Optimization-based Design of Wireless Sensor Networks for Gas Monitoring Systems in Underground Mines

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Schedule

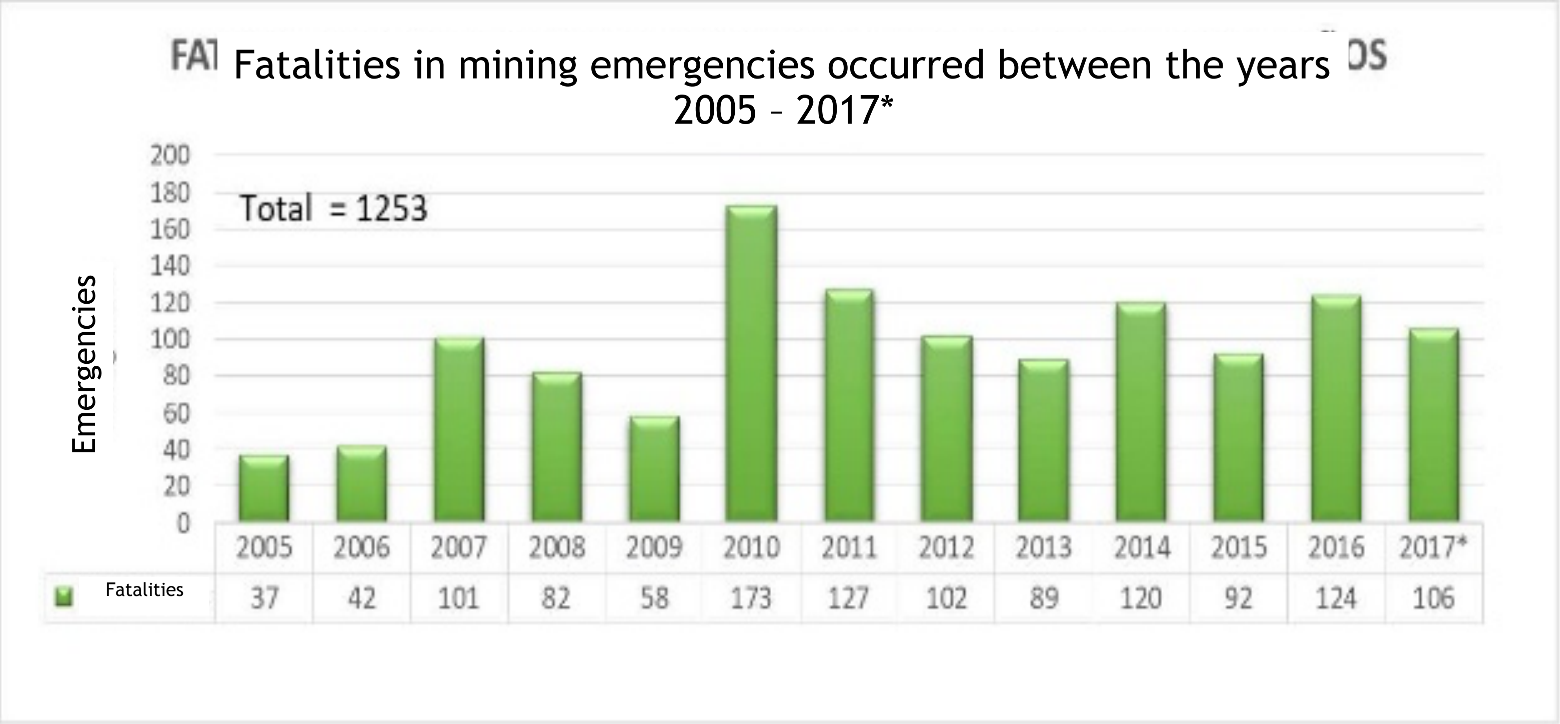
- Context
- Optimization strategy
- Results
- Conclusion and future work

Schedule

- Context
  - Problem statement
  - Research questions
  - Related work
- Optimization strategy
- Results
- Conclusion

Context

Coal is an important mineral in the Colombian economy



Context – WSN Challenges

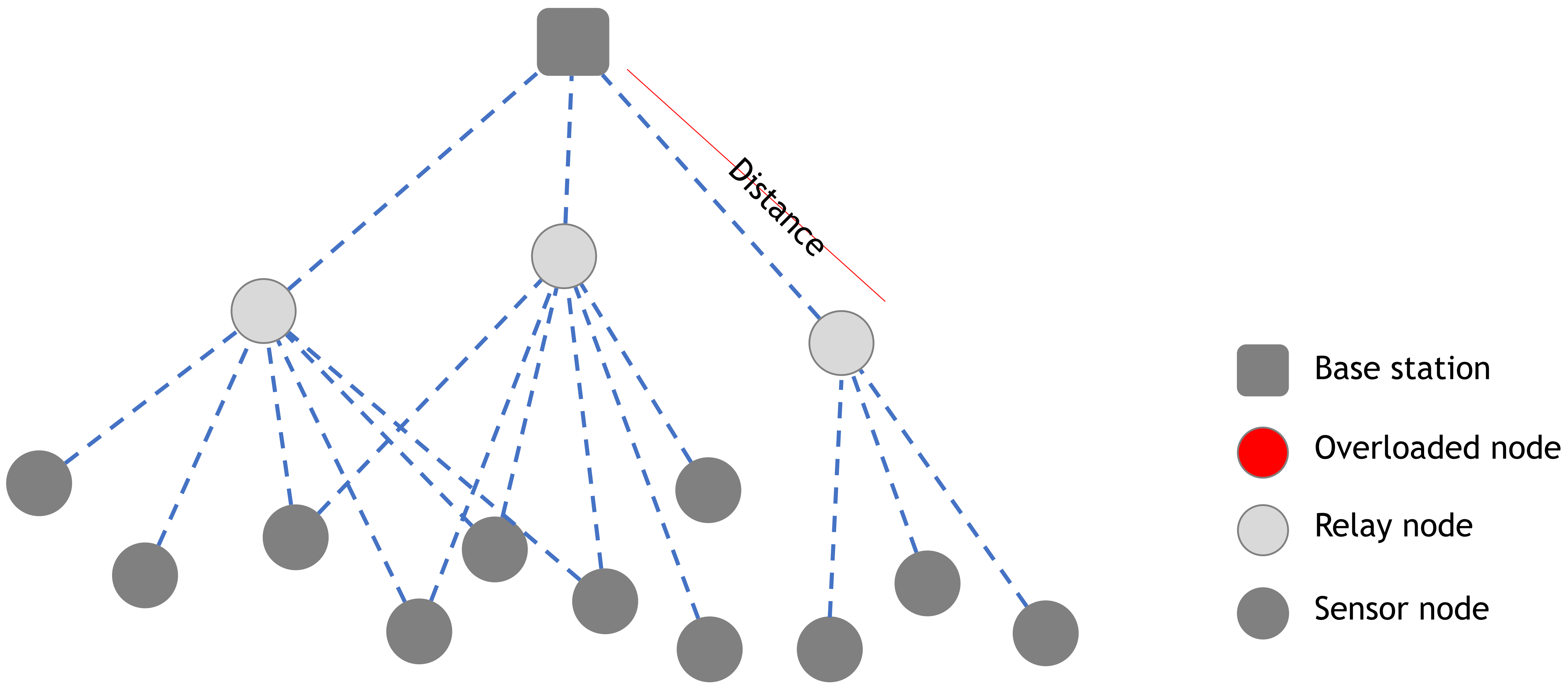
- Cost
  Cost of infrastructure (number of sensors and number of repeaters)

- Lifetime
  Operational time of the network during which it is able to perform the dedicated task(s)

- Coverage
  A measure of the coverage of physical space that sensors are able to observe.

- Data fidelity
  The ability for data to retain its granularity and meaning.

WSN – Energy consumption



Related Work

Research	Lifetim e	Cost	Coverag e	Context	Model	Simple / Heuristic
Jiang. [11]	X			Mining	A 2D tunel	Simple
Wang. [20]	X			Mining	A 2D tunel	Simple
Zhou. [30]			X	Mining	A 3D tunel	Simple
Ragaban. [17]	X			Other	--	Heuristic
Xu, K. [17]	X	X	X	Other	--	Simple
This Research	X	X	X	Mining	Whole mine	Simple

Research Questions

- How many nodes must be deployed to guarantee a given lifetime at minimum cost (and where should they be placed)?
- How much can the WSN lifetime be extended by optimizing the configuration of the previously specified number of nodes?

Optimization Methodology Overview

Stakeholder

lifetime

Optimization process

Stage 1

Min *Deployment Cost*

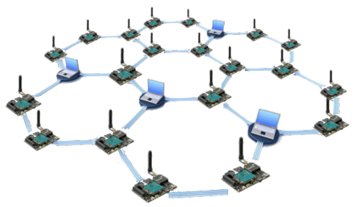
s. t. *Constraint 1*
Constraint 2
Constraint 3
lifetime

Number of nodes

Stage 2

Min *Energy consumption*

s. t. *Constraint 1*
Constraint 2
Constraint 3
Constraint 4
Number of nodes



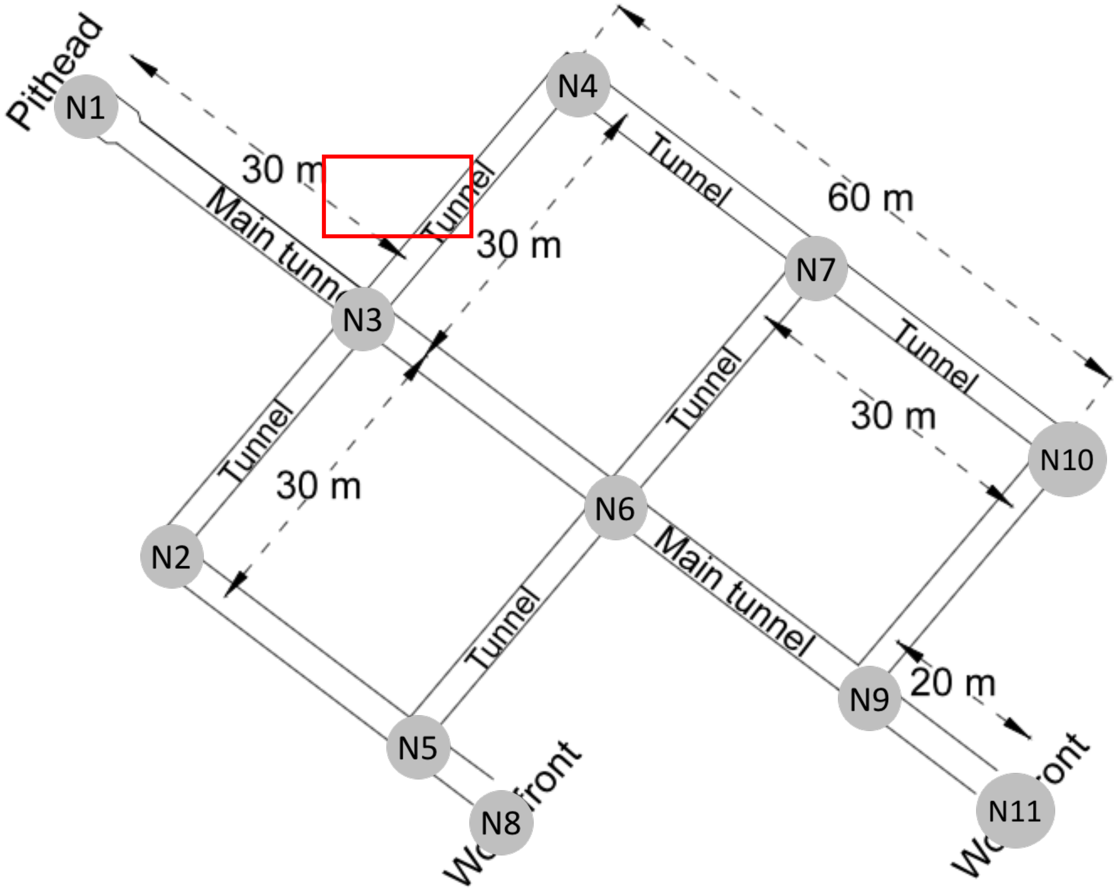
Configuration WSN

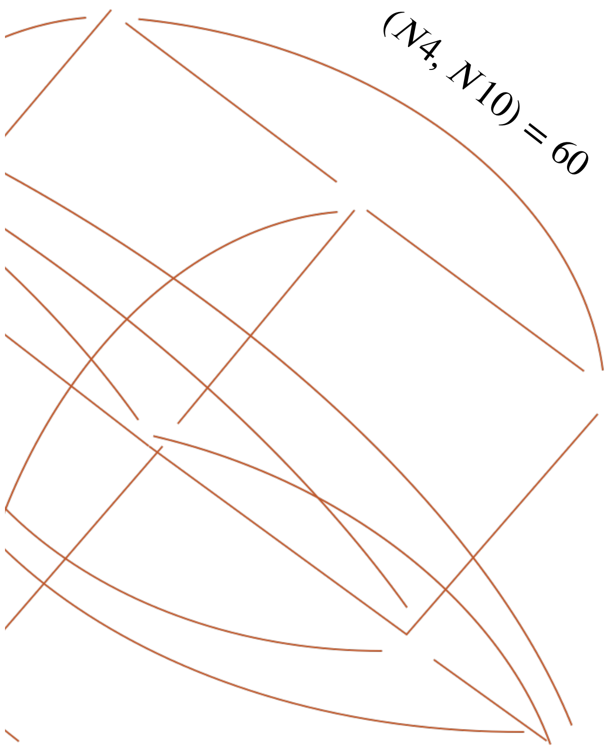
Schedule

✓Context

- Optimization strategy
  - Network representation
  - Decision variables
  - Mixed integer programming model
  - Implementation
- Results
- Conclusion

Network Representation





Layout of a small mine Graph-based representation

Decision Variables

Mixed Integer Programming Model

Objective Function

$$min \quad (1-\propto) * \sum_{i \in N} cx_i + \propto * z$$

First Stage

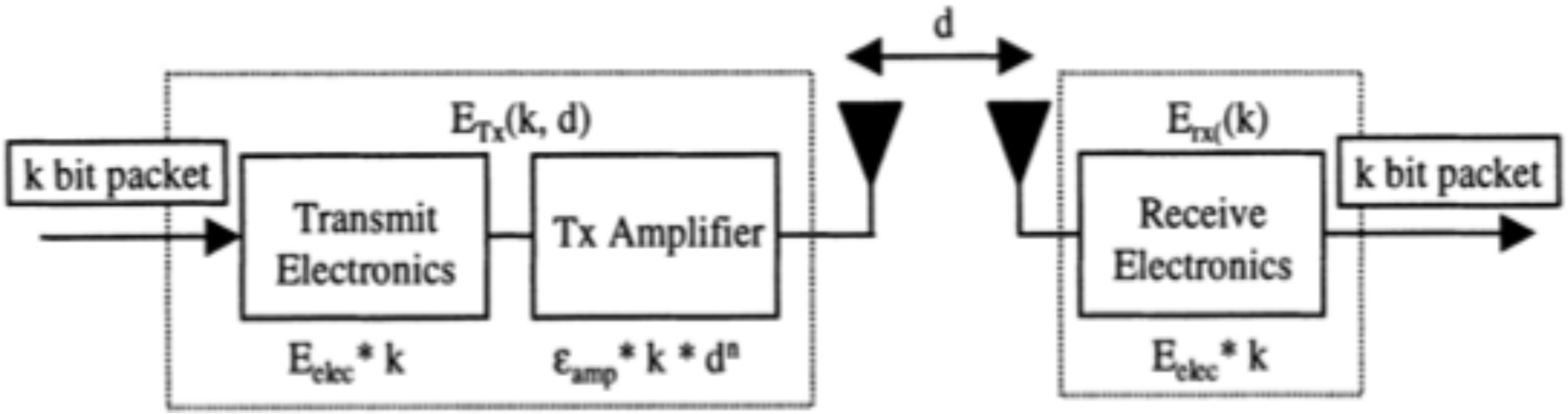
$\propto = 1$

Second Stage

$\propto = 0$

Minimize energy consumption

Energy Consumption Model



Heinzelman et al. (2002)

Data Transmission:

$$E_{TX}(k,d) = \begin{cases} k * E_{elec} + \left(k * E_{fs} * d^2\right) & d < d_0 \\ k * E_{elec} + \left(k * E_{mp} * d^4\right) & d > d_0 \end{cases}$$

Data Reception: $E_{RX}(k) = k * E_{elec}$

Parameters

Parameter	Definition
	Set of nodes
	Set of mandatory nodes
	Set of Edges
	Set containing the base station node
	Distance between nodes i and j
	Monitoring frequency per minute
	Lifetime in days
	Cost of a sensor node

Parameter	Definition
	Transmission energy (sending from node i to j)
	Reception energy (sending from node i to j)
	Energy consumed by data processing in a node
	Energy consumed by data acquisition in a node

Parameter	Definition
	Energy consumed (transmission and reception per bit)
	Transmission energy dissipated by freespace model amplifier
	Power capacity of the battery
	Transmission energy dissipated by the multi-path model amplifier
	Number of bits per packet

Constraints

1. ***Mandatory sensors at specific nodes***

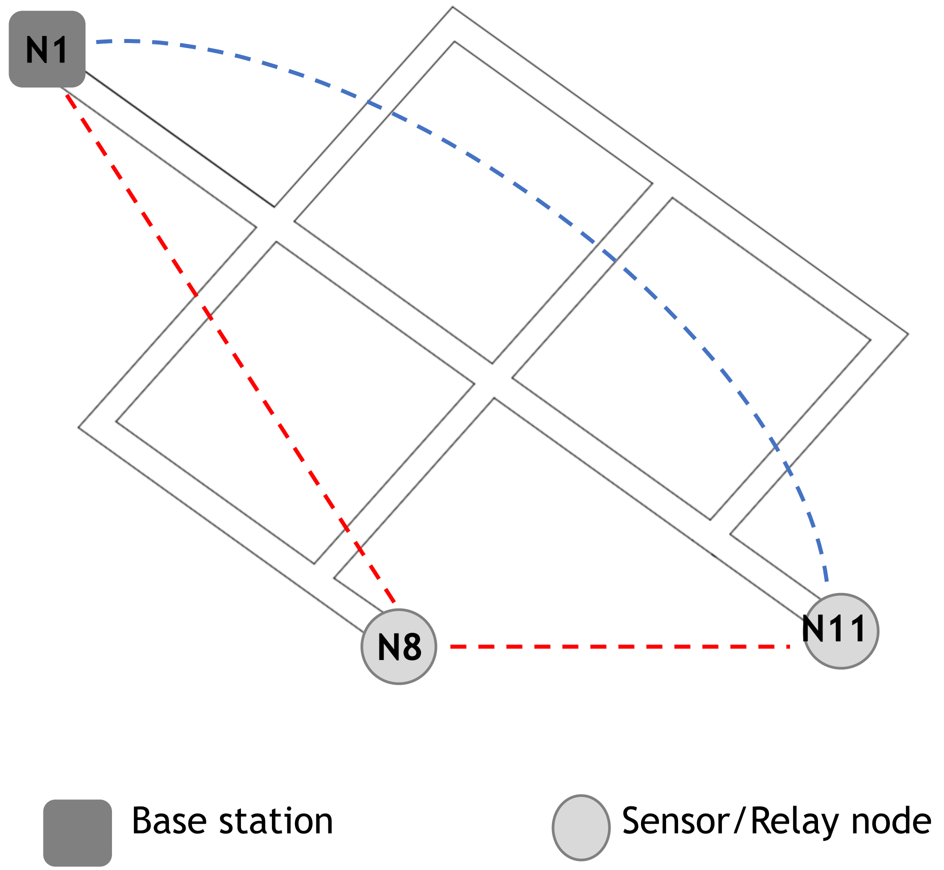
$$x_i = 1, \ \forall i \in O$$

$$\epsilon_i = 1, \ \forall i \in O$$

2. ***Connectivity constraints***

$$y_{ij} + 1 \geq x_i + x_j, \quad \forall (i, j) \in A$$

$$y_{ij} \leq \frac{x_i + x_j}{2}, \quad \forall (i, j) \in A$$



Constraints

3. Flow conservation constraint

$$\sum_{j:\ (i,j)\in A} w_{i,j,t} - \sum_{j:\ (j,i)\in A} w_{j,i,t} = -\sum_{l\in O} \epsilon_l - 1, \quad \forall i \in S,\ \mathrm{t} \in \mathrm{T}$$

Number of data packets received is equal to the number of sensor nodes

$$\sum_{j:\ (i,j)\in A} w_{i,j,t} - \sum_{j:\ (j,i)\in A} w_{j,i,t} = \epsilon_i, \quad \forall i \in N \mid i \notin \mathrm{O}, i \notin S, t \in \mathrm{T}$$

The received data packets are equal to data packets sent

Constraints

4. Lifetime constraint

$$\left(\left(E_p + E_a\right) * \varepsilon_i + \sum_{j:\ (i,j)\in A} E^t_{i,j} w_{i,j,t} + \sum_{j:\ (j,i)\in A} E^r_{j,i} w_{j,i,t}\right) * m \leq \quad \beta,\ \forall i \in N,\ t \in \mathrm{T}$$

Stage 1

$$\left(E_p + E_a\right) * \varepsilon_i \sum_{j:\ (i,j)\in A} E^t_{i,j} w_{i,j,t} + \sum_{j:\ (j,i)\in A} E^r_{j,i} w_{j,i,t} \leq \ z, \quad \forall i \in N,\ t \in$$

T

Stage 2

5. Maximum nodes

$$\sum_{i \in N} x_i \leq k$$

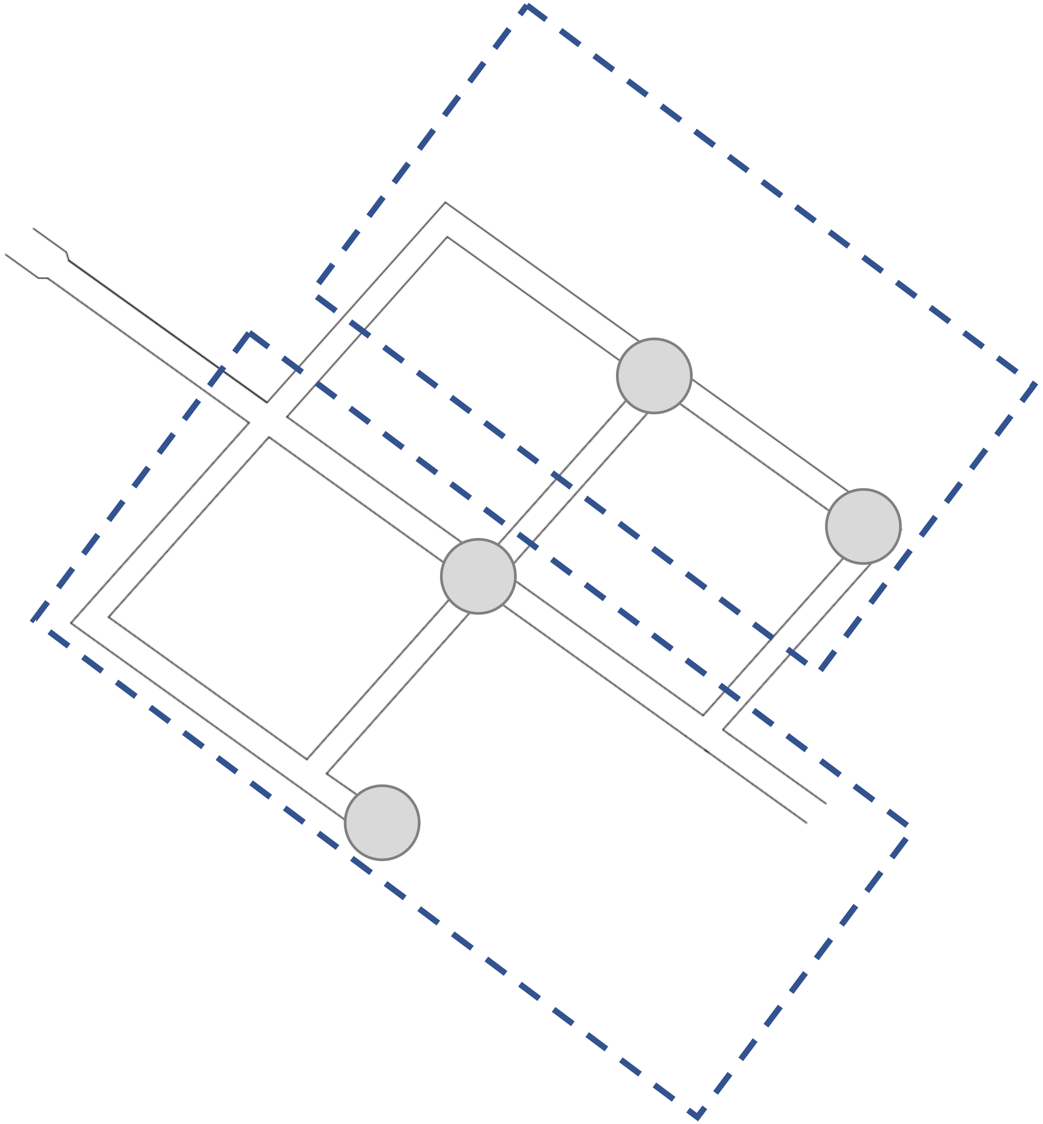
Stage 2

Constraints

6. *Coverage constraint*

$$\sum_{i \in M_g} \mathrm{x}_i \geq u, \forall \mathrm{g} \in K \mid \bigcup_{g \in S} M_g = N$$

$$u = 2$$



Implementation of the optimization model

Software

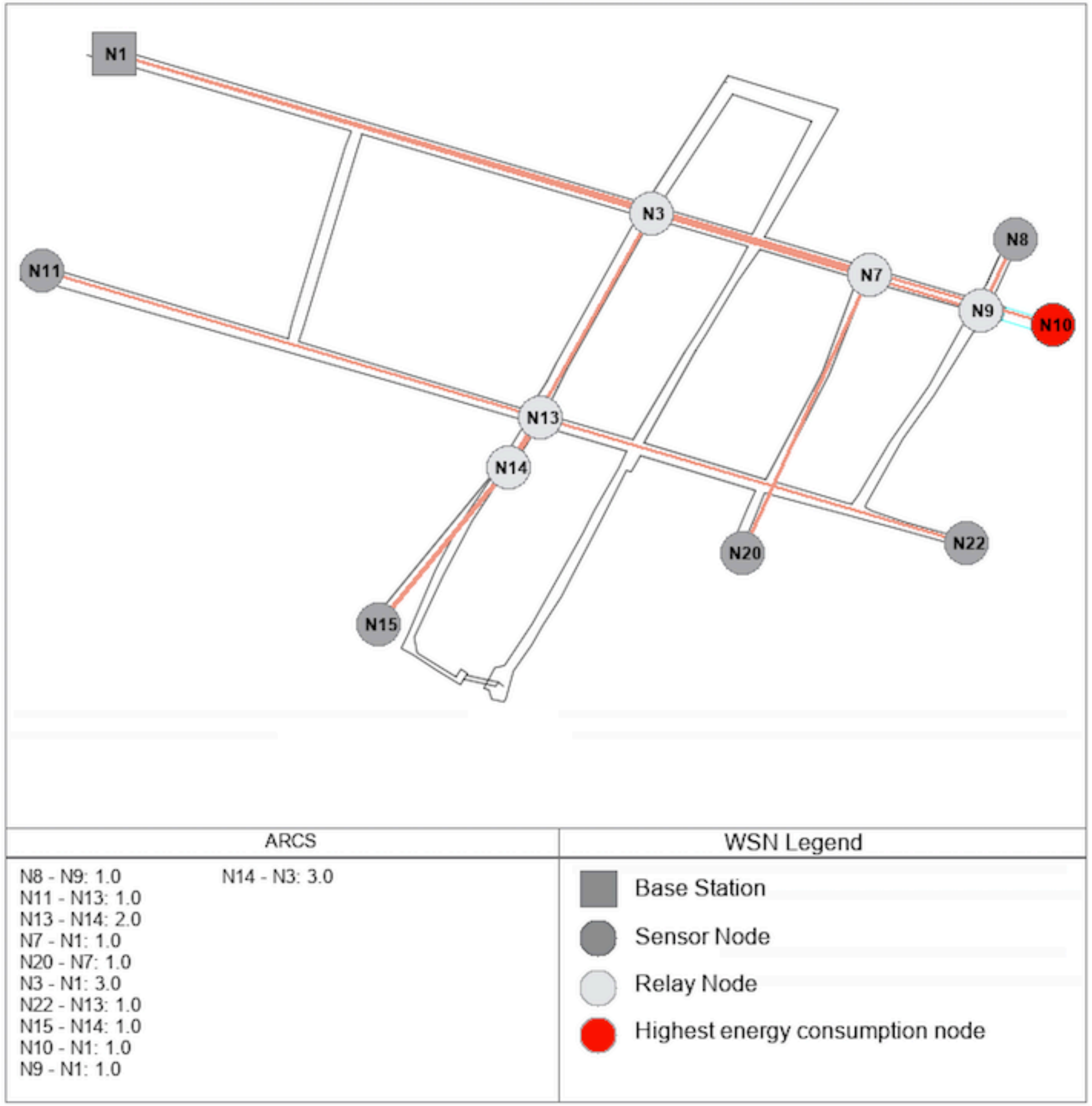
Parameters IN

Mine layout IN

python™

GUROBI OPTIMIZATION

OUT



Optimization Solvers

Solvers

- IBM CPLEX
- FICO Xpress
- GUROBI OPTIMIZATION
- mosek
- GLPK
- COIN|OR (Computational Infrastructure for Operations Research)
- lp_solve

Modeling packages

- GUROBI OPTIMIZATION
- IBM DOcplex
- GAMS
- PuLP
- PYOMO

Gurobi: Modeling with Python


```python
#---MODEL DEFINITION---
m = Model("mip1")

#---DECISION VARIABLES---
x = m.addVars(nodes, vtype=GRB.BINARY, name="x")
y = m.addVars(arcs, vtype=GRB.BINARY, name="y")

#---CONSTRAINTS---
# Mandatory sensors constraint
m.addConstrs((x[i] == 1 for i in nodesM), "SensorO")

# Conectivity constraint
m.addConstrs((y[i] >= x[i[0]] + x[i[1]] - 1 for i in arcs),
    "LineOfSightA")
m.addConstrs((y[i] <= (x[i[0]] + x[i[1]]) / 2 for i in arcs),
    "LineOfSigthB")

#---OPTIMIZE MODEL---
m.optimize()
```

Schedule

✓Context

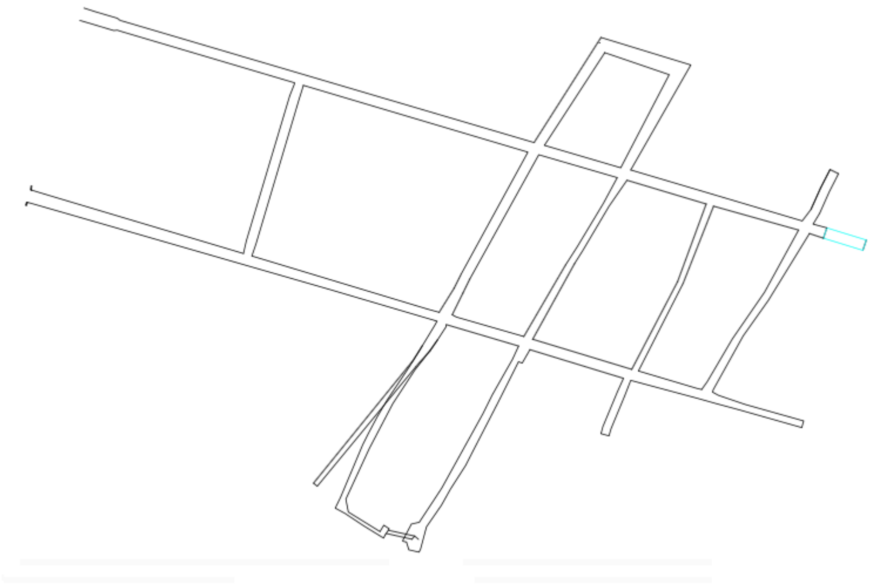
✓Optimization strategy

- Results
  - Case studies
  - Computational results
  - Real experiment

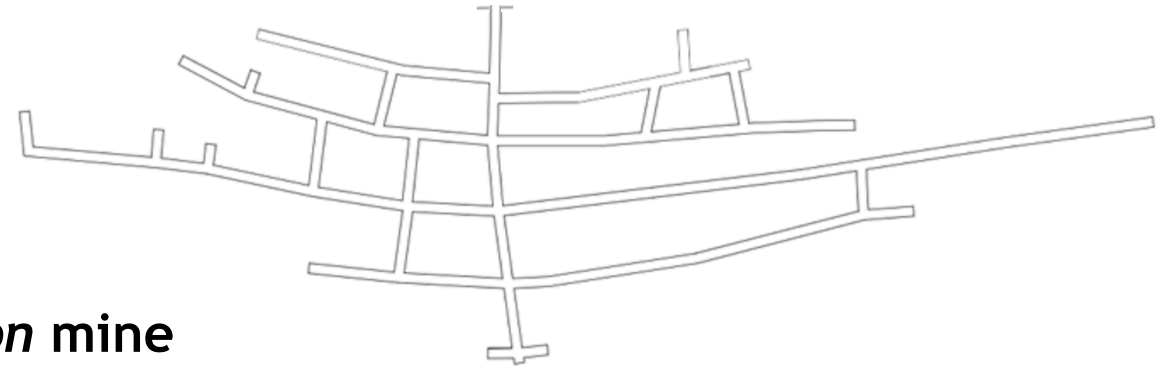
- Conclusion

Case Studies

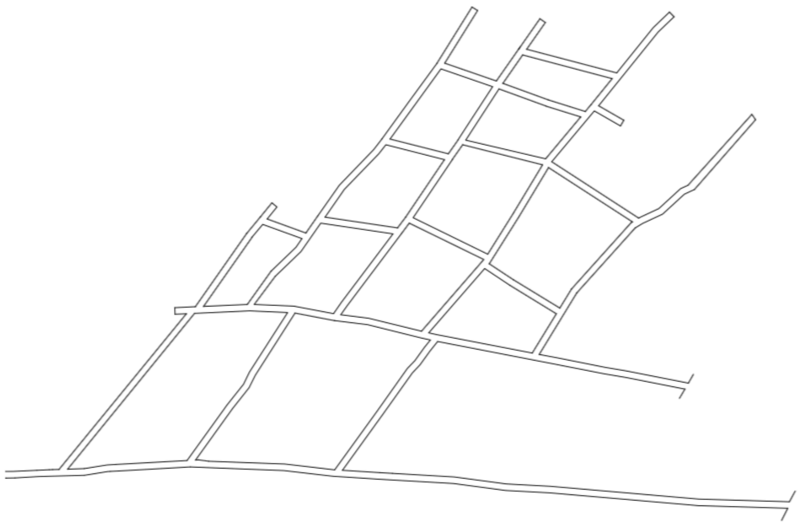
SENA Training mine



***El Alisal* mine**



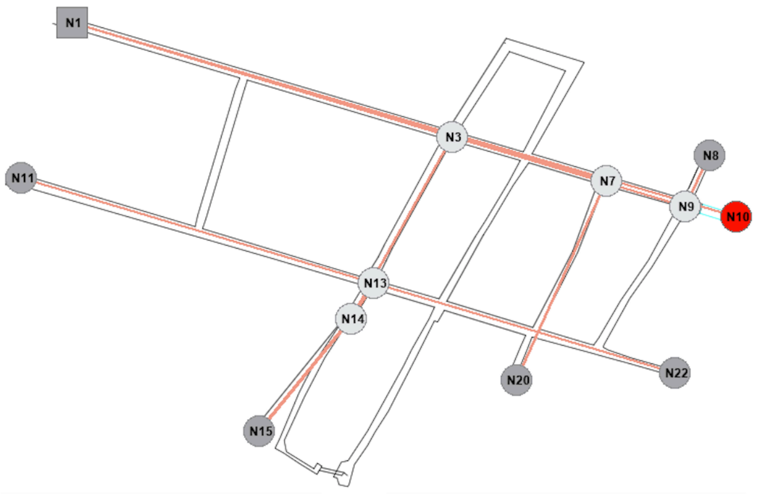
***El Higuerón* mine**



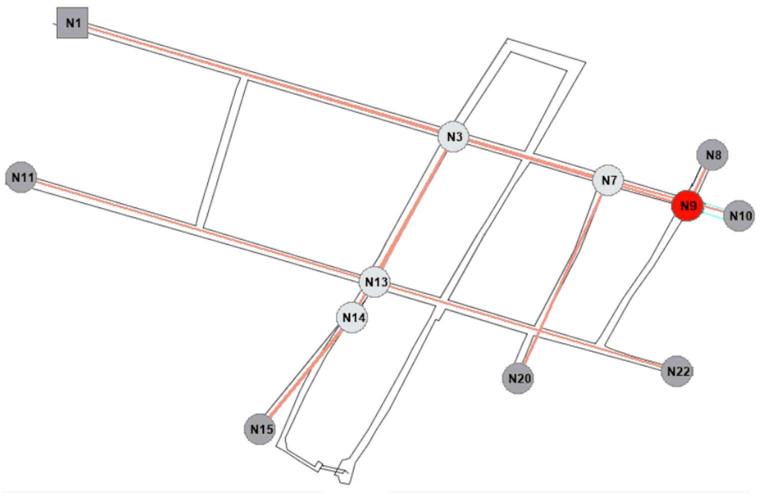
SENA Training Mine

Number of nodes = 12 → Lifetime = 205.9 days

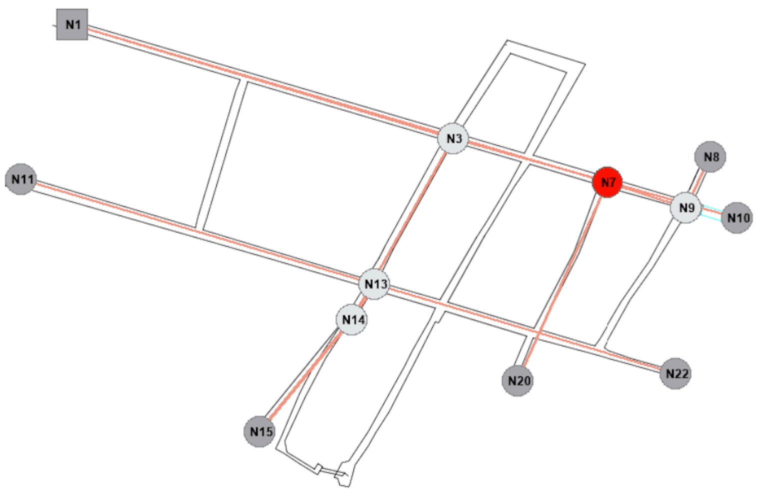
TW1



TW2



TW3



Sensor/Relay node

Sensor/Relay node

Highest energy consumption node

Base station

Summary of Results

Mine	Number of nodes	Lifetime T=1 (days)	Lifetime T=2 (days)	Lifetime T=3 (days)	Lifetime T=4 (days)
SENA	12	166.5	204.5	205.9	218.4
	13	511.1	545.2	565.6	547.2
	14	511.1*	568.4	613.4	632.3
	15	511.1*	568.4*	639.4	639.4
	16	511.1*	568.4*	639.4*	654.3
El Higueron	19	711.2	754.1	769.2	764,8
	20	732	836.6	870.4	845.1
	21	732*	853.5	873.2	900.1
	22	732*	853.5*	914.5	915.5
	23	732*	853.5*	919.2	919.2
El Alisal	23	321.6	321.6	321.6	321.6
	24	420.7	420.7	420.7	420.7
	25	643.2	643.2	643.2	645.1
	26	677.6	741.5	726	741.5
	27	832.1	832.1	832.1	832.1

Computational Results

- Watts Strogatz Graph

Nodes/Edges	Runtime		% gap	
	Stage 1	Stage 2	Stage 1	Stage 2
100/500	65	10800	0	1.4
72/288	10	10800	0	1.3
49/147	5	275	0	0

Real Experiment - Objectives

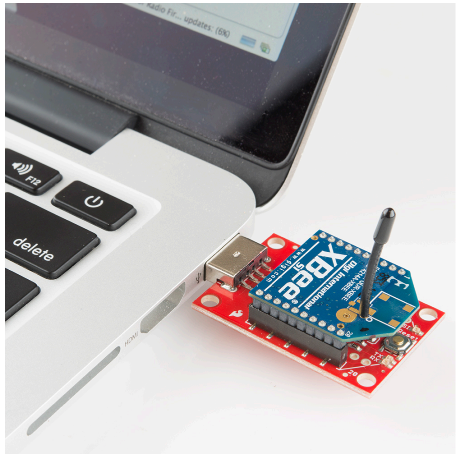
- Find the maximum communication distance between two nodes.

- Test a hypothesis: it is possible to establish a communication between the nodes of the WSN only if there is a line-of-sight between them.

- Verify whether the optimization model gives as output a nodes distribution that is operational.

Prototype design - WSN

Base station

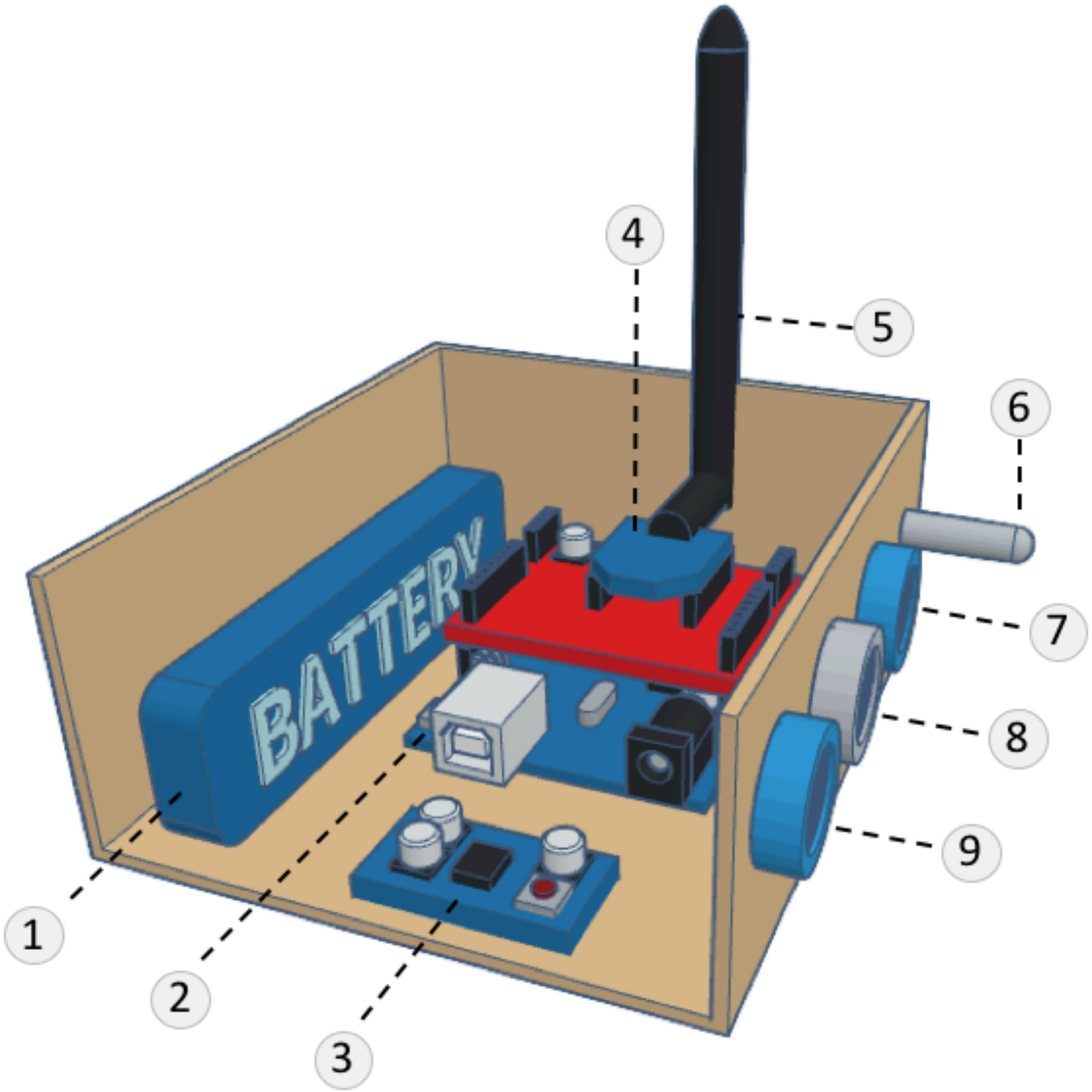


python™

Relay nodes

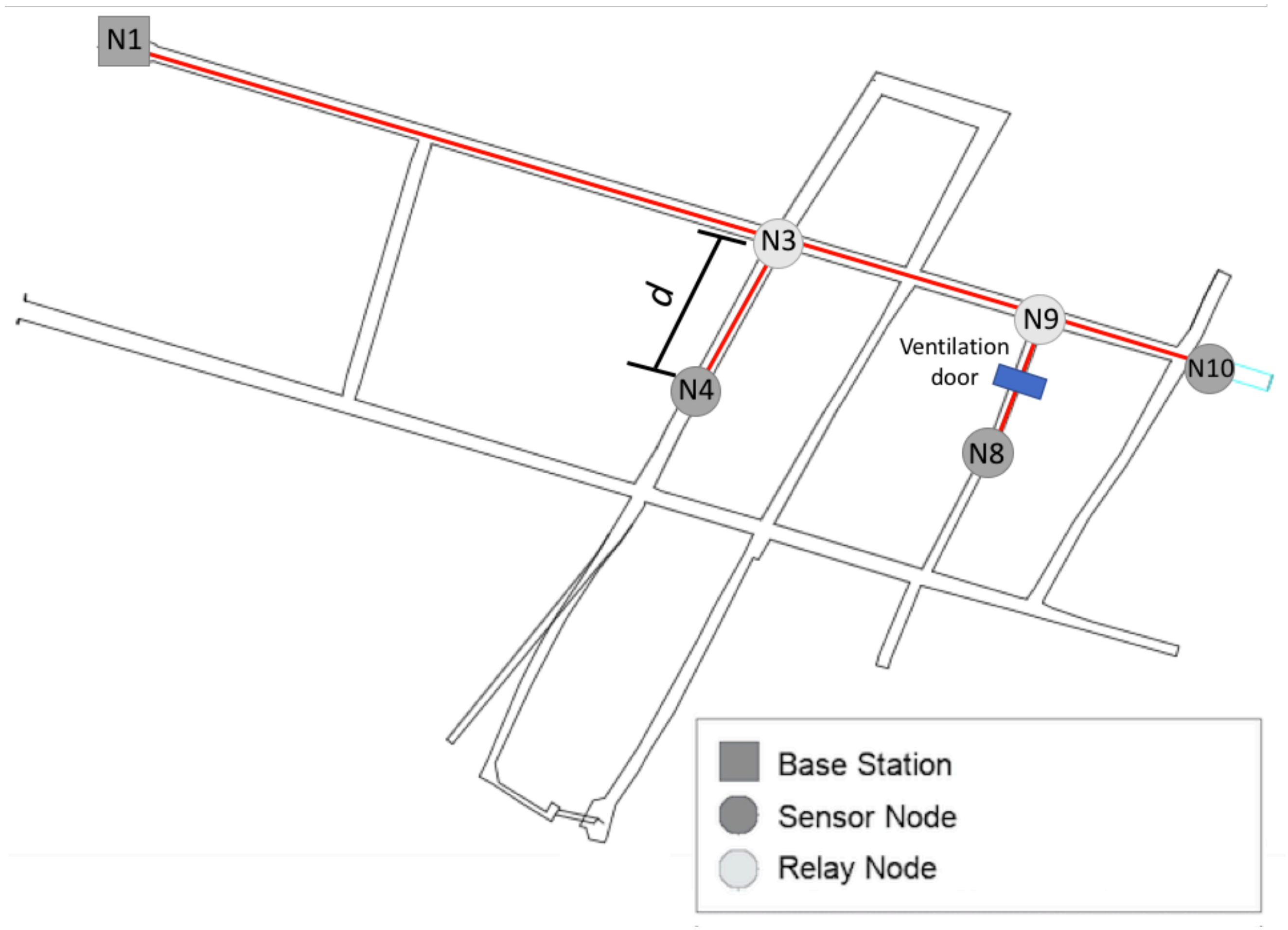
Sensor nodes

Prototype design – Sensor node



1. LIPO Battery 3000 mAh
2. Arduino Mega 2560
3. DC - DC Converter
4. XBee PRO S3B
5. Antenna RP-SMA 3.5 dbi
6. Temperature sensor
7. Methane sensor
8. Carbon dioxide sensor
9. Oxygen sensor

Prototype Implementation



Schedule

- ✓Context
- ✓Optimization strategy
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Conclusion

- We propose a two-stage lexicographic optimization methodology to minimize the deployment costs and maximize the lifetime of WSNs for gas monitoring in mines
- The proposed methodology has been tested using three realistic case studies, producing results that meet requirements.
- The distance between nodes and the number of data packets are parameters that highly influence the lifetime of the WSN.
- In most cases, dynamic routing increases the lifetime of the WSN

Thank you

Additional Slides

Parameter	Definition
N	Set of nodes
$O \subseteq N$	Set of mandatory nodes
A	Set of edges
S	Set containing the base station node
K	Set of sections of the layout of the mine
M_g	Set of nodes in the section g
u	Number of sensors to be deployed in a section
T	Number of time windows by day
d_{ij}	Distance between nodes i and j
c	Cost of a sensor node
E_e	Energy consumed (transmission and reception per bit)
E_f	Transmission energy dissipated by freespace model amplifier
l	Lifetime in days
β	Power capacity of the battery
E_m	Transmission energy dissipated by the multi-path model amplifier
δ	Cross over distance

Parameter	Definition
k	Number of bits per pack
$E_{ij}^{(t)}$	Transmission energy (sending from node i to j)
$E_{ij}^{(r)}$	Reception energy (sending from node i to j)
E_p	Energy consumed by data processing in a node
E_a	Energy consumed by data acquisition in a node
ϕ	Monitoring frequency per minute
m	Number of gas measurements to be made
α	Binary parameter equal to "0" for the first stage and equal to "1" for the second stage
κ	Number of nodes determined in the first stage