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

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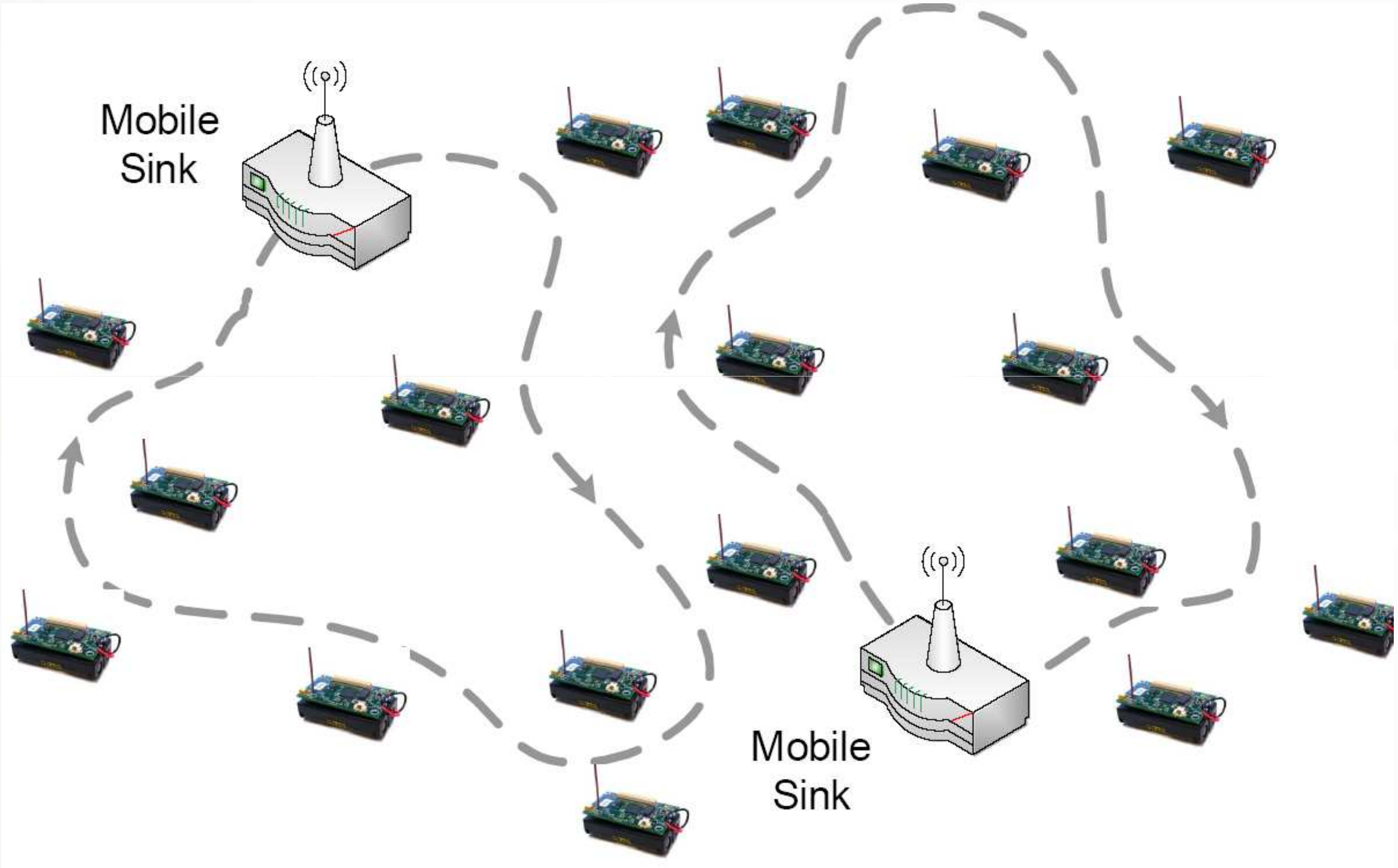
- **WSNs with Mobile Sinks**
  - **Advantages and Challenges**
- **Reliable & Energy Efficient Data Delivery to MSs**
  - **Adaptive Hybrid Protocol**
- **Simulation Results**
- **Experimental Measurements**
- **Conclusions**

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

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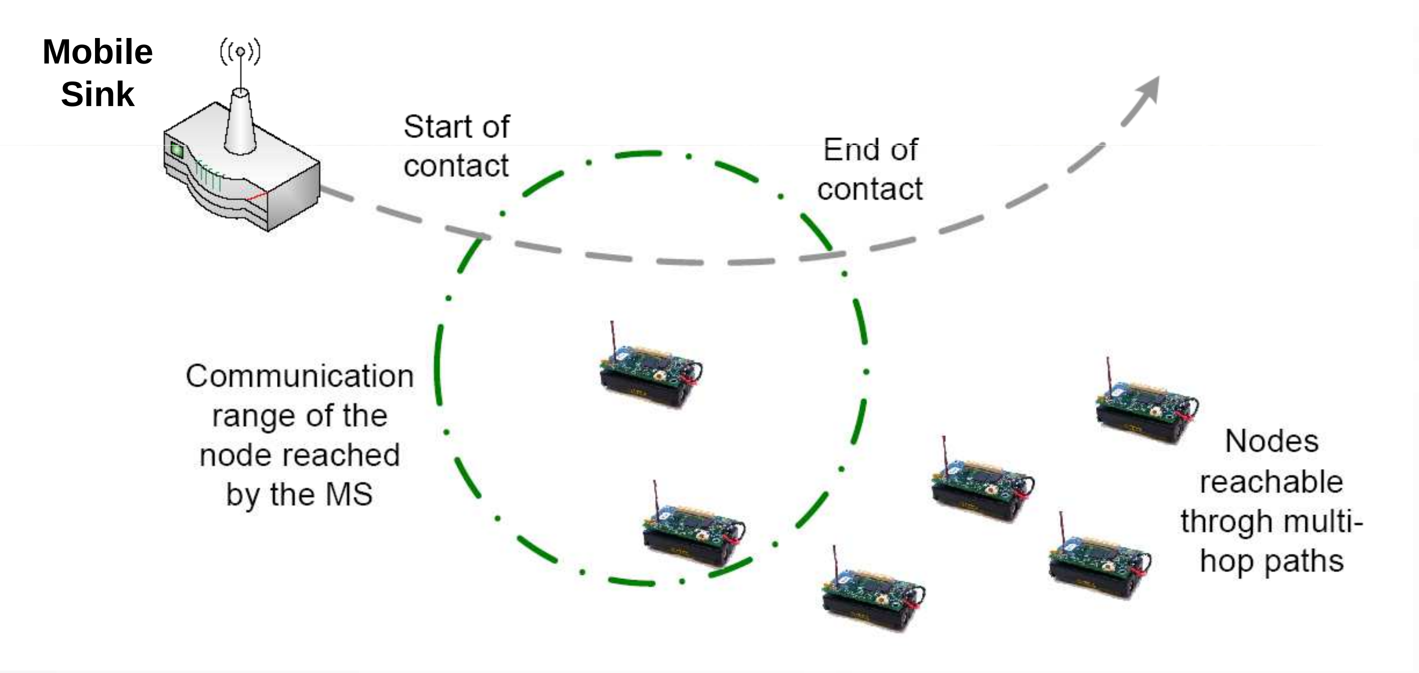
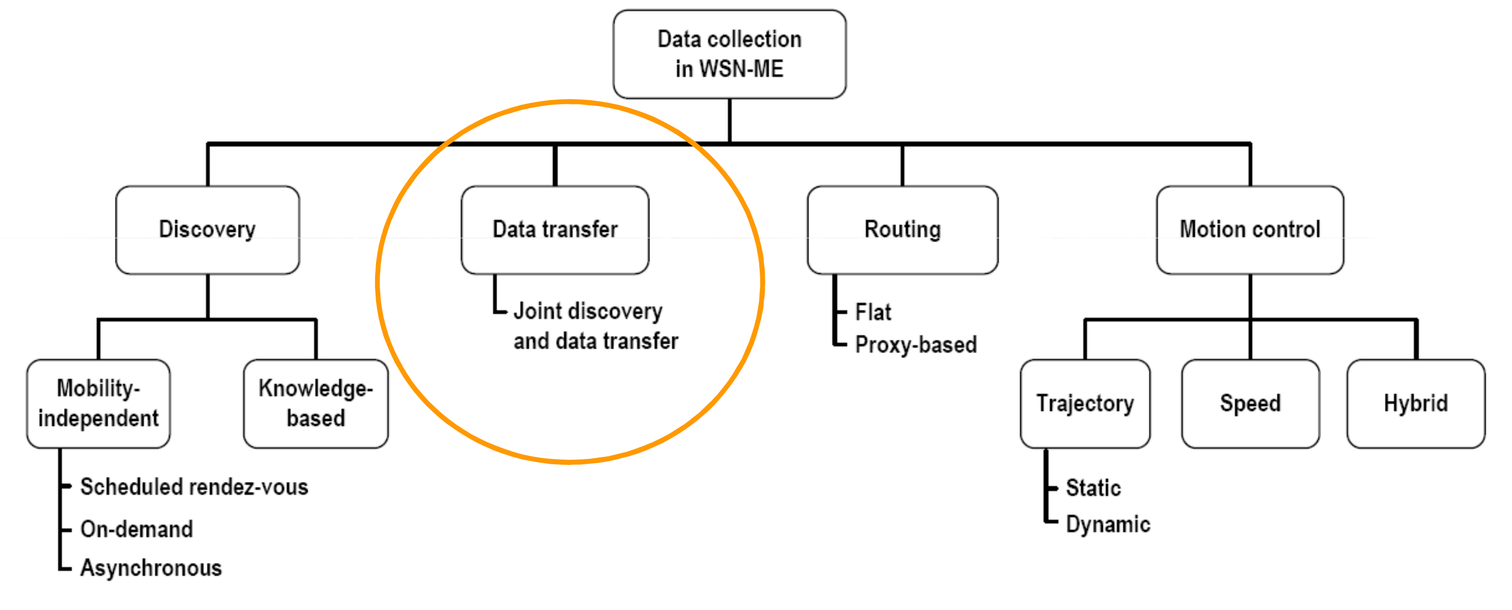
Challenges

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



Approaches to Data Collection

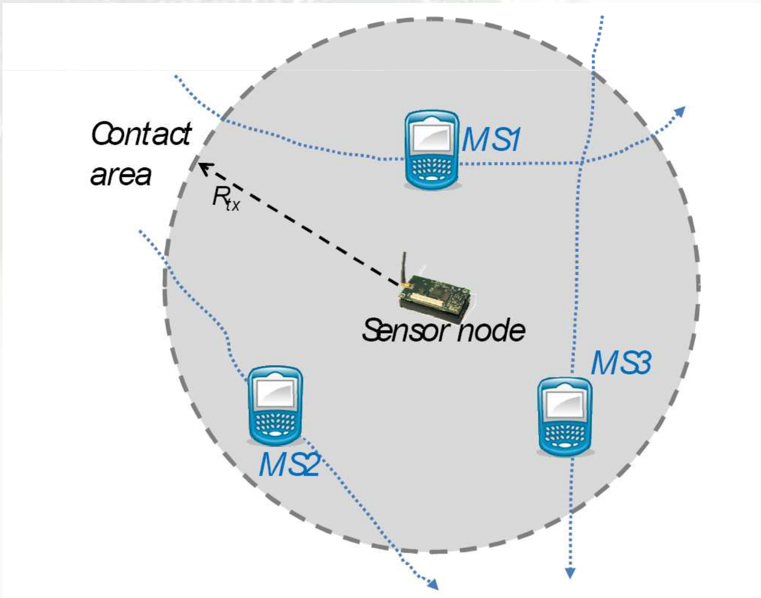


Reliable and Energy-efficient Data Delivery to Mobile Sinks

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?

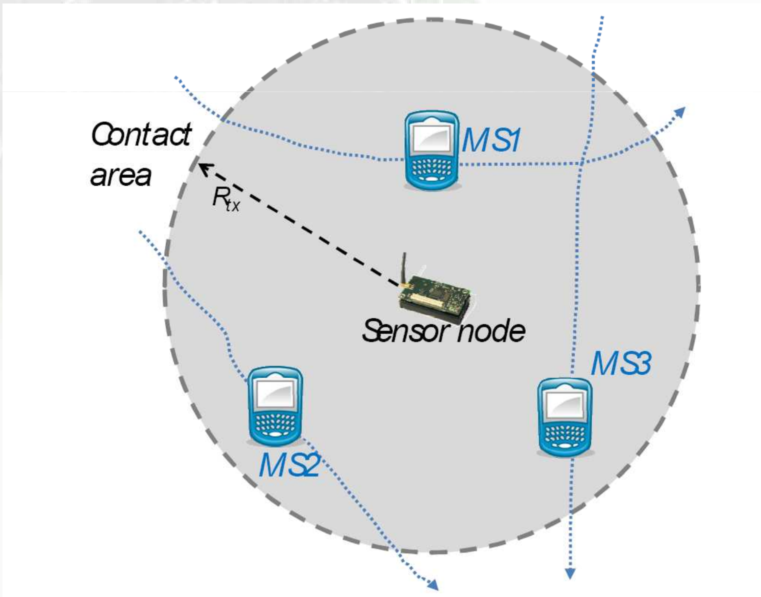
Reference Scenario

- **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

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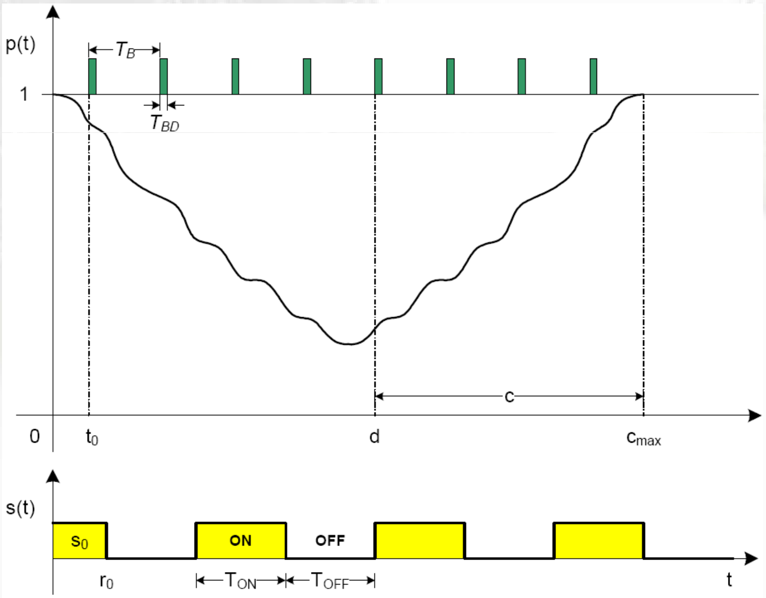
- **Challenges**
  - **The discovery phase further reduces the residual contact time**



Data Transfer

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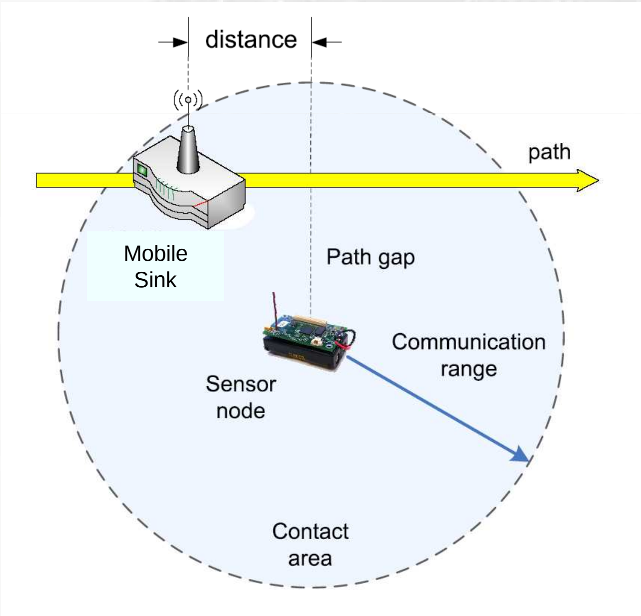
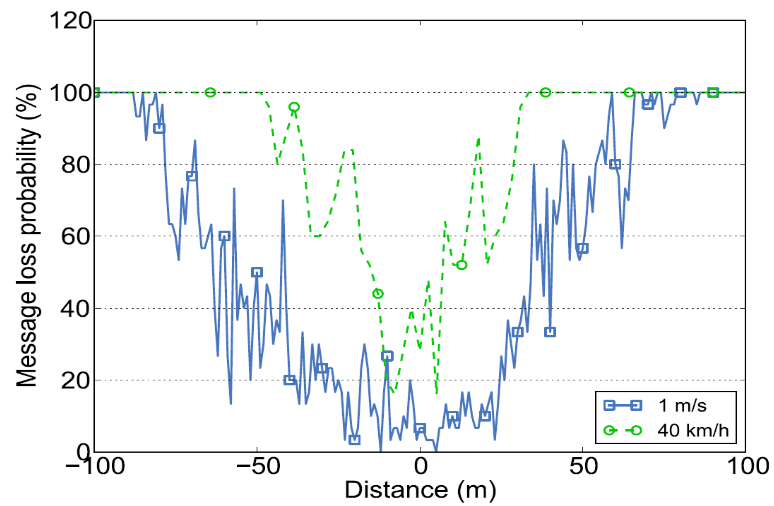
- **Challenges**
  - **Communication is impaired by message losses**
  - **This reduces the available bandwidth**





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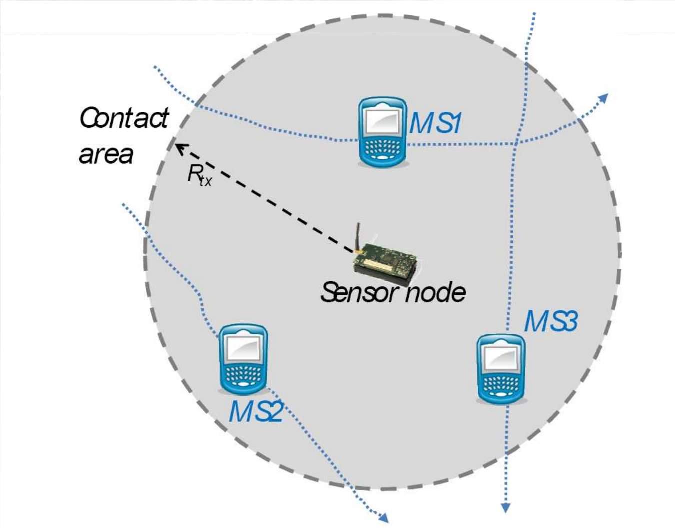
- Challenges
  - Multiple MSs simultaneously in contact
    - ⇨ They typically enter the contact area at different times
    - ⇨ They have different contact durations
    - ⇨ Tthey experience different conditions (e.g., message loss)



Data Transfer Protocol

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- 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**
  - Kansal, A. and Somasundara, A. and Jea, D. and Srivastava, M. B. , Intelligent Fluid Infrastructure for Embedded Networks. Proc *ACM International Conference on Mobile Systems, Applications and Services (MobiSys 2004),* Boston, MA, 6-9 June, pp. 99-110.
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  - Basagni, S. and Carosi, A. and Melachrinoudis, E. and Petrioli, C. and Wang, M. Controlled Sink Mobility for Prolonging Wireless Sensor Networks Lifetime. ACM Wireless Networks (WINET), Vol. 14(6), 2008, pp. 831-858.
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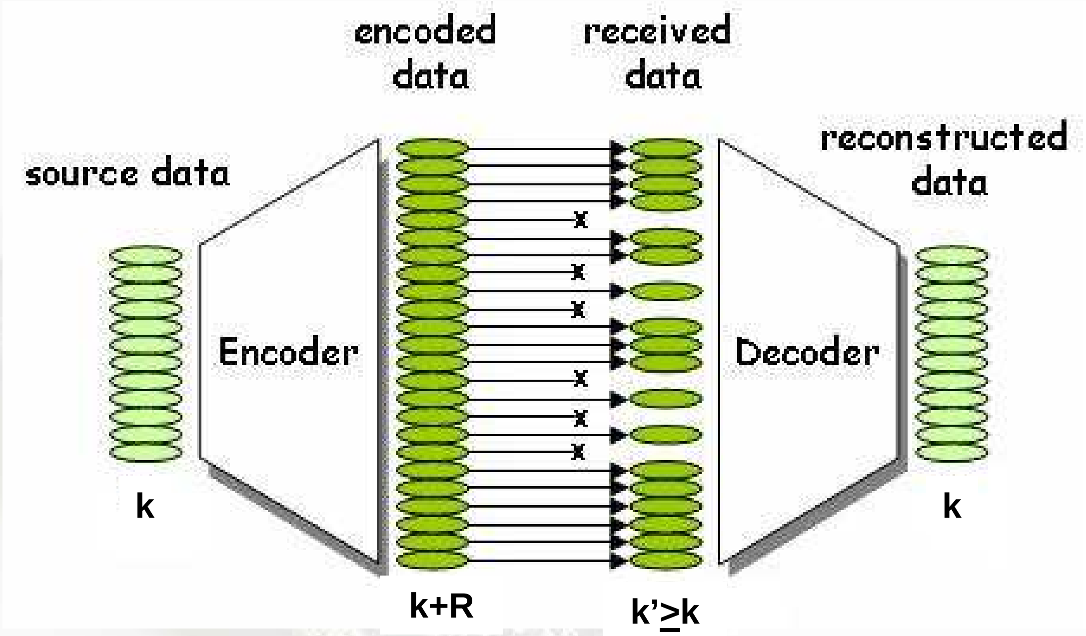
  - Anastasi, G., Conti, M., Monaldi, E., Passarella, A., An Adaptive Data-transfer Protocol for Sensor Networks with Data Mules. *Proc. IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2007),* Helsinki, Finland, 18-21 June 2007.

Selective Repeat

- 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?

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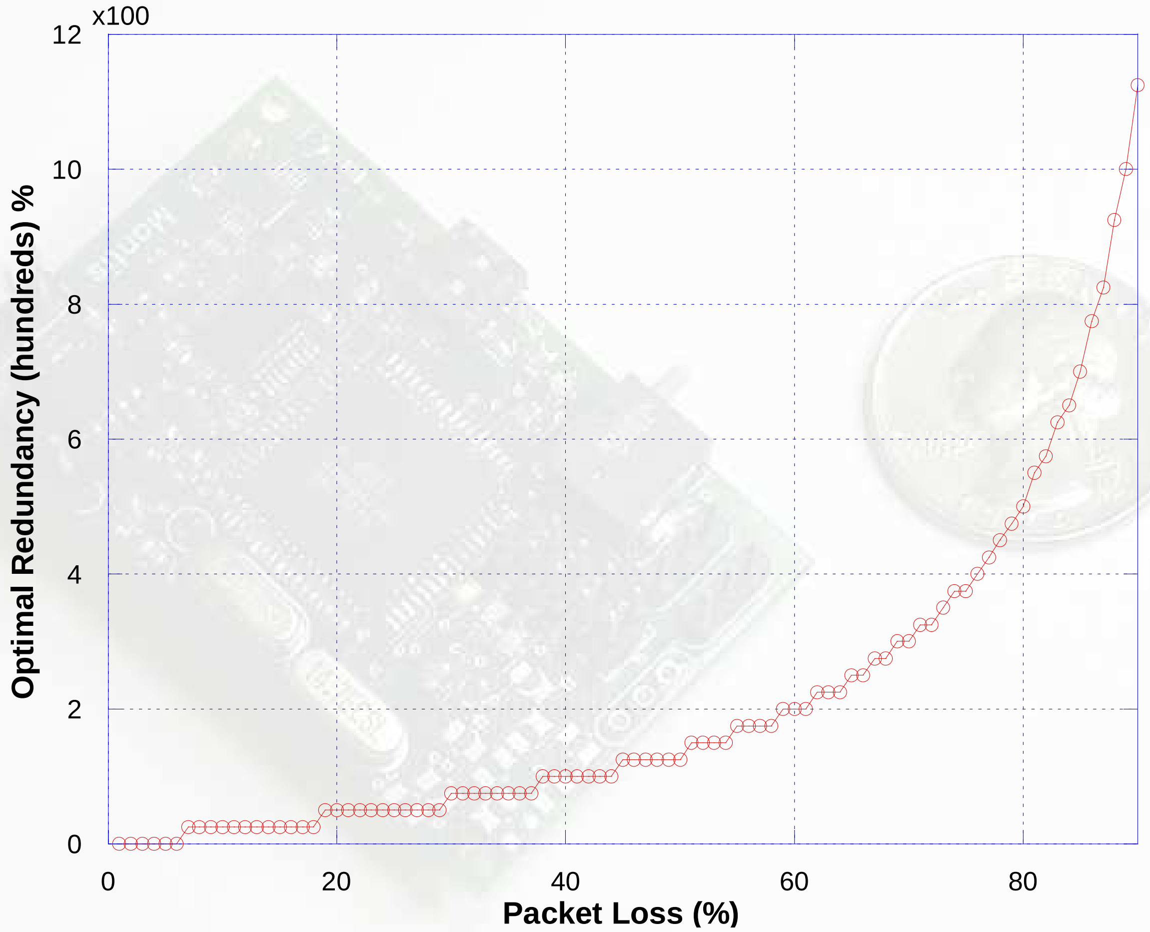
$$\eta = \frac{k \cdot S_{MSG}}{(k+R) \cdot \delta_{MSG} \cdot P_{tx}} \cdot P_{succ}$$

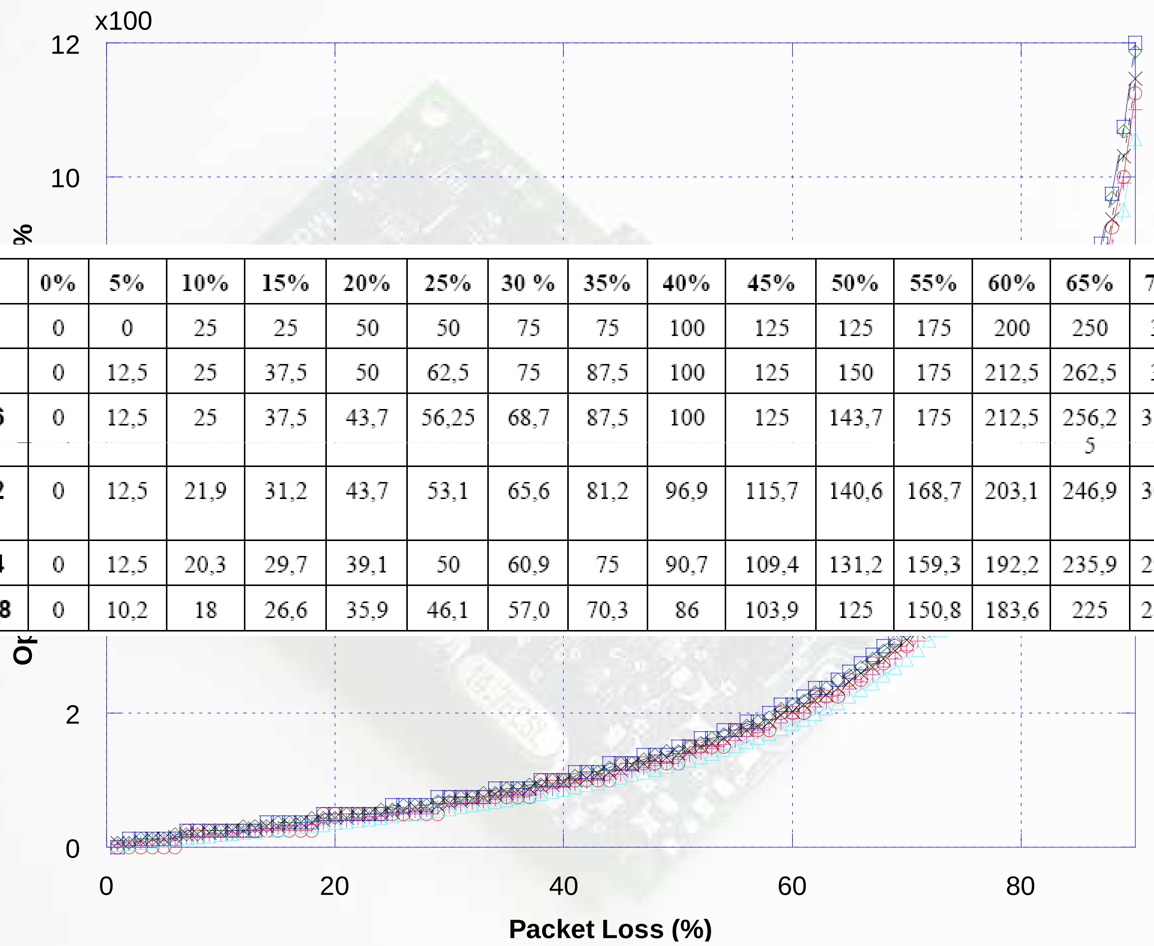
where:

- 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)



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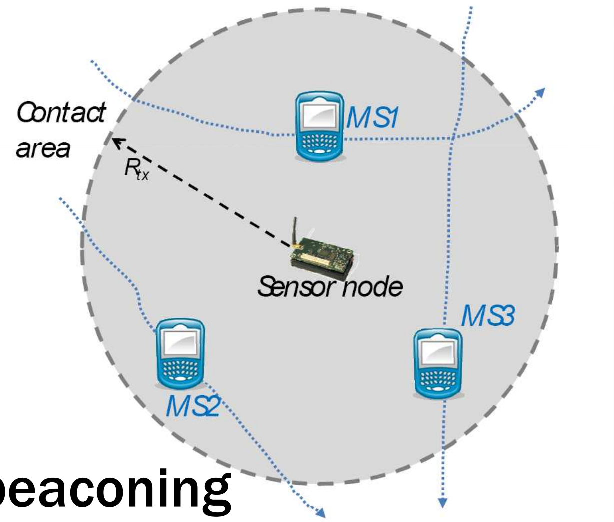
- **Multiple MS scenario**
  - **The required redundancy is different for different MSs**
  - **For a given MS, the required redundancy varies over time**

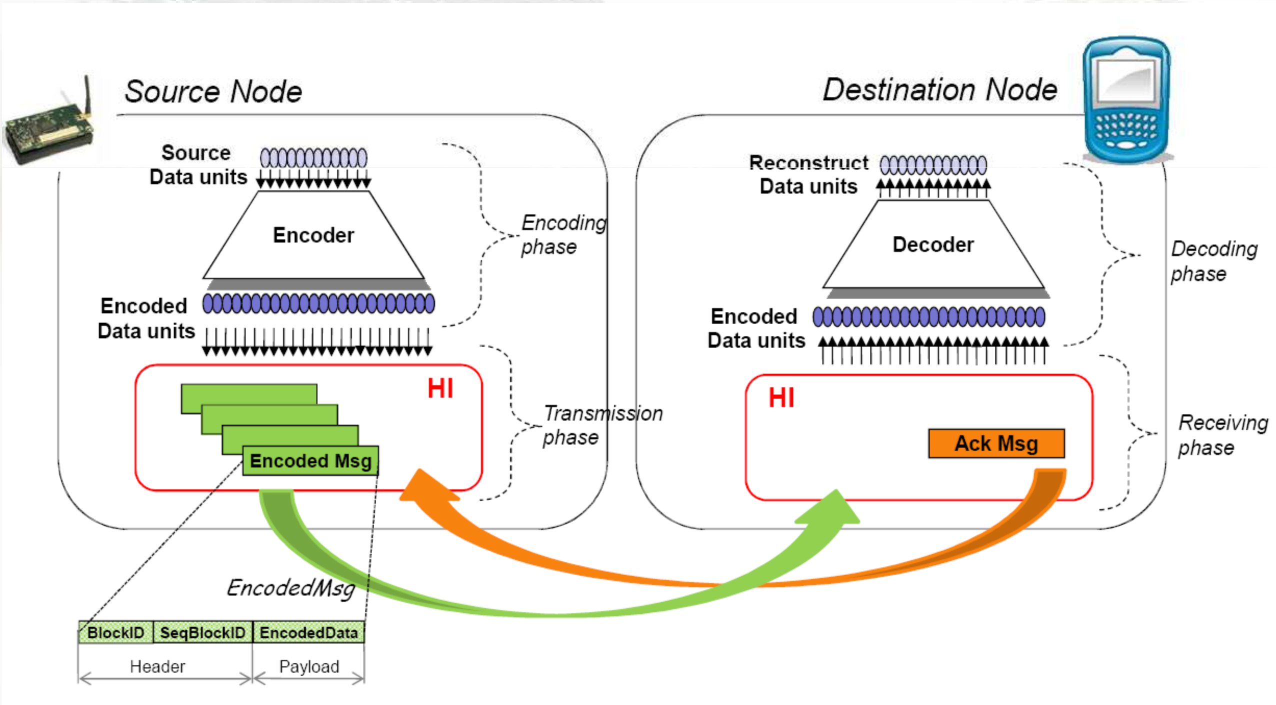
    ⇨ **Redundancy should be adaptive**



  - **ACKs are required for implicit beaconing**

Hybrid Approach

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



Basic idea

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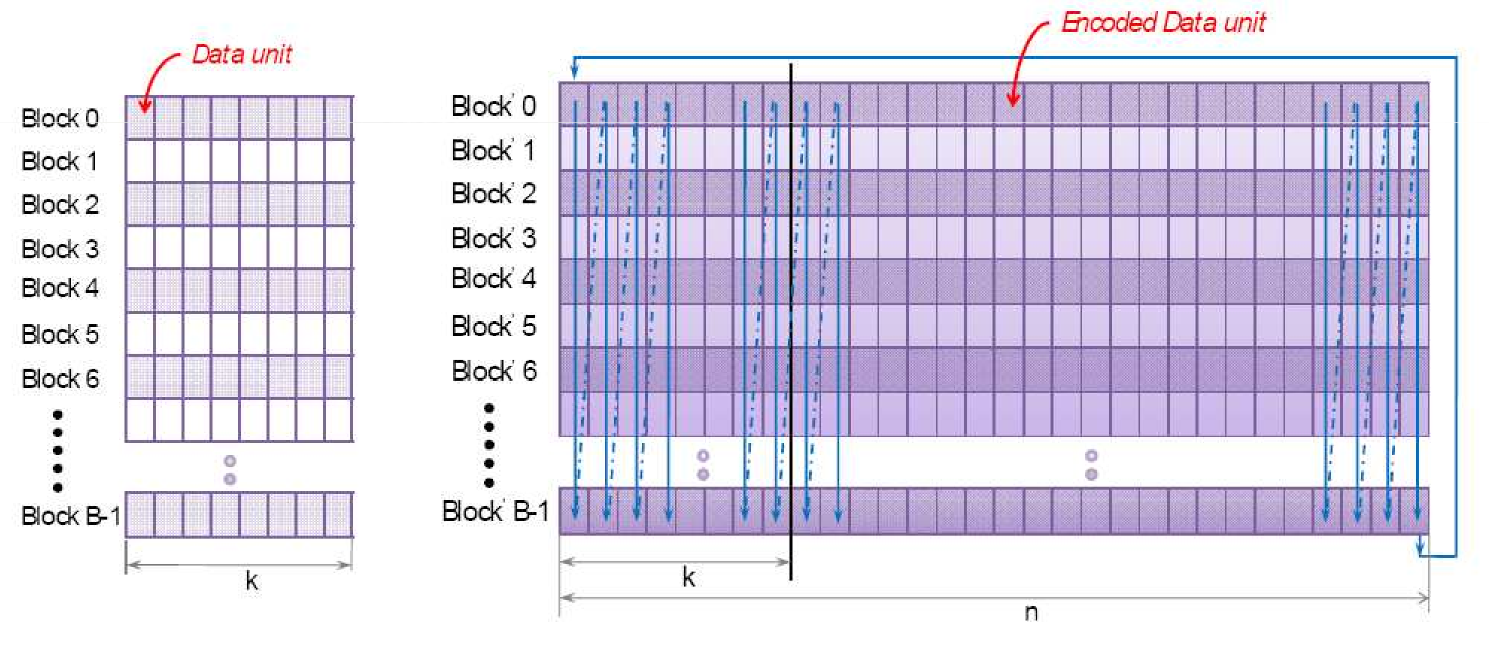
- The bundle is divided in B blocks
- Each block is then encoded separately
- Codes are generated in advance…
- … and sent out on demand
- The number of transmitted codes depends on feedbacks received from MSs (through ACKs)

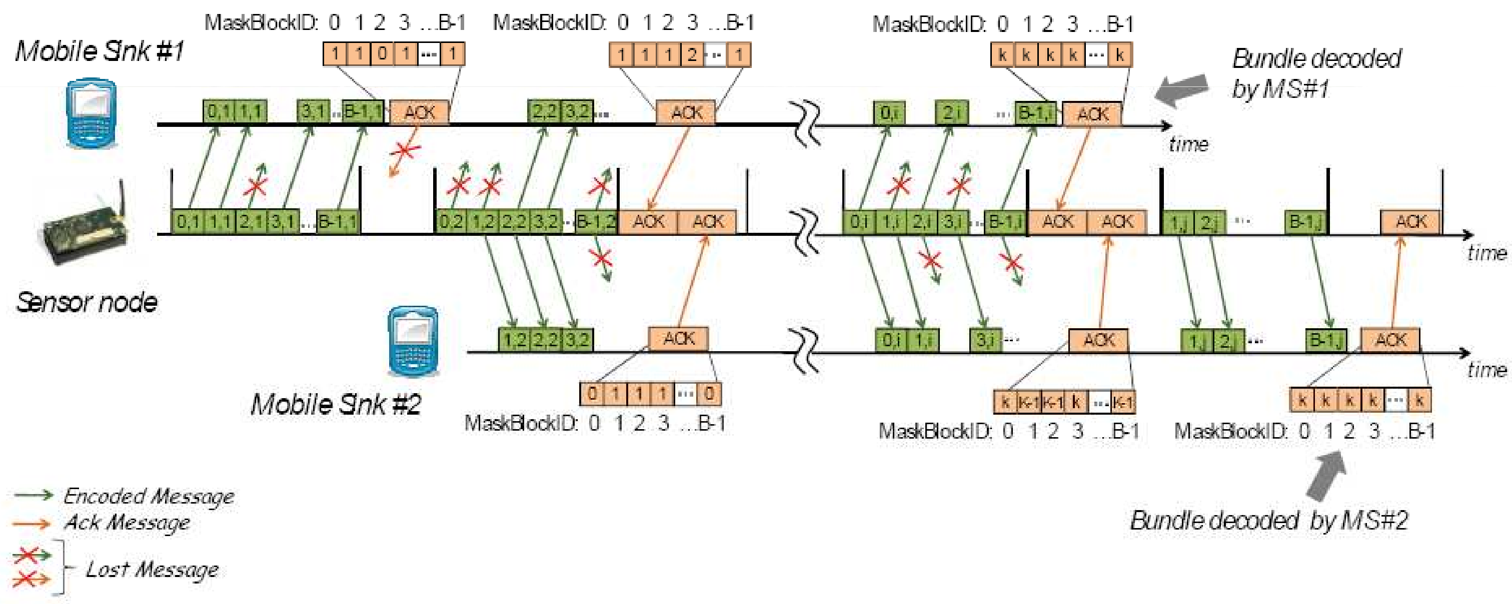
Interleaved Transmission

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



Adaptive Redundancy

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



Simulation Setup

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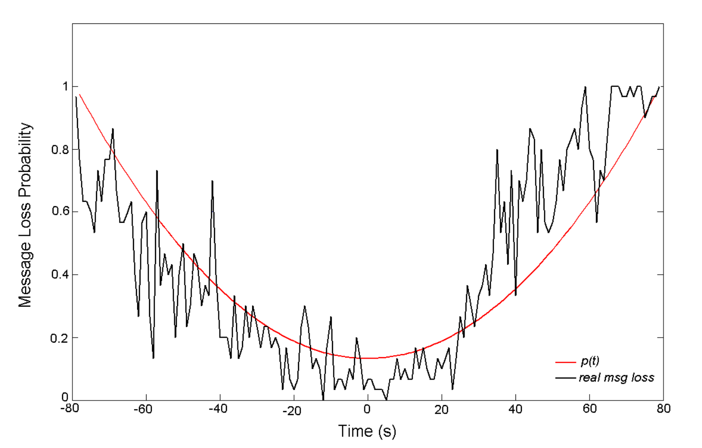
- Ad Hoc Simulator
  - HI Protocol and SR Protocol
  - Discovery based on periodic beaconing emission by MSs
- Scenario
  - Single Sensor, Multiple MSs
  - MSs move along linear paths, at a fixed distance from the sensor
- Message Losses

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



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)

Total Number of ACKs generated by all MSs

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

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}	$16^{*}\delta_{ACK}$
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

Simulation Results

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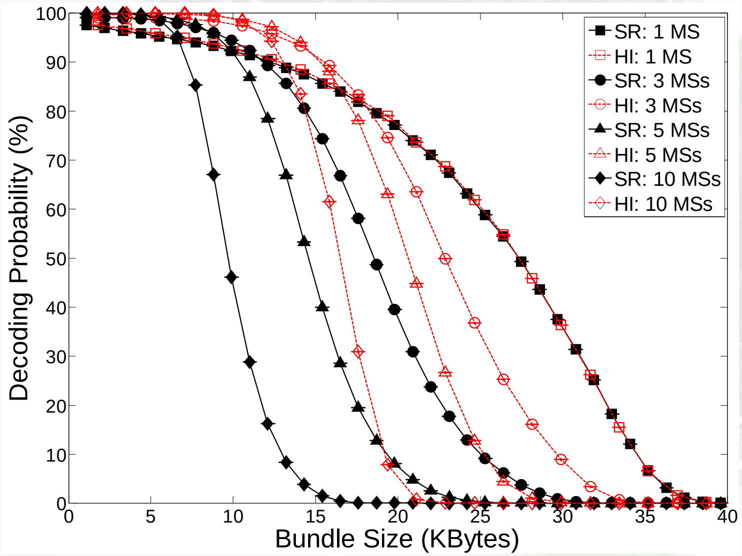
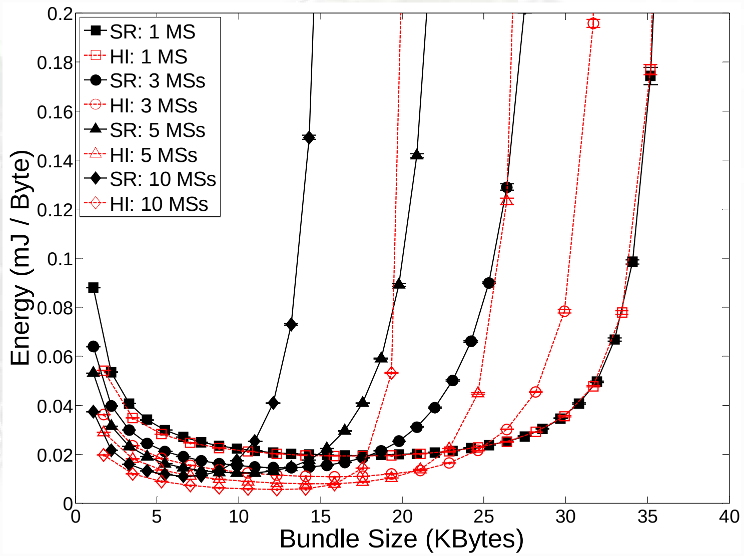
- Increasing number of MSs
- All MSs move at the same speed (40 Km/h)





Simulation Results

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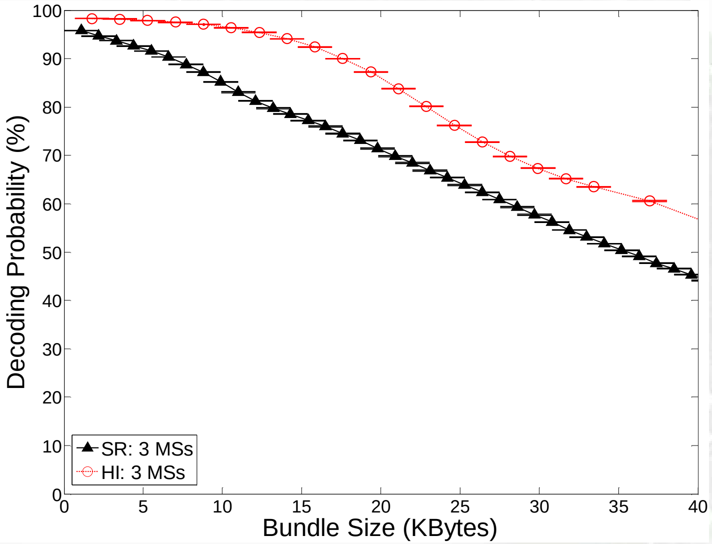
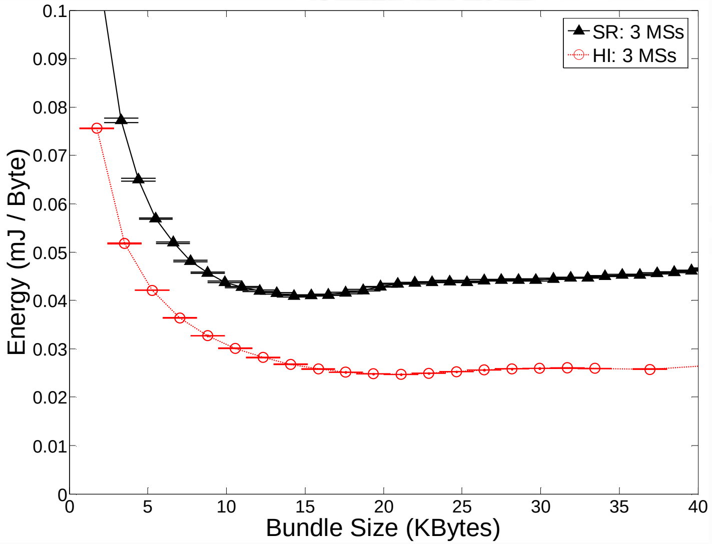
- **3 Mobile Sinks**
  - **with different paths and speeds**
    - ⇨ 3.6 Km/h, 20 Km/h, 40 Km/h





Simulation Results

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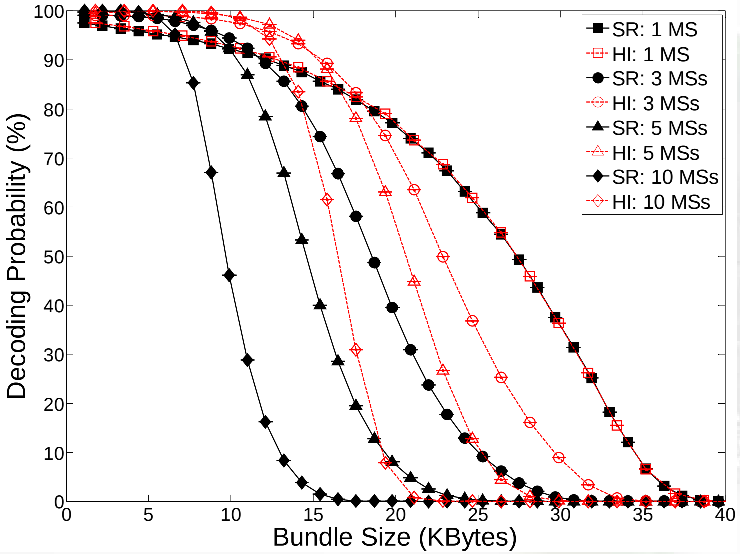
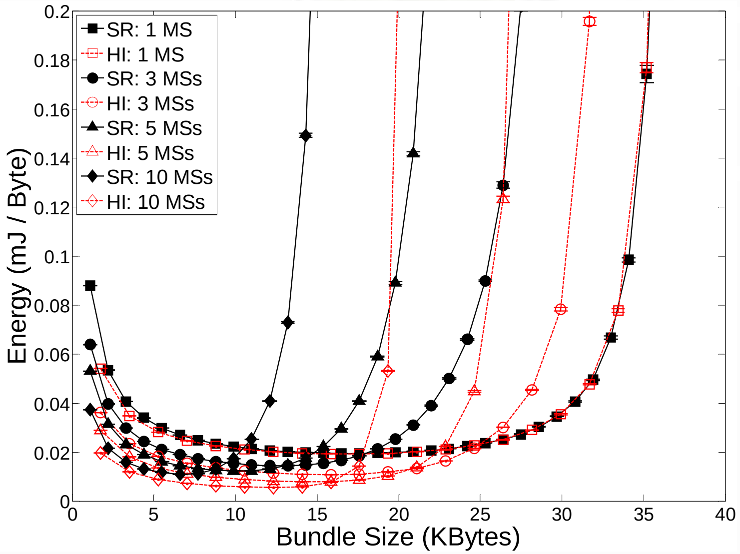
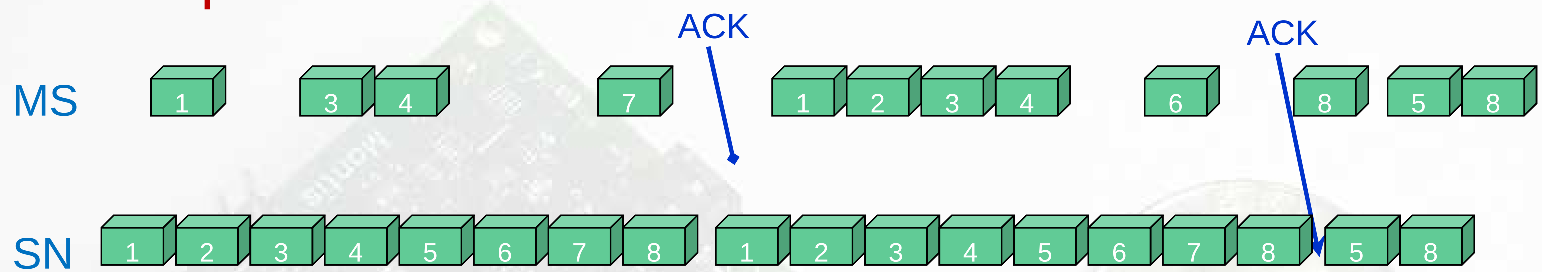
- **Single MS**
  - **Moving at 40 Km/h**



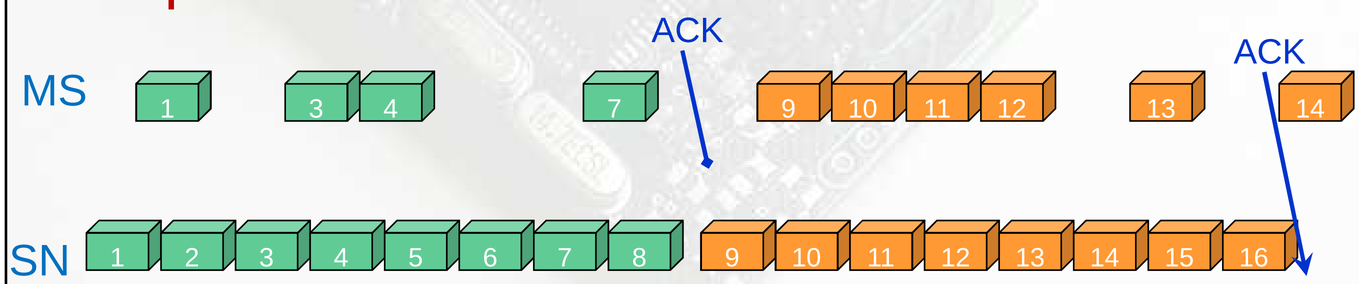


Short Bundles

SR protocol



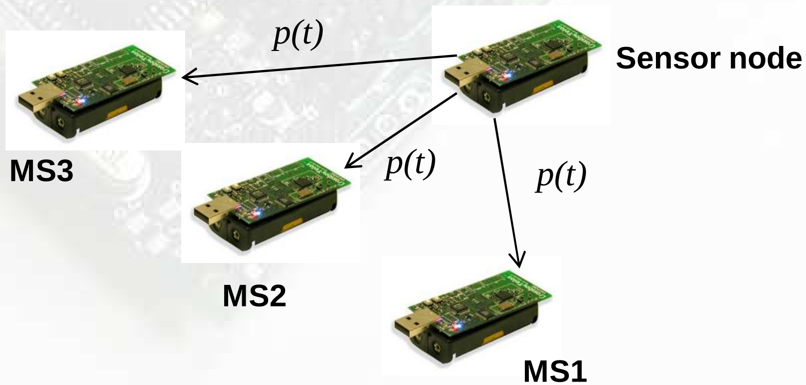
HI protocol



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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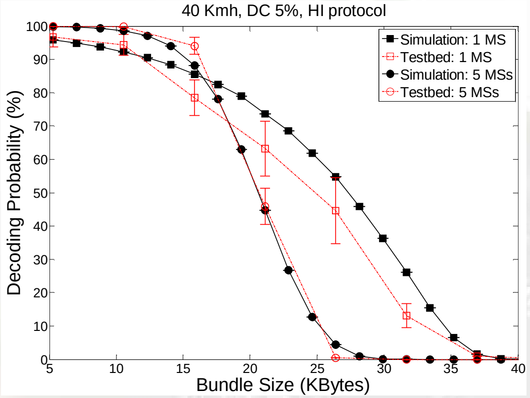
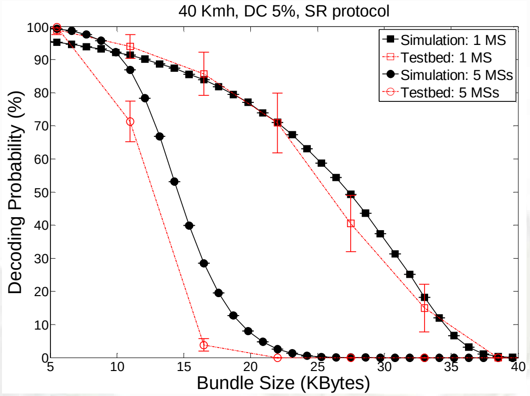
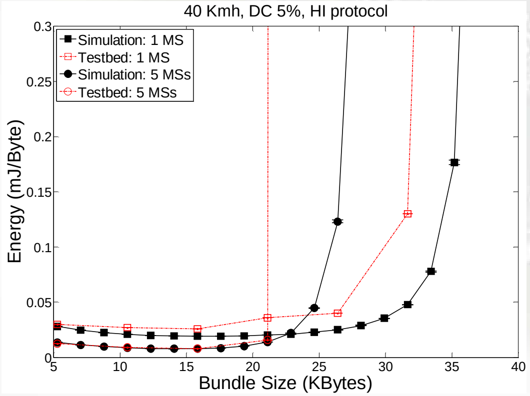
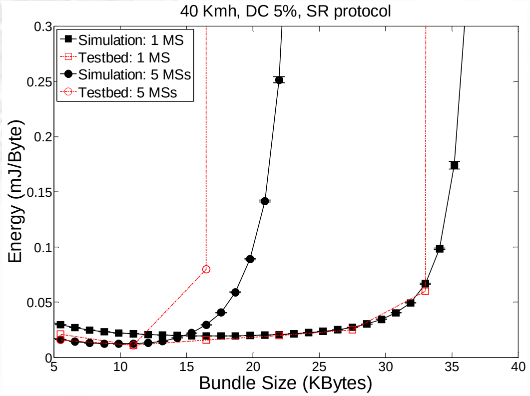
HI

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)

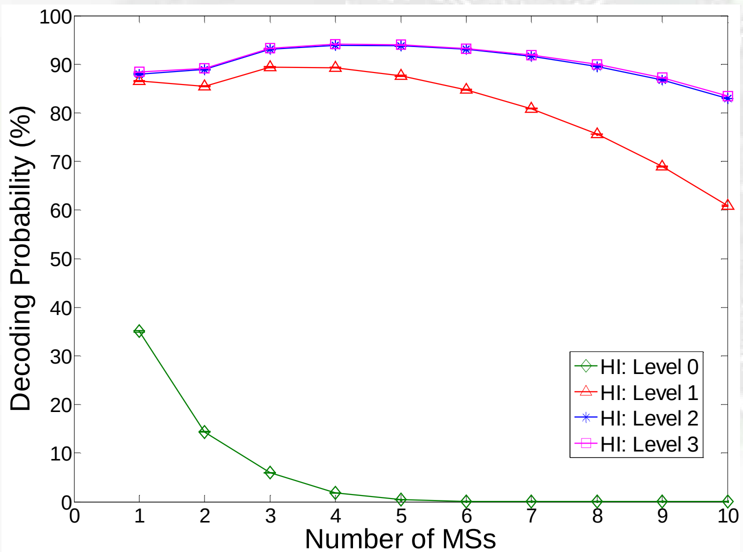
Memory requirements

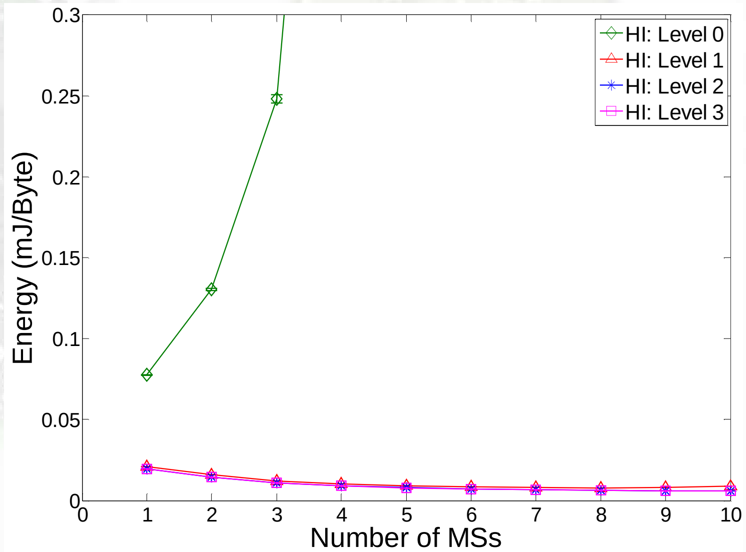
- **Memory Requirements**
  - **256-code block (8+248) = 256*110 bytes = 28 KB**

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

Impact of Redundancy

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





Resource Requirements

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- Energy Consumption for coding
  - 256 codes ➔ 40.5 μJ/byte
  - 32 codes ➔ 3.9 μJ/byte
    - ⇨ Negligible wrt energy spent for transmission (~30 μJ/byte with 1 MS)
- Memory Requirements
  - 256-code block (8+248) = 256*110 bytes = 28 KB
  - 32-code block (8+24) = 32*110 bytes = 3.5 KB
- Memory Availability
  - Tmote Sky: 32 KB
  - Jennic: 96 KB
  - SunSpot: 512 KB

Conclusions

- **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

- G. Anastasi, E. Borgia, M. Conti, E. Gregori, A Hybrid Adaptive Protocol for Reliable Data Delivery in WSNs with Multiple Mobile Sinks, *The Computer Journal*, to appear.
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- G. Anastasi, E. Borgia, M. Conti, E. Gregori, HI: A Hybrid Adaptive Interleaved Communication Protocol for Reliable Data Transfer in WSNs with Mobile Sinks, *Proceedings of IEEE Percom 2009 Workshops, International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2009),* Galveston, USA, March 9, 2009.

Thank you!