A Prototype Development of Reliable Sensor Network Based Structural Health Monitoring System For Railway Bridges

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Outline

- Introduction
- Application Details and Design
- Transport Protocol
- Experiments and Results
- Past and Related Work
- Conclusion and Future Scope for Work

Introduction

- Motivation
- Problem Statement
- Requirements and Challenges
- Thesis Contributions

Motivation

- India has 1,20,000 railway bridges spread over large geographical regions
- 40 % of these are over 100 years old and many are weak and in distressed condition
- With the passage of time railway equipment loads increased over bridge design values
- Critical to monitor the health of these bridges to ensure safety

Existing Techniques

- Mostly wired solutions, equipment is expensive and bulky
- Large setup time, requires expertise in technically trained manpower
- Maintenance problems as with any wired solution

Problem Statement

"Design and develop an automated, easily deployable sensor network based structural health monitoring system, which acquires the vibration data of a remotely located railway bridge and reliably transfer it to the central repository "

Requirements & Challenges

Requirements

- Acquire vibration data with high fidelity
- Frequency band of vibration data 0.25 to 20 Hz
- Acquire data for minimum 40 seconds
- Vibration data need to be synchronized within certain error band
- Reliable transfer of data
- Analysis of acquired data
- Minimum maintenance

Challenges

- Conserve power
  - Make node sleep wakeup
  - Low power hardware
- Event Detection
- Keep nodes connected
- Mobile data transfer
- Limited capabilities of the platform

Thesis Contributions

- Design and implementation of DMA based data acquisition system which provide high fidelity
- Design and implementation of application specific reliable transport protocol for transfer

  of data both in static and mobile mode
- Design and development of data analysis tools, meeting the requirement of structural

  engineers
- Design and development of debugging tool
- Study of compression techniques for their applicability in BriMon
- Integration of above elements with the elements developed by Phani Kumar Valiveti
  - Routing
  - Event detection
  - Time synchronization
  - Sleep wakeup

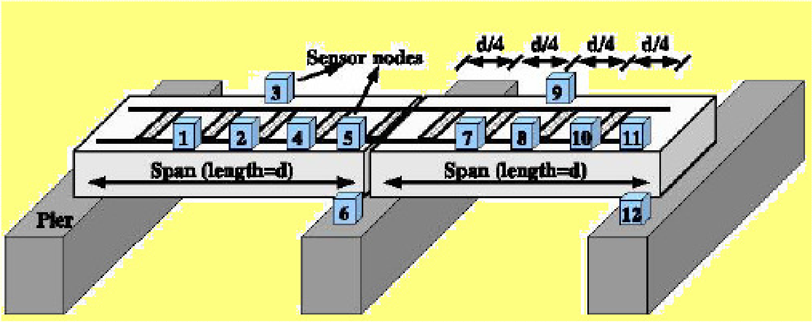
Application Architecture

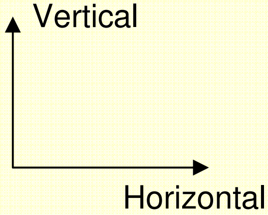
- Application details
  - What and where to measure
  - Short term monitoring
  - Long term monitoring
- Long term monitoring design
- Hardware
- Data acquisition system
- Data compaction and compression
- Debugging tool
- Data analysis tool

Application Details

What and where to measure

- Forced and free vibrations of the bridge
- Placement of sensors on the bridge





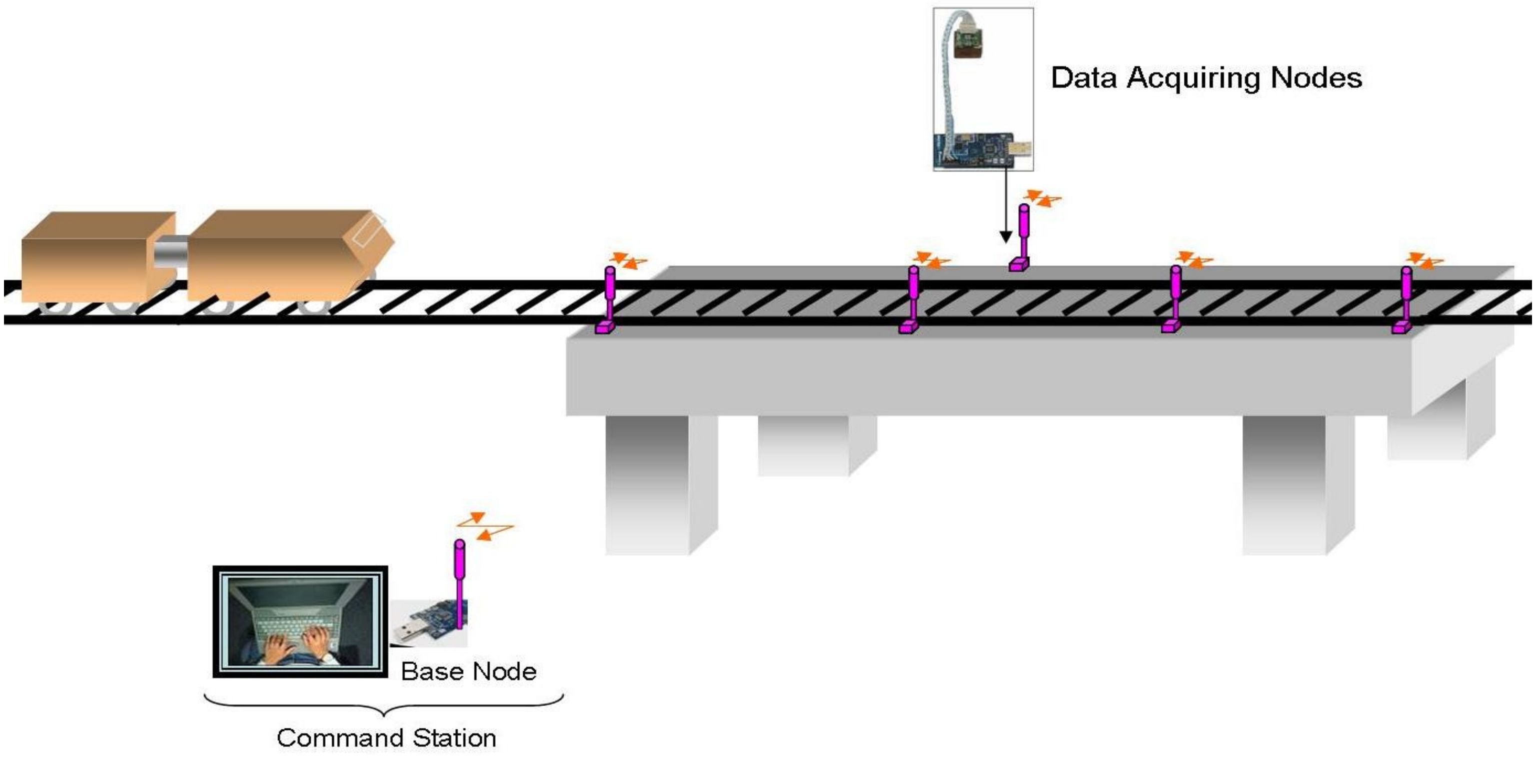
Short term monitoring

- Monitor the bridge for short duration
- On site analysis of the data
- Manual operation

Long term monitoring

- Monitor the bridge for long duration
- Event detection, sleep wakeup
- Data transferred to data analysis centre
- Automatic operation

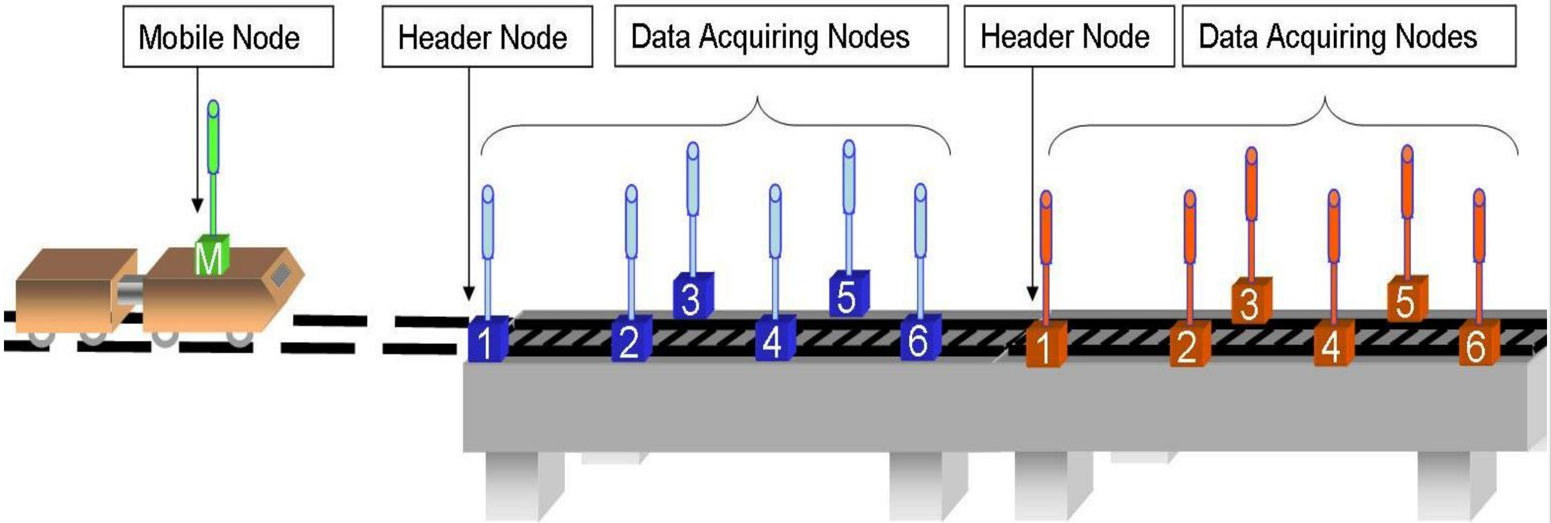
Short Term Monitoring



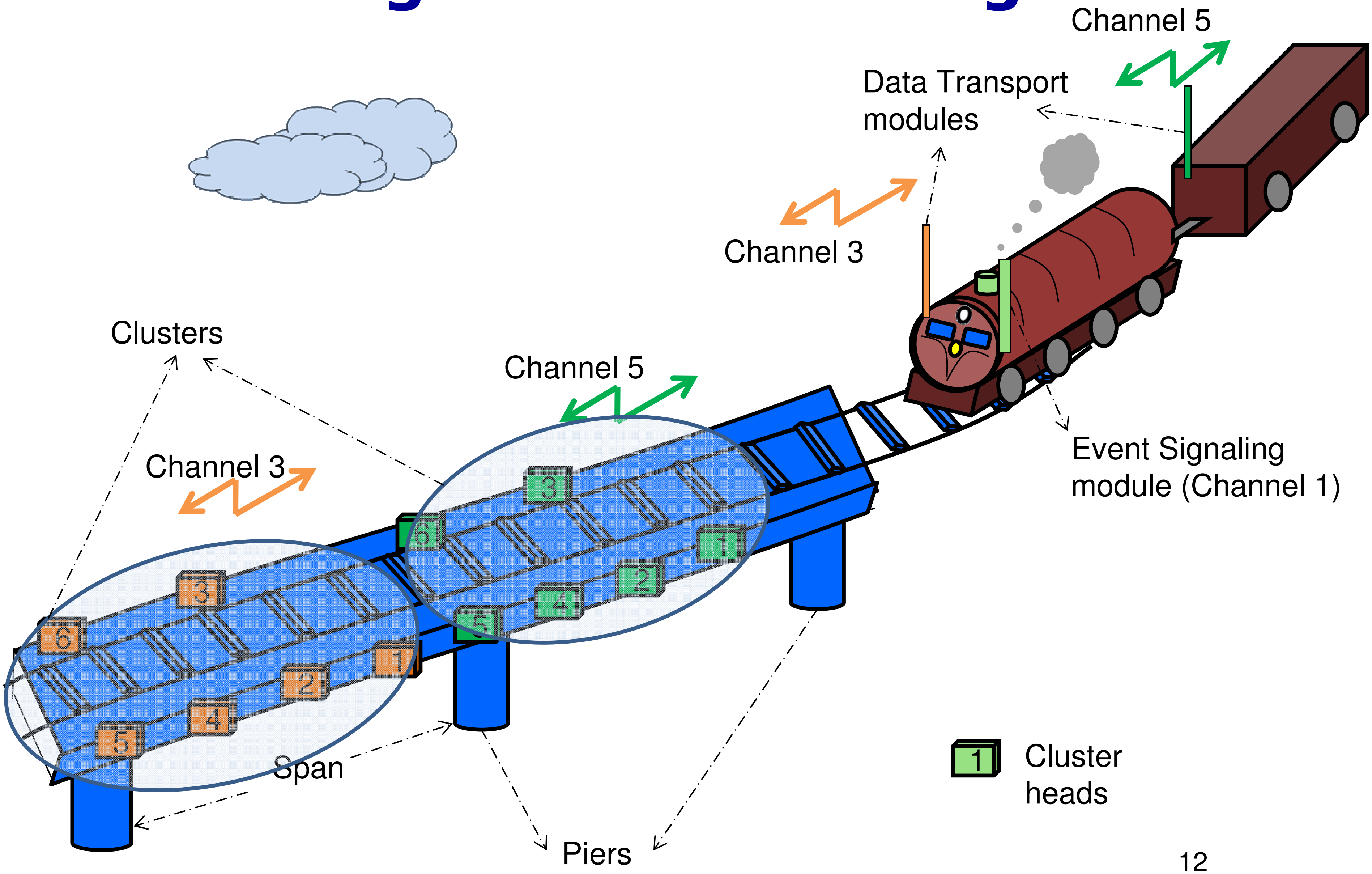
Long Term Monitoring

Challenges

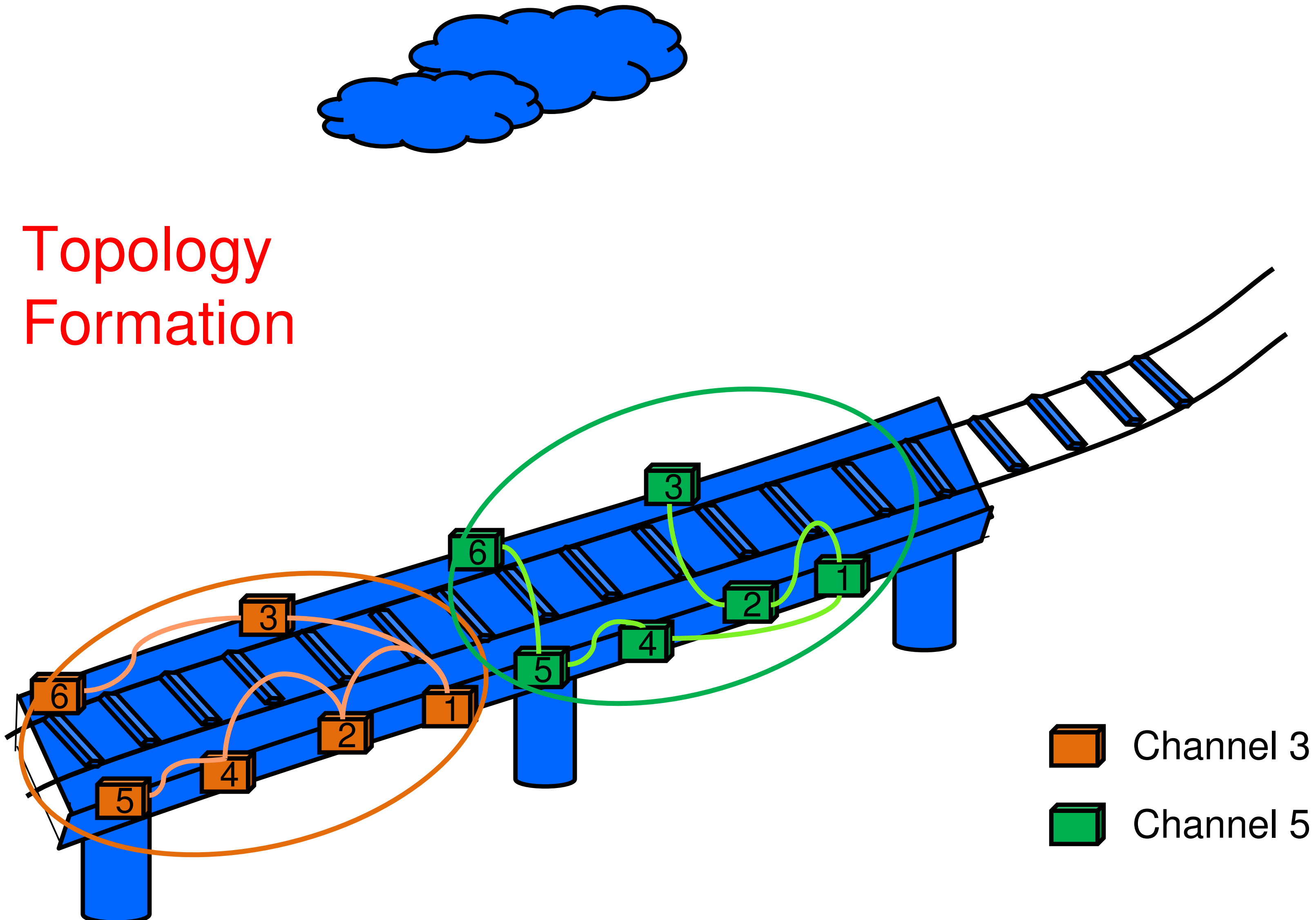
- Event detection
- Time synchronization
- Mobile data transfer



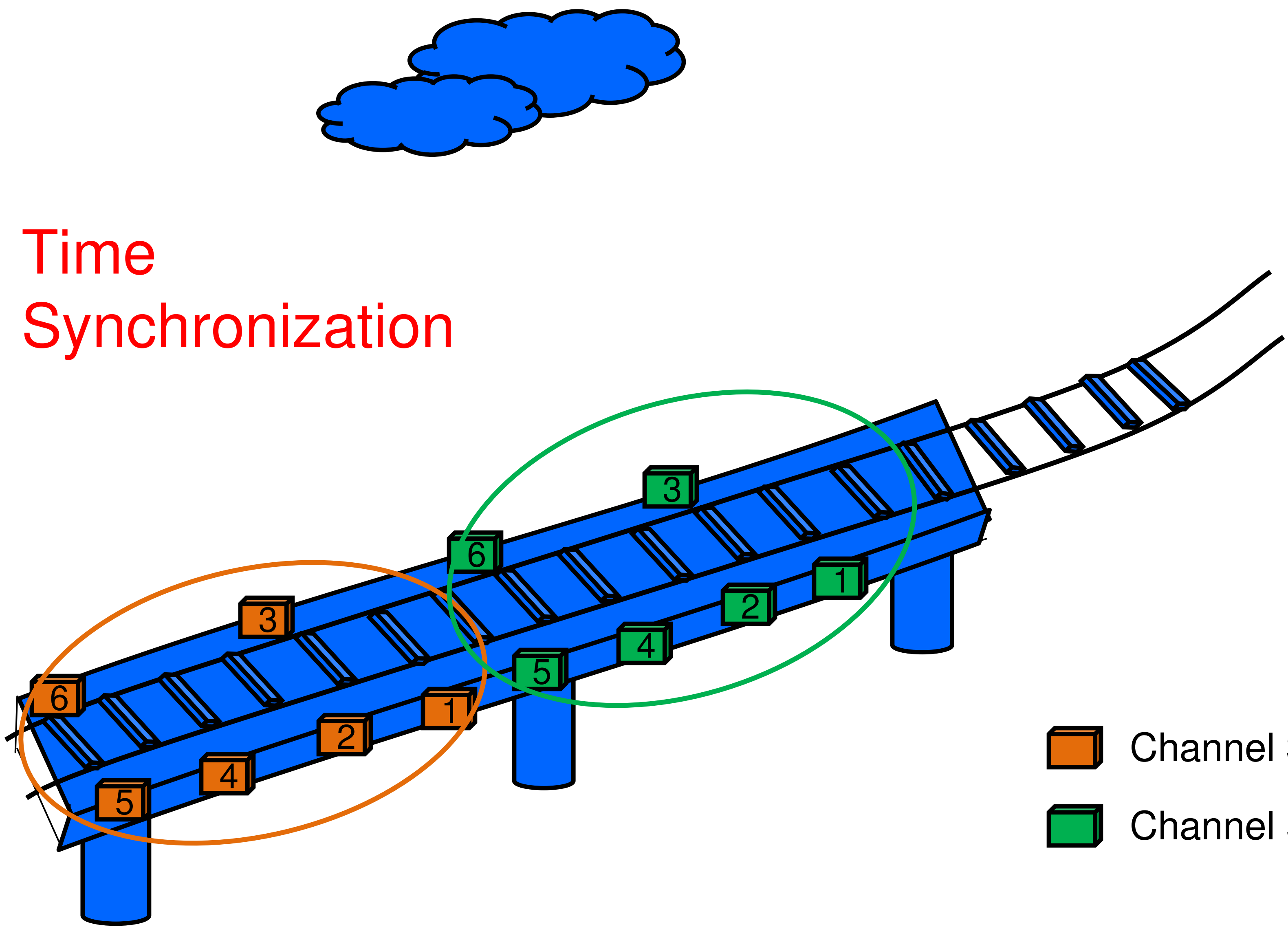
Long Term Monitoring



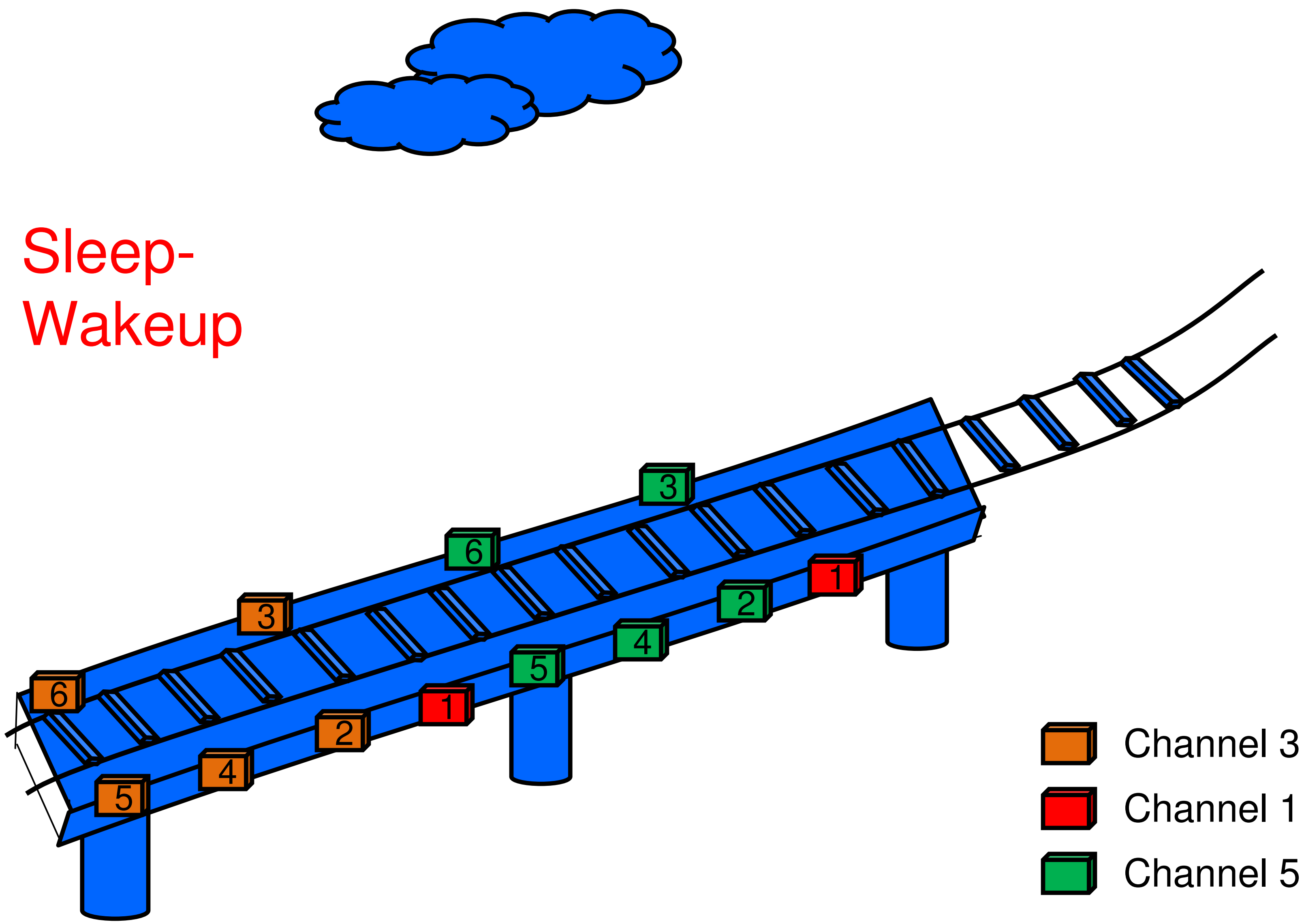
Topology Formation



Time Synchronization

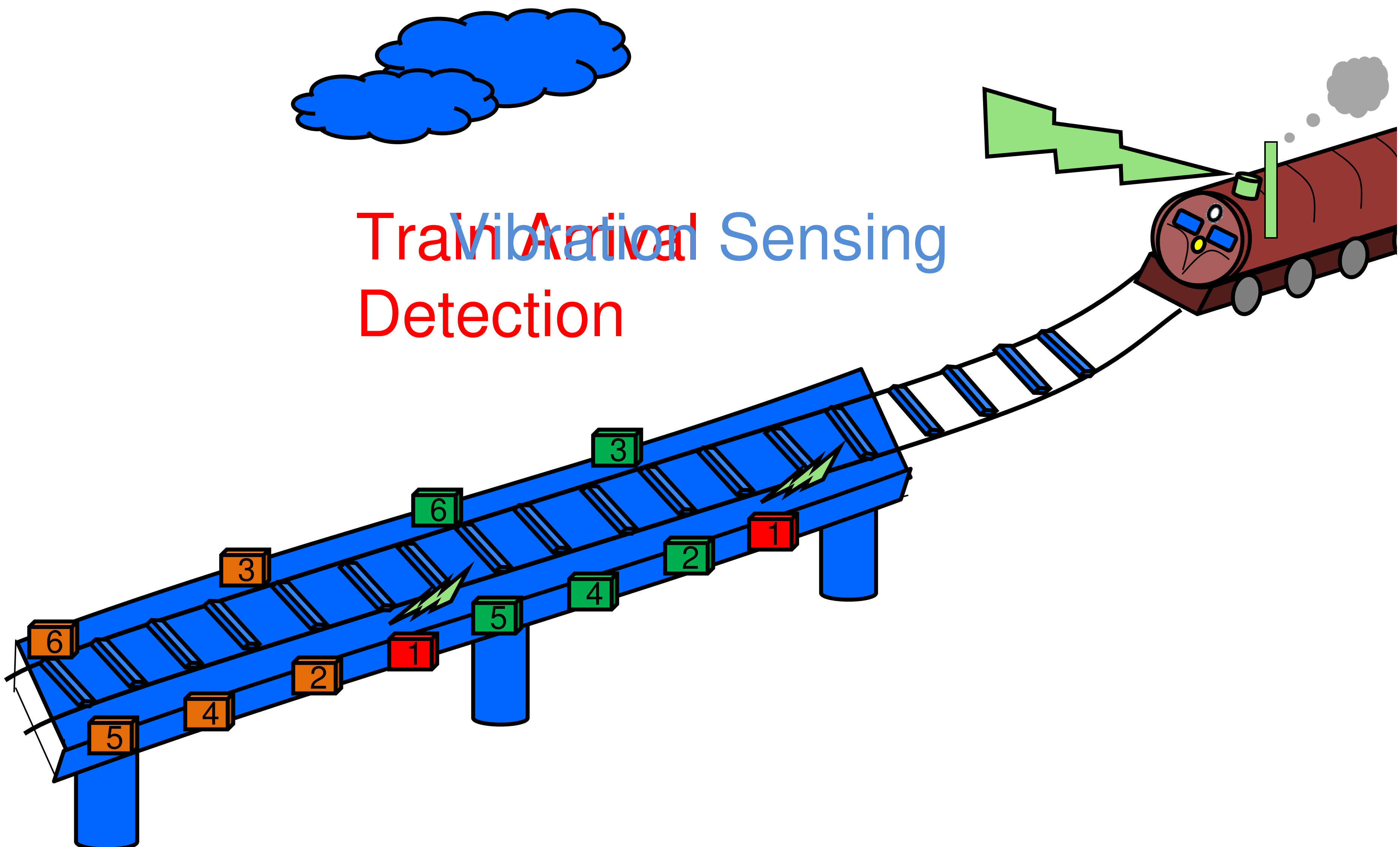


Sleep-Wakeup

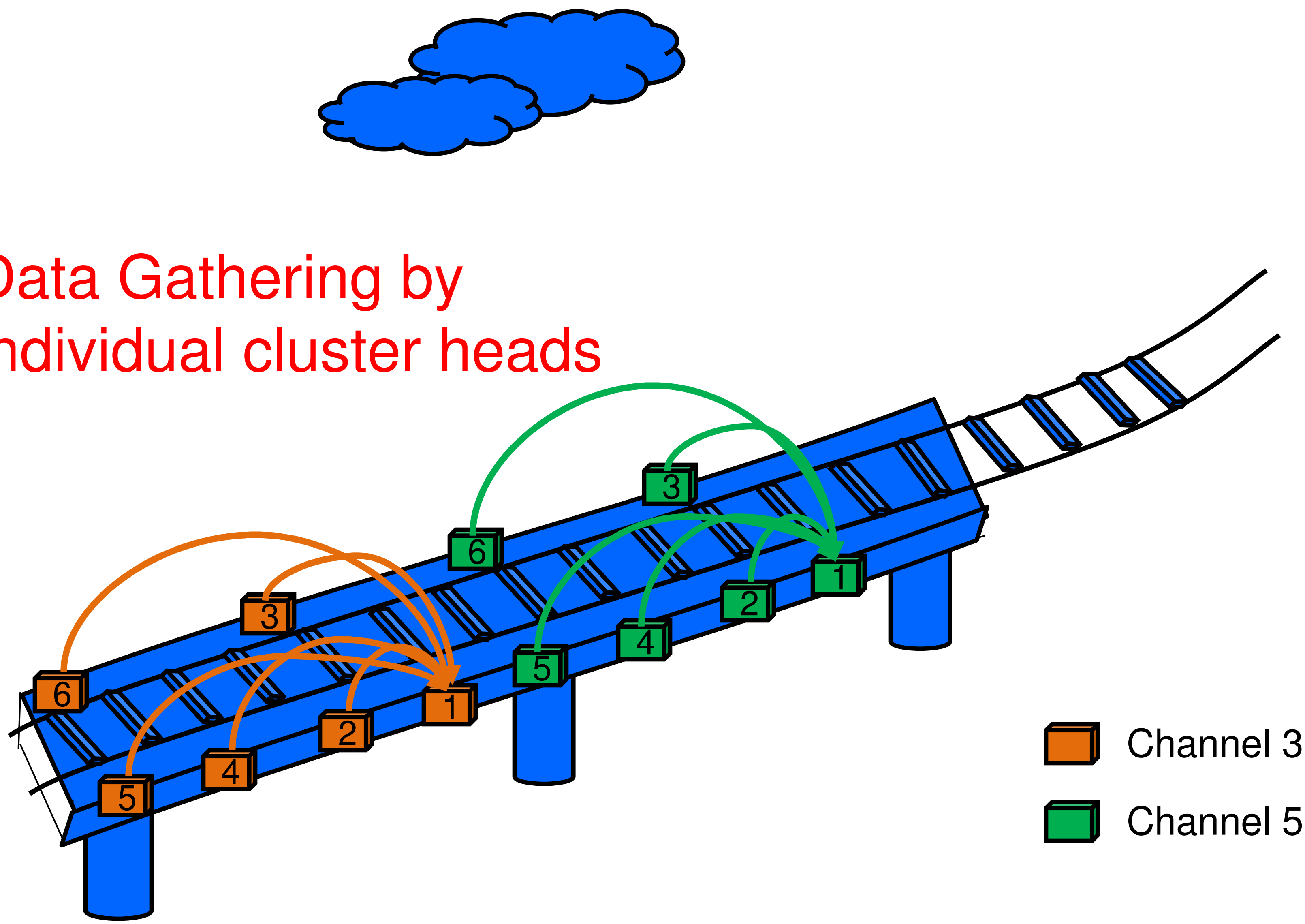


Train Arrival Detection

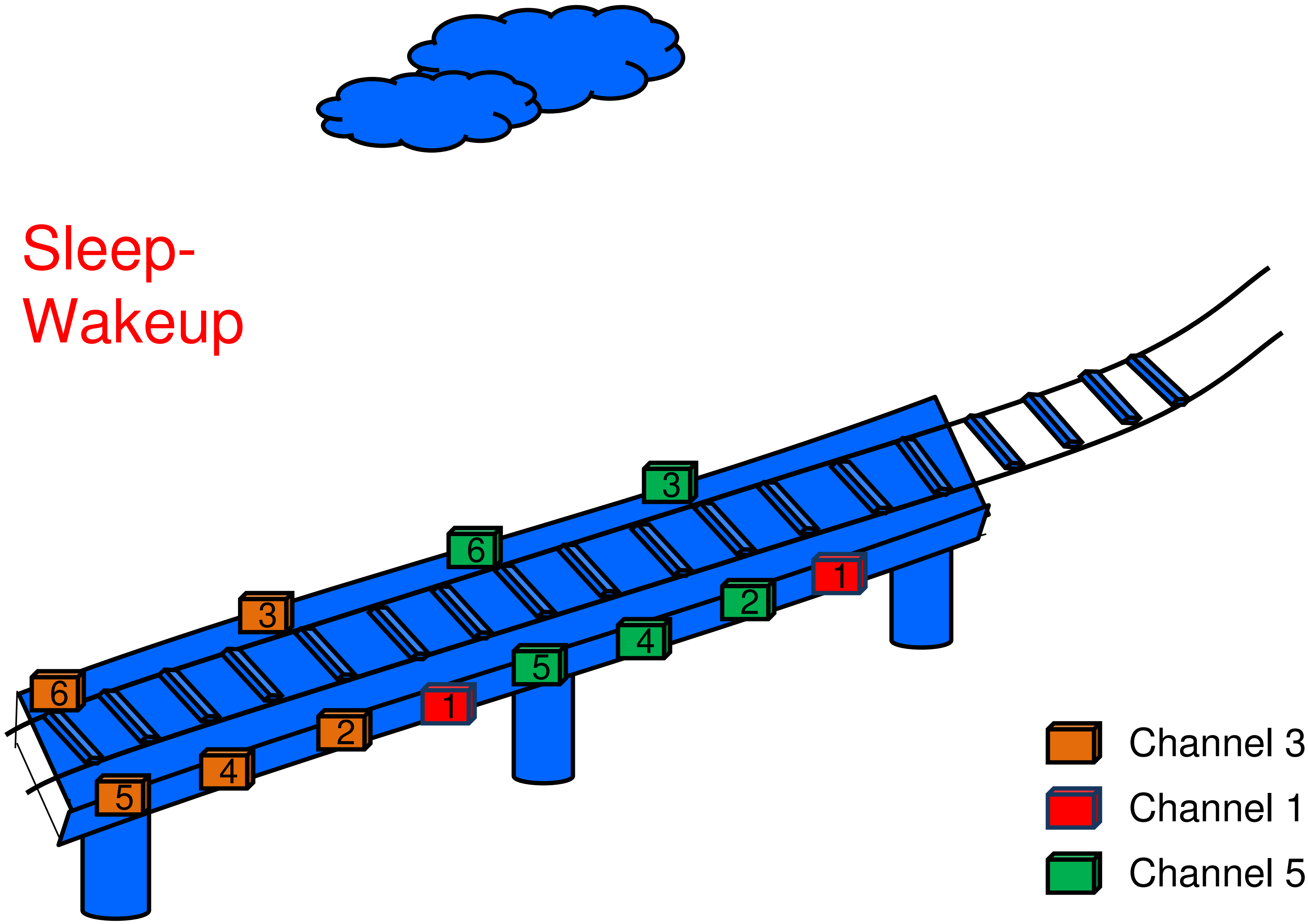
Vibration Sensing

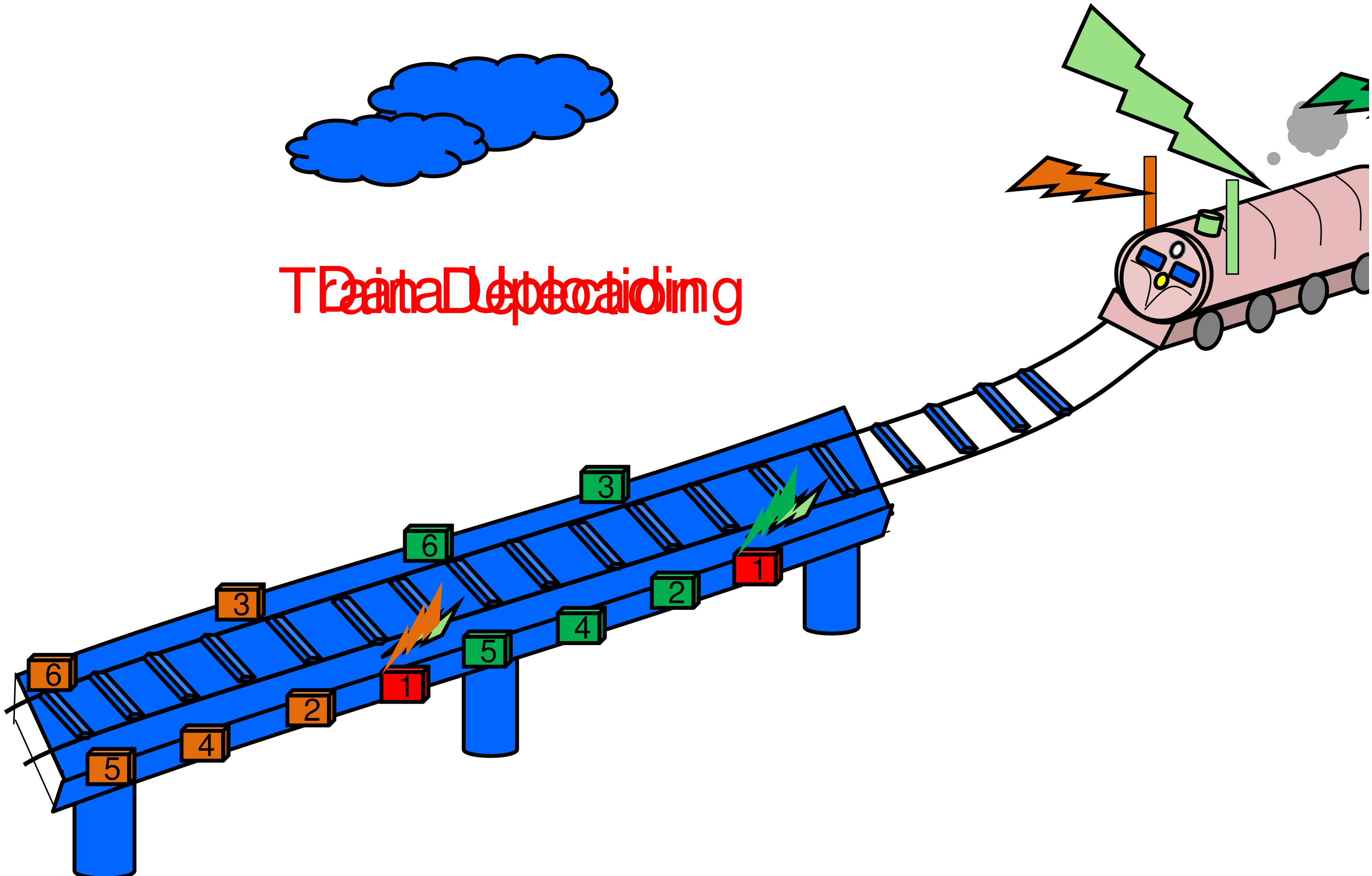


Data Gathering by individual cluster heads

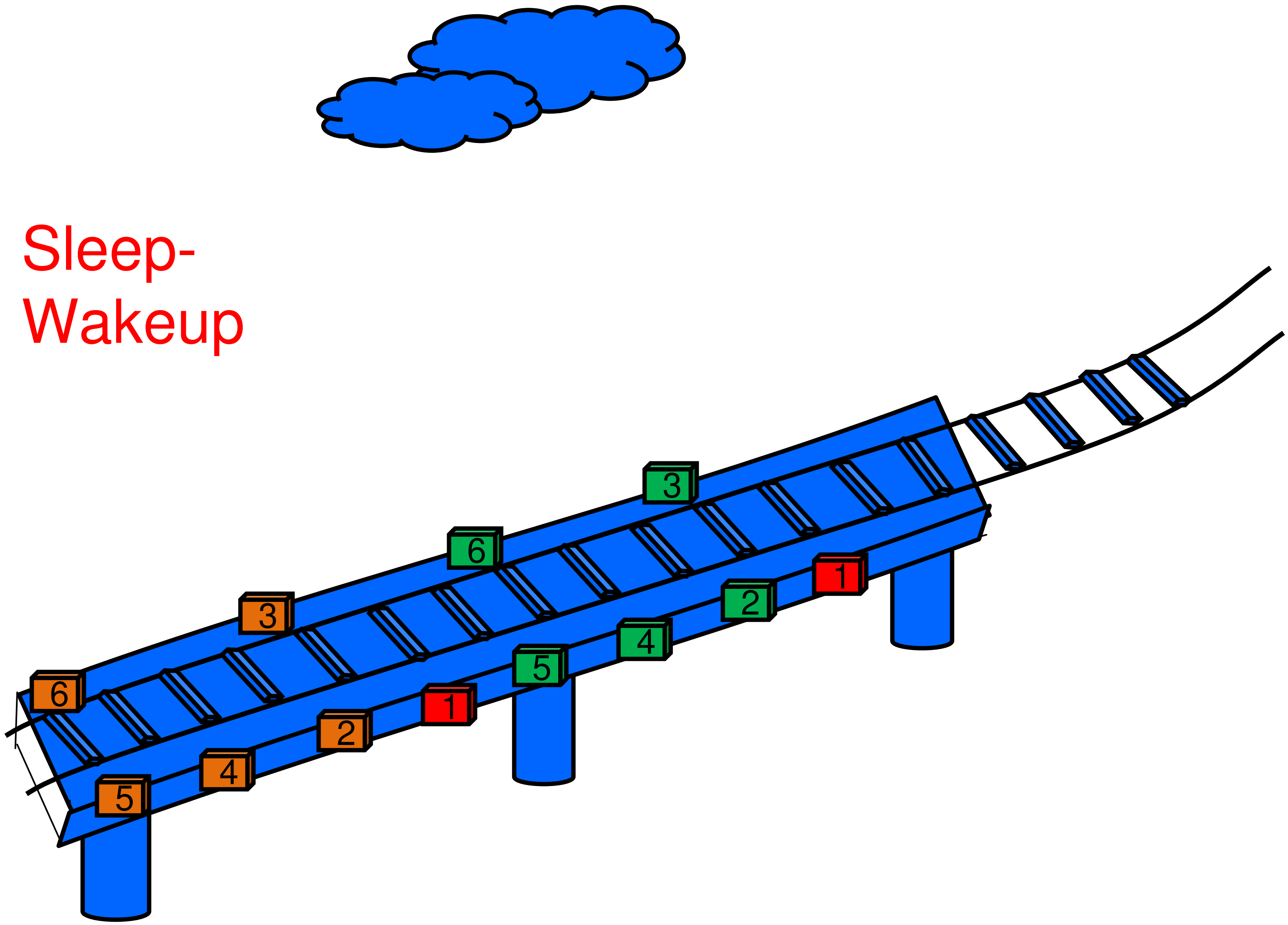


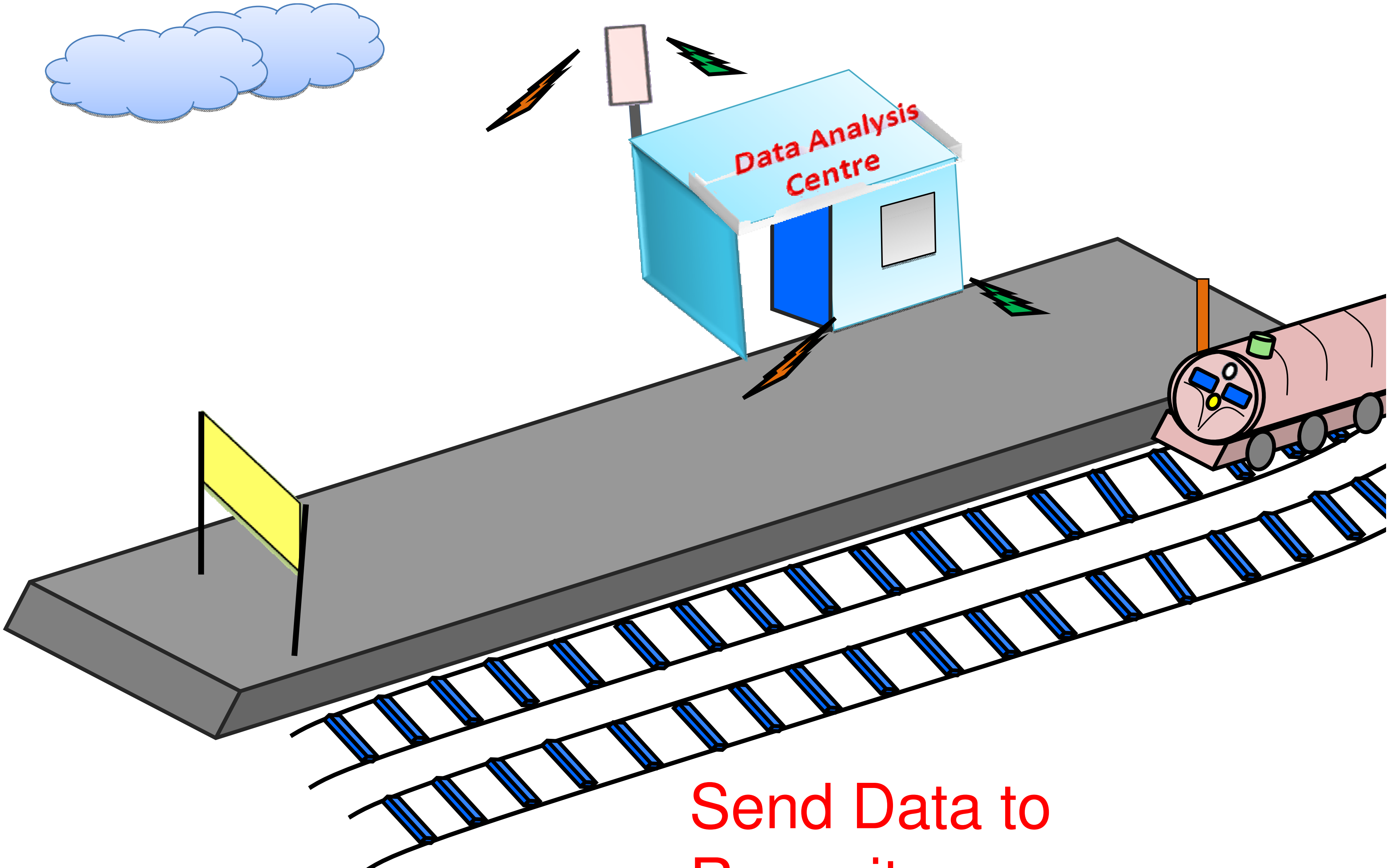
Sleep-Wakeup




Train Duplication
Data Uploading
6
3
6
3
2
1
5
4
2
1
5
4
6
3

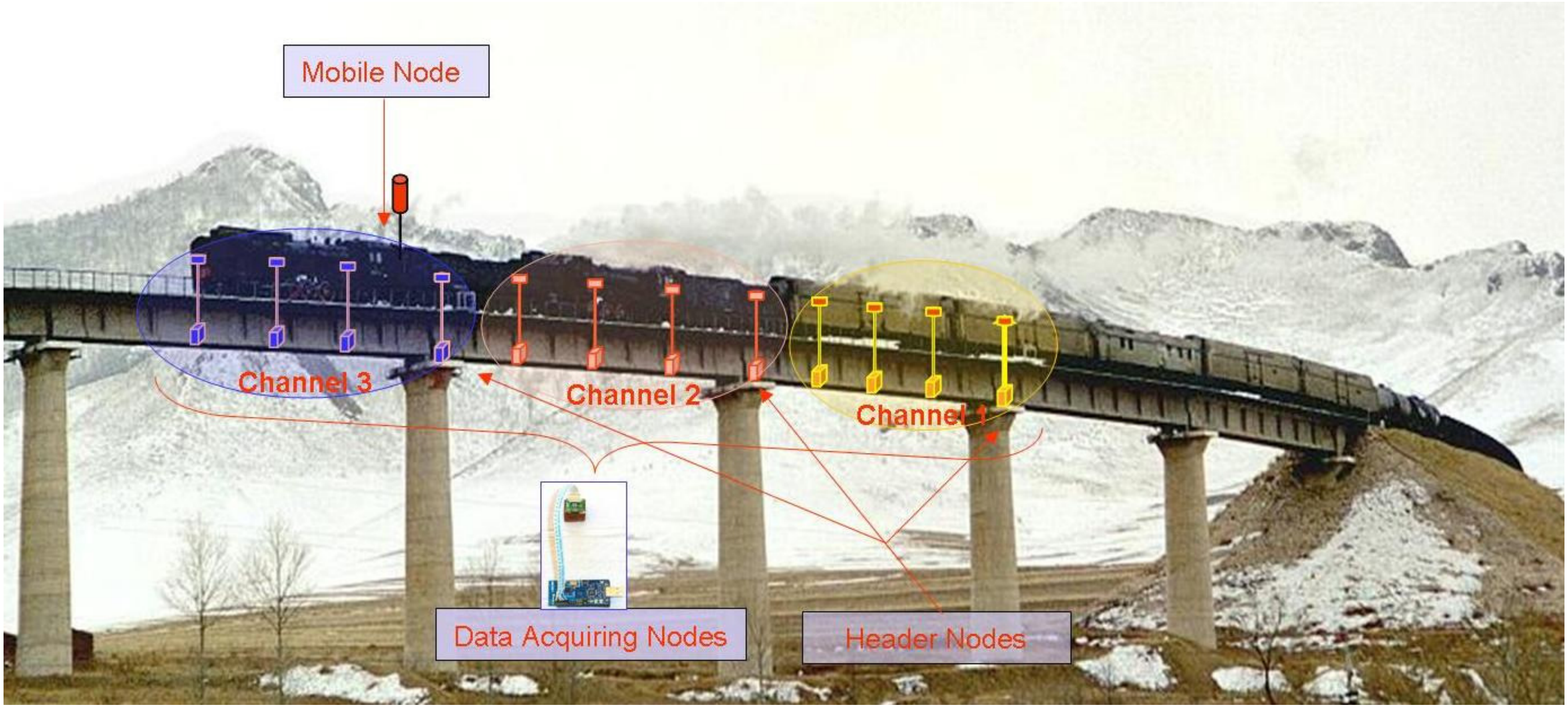
Sleep-Wakeup





Send Data to Repository

Deployment Long Term Monitoring



Hardware

Accelerometers

Parameter	ADXL203	MMA7260Q
Company	Analog Devices	FreeScale Semiconductors
Package	8-Terminal Ceramic LCC	16-pin QFN
No of axis	2	3
Resolution	1mg	-
Sensitivity	1000mV/g	800mV/g
Noise performance	$110\mu g/\sqrt{Hz}$	$350\mu g/\sqrt{Hz}$
Bandwidth	0.5-2500Hz	XY-350Hz Z-150Hz
Acceleration range	±1.7g	±1.5g, ±2g, ±4g, ±6g
Supply voltage	2 to 5 V	2.2 to 3.6V
Output voltage at 0g	2.4V-2.6V	1.485V-1.815V
Current consumption	$700\mu A$	$500\mu A$

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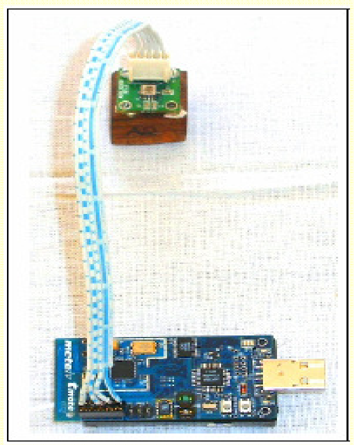
Hardware

Tmote

- 250kbps, 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver
- 8MHz MSP430 microcontroller (10k RAM, 48k Flash)
- 1 MB external flash for data storage
- Integrated ADC, DAC, and DMA Controller
- Integrated onboard antenna with 50m range indoors / 125m range outdoors
- 16-pin expansion support and optional SMA antenna connector
- TinyOS support



Data Acquisition System

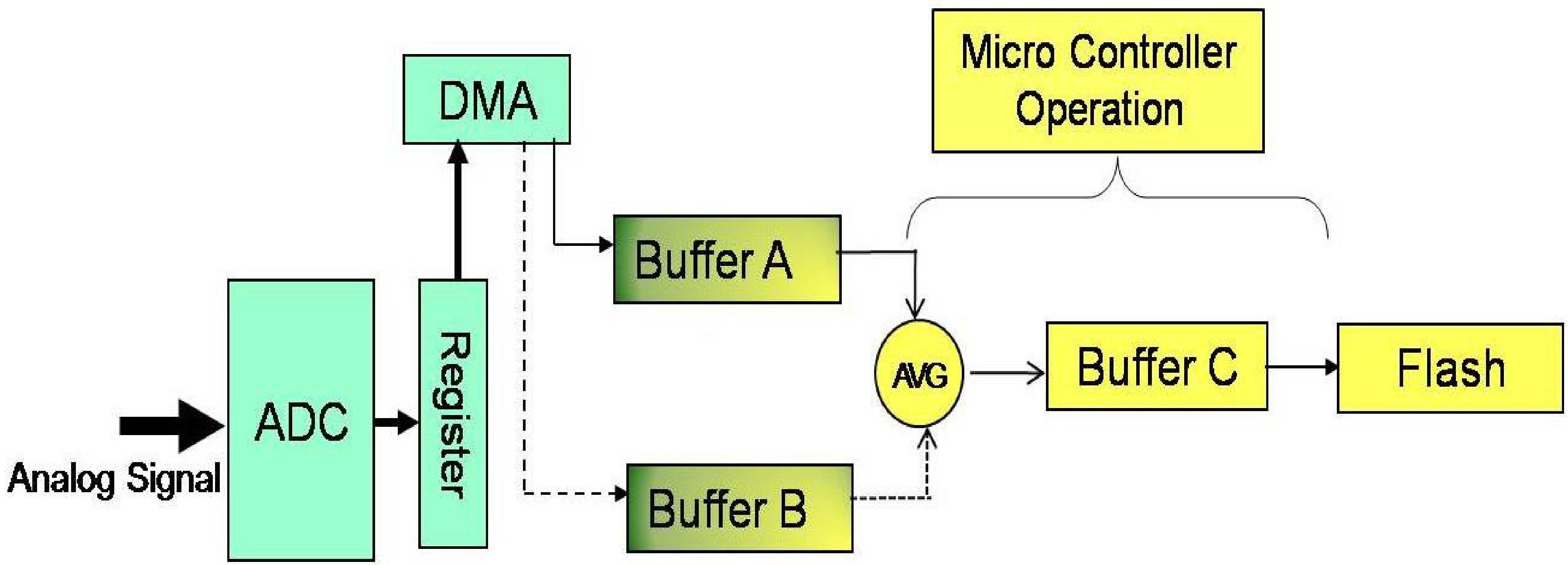
Requirements

- Frequency band of interest 0.25HZ to 20 Hz
- Sampling duration minimum 40 seconds
- High fidelity of acquired data
  - **10 milli g resolution**
  - **High frequency sampling**
- Time synchronization of samples

Constraints and solution

- Limited RAM (10 KB) forces us to make use of both RAM buffers and flash for data acquisition
- Only one ADC (12 bit) on tmote , which is multiplexed between the channels acquired. The switching time more than 10 ms hence we acquire only one channel at a time
- DMA based sampling to prevent loss of data and also to reduce jitter among the samples

DMA Based Data Acquisition



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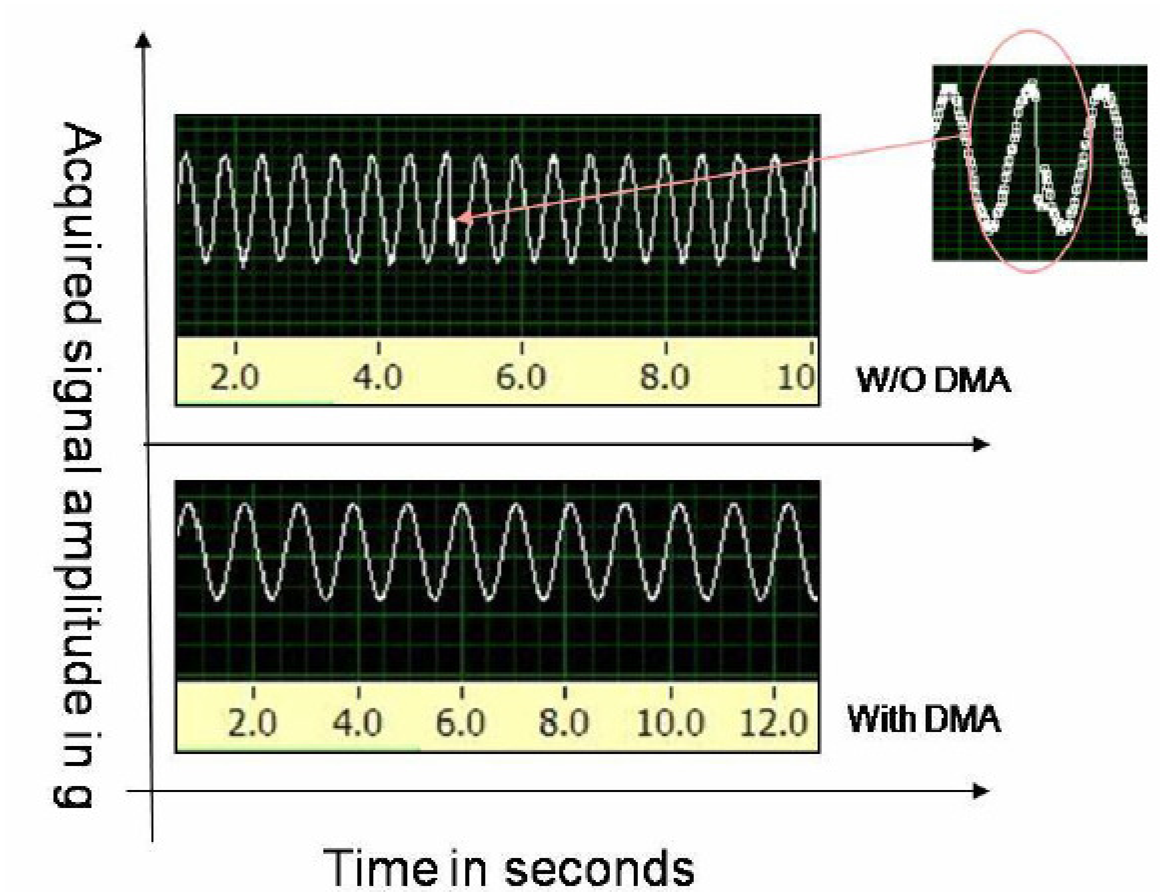
DMA Based Data Acquisition

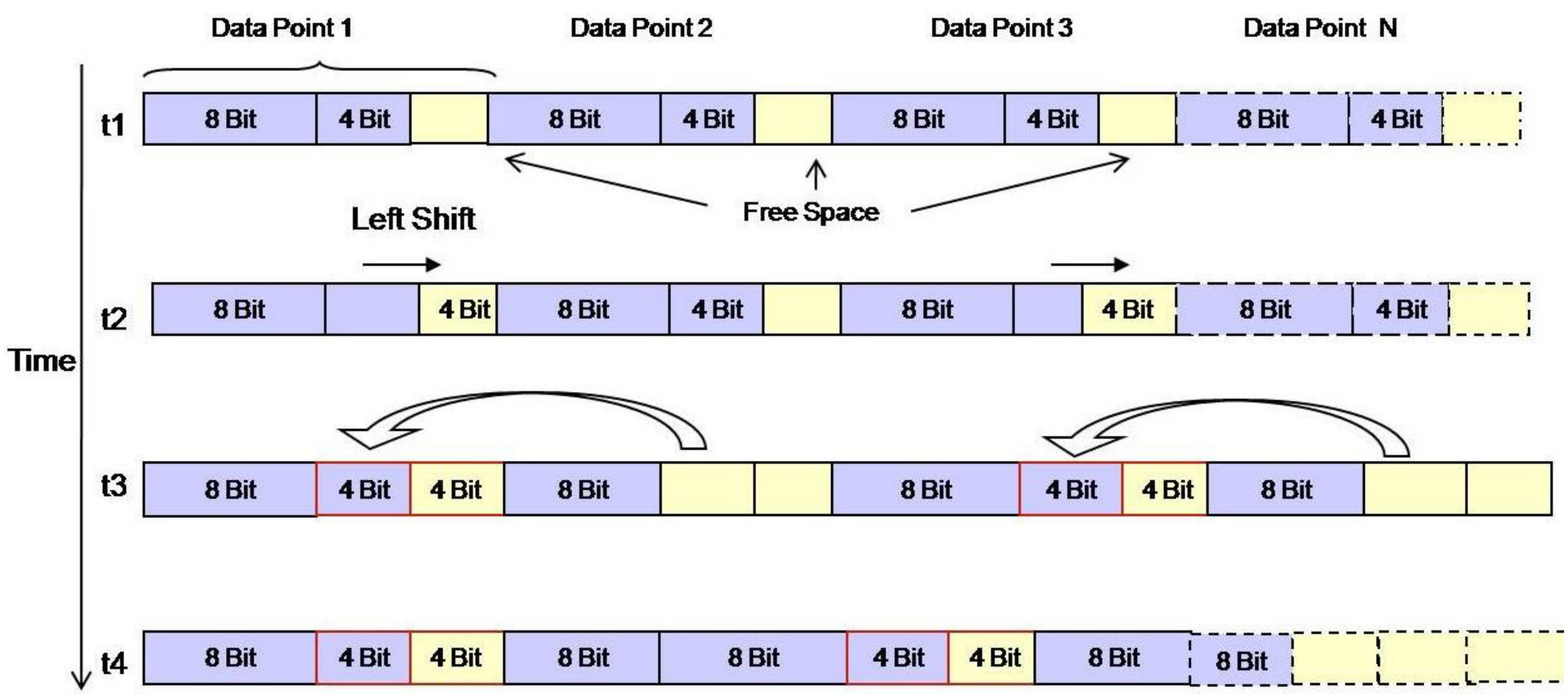


Data Compaction and Compression

Requirements

- Minimize the number of data transmission required
- Lossless compression

Compaction



Compression

Techniques studied

- Delta encoding
  - Compression upto 50% when signal is of very low frequency but not suitable for frequency band > 5Hz
  - 5 to 7% compression on sample bridge data
- Run length encoding
  - Useful when lot of repetition in data samples
  - Poor result on sample bridge data. Most of the time file was inflated.
- LZW
  - Dictionary based technique
  - Requires lot of memory. For example for 9 bit code words, it requires 4KB of memory for implementation.
  - Up to 19 % compression on sample bridge data

Debugging Tool

- Used to test or debug the system when it is deployed. Some of the usages are
  - Test links between the nodes
  - Find node voltages of the nodes
  - Test the system for its functionality by issuing the commands from command station
- The tool consist of command station and base node

```
=============================================
     Welcome To BriMon Control Panel
=============================================


     Enter One Of The Option
     -----------------------

     0-->TestLink                1-->Led On
     2-->Led Off                 3-->Collect Data
     4-->Transmit Data           5-->Reinitialize System
     6-->Format Flash            7-->Start Routing
     8-->Exit                    9-->Erase Flash
     10->Get Node Voltages       11-->TIME_SYNC
     12->Collect_Node_Log        13-->SET_LINK_THH

     ::
```

Data Analysis Tool

- Used for analysis of vibration data of bridge
- Some features of the tool are
  - Developed in LabView 7.1
  - User friendly graphical user interface (GUI)
  - Provision of digital filter with an option to enable or disable it
  - Provision to select portion of waveform for data analysis
  - Provide information both in time and frequency domain
  - Pick up data from input file
  - Accept input data as compressed or uncompressed
  - GUI has view magnifying options
  - Provision to select the sampling rate
  - The dominant frequency components of the waveform displayed along with their amplitudes.

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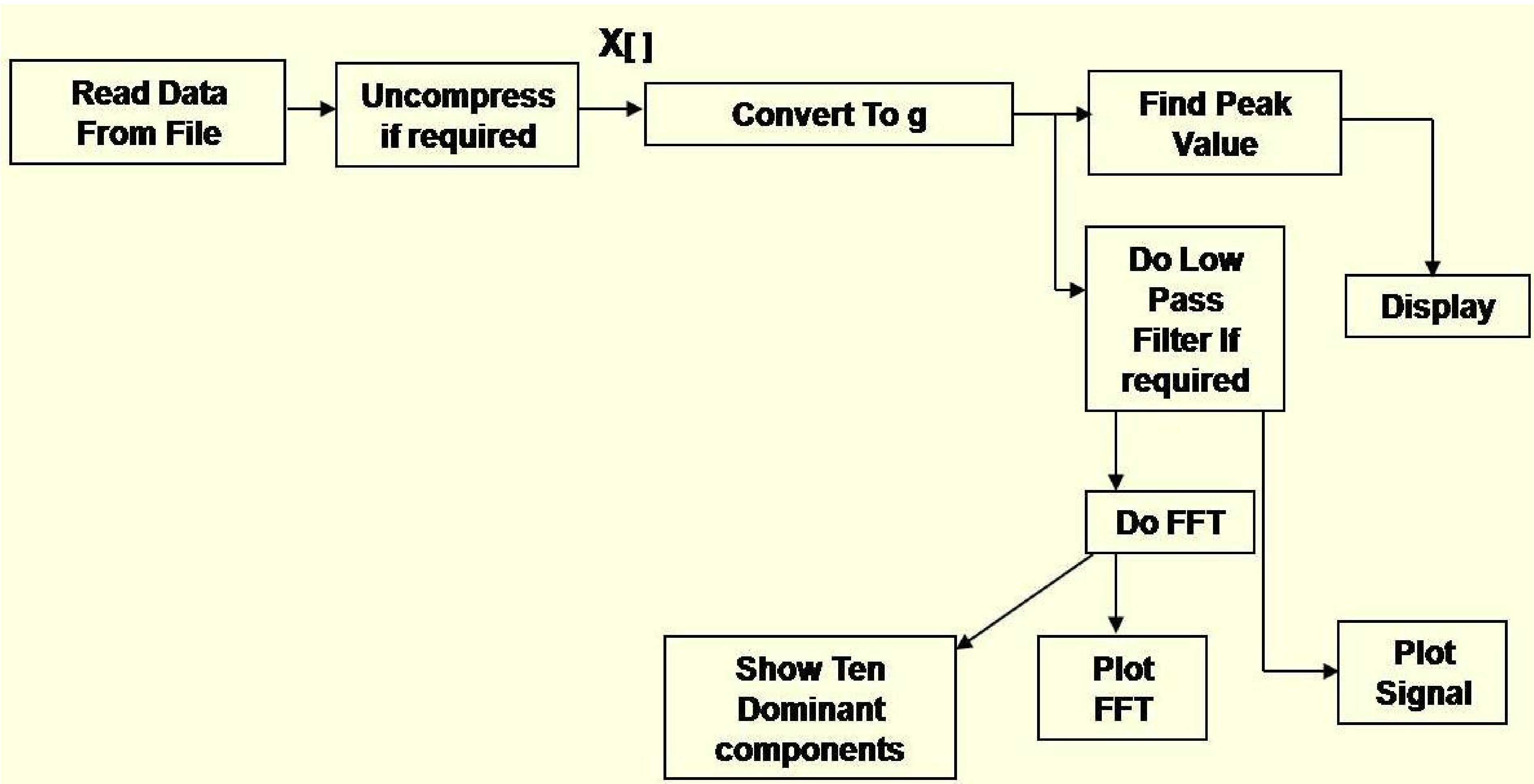
Data Analysis Tool



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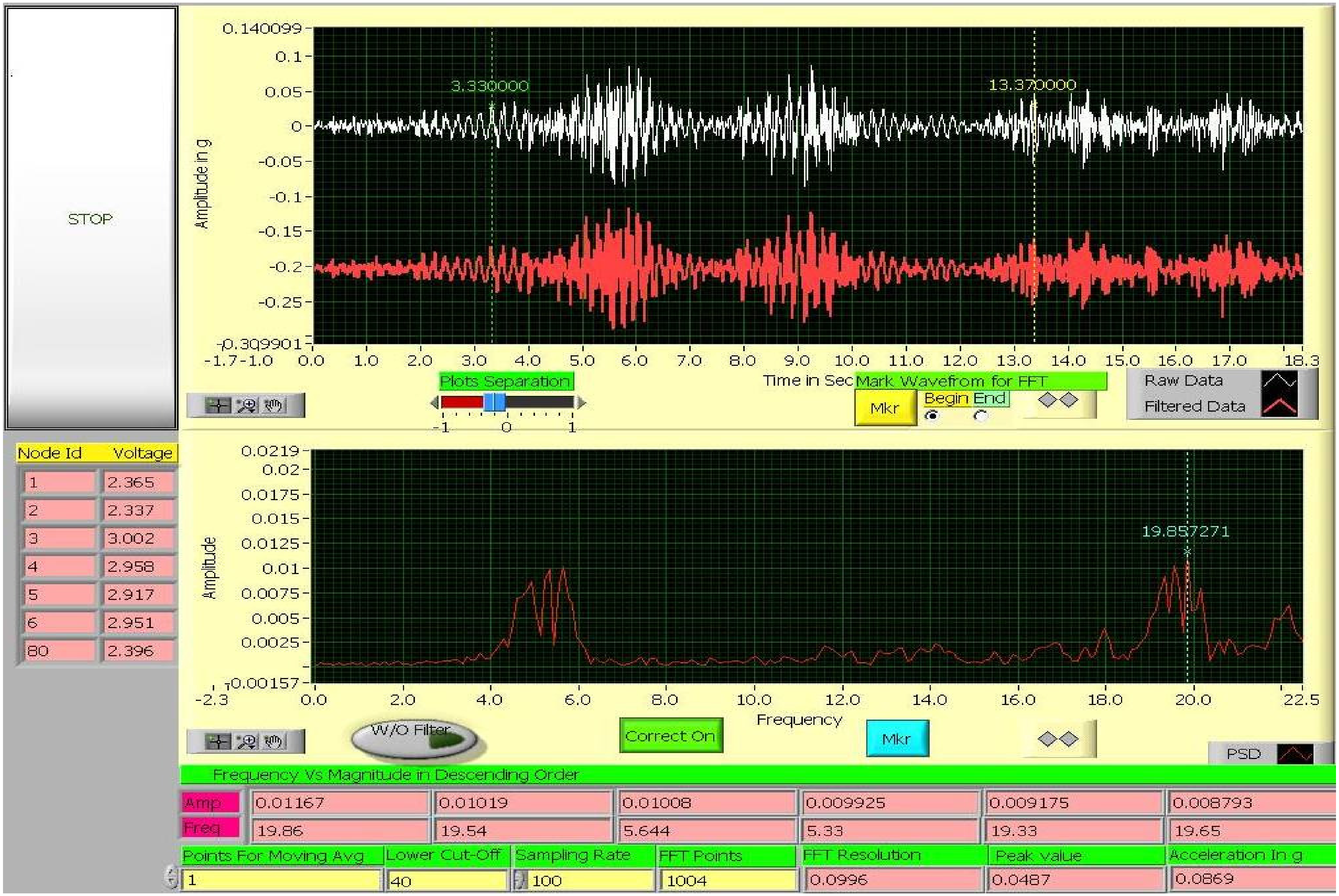
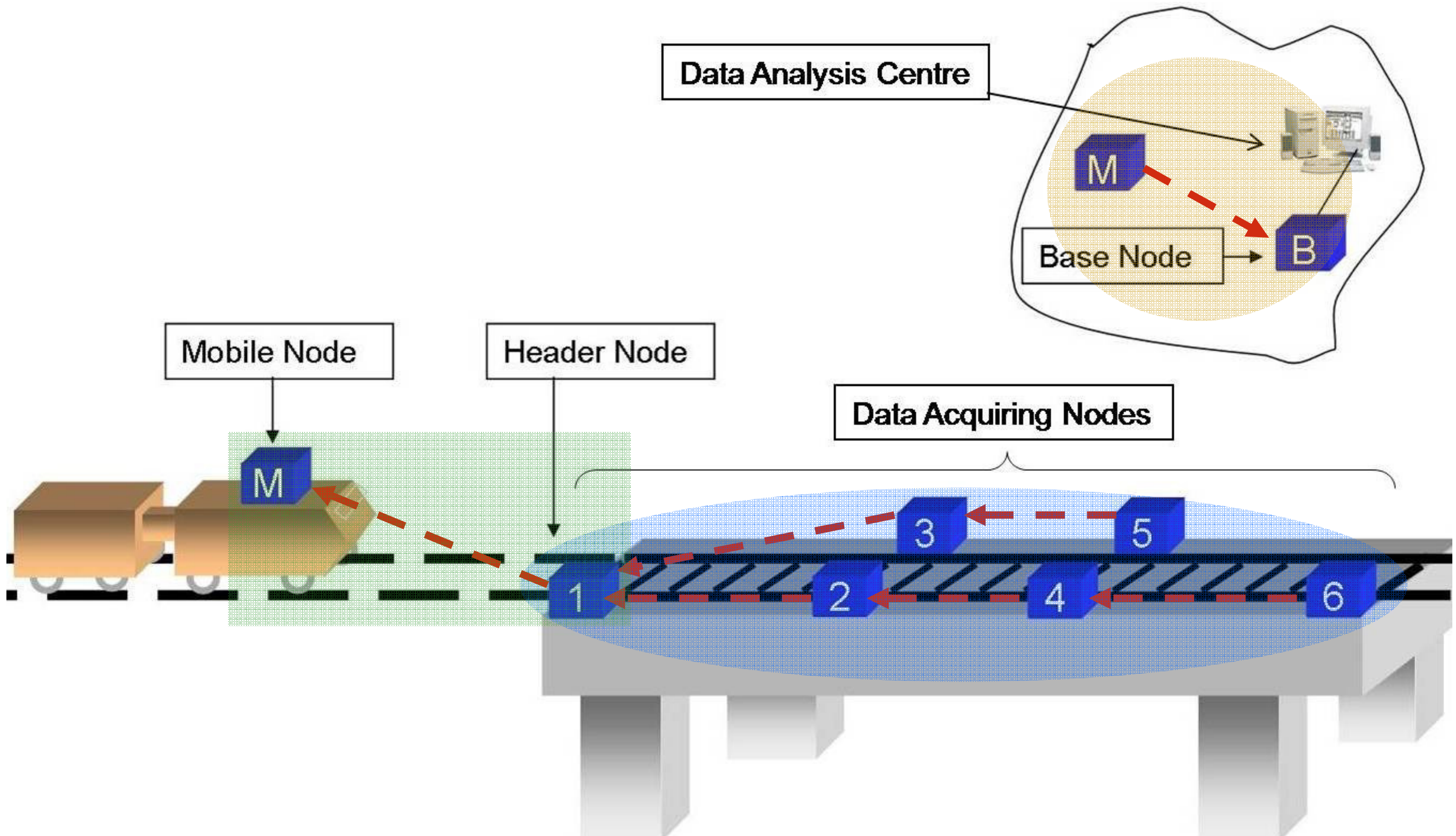
Data Analysis Tool GUI



Transport Protocol

- Application requirements and constraints
- Protocol description
- Flow control

Application Requirement and Constraints



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Application Requirement and Constraints

Constraints

- Limited RAM (10 KB) so we make use of both RAM and flash for data transfer
- Flash and radio share the same bus so need for careful arbitration between them
- Problem of flow control due to which we need to have some inter packet pause between the packets transmitted

Protocol Description

Single hop data transfer mechanism

- Read block of data from flash
- Send block to the transport layer
- Transport layer divide the block into packets
- Packets send one after the other using SACK based technique
- At the receiver, the packets are received and assembled into block
- The block of data is then passed on to the application layer.
- The block is then written to the flash

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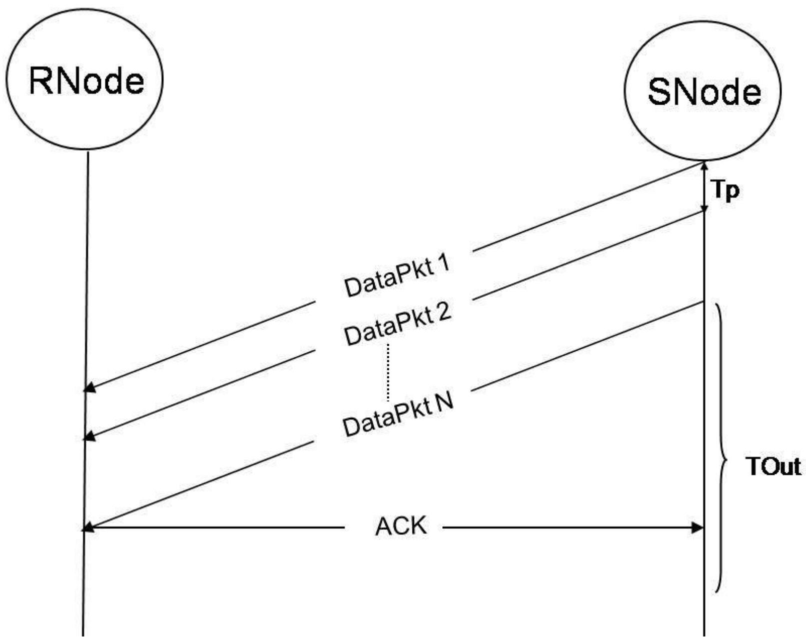
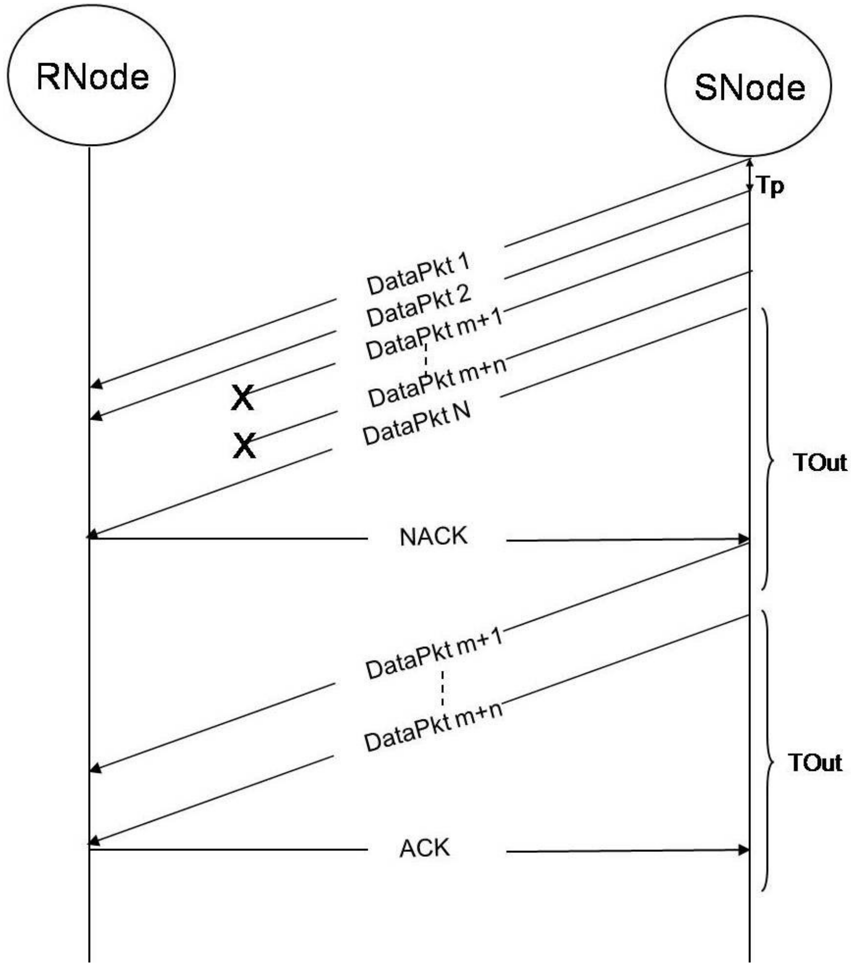
Single Hop Data Transfer Recovery of Lost Packets



No loss of packets



Loss of packets

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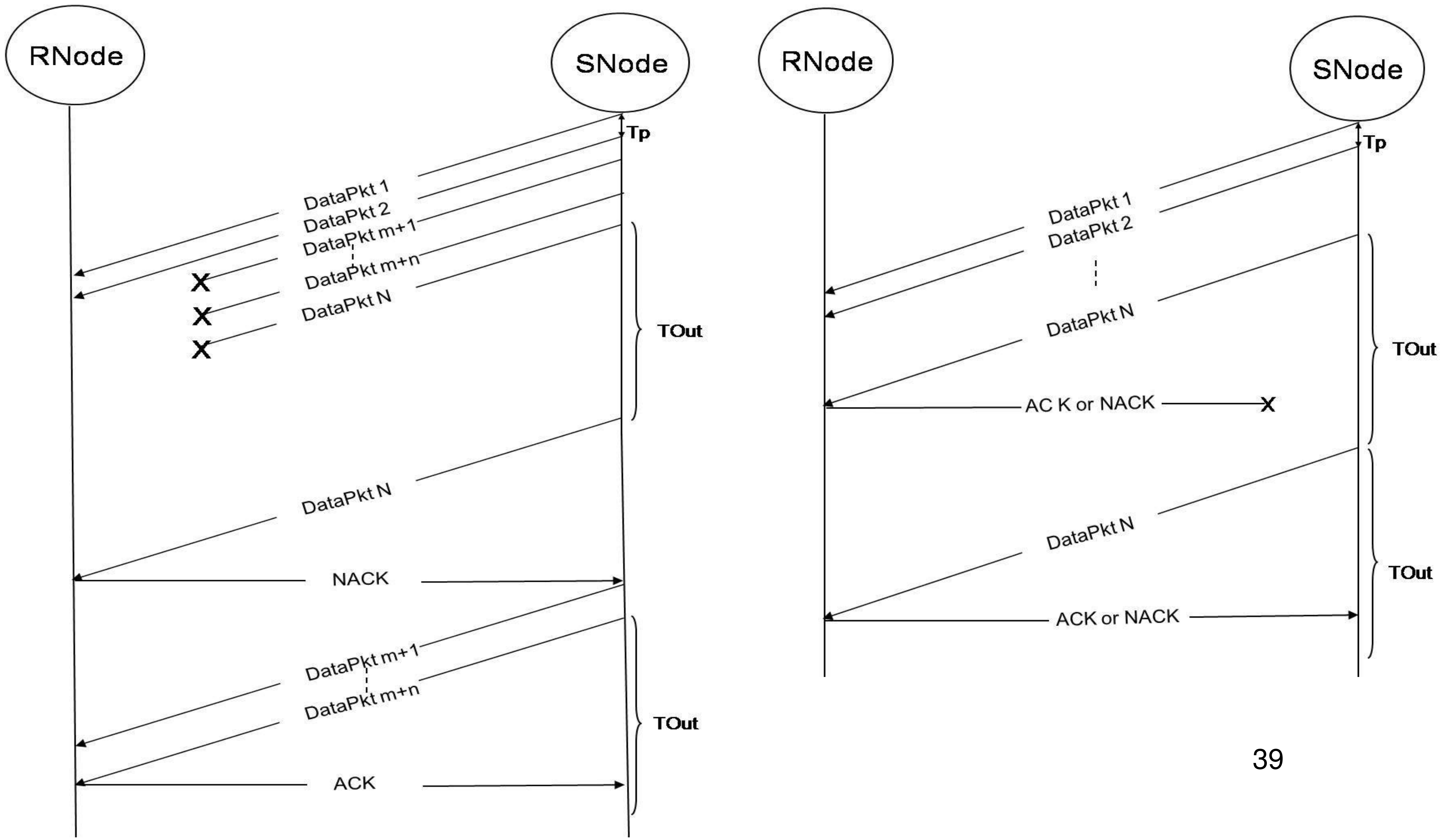
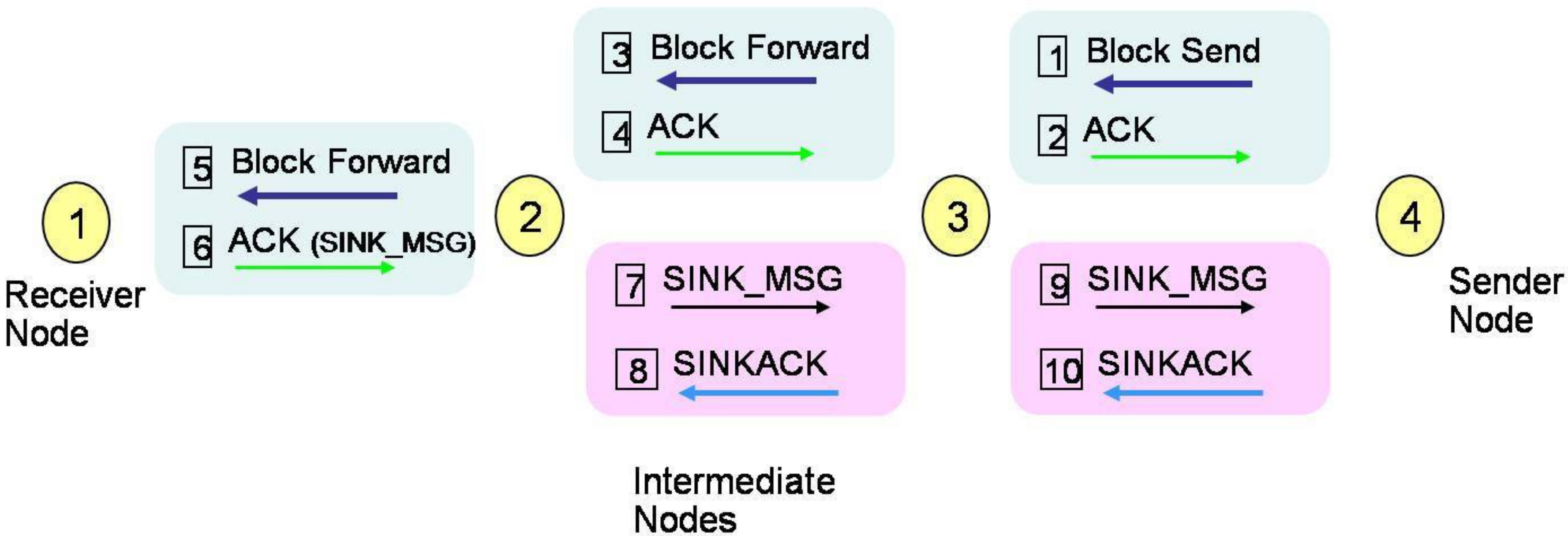
Single Hop Data Transfer Recovery of Lost Packets

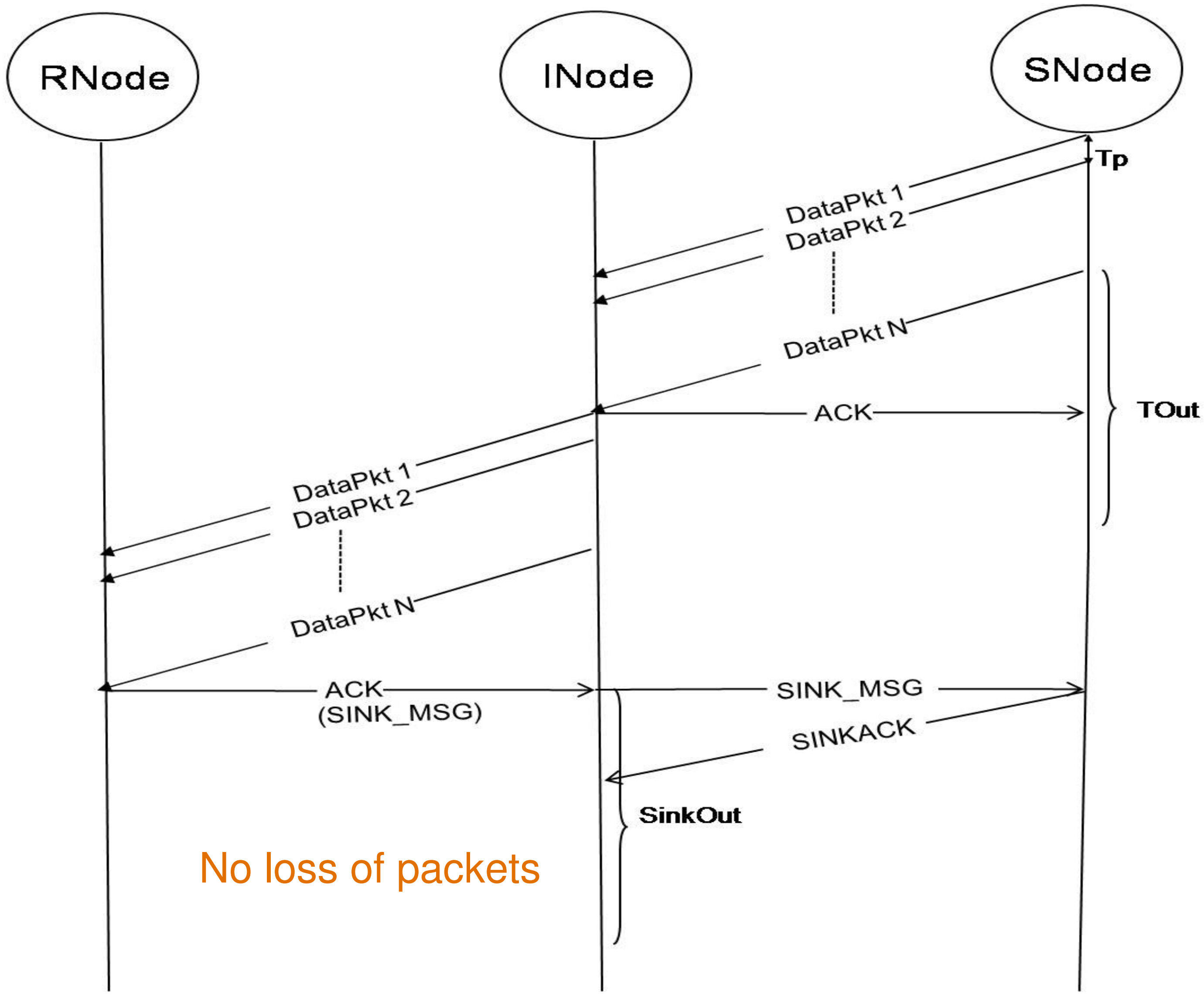


Protocol Description

Multi hop data transfer mechanism



Multi Hop Data Transfer Recovery of Lost Packets



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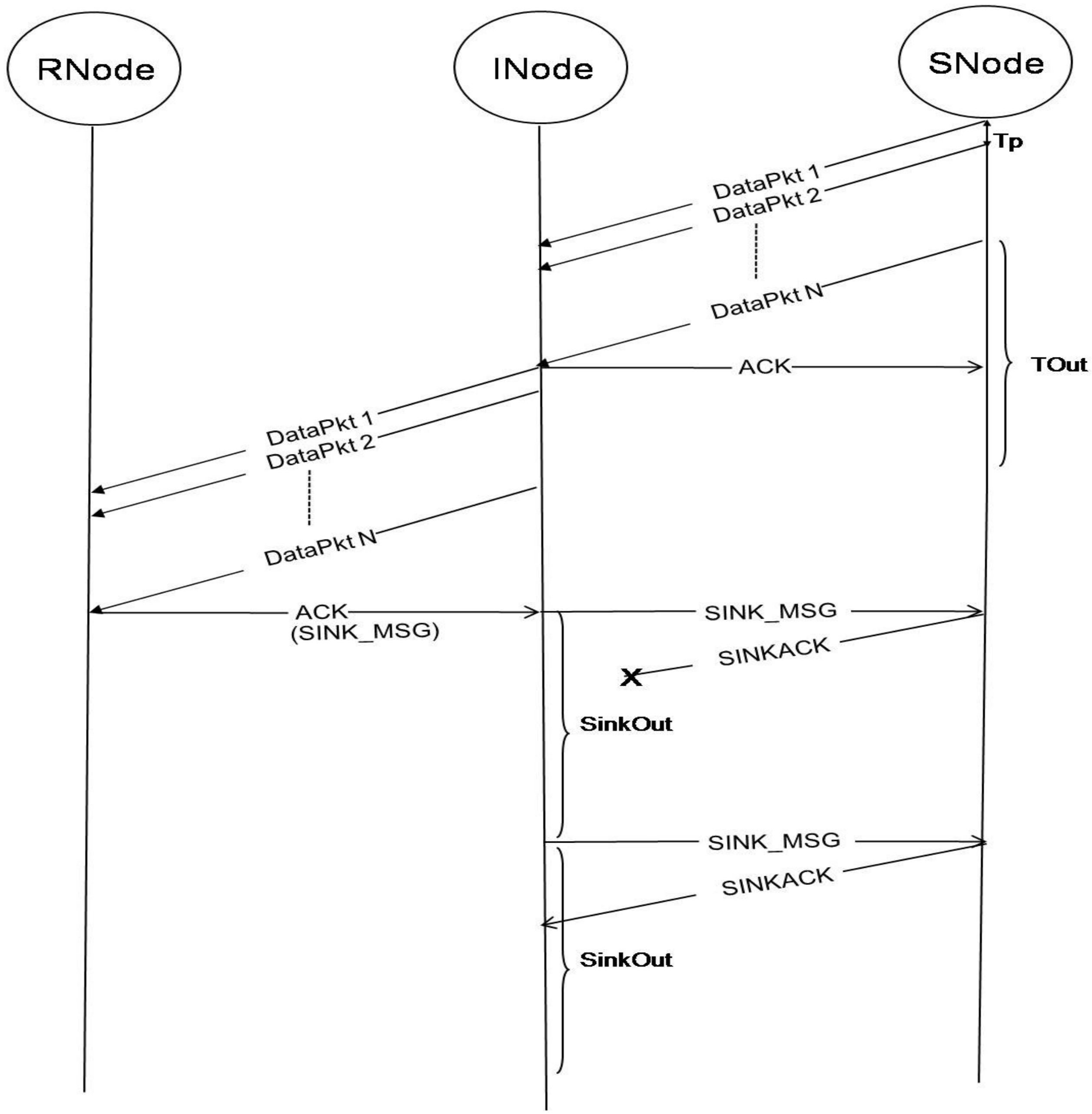
Multi Hop Data Transfer Recovery of Lost Packets



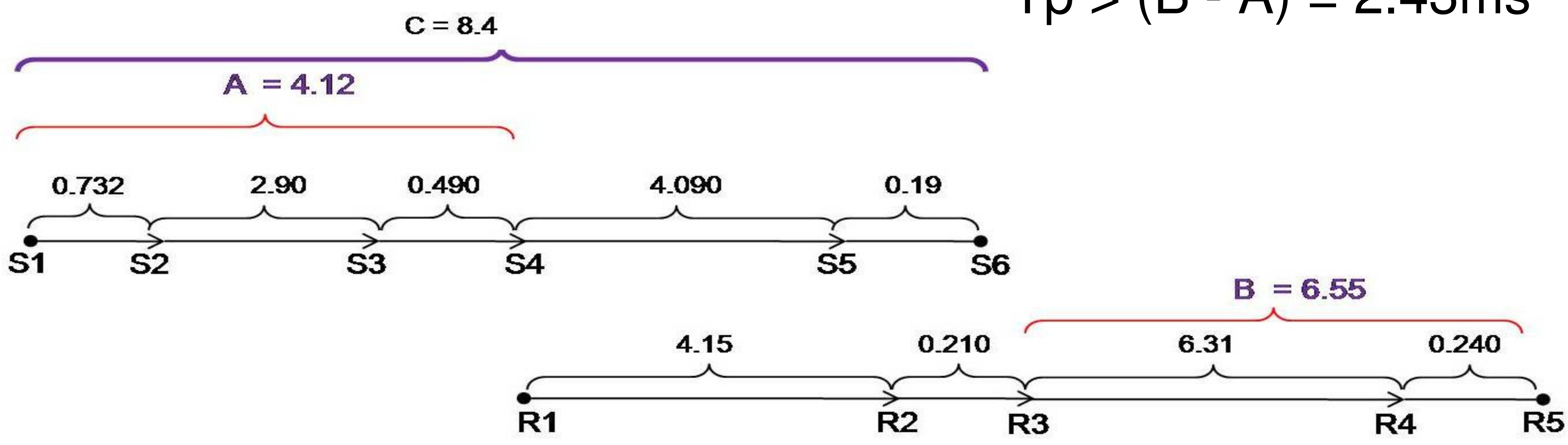
Flow Control

Sender and receiver side events when a packet is transmitted

Event	Description
S1	Send Command Issued
S2	Start of transmission from Micro-controller to Radio on SPI bus
S3	End of Data Transfer over SPI bus
S4	SFD start i. e. sending a few packets over air
S4	Tx of packet over radio done
S6	SendDone Event triggered

Event	Description
R1	Received SFD interrupt
R2	Complete packet received
R3	Start of Data Transfer from radio to micro-controller over SPI bus
R4	End of Data Transfer over SPI bus
R5	ReceiveEvent Message Triggered

Tp > (B - A) = 2.43ms



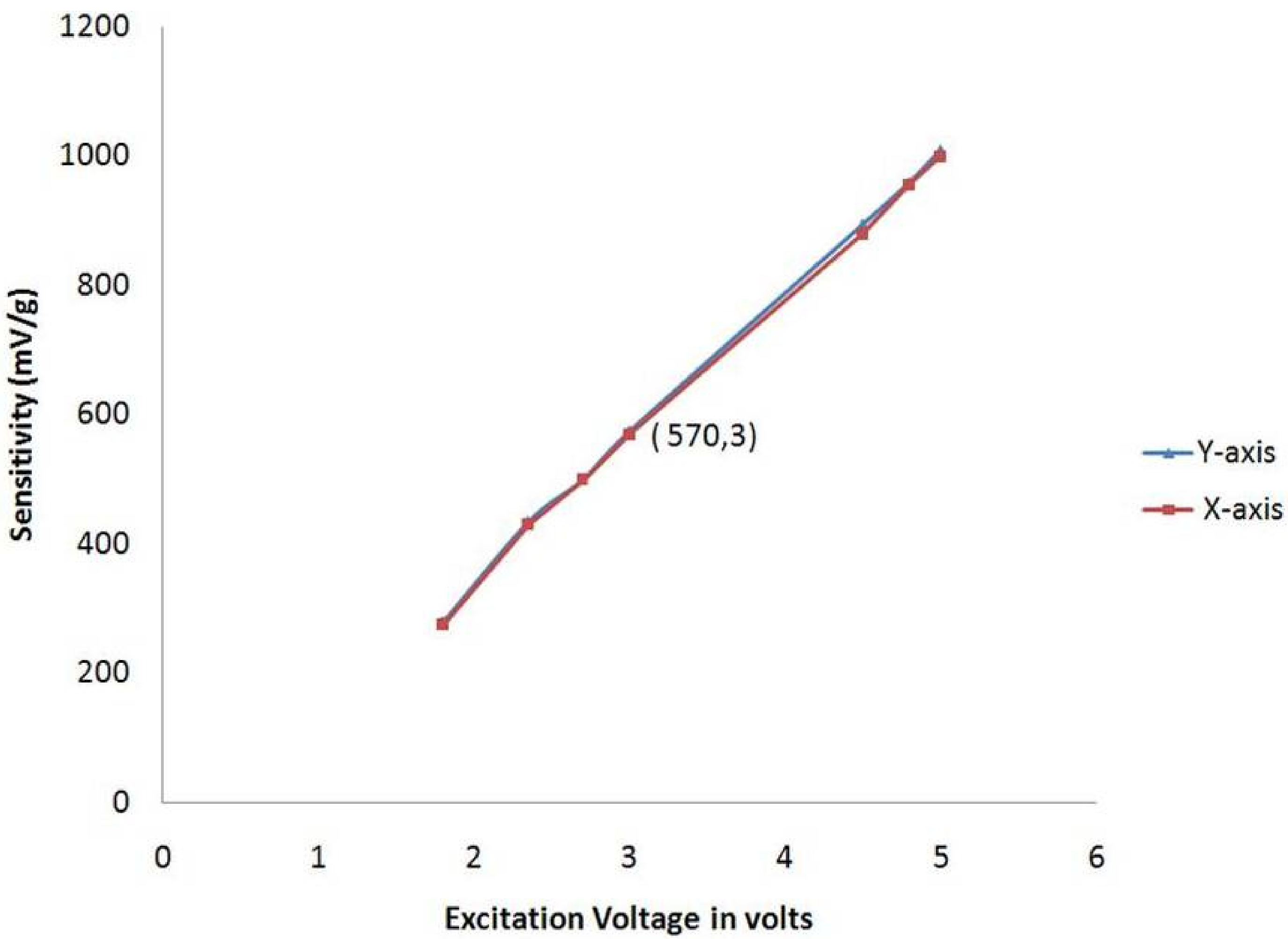
Experiments and Results

- Sensor calibration
- Experiment on road bridge
- Transport protocol evaluation
- Mobile data transfer

Sensor Calibration

Gravity test

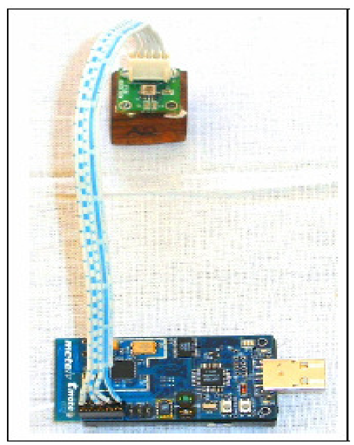
- To find variation of the sensitivity of the accelerometer with excitation voltage



Sensor Calibration

Noise level measurement

- To find noise level of the accelerometer
- Experiment was conducted on the air strip
- The accelerometer data was acquired for 20 seconds
- RMS noise level was found as 2.93 milli g which is higher than rms noise level of 0.983 milli g under ideal conditions but much lower than 10 milli g value required by the application

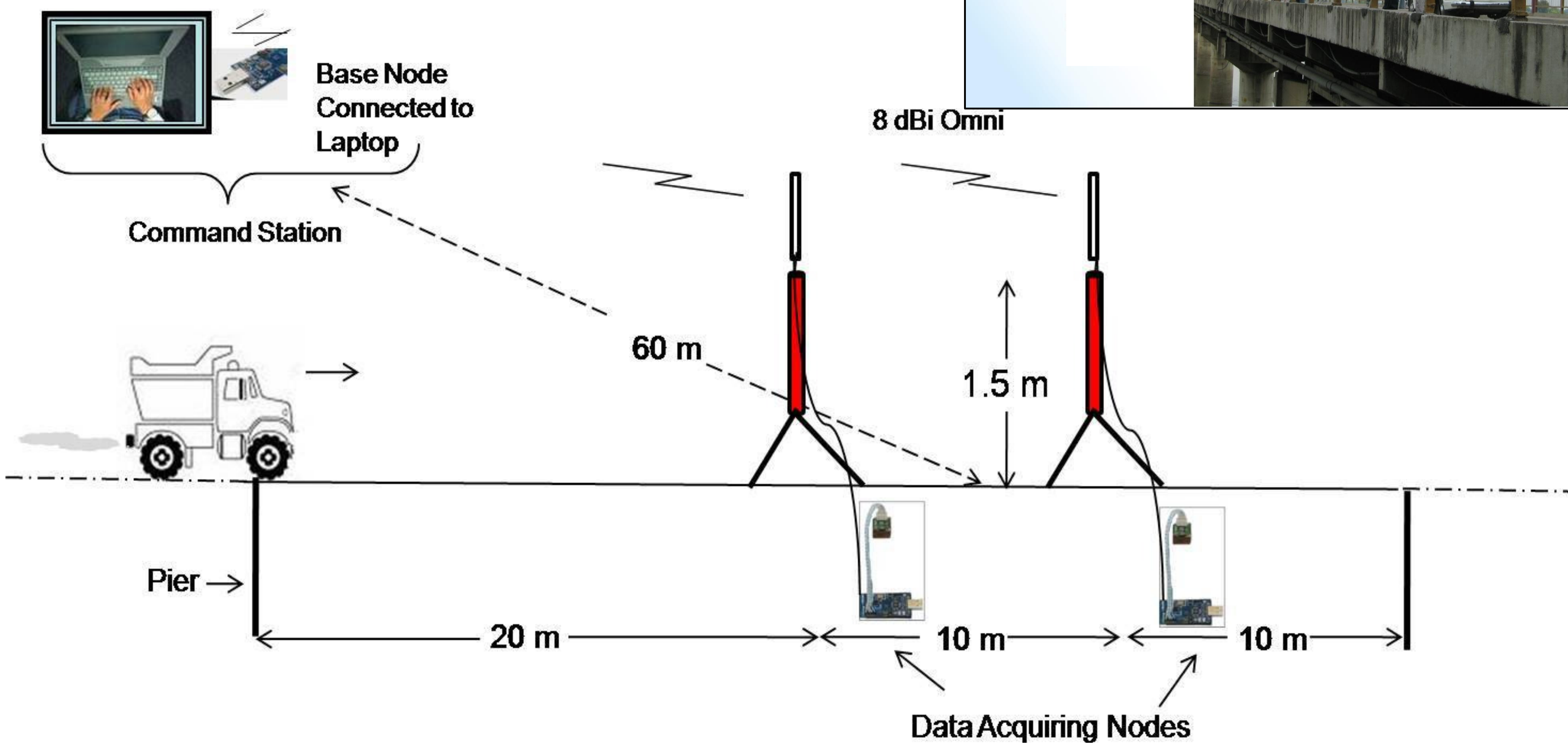


Experiment on Road Bridge

Aim of the experiment

- Test the system on actual bridge
- Wanted to demonstrate the system to structural engineers

Experiment setup

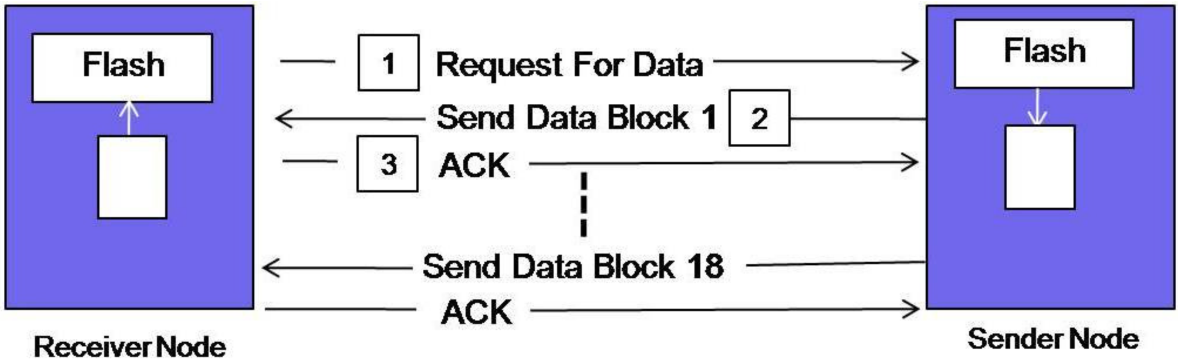


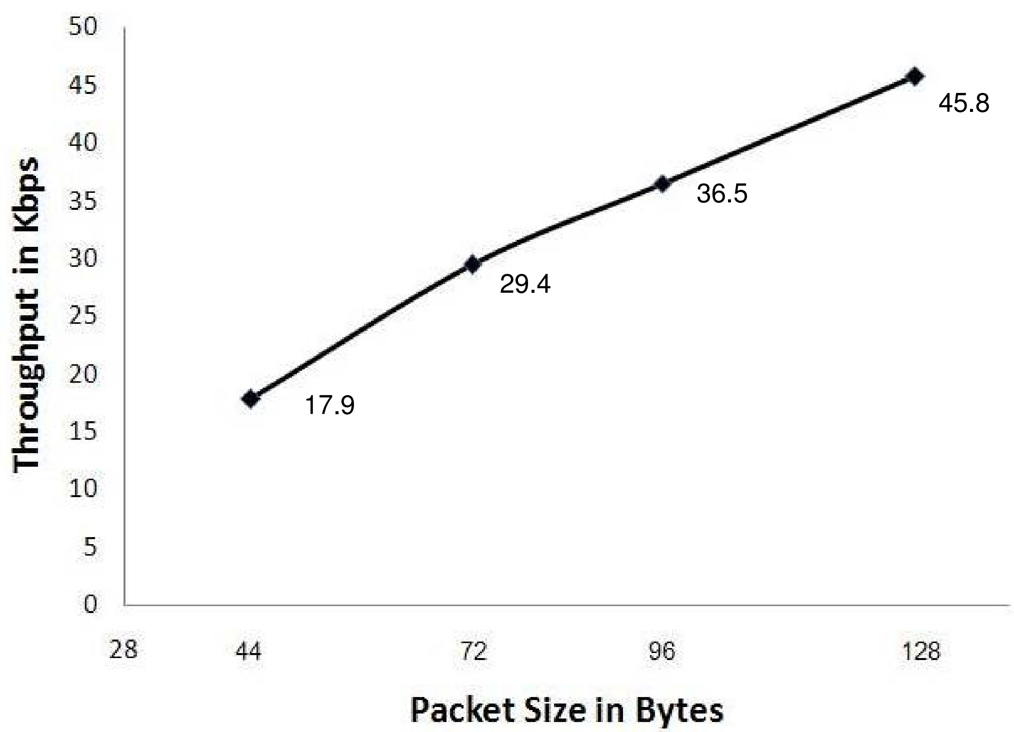
Transport Protocol Evaluation

- Throughput
- Reliability
- Performance for different data sizes
  - Single hop case
  - Multi hop case
- Performance comparison with PSFQ

Throughput Measurement

Experiment setup and result

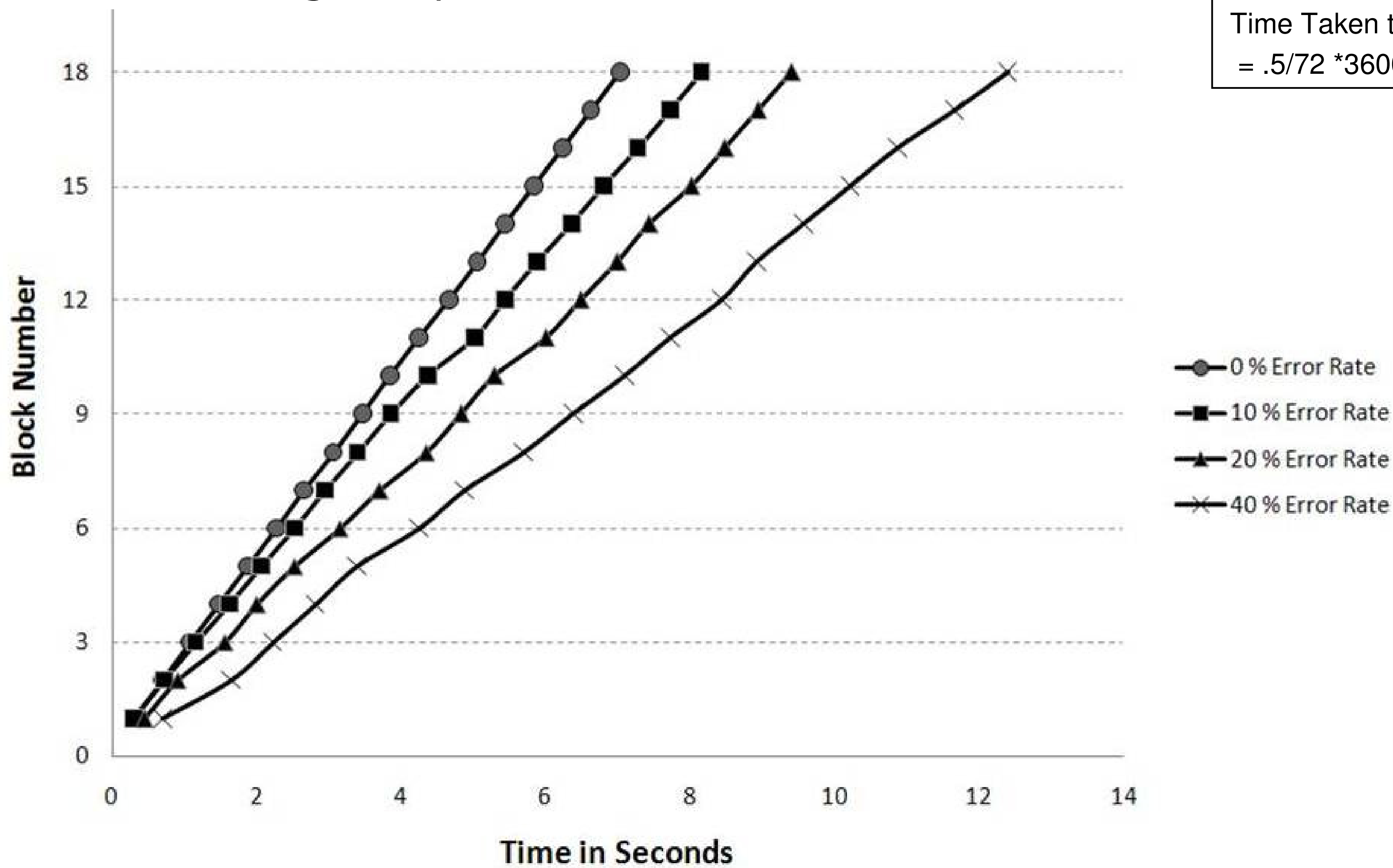




Reliability

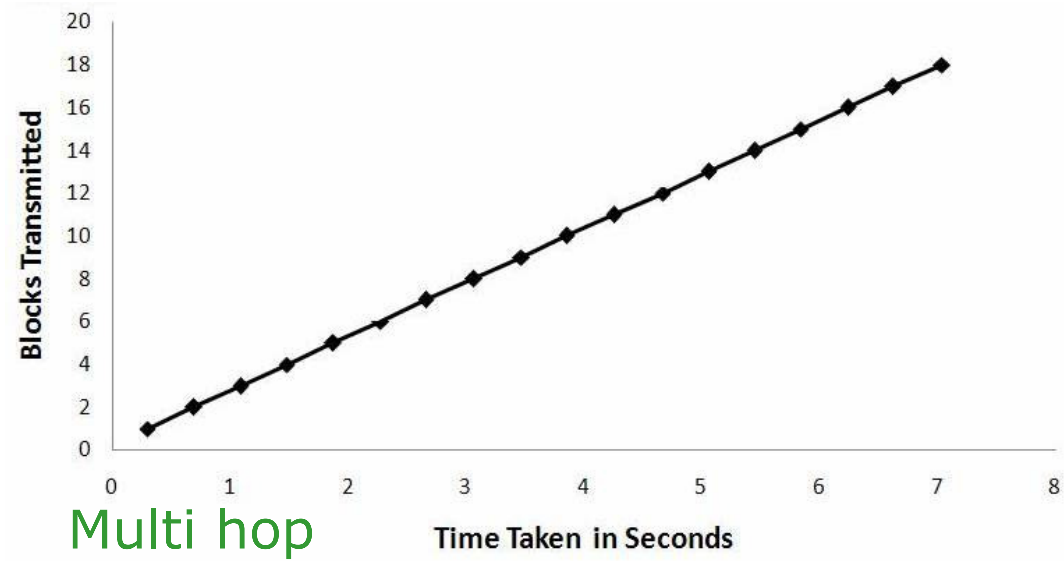
- The system was tested for reliable transfer of data by introducing packet losses up to 80%
- Main aim was to check timely recovery of data in single hop case

Train Speed= **72Km/h**
Time Taken to travel **500 m**
= .5/72 *3600 = **25 Seconds**

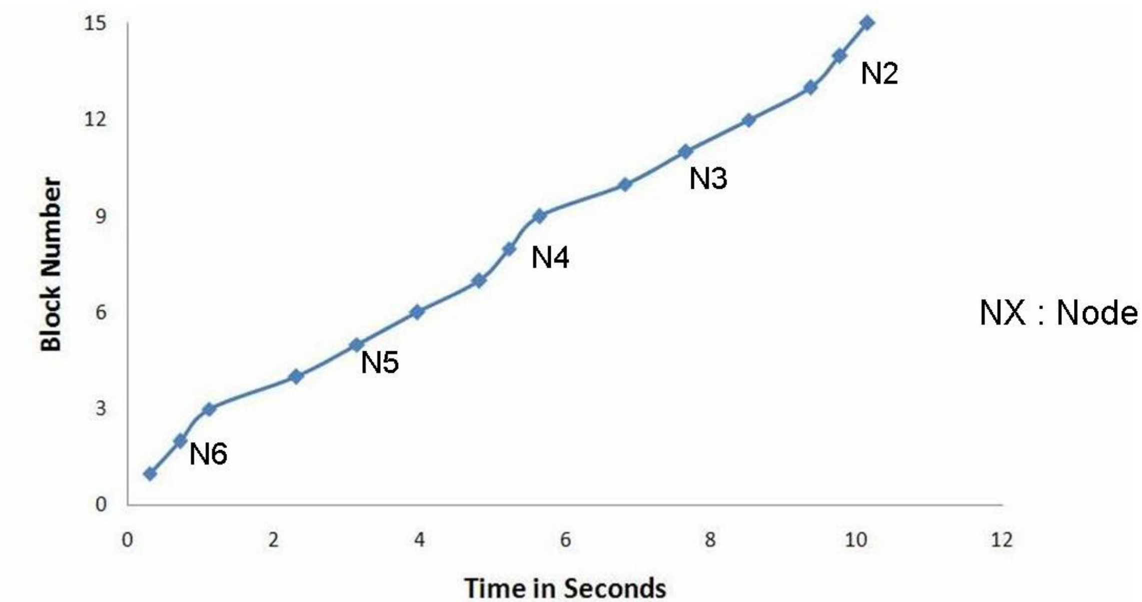


Performance for Different Data Sizes

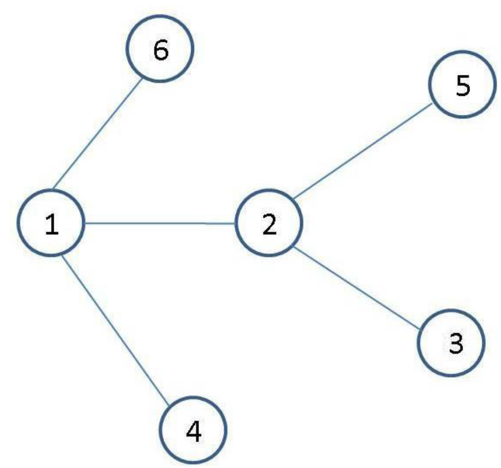
Single hop



Multi hop

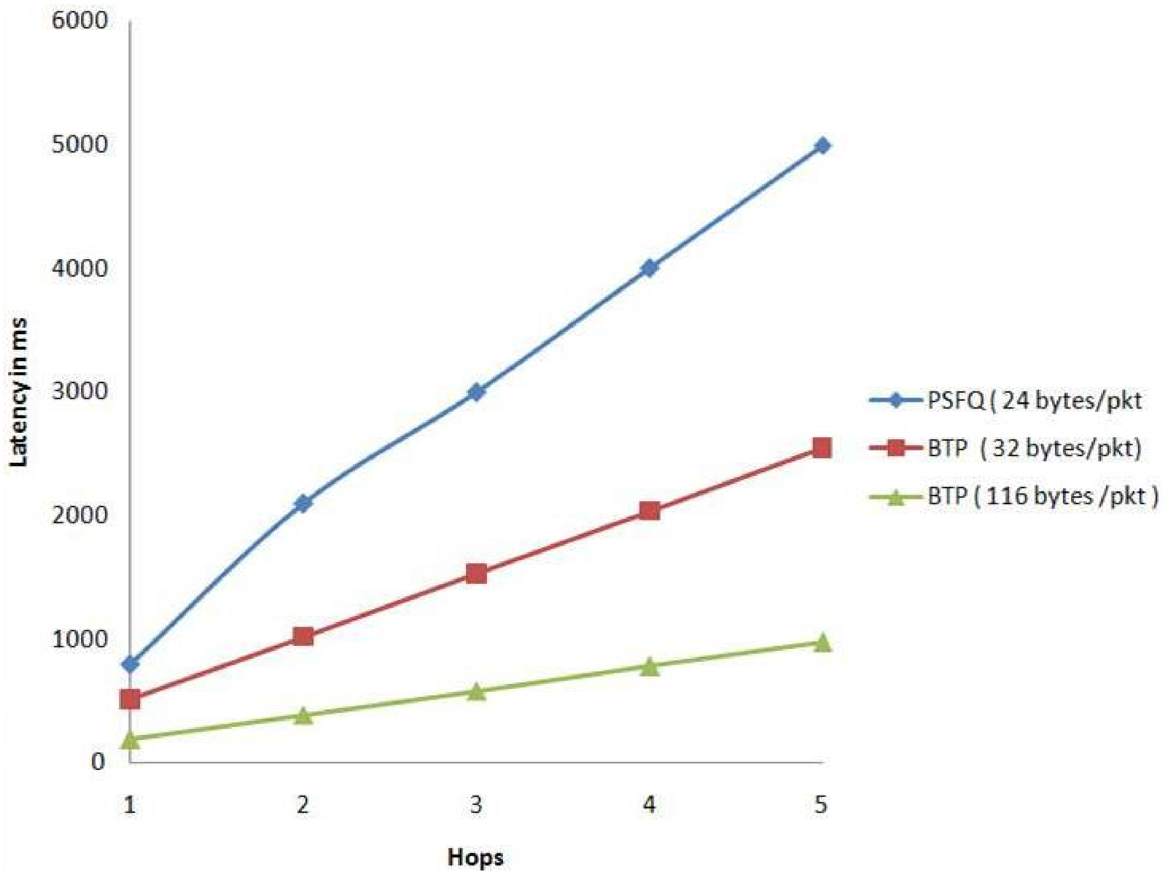


NX : Node X



Performance Comparison with PSFQ

- In PSFQ they could not achieve higher transmission rates at 0% error rates due to pump slowly paradigm of the protocol
- Beyond 10% error rates, they could not achieve completion of data transfer even in single hop case
- Due to inter-hop interference the performance of the protocol is very poor
- Minimum latency level they achieve is much higher than achievable in our protocol

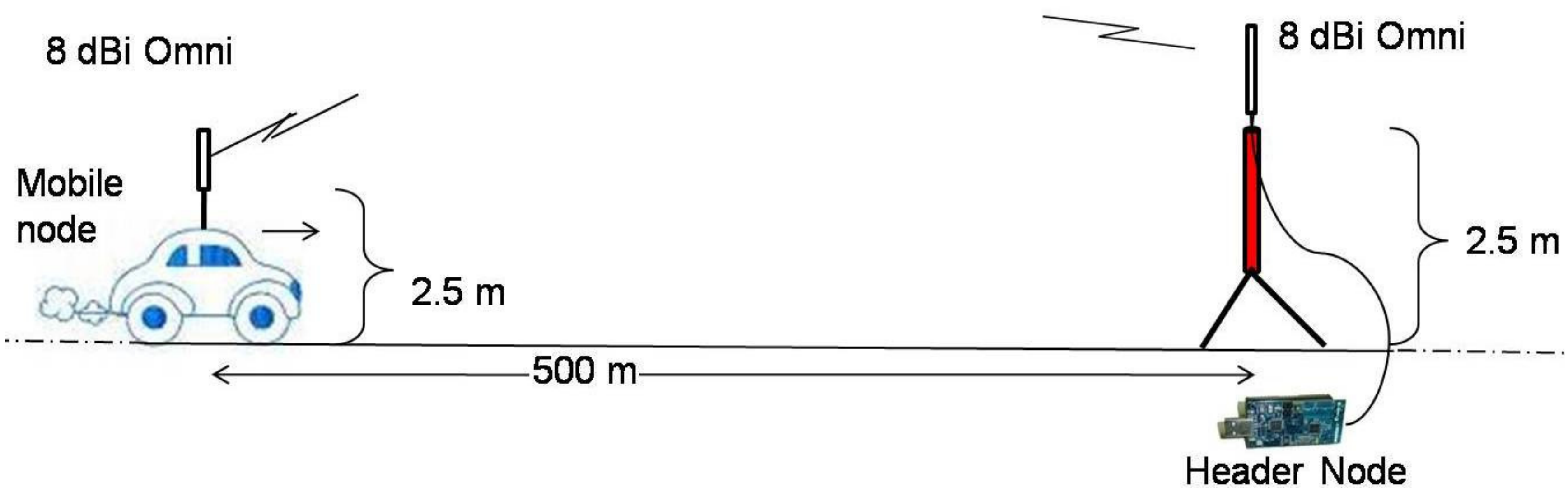


Mobile Data Transfer

Aim

- Aim was to see if we can reliably transfer the complete data to mobile node at different speeds in an outdoor environment
- If the data could be reliably uploaded to mobile node within minimum expected contact duration of 25 seconds for train speed of 72 Km/h

Experiment setup



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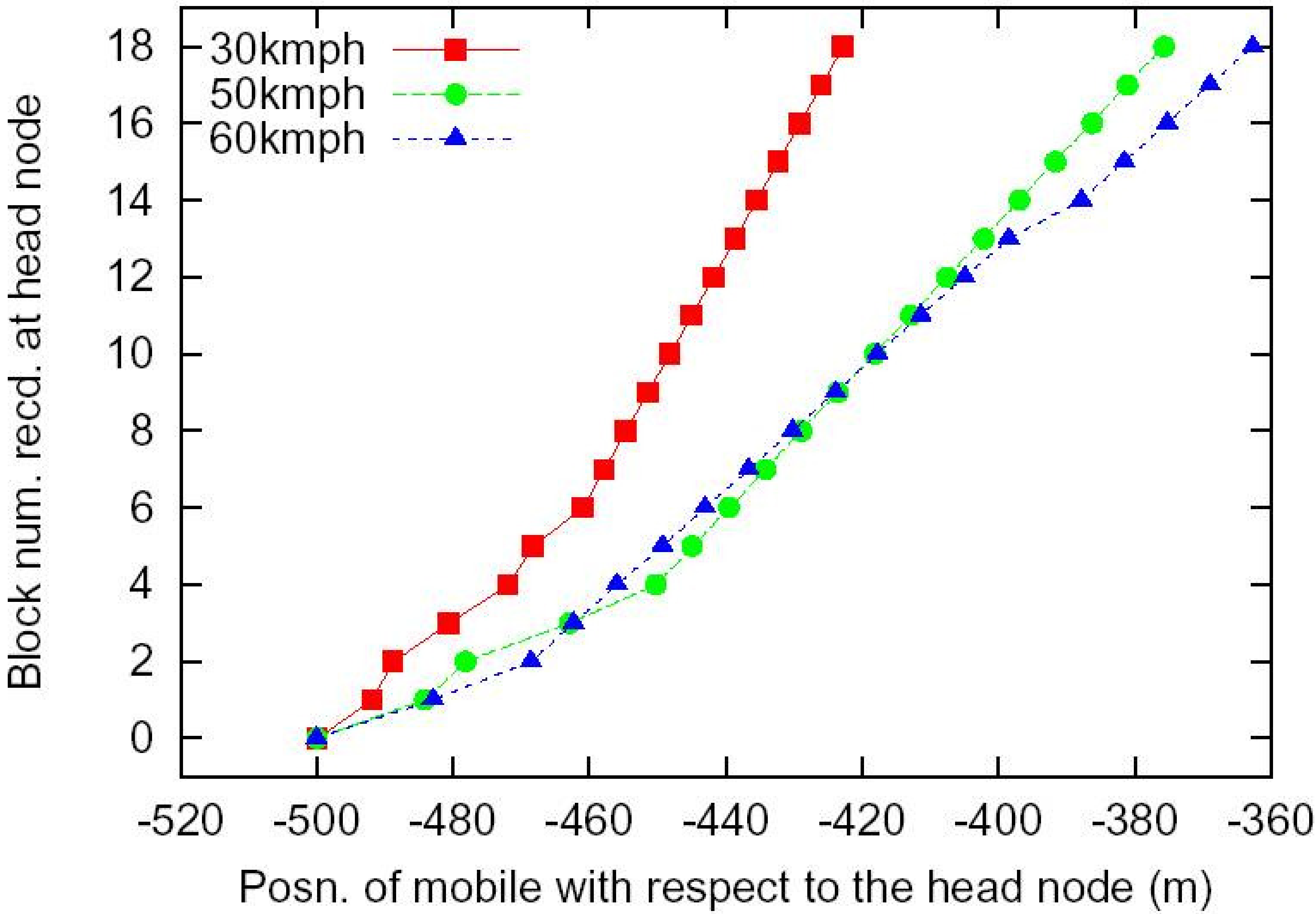
Mobile Data Transfer

Result

- The data is reliably transferred to mobile node irrespective of its speed
- The data is transferred much before minimum expected contact duration

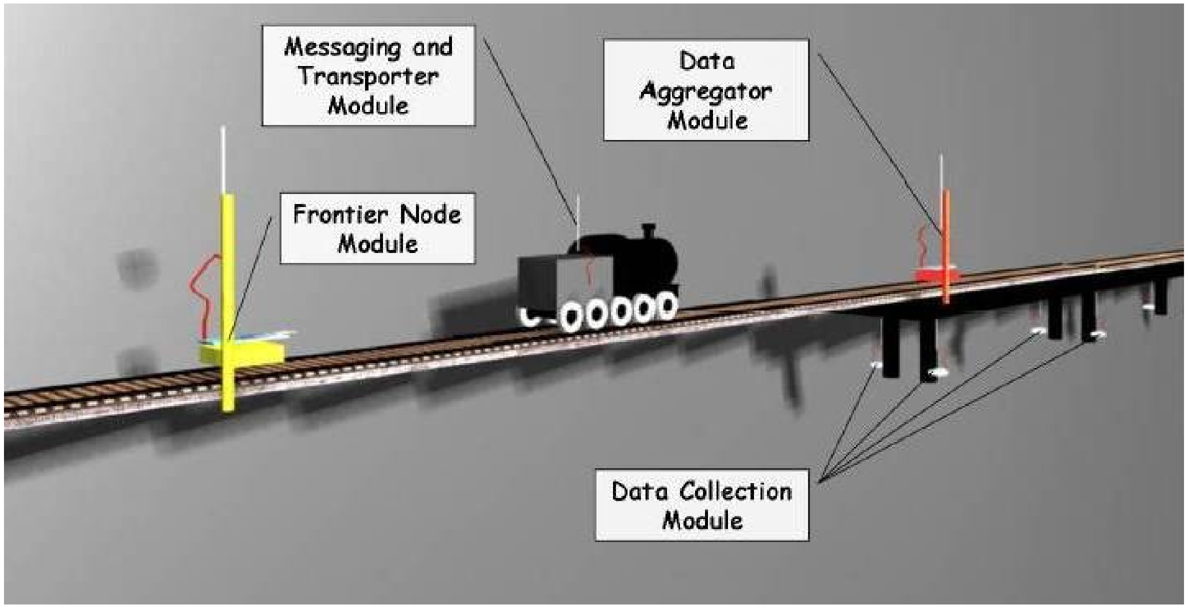


Past and Related Work

- Previous work on BriMon
- Related work

Previous Work on BriMon

Architecture



Differences between previous architecture and our design

- Platform used
- Complete bridge considered as one element
- Scaling
- Multiple channels
- Frontier nodes
- Power requirements

Takeaways

- Use same motes and accelerometers
- Same power switching circuits

Related Work

Application design

	Habitat Monitoring	WISDEN	Industrial Sensor Network	Volcano Monitoring	BriMon
Deployment Duration	Long Term (6 Months)	Short term	Few Months (2 Months)	Few Weeks (3 Weeks)	Long Term
Architecture	Tiered	Flat	Tiered	Tiered	Flat
Platform	Mica2	Mica2 and Micaz	Micaz and Imotes	Tmotes	Tmotes
Sensors Used	Temperature, Pressure& Humidity	Accelero-meters	Accelero-meters	Seismo-acoustic sensors	Accelero-meters
Data Collection Model	Periodic	Continuous	Periodic	Continuous and Event based	Event based
Mobile Data Transfer	No	No	No	No	Yes
Multi-channel Data Transfer	No	No	No	No	Yes
On Mote Computing	Raw data collection	Raw data collection	Raw data collection	Event detection	Raw data collection, averaging & compaction
Compression	Yes	Yes	No	No	Partial*

*10 point averaging and compaction

Related Work

Transport protocols

Attribute	CODA	ESRT	RMST	PSFQ	GARUDA	SenTCP	BTP
Direction	Upstream	Upstream	Upstream	Downstream	Downstream	Upstream	Upstream
Reliability	No	Yes*	Yes	Yes	Yes	No	Yes

Conceptual differences between BTP and PSFQ

- PSFQ basically designed for downstream data transfer
- PSFQ follow pump slowly paradigm whereas BTP follows pump quickly paradigm
- PSFQ suffers from inter hop interference where as in BTP there is minimal or no inter hop interference

Conclusion and Future Scope for Work

Conclusion

- India has 127000 railway bridges out of 40% are over 100 years old. It is critical to monitor the structural health of these bridges
- The system we develop is easily deployable, and requires minimum maintenance
- The protocols and tools we develop though are application specific can be used for other similar kind of applications in sensor network domain

Future scope for work

- Start time of data acquisition, by all nodes synchronized but end time of data acquisition need to be synchronized
- Use separate ADC card for data acquisition from more than one axes at the same time
- Implementation of LZW compression to further reduce the amount of data that need to be transferred.

Questions

Thank you !!