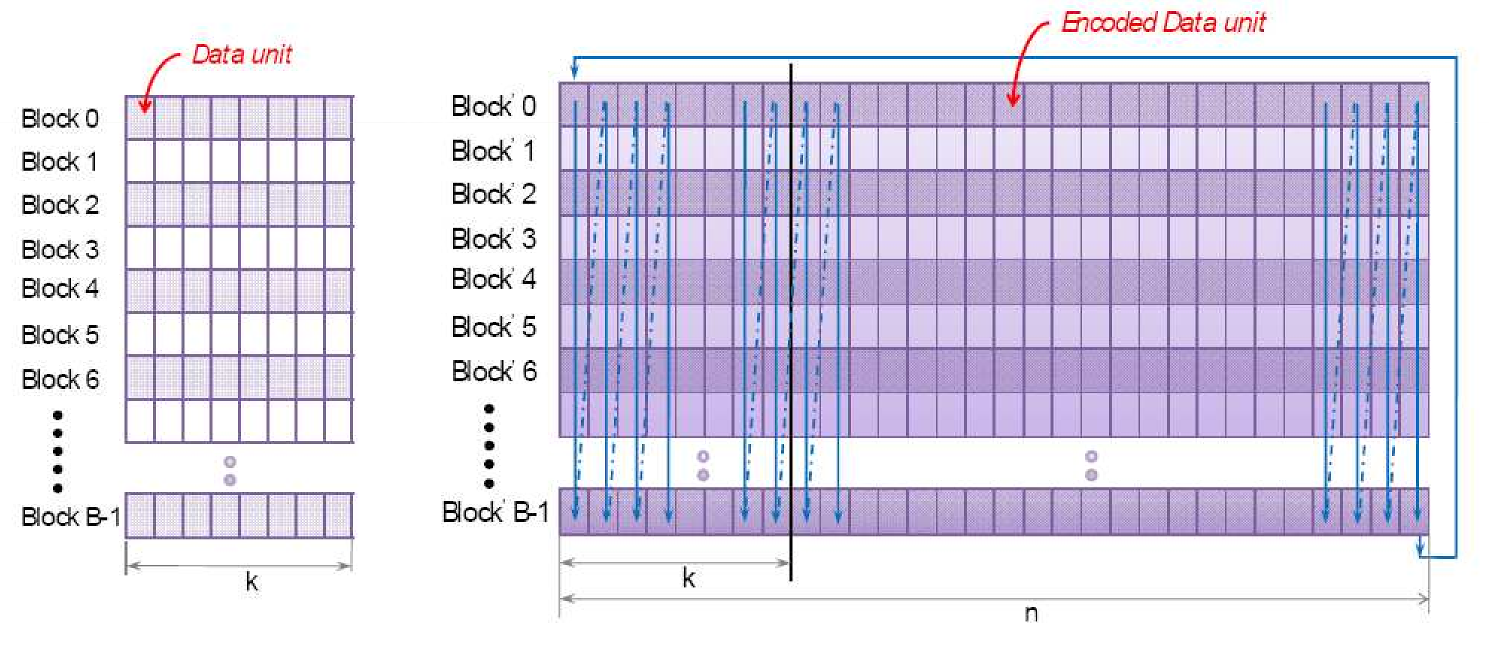


Basic idea

- The bundle is divided in B blocks
- Each block is then encoded separately
- Codes are generated in advance…
- … and sent out on demand
- The number of transmitted codes depends on feedbacks received from MSs (through ACKs)

Interleaved Transmission

- **HI: Hybrid <u>Interleaved</u> Data Delivery**
  - **Messages to transmit are picked from consecutive blocks**
  - **Uniform distribution of message losses among blocks**



Adaptive Redundancy

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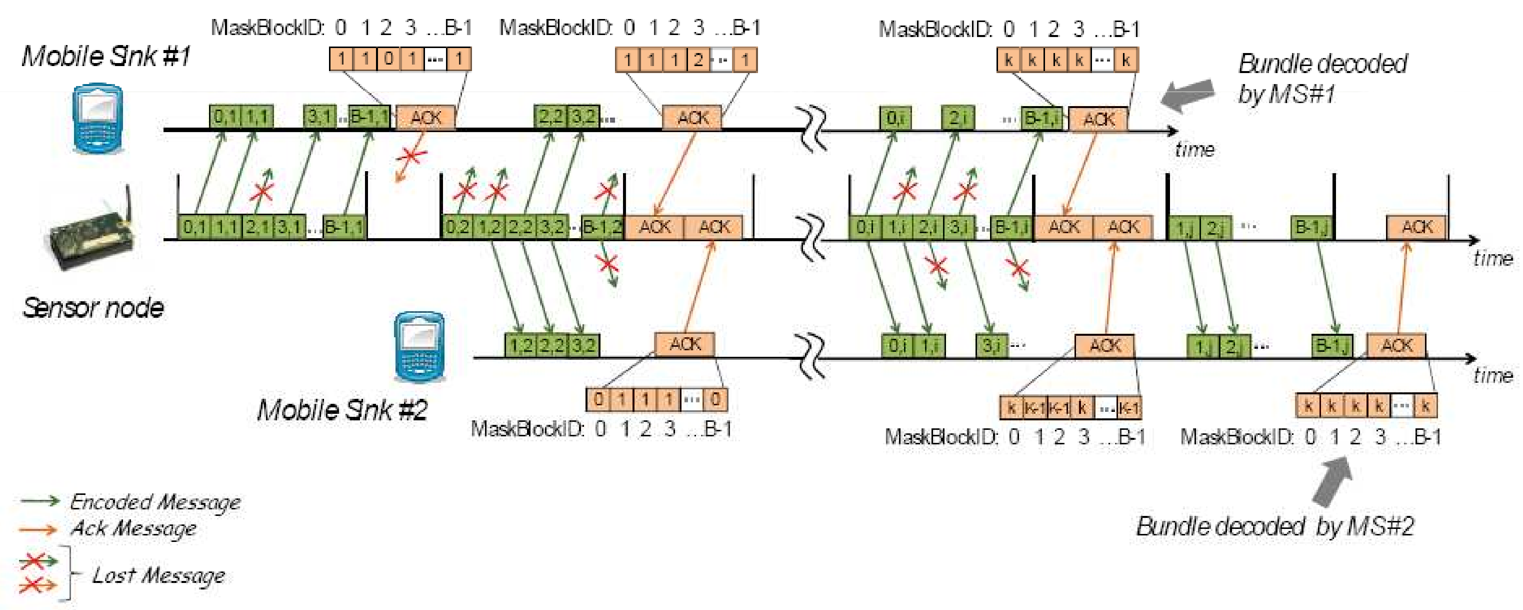
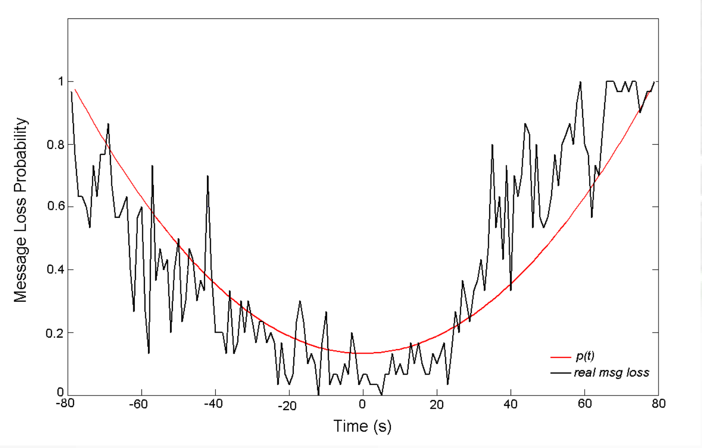
- **Each encoded message includes**
  - **Block identifier (0, 1, …, B-1)**
  - **Sequence number within the block (1, 2, …)**
  - **Encoded data unit**



Simulation Setup

- Ad Hoc Simulator
  - HI Protocol and SR Protocol
  - Discovery based on periodic Beacon emission by MSs
- Scenario
  - Single Sensor, Multiple MSs
  - MSs move along linear paths, at a fixed distance from the sensor
- Message Losses

$$p(t) = a_2\left(t - \frac{c_{max}}{2}\right)^2 + a_1\left(t - \frac{c_{max}}{2}\right) + a_0$$



Parameter	v=3.6 km/h	v=20 km/h	v=40 km/h
c_{max}	158s	30s	17s
a_0	0.133	0.3828	0.4492
a_1	0 s^{-1}	0 s^{-1}	0 s^{-1}
a_2	0.000138 s^{-2}	0.0028 s^{-2}	0.0077 s^{-2}

G. Anastasi, M. Conti, E. Monaldi, A. Passarella, An Adaptive Data-transfer Protocol for Sensor Networks with Data Mules, *Proc. IEEE WoWMoM 2007*, Helsinki, Finland, June 18-21, 2007.

Performance Metrics

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- **Decoding Probability**
  - probability of receiving the minimum amount of codes for a MS being able to decode the original data bundle
  - in the SR protocol, probability of receiving the complete bundle
- **Energy Consumption**
  - average total energy consumed by the sensor node per each byte correctly transferred to MS(s)

$$Energy = \frac{\left(m \cdot \delta_{MSG} \cdot P_{tx}\right) + \frac{m \cdot \delta_{MSG}}{T_{ACK}} \cdot N_{MS} \left(\delta_{ACK} \cdot P_{rx}\right)}{B_{tot}}$$

Total Number of ACKs generated by all MSs

Energy spent for sending m data messages

Total # of bytes decoded by all MSs

Energy spent for receiving ACKs from all MSs

Simulation Parameters

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Parameter	Value
k, n (HI protocol)	8, 256
Message/ACK Size	110 bytes
Message Transmission Time δ_{MSG}	17 ms
ACK Transmission Time δ_{ACK}	17 ms
ACK Period T_{ACK}	16* δ_{ACK}
Beacon Period T_B	100 ms
N_{ACK} (40Km/h, 3.6Km/h)	8, 24
Duty Cycle (D)	5%
Transmission Power P_{tx}	52.2 mW
Reception Power P_{rx}	56.4 mW

Impact of Redundancy

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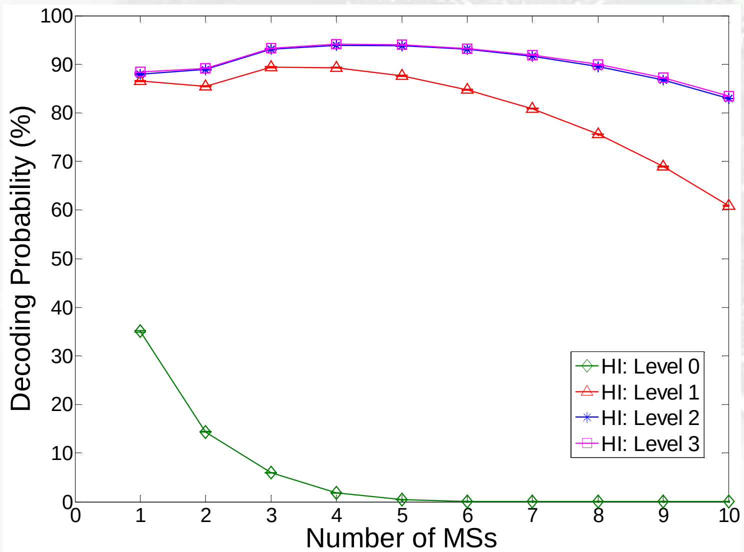
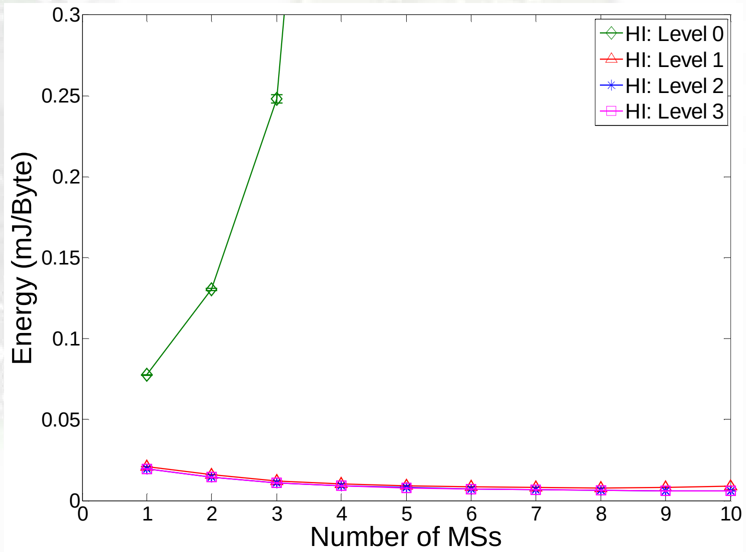
Redundancy Level	k	*R*	*k+R*
Level 0	8	0	8
Level 1	8	8	16
Level 2	8	24	32
Level 3	8	248	256





Simulation Results

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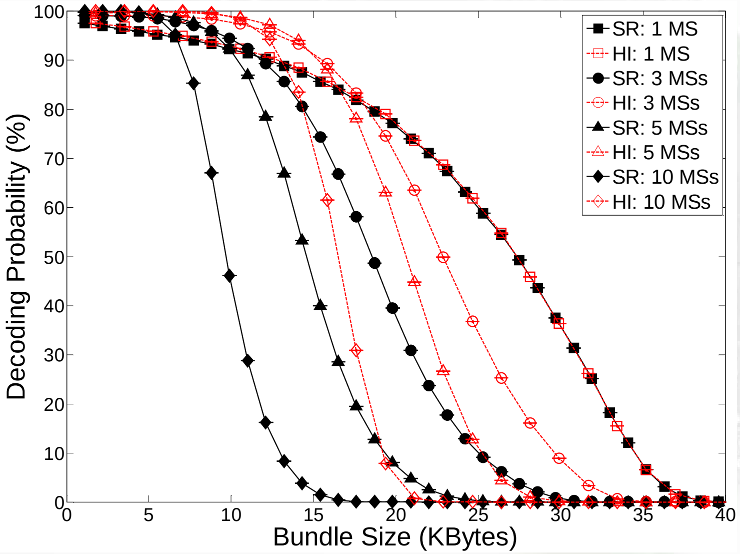
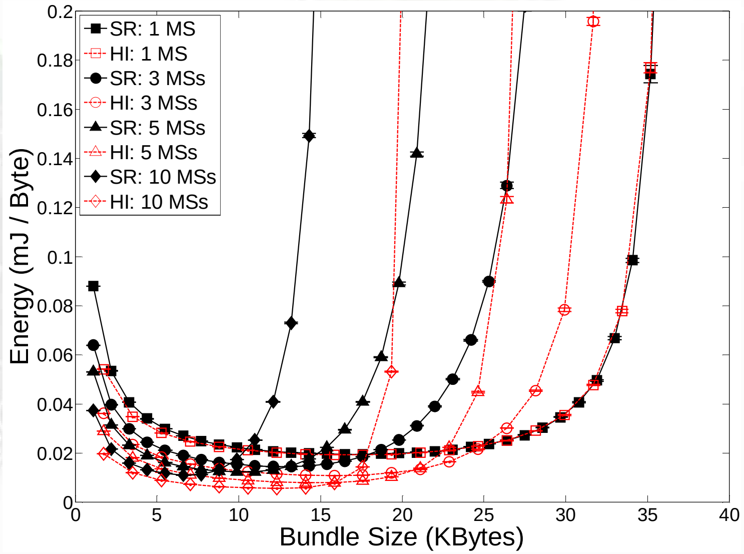
- Increasing number of MSs
- All MSs move at the same speed (40 Km/h)





Simulation Results

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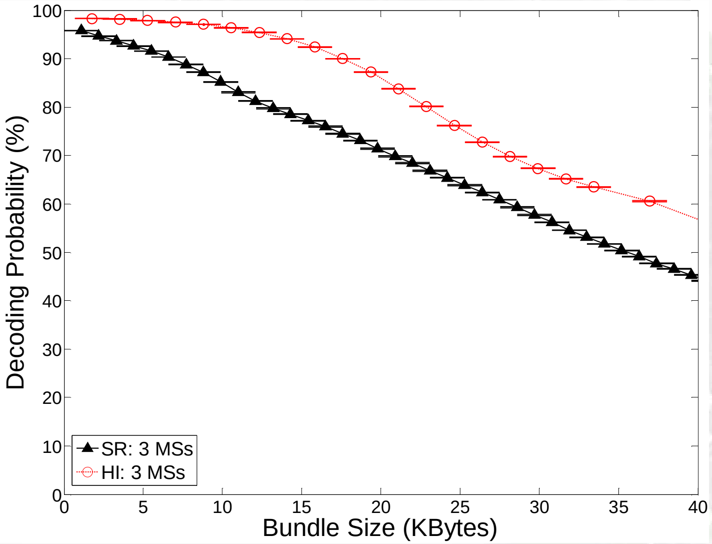
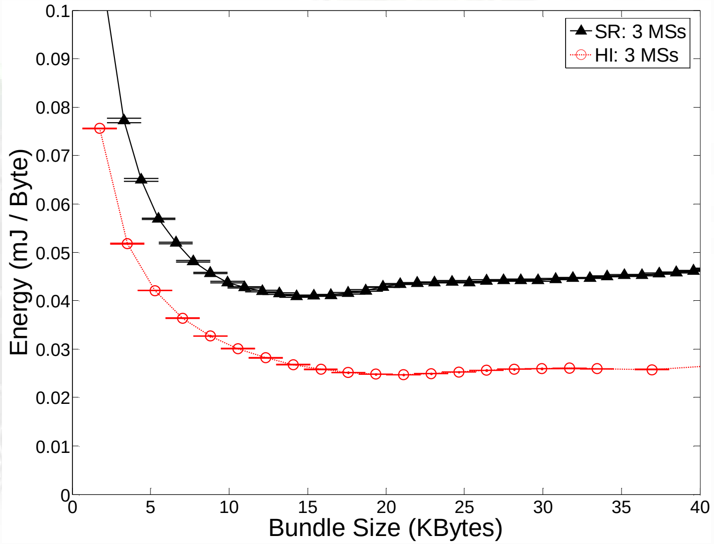
- 3 Mobile Sinks
  - with different paths and speeds
    - 3.6 Km/h, 20 Km/h, 40 Km/h





Simulation Results

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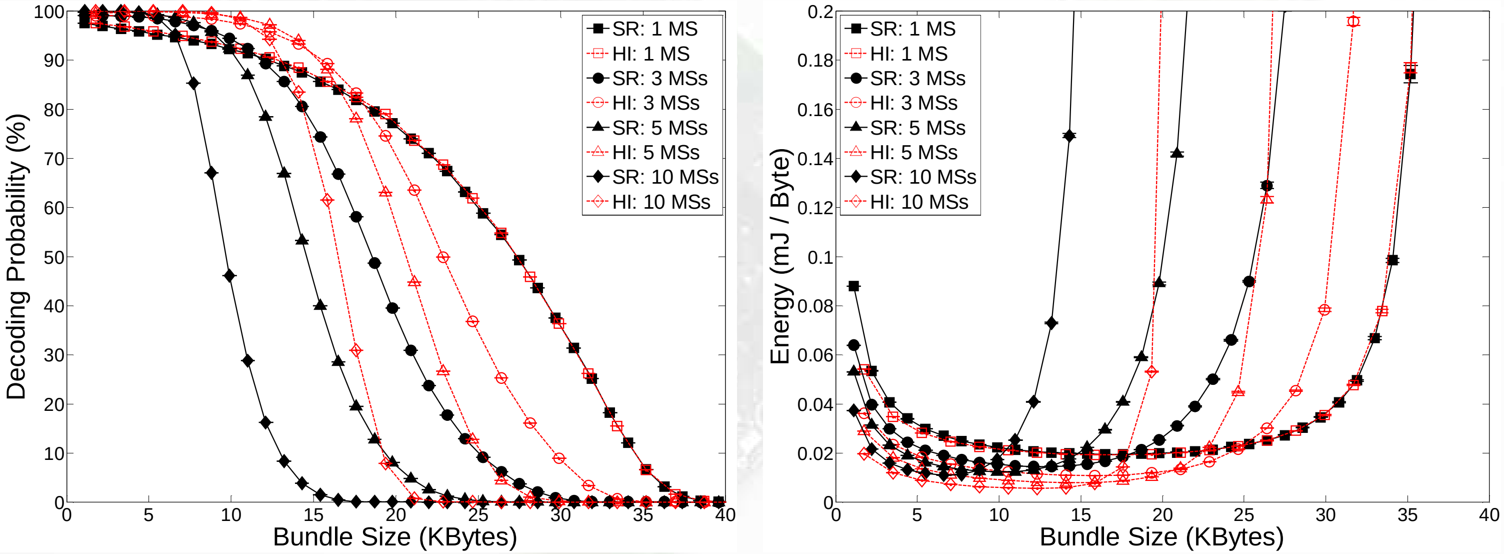
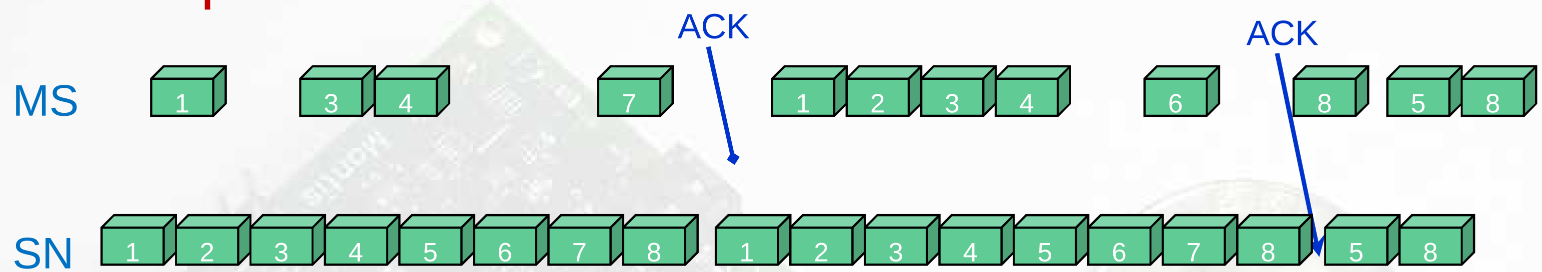
- Single MS
  - Moving at 40 Km/h

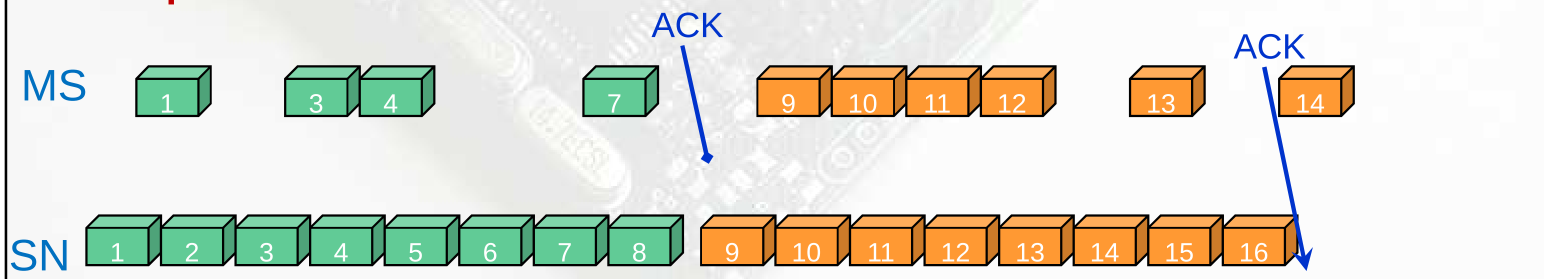


Short Bundles

SR protocol



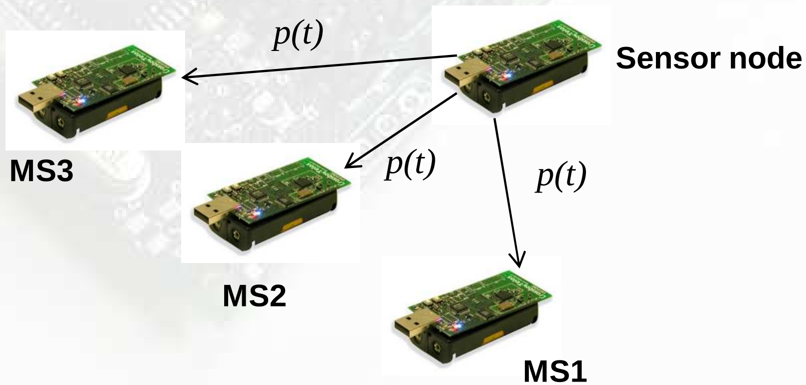
HI protocol



Validation with real sensor nodes

- T-mote Sky
  - TinyOS Operating System
  - IEEE 802.15.4 PHY
  - Mobility and message loss

$$p(t) = a_2\left(t - \frac{c_{\max}}{2}\right)^2 + a_1\left(t - \frac{c_{\max}}{2}\right) + a_0$$



Experimental vs. Simulation Results

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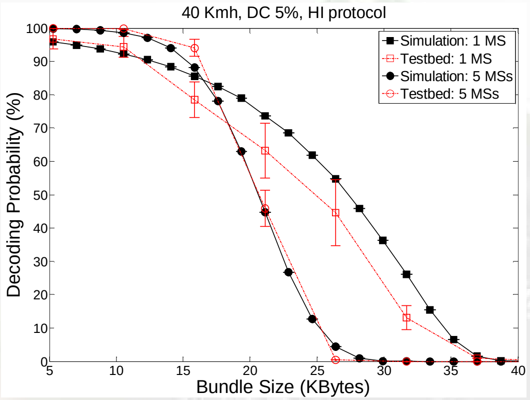
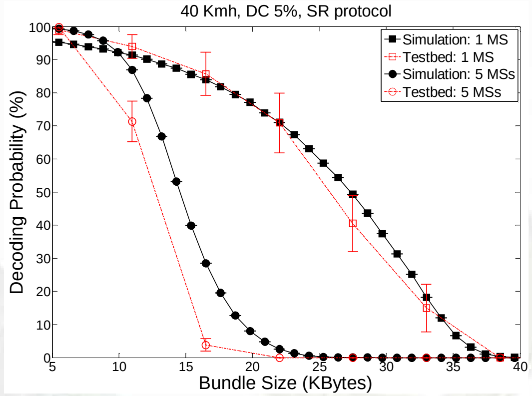
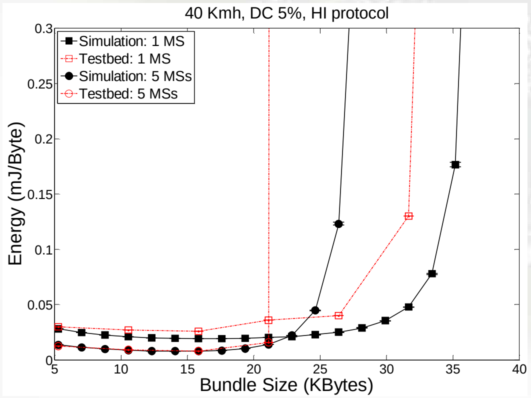
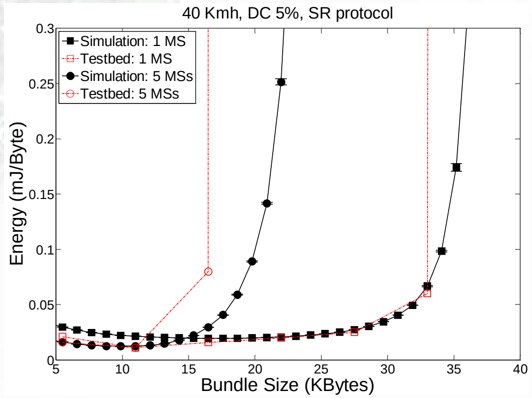
HI



SR







Energy Cost of Coding

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- Coding/decoding consumes energy
  - Decoding is not an issue as MSs are resource rich
  - Coding may be an issue

- Energy Consumption for coding
  - CPU Power consumption: 3 mW
  - 256-code blocks ➔ 40.5 μJ/byte
    - ⇨ Larger than the energy consumed for transmission ~30 μJ/byte (with 1 MS)
  - 32 code blocks ➔ 3.9 μJ/byte
    - ⇨ Negligible wrt energy spent for transmission

Memory requirements

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- Memory Availability
  - Tmote Sky: 32 KB
  - Jennic: 96 KB
  - SunSpot: 512 KB

- Memory Requirements
  - 256-code block (8+248) = 256*110 bytes = 28 KB
  - 32-code block (8+24) = 32*110 bytes = 3.5 KB

Conclusions

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- Reliable & Energy Efficient Data Transfer in Sparse WSNs with Multiple MSs
  - Sporadic and short contact times
  - Communication affected by message losses
- HI protocol
  - Erasure Coding + ACKs
  - Coding is performed in advance
  - Number of transmitted codes depends on loss conditions
- Simulation + Experimental Evaluation
  - HI outperforms SR even when there is a single MS
  - Energy for coding is negligible wrt energy for transmission

References

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Thank you!