Voice Over Sensor Networks

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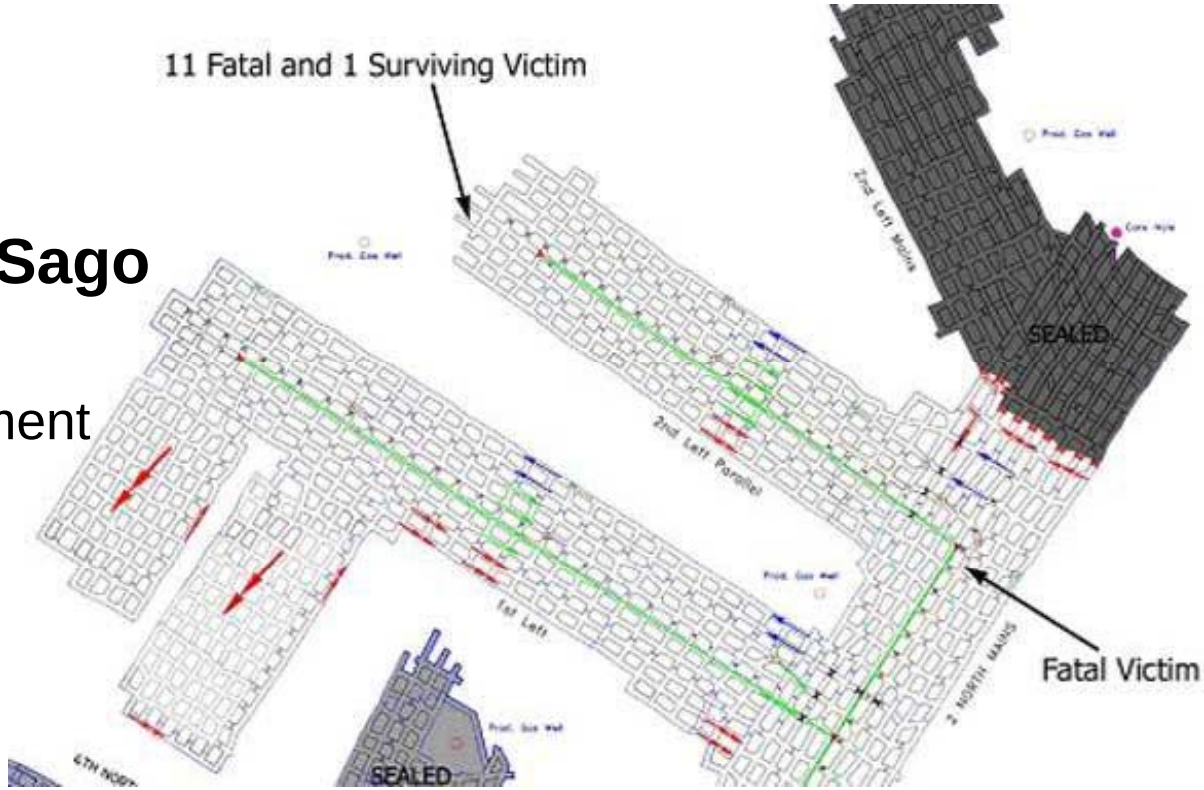
Outline

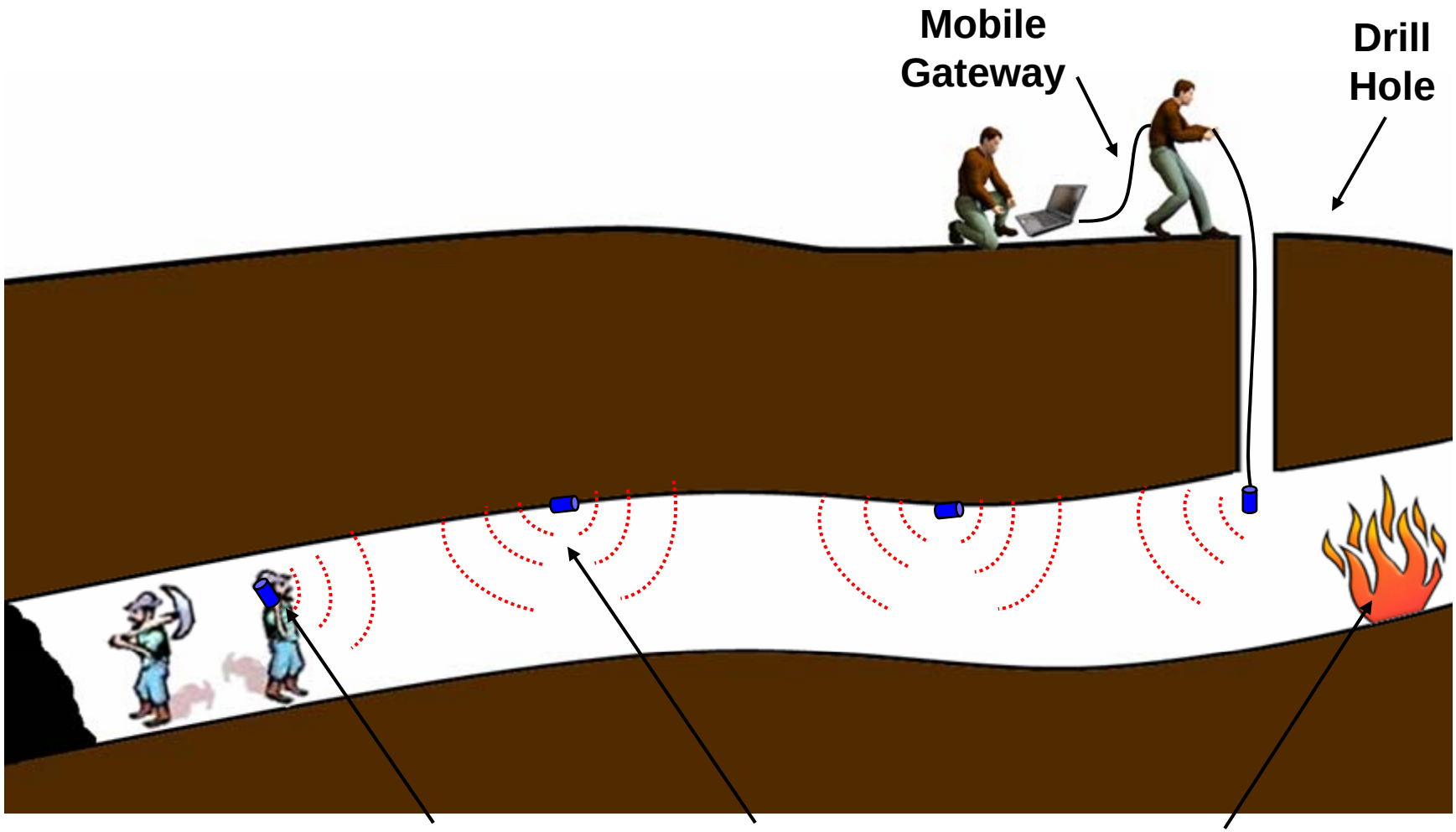
- Motivation
  - Coal Mining Application
- FireFly Sensor Networking Platform
- Network Scheduling
- Voice Performance

Coal Mining Disasters

- **Sago Mine**
  - January 2, 2006
  - Explosion
  - 12 Dead, 1 Injured
- **29 Accidents Since Sago**
  - 34 Deaths (U.S.A.)
  - Collapse, Fire, Equipment Failure

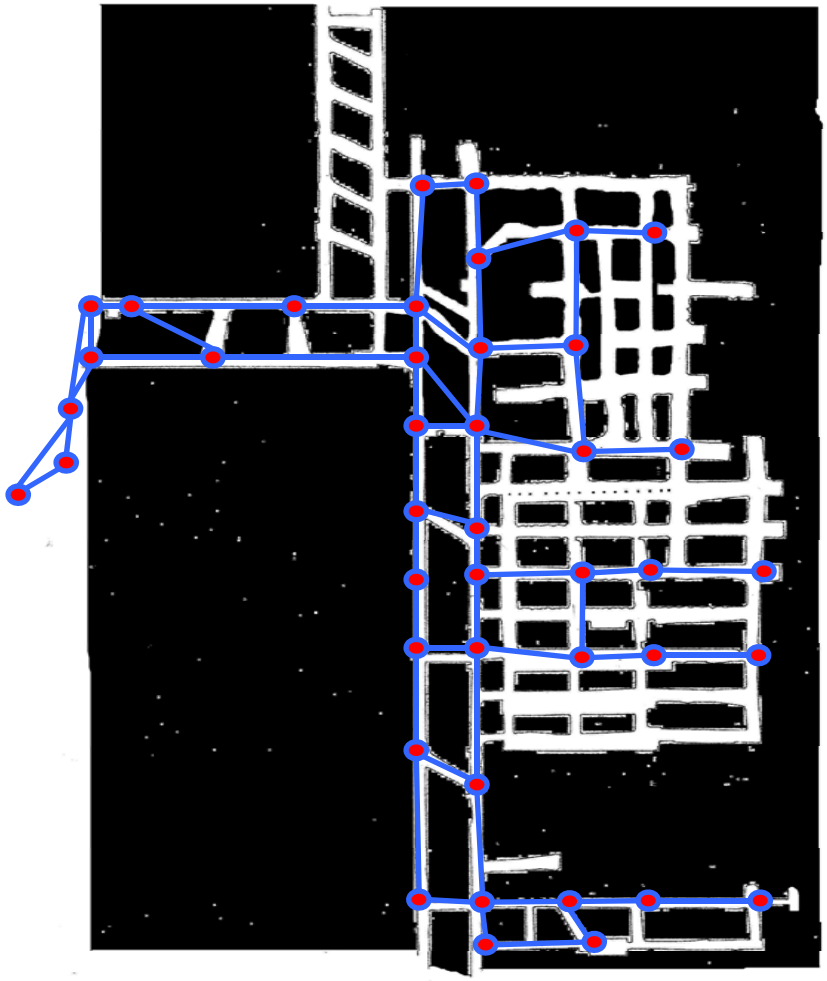


How Can a Sensor Network Help?



NIOSH Research Coal Mine

near Pittsburgh



NIOSH: National Institute for Occupational Safety and Health

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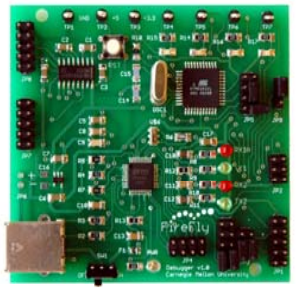
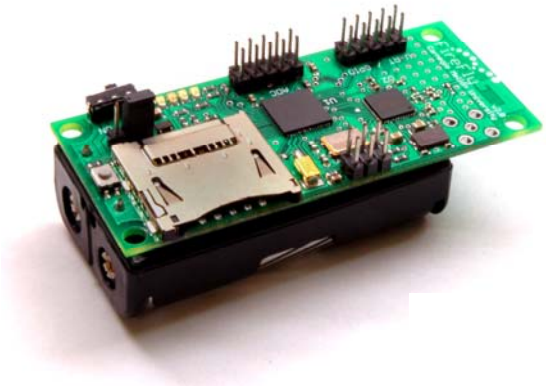
FireFly
Sensor Networks



Development Interface

Energy Harvesting

Vision Sensor



FireFly 2.0 Node

eWatch

Time Synchronization

Various Sensors

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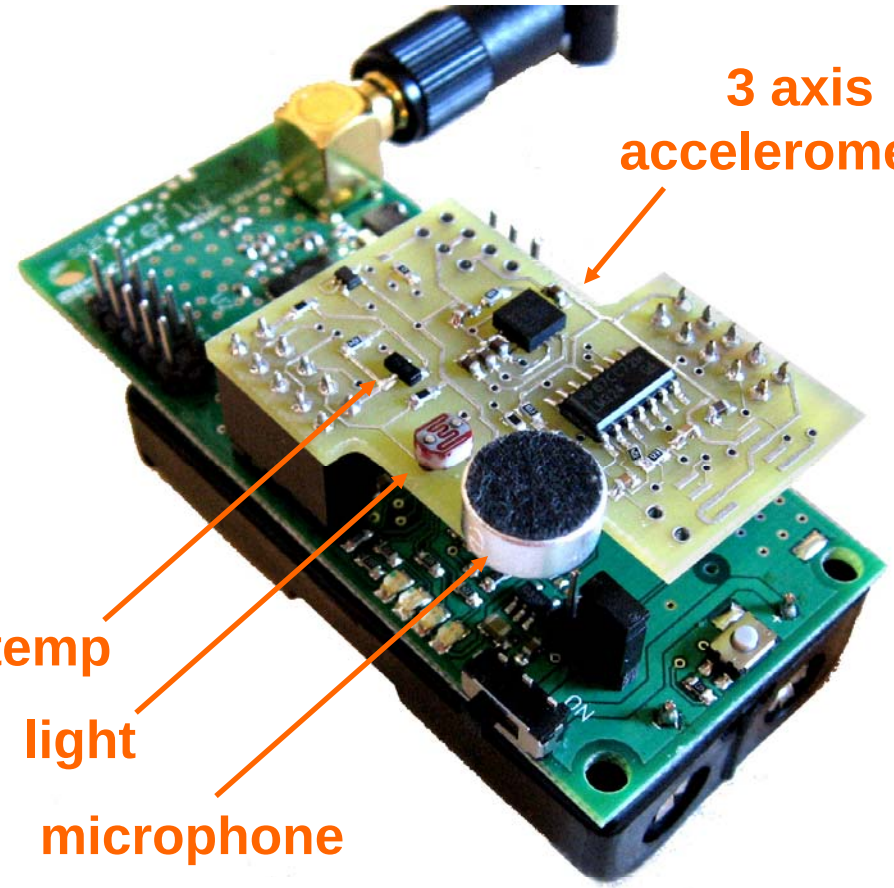
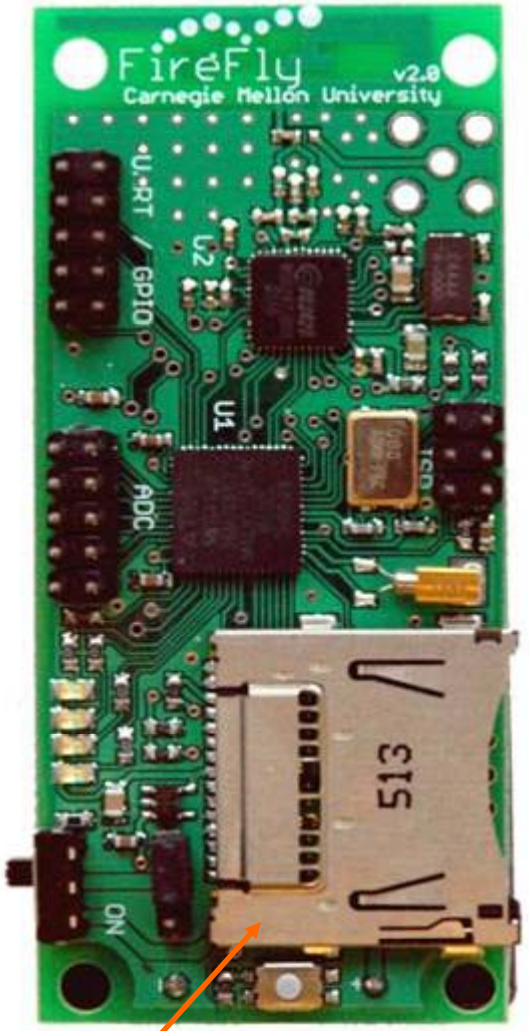
FireFly 2.0 Audio Node





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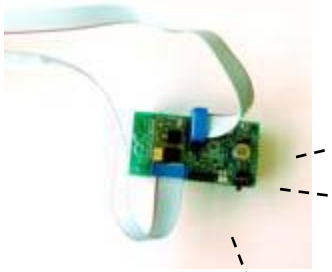
FireFly Network Architecture

Base Station

USB

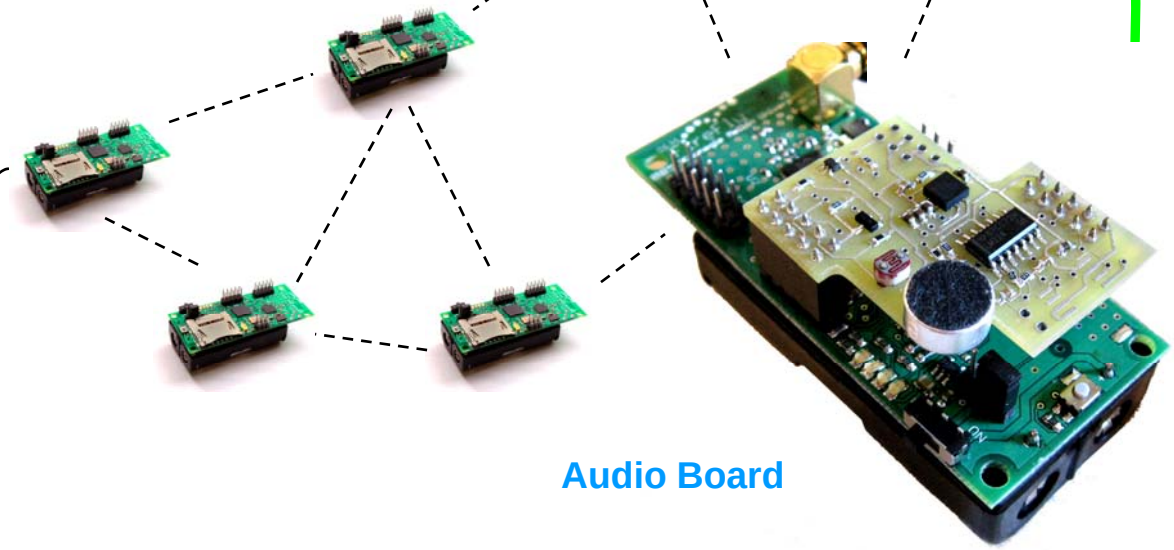
Gateway

Global Time Beacon



Speakers

Mobile Packet Sniffer



Audio Board

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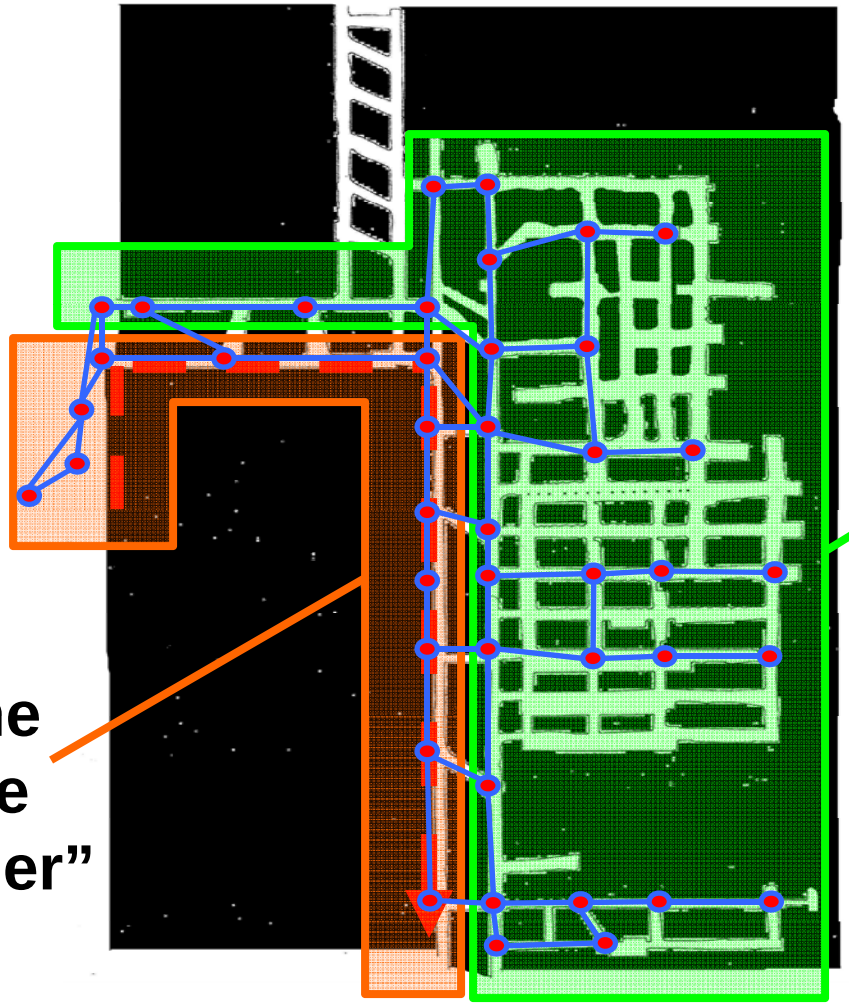
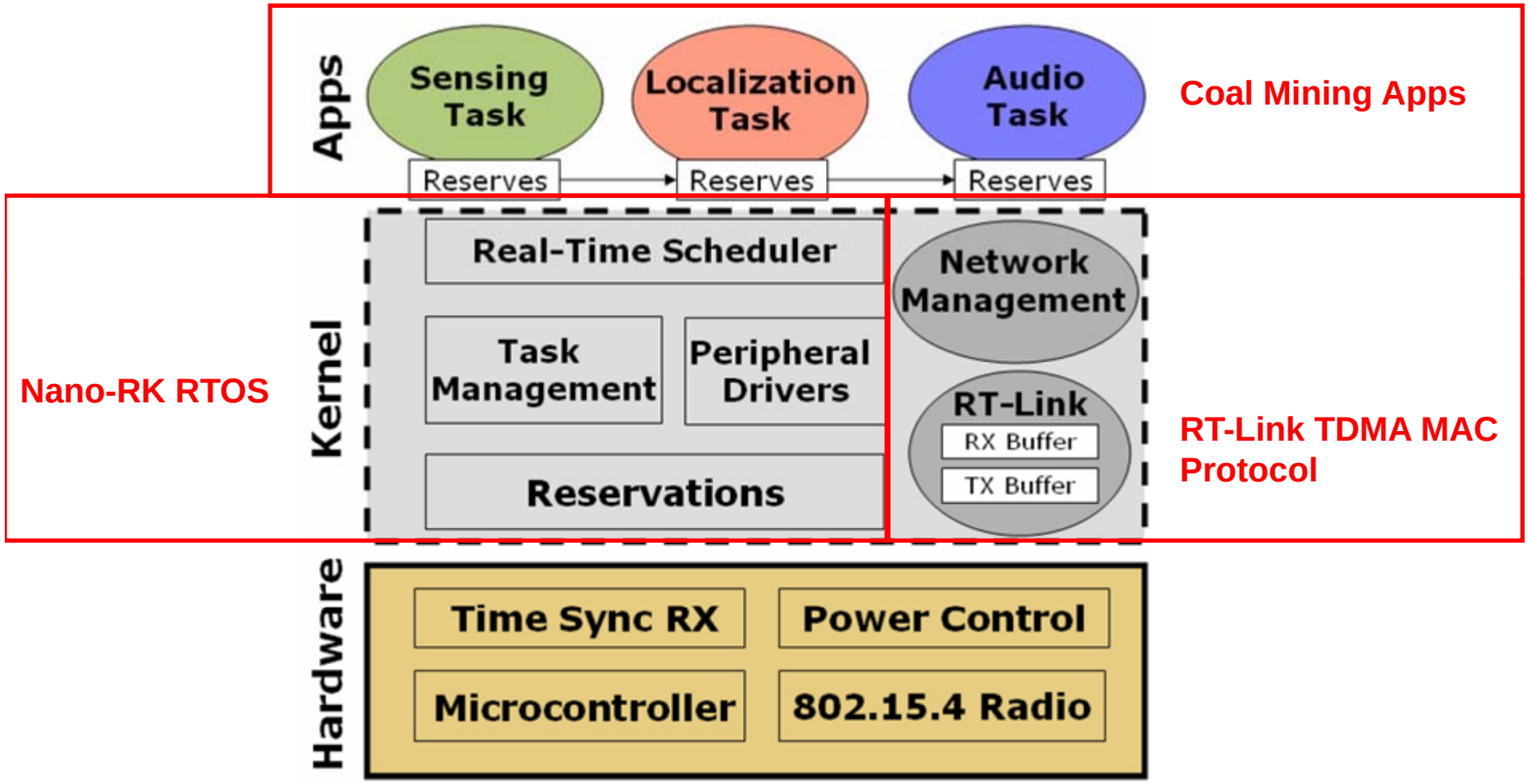
NIOSH Research Coal Mine



In-Band Time Synchronization

Global Time Sync Pulse "Leaky Feeder"

Software Architecture



RK: Resource Kernel

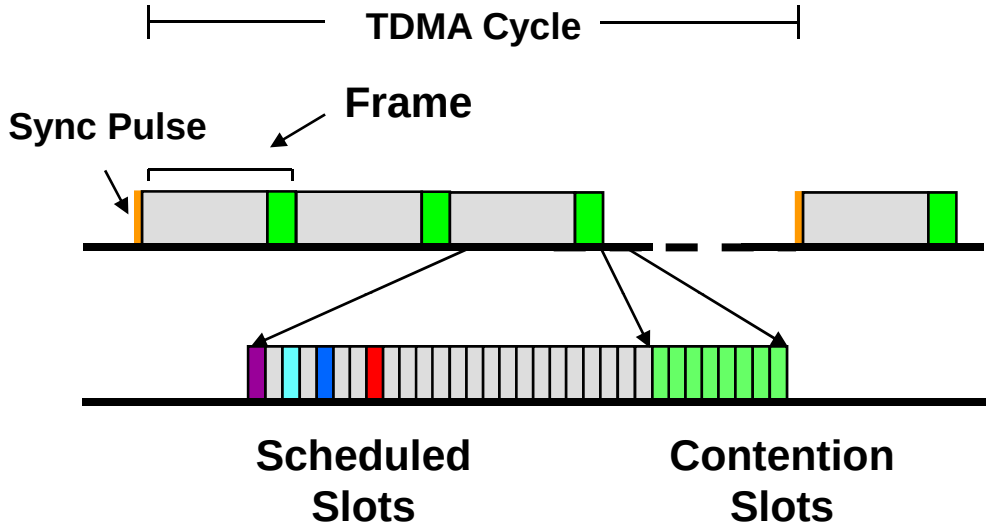
Nano-RK RTOS

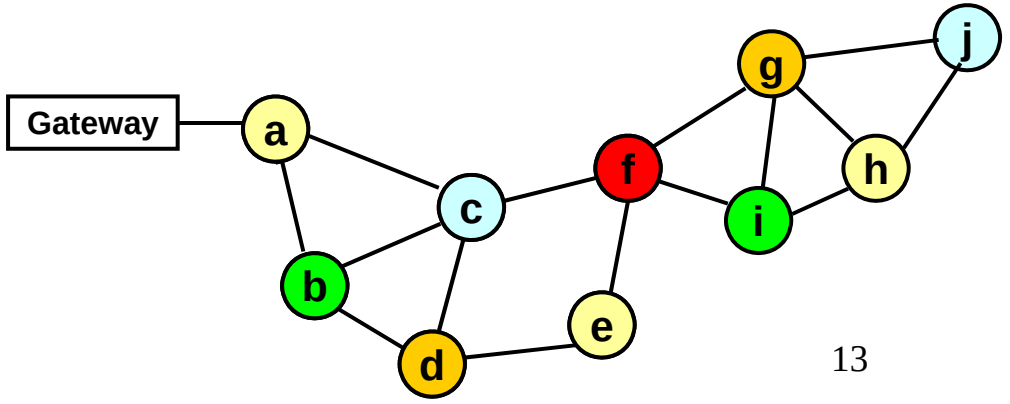
- **Real-Time Preemptive Multitasking**
  - Priority-driven: mapped from reservations
  - Interleaved processing and Communications
- **Resource Reservations ("Resource Kernel") per task**
  - CPU cycles, Network packets, Sensor / Actuator accesses

  → Virtual Energy Reservation (aggregated across components)
- **Energy-Efficient Time Management**
  - TDMA: go to sleep whenever possible (predictable and analyzable)
  - POSIX Style time Representation
  - Variable Tick Timer enables waking up only when necessary
- **Fault Handling**
  - Canary Stack Check, Reserve Violation, Unexpected Restarts, Low Voltage

RT-Link TDMA Link Layer

- **Fine-Grained Global Time Synchronization**
- **Collision-Free Energy-Efficient Communication**





Coal Mining Applications

- **Periodic Sensing Task**
  - **Every TDMA cycle (~6 seconds) sensor values are sent**
- **Location Task**
  - **Infrastructure Nodes Report List of Mobile Nodes in Range**
  - **RSSI values available if finer grained location required**
- **Audio Task**
  - **Sample Audio every 250μs (Nano-RK Driver)**
  - **ADPCM Compress Buffer (45μs per byte)**

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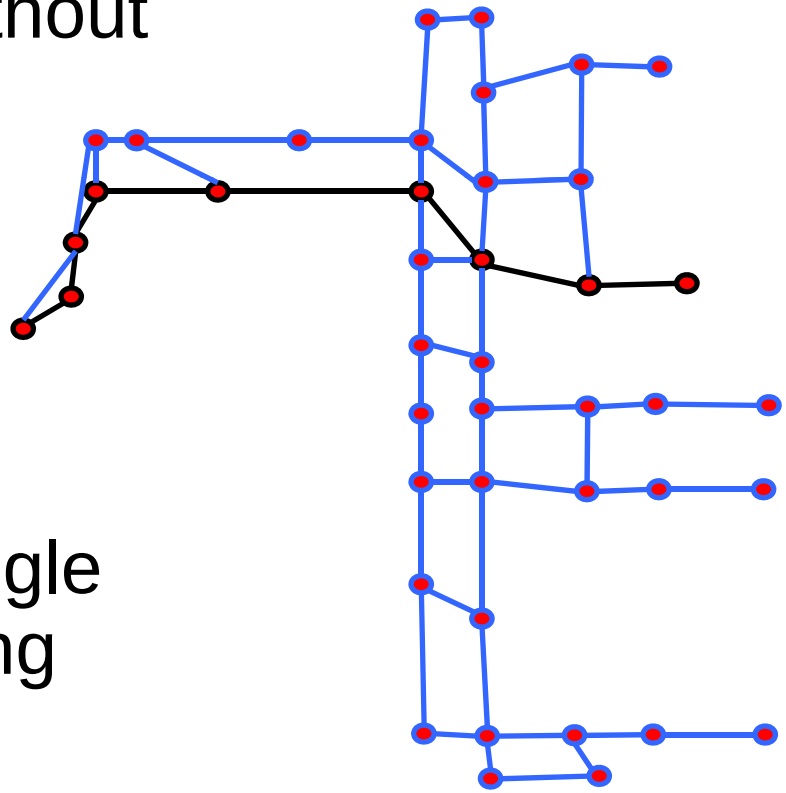
- Voice Performance

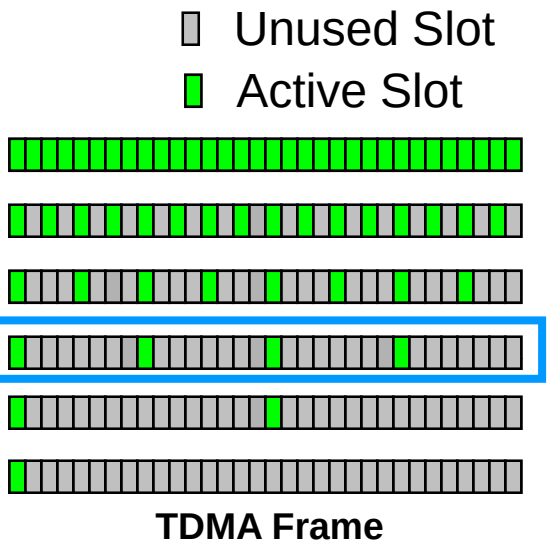
Voice Scheduling Challenges

- Schedule Voice Along With Lower-Rate Sensor Data without Interference
- Balance Upstream / Downstream Voice Latency
- On-Demand Gateway to Single Mobile Node Voice Streaming



RT-Link Multi-Rate Support

Rate Index	Slot Interval	Max. Goodput (kbps)
0	-	0
1	1	149.3
2	2	74.6
3	4	37.3
4	8	18.6
5	16	9.3
6	32	4.6



RT-Link Rate	Raw 32Kbps	ADPCM-1 16Kbps	GSM-1 13Kbps	ADPCM-2 12Kbps	ADPCM-3 8Kbps	GSM-2 7Kbps	Avg. Hop Delay	Packet Redundancy
1	4	9	11	12	18	21	6ms	Single
2	2	4	5	6	9	10	12ms	Single
3	1	2	2	3	4	5	24ms	Single
4	1	2	2	2	4	4	24ms	Double
5	0	0	0	0	4	4	48ms	Double

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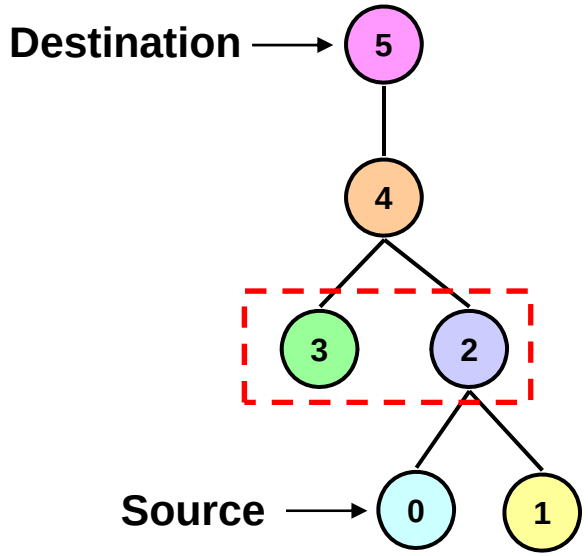
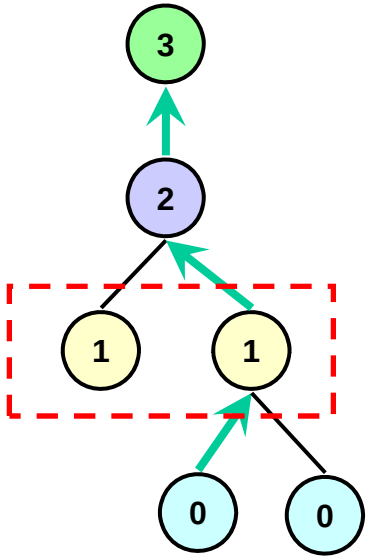
Voice Codecs: Concurrent Streaming

Point-to-Gateway Scheduling



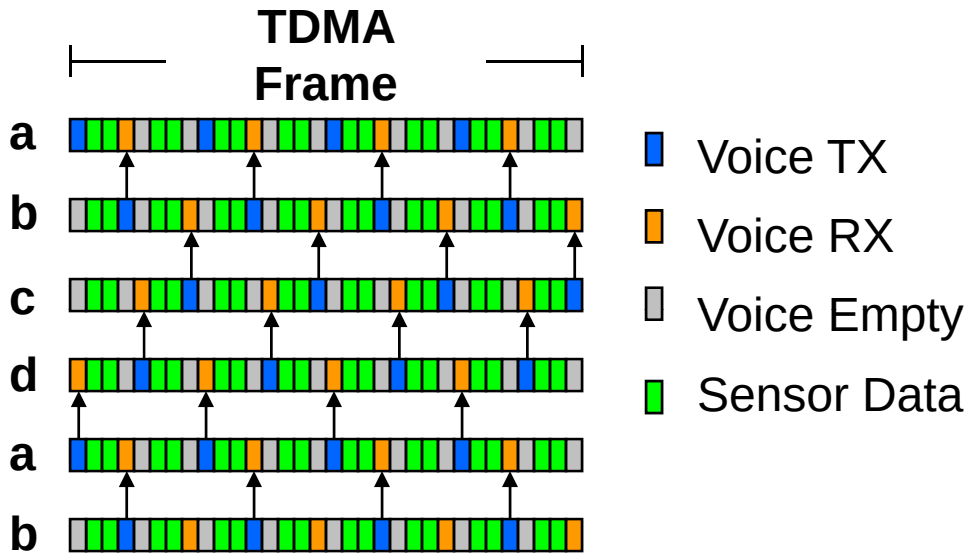
Typical D-2 Coloring (Tree)



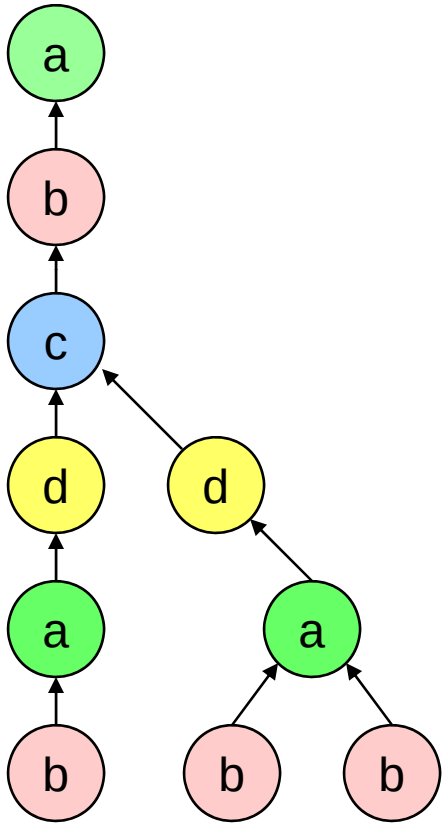
Simplified Voice Schedule (Equivalent to a Chain)

- Schedule to Support a Single Flow to the Gateway
- Nodes at Each Depth Can Share Slots for a Single 2-way Voice Stream in the System

Share Slots With Lower-Rate Data



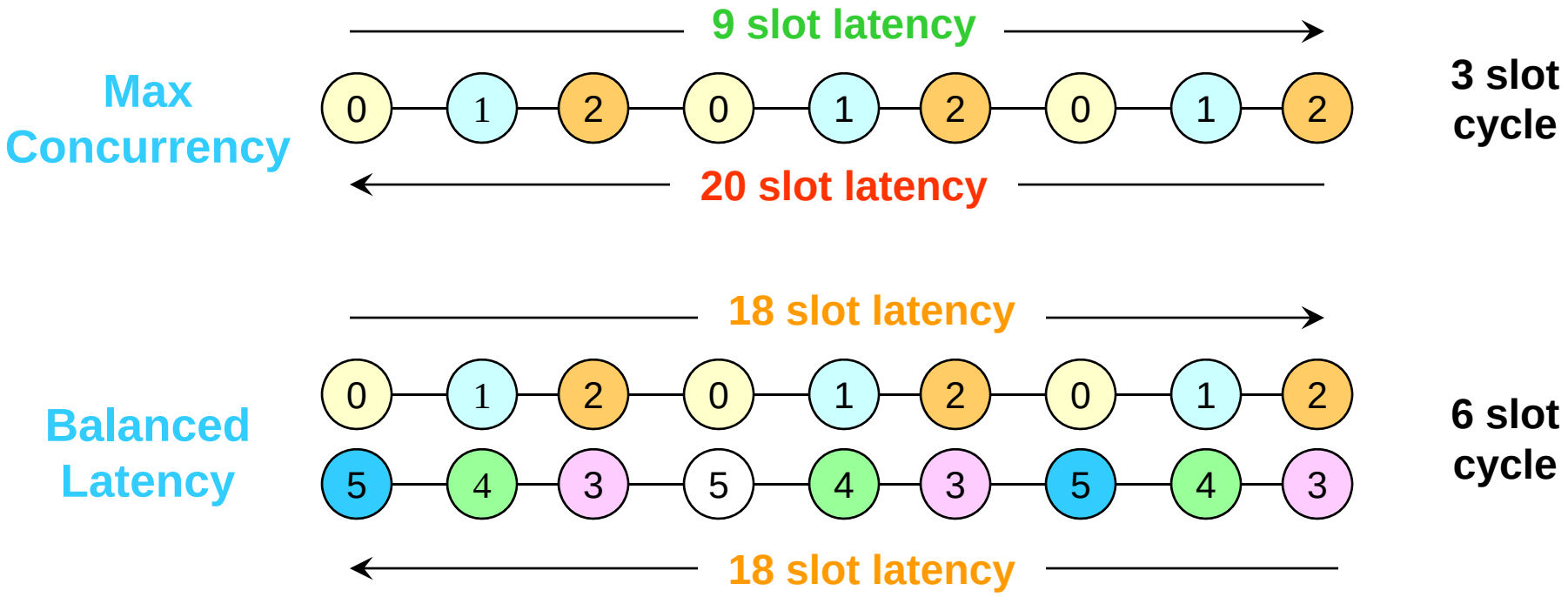
	TX Slots	RX Slots
a	0, 8, 16, 24	3, 11, 19, 27
b	3, 11, 19, 27	7, 15, 23, 31
c	7, 15, 23, 31	4, 12, 20, 28
d	4, 12, 20, 28	0, 8, 16, 24



Example Topology

Balanced Latency

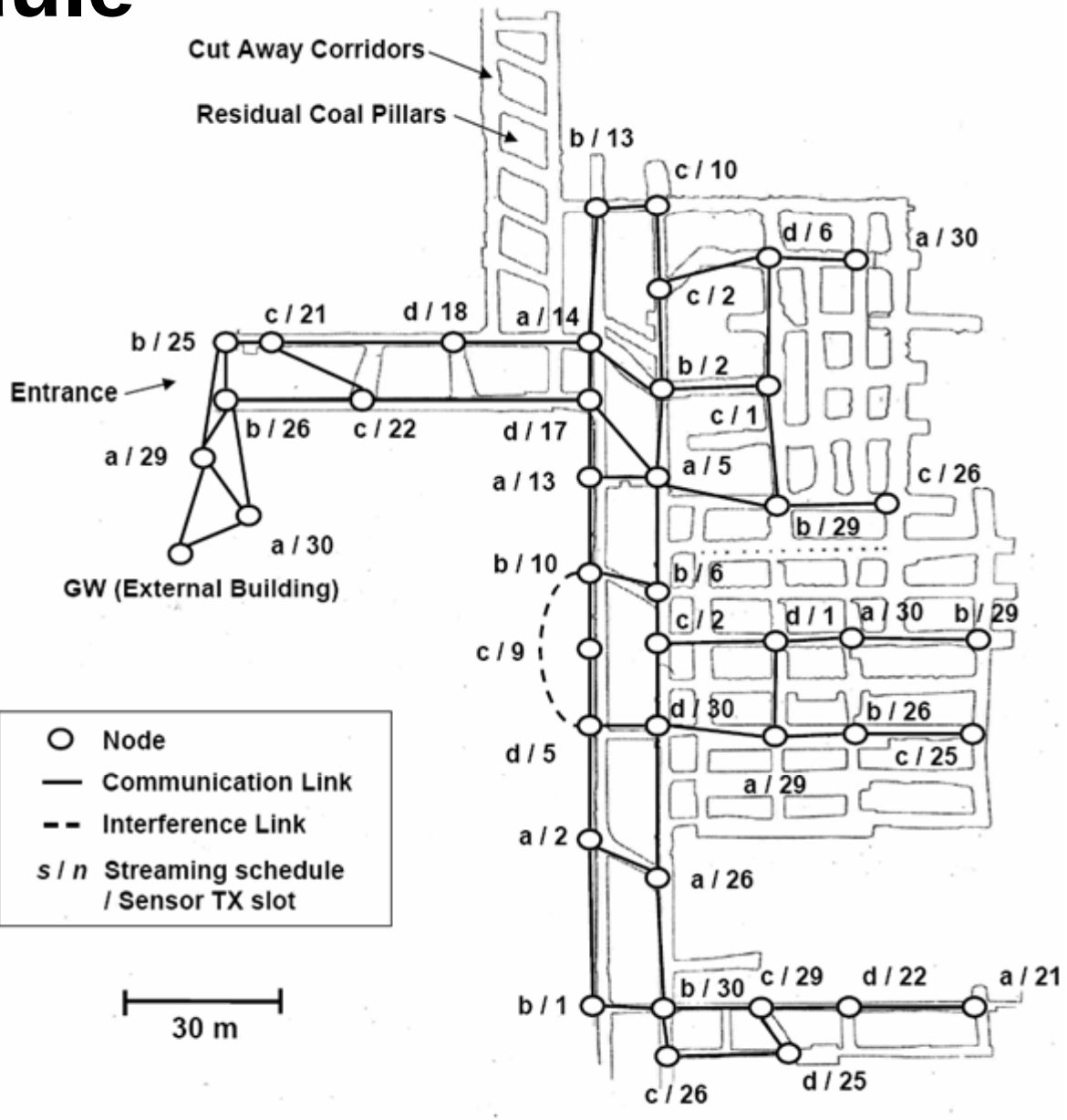
- Minimum Delay and Balanced Latency is more important than Maximizing Concurrency



Example Schedule

- Schedule Applied to NIOSH Experimental Coal Mine Topology

	TX Slots	RX Slots
a	0, 8, 16, 24	3, 11, 19, 27
b	3, 11, 19, 27	7, 15, 23, 31
c	7, 15, 23, 31	4, 12, 20, 28
d	4, 12, 20, 28	0, 8, 16, 24



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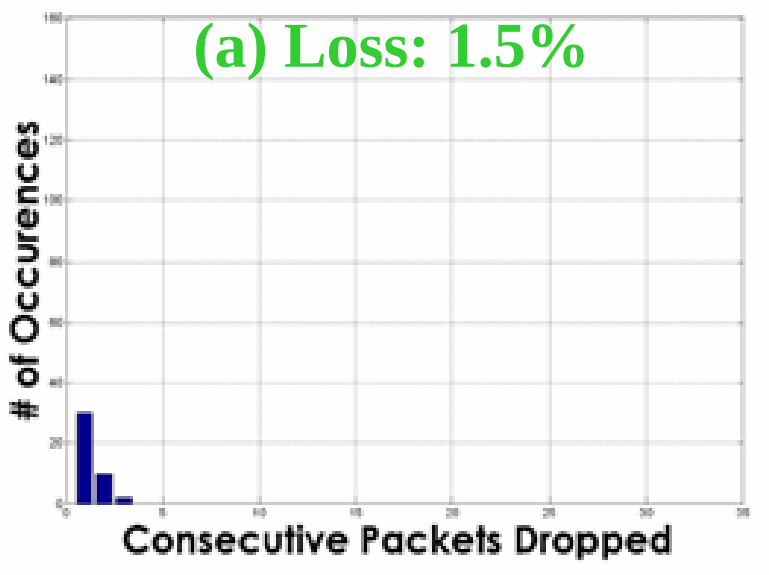
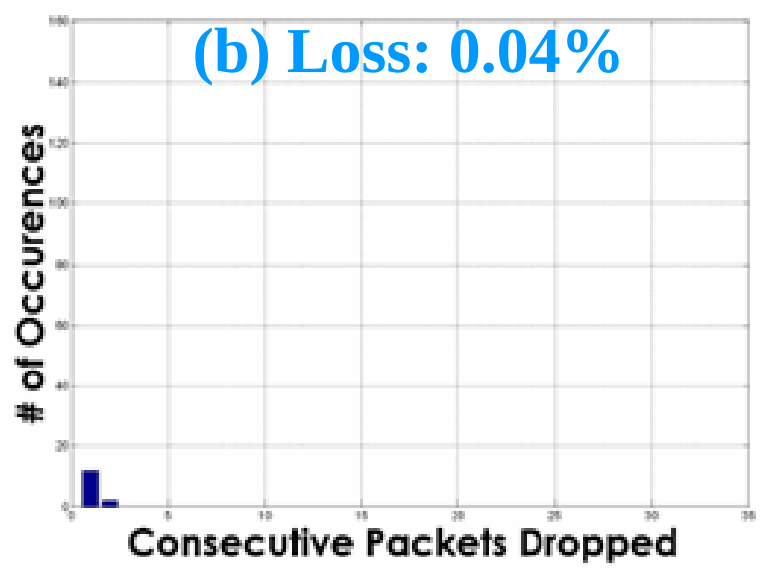
4KHz Compression Samples

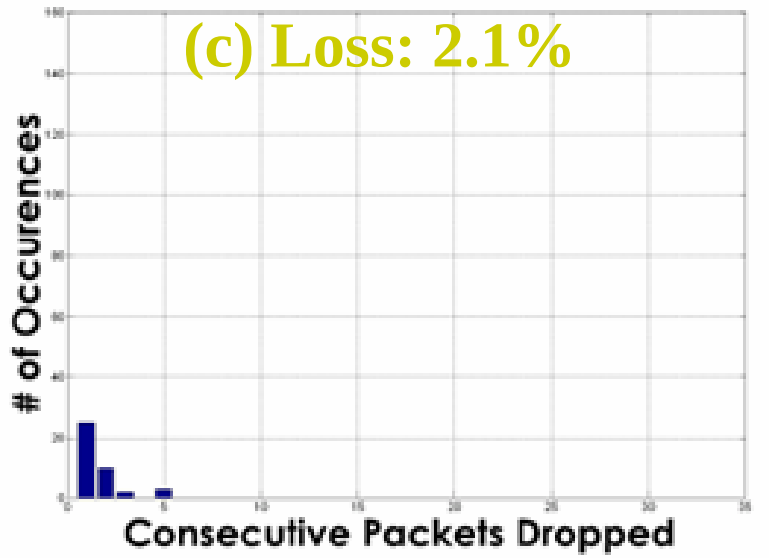
Gender	Compression	Data Rate	Clip
Male	Raw	32 Kbps	
Male	ADPCM 4bit	16 Kbps	
Male	ADPCM 2bit	8 Kbps	
Female	Raw	32 Kbps	
Female	ADPCM 4bit	16 Kbps	
Female	ADPCM 2bit	8 Kbps	

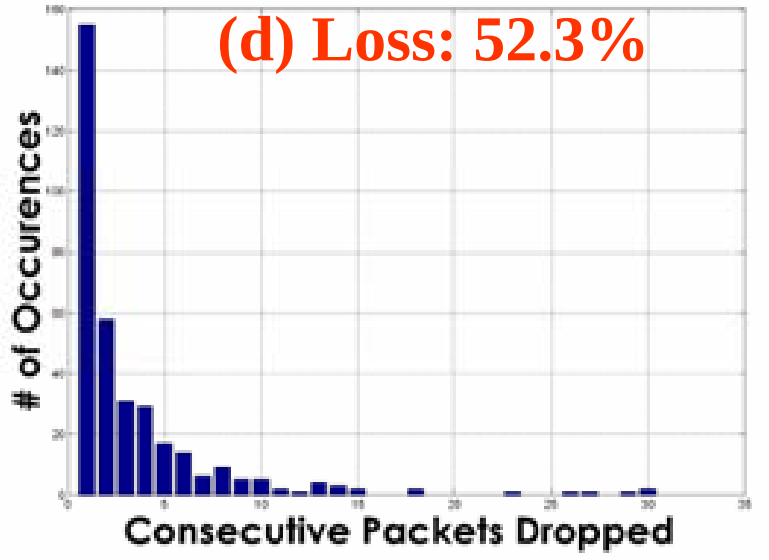
“I’d like to wear a rainbow everyday and tell the world that everything is OK…”

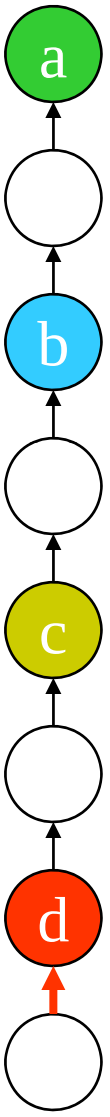
Packet Loss Distributions



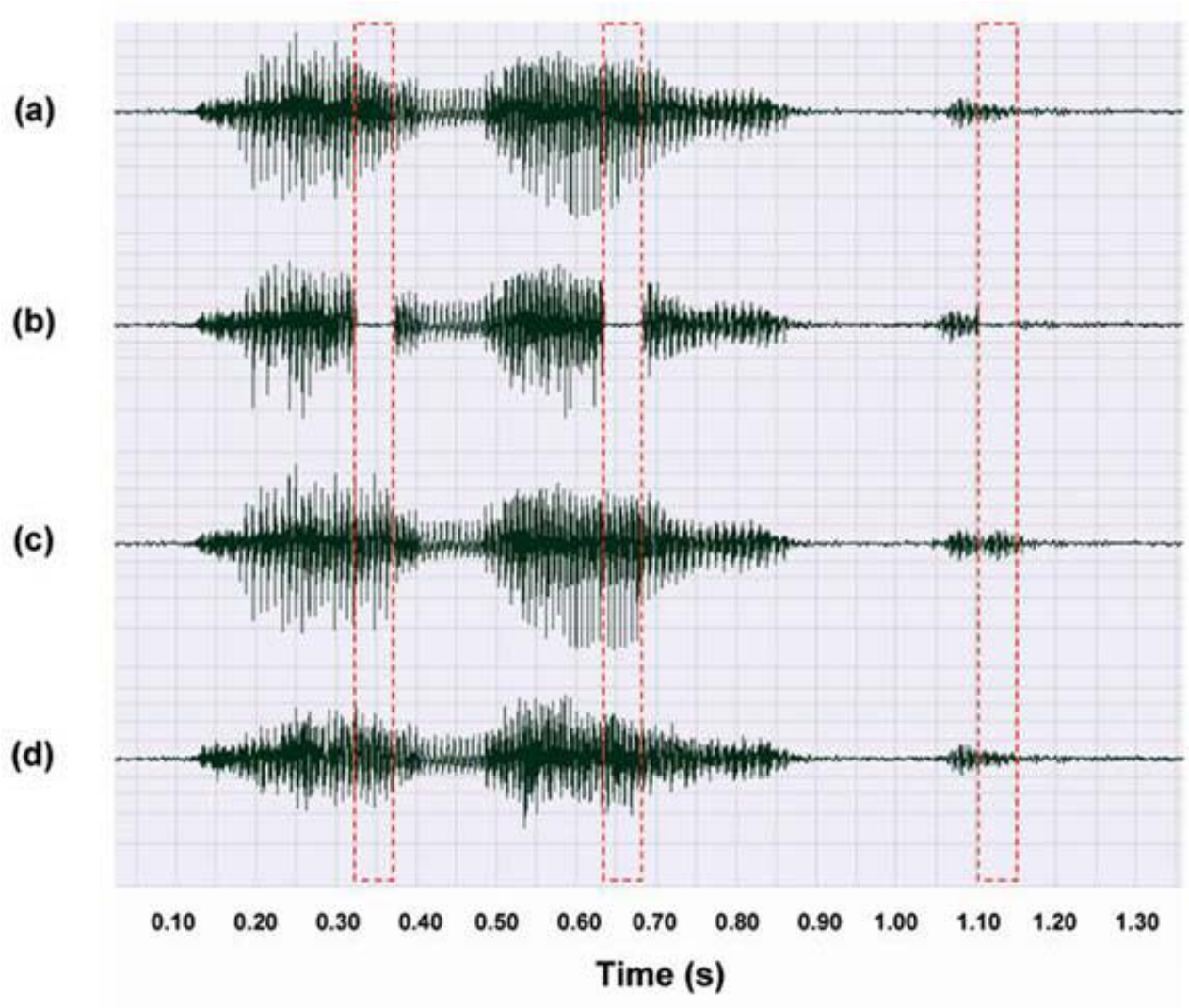








Error Concealment



2:1 ADPCM (4 bit)
Error-free voice sample

2:1 ADPCM (4 bit)
25% Packet error

2:1 ADPCM (4 bit)
Replay last packet

4:1 ADPCM (2 bit)
Transmit duplicate packets

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"I'd like to wear a rainbow everyday and tell the world that everything is OK…"

Power Consumption and Node Lifetime

Operation	Power	Time	Energy
4-bit ADPCM	21 *mW*	43 μs	903 *nJ*
2-bit ADPCM	21 *mW*	37 μs	777 *nJ*
ADC Sampling	21 *mW*	3 μs	6.3 *nJ*
RX Packet	59.1 *mW*	4 *ms*	236 μJ
TX Packet	52.1 *mW*	4 *ms*	208 μJ
Misc. CPU	21 *mW*	1 *ms*	21 μJ

Battery	Sensing	Streaming
2 x AA	1.45 years	16 days
2 x D	8.8* years	97 days
4 x D	17.6* years	194 days

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** longer than battery shelf-life*

Conclusions

- End-to-end voice-streaming for safety-critical operating environments
  - Demonstrated coal mine safety system
  - Use for real-time localization and audio communications
  - Extensible to include other communications
- Demonstrated Technique for Scheduling High-Rate On-Demand Communication Along With Low-Rate Periodic Data In Wireless Sensor Networks
  - Voice Streaming and Sensor Data in a TDMA WSN
- Evaluated Performance of End-to-End Voice Streaming For Low-Cost Wireless Sensor Nodes

Future Work: Deployment and Usability

Questions?