IC1301 -WiPE

Graph theory and its application in space wireless technologies

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WIPE
COST IC1301

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Scope of the presentation

- Some slides about SpaceForest
- Slimming of Ariane 5 rocket - problem to solve
- Introduction to Wireless Sensor Networks and their topologies
- Introduction to graph theory
- Optimal Wireless Sensor Network used as a solution of the problem
- Determination of velocity and location using wireless measurement of acceleration
- Summary

About SpaceForest

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Location: Poland

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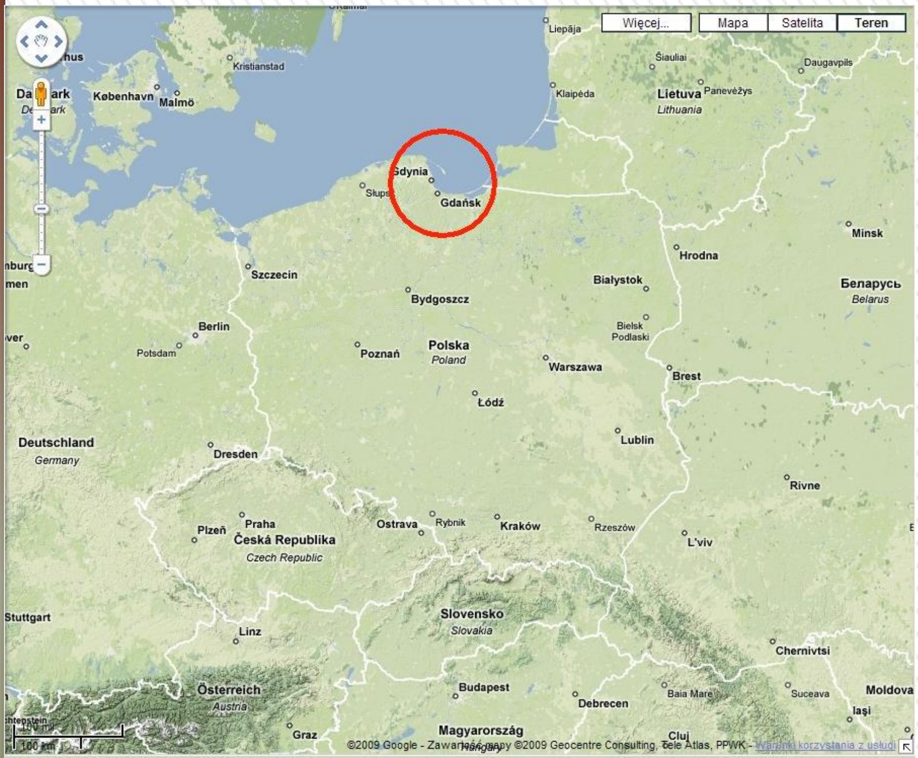

Pomeranian Science and Technology Park, Gdynia, Poland

About SpaceForest

SpaceForest innovative solutions

SpaceForest creates and actively explores innovative ideas. Our company specializes in Artificial Intelligence (AI) and Video Recognition (VR) solutions, which are used in optimization of industrial processes. SpaceForest works on diverse tasks in many different areas of engineering related to electronics, IT and space-tech.

TrimSolutions computer aided tuning

the software for post-production computer aided tuning of microwave filters

TrimSolutions software is applicable in tuning of very high frequency telecommunication single and multimode **satellite** filters up to **Ka band** (40 GHz)

DEWI Project

Call: **ARTEMIS** 2013; European Commission

Project: **DEWI Dependable Embedded Wireless Infrastructure**

(3rd place of 22 Artemis projects)

Business Needs: **Reduction** of aircraft **weight** by removing wires and using **WSN** (Wireless Sensor Network)

Demonstrator: **TEST ROCKET with WSN**.

The EC project „DEWI - Dependable Embedded Wireless Infrastructure“ with **58 partners** from **11 countries** focusses on the development of **wireless sensor networks**, communication and applications. DEWI will provide key solutions for wireless seamless connectivity and interoperability in smart cities and infrastructures by considering everyday physical environments of citizens and professional users in airplanes, cars, trains as well as buildings. The results will be presented to the public via practical demonstrations in the areas of aeronautics, automotive, rail and building. Furthermore DEWI provides essential contributions to interoperability, standardization and certification.

DEWI Project

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OBJECTIVES

- Strengthening of Europe's leading position in the area of „Embedded (Wireless) system and Smart (mobile) environment“
- Development of wireless sensor networks and applications for citizens and professional users in more than 20 industry-driven use cases
- Clear practical demonstrations in the areas of aeronautics, automobile, railroad and building automation
- Essential contributions to interoperability, standardization and certification of wireless sensor networks and wireless communication

AUTOMOTIVE

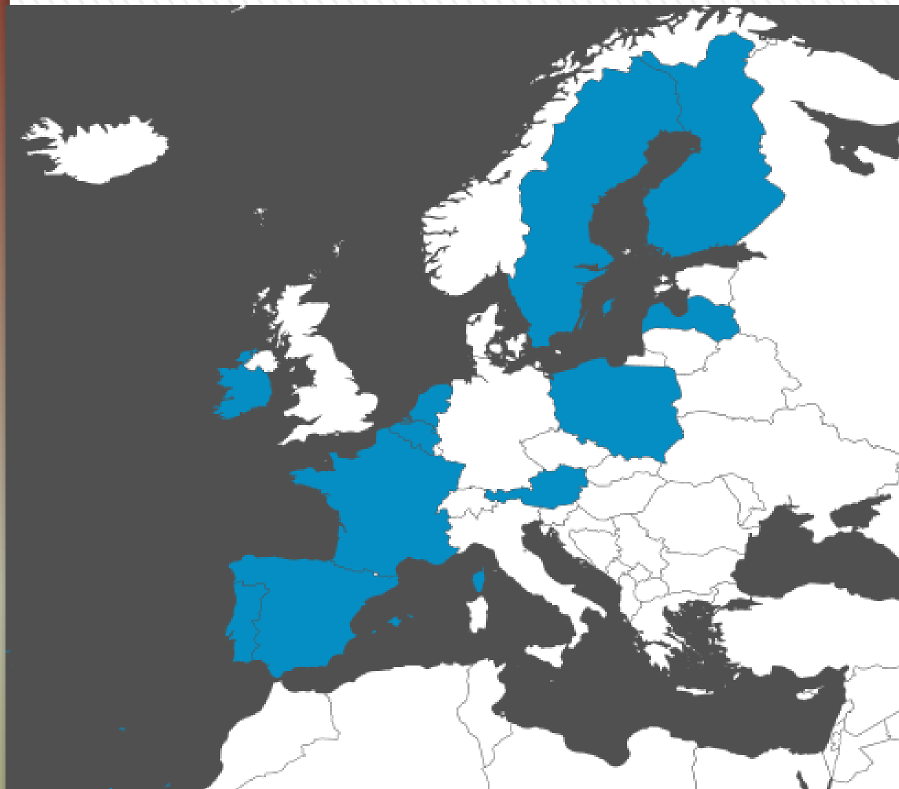
AERONAUTICS

BUILDING

RAIL

INTEROPERABILITY

DEWI Partners



Austria
Belgium
Finland
France
Ireland
Latvia
Netherlands
Poland
Portugal
Spain
Sweden

About DEWI Project

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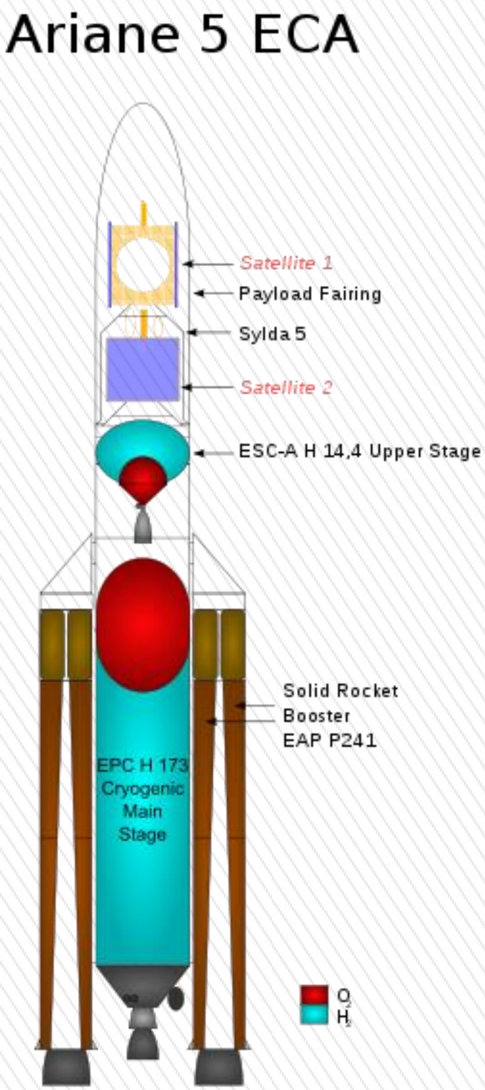
DEWI Outcome demonstrator – flying rocket

The expected test rocket scale:
6 [m] the rocket high
0,3 [m] diameter of the rocket
50 [kg] a total vehicle weight
1 [Ton] of the engine thrust
5 [s] of the burn time

Main problems:

Flight data aqusition tools: Designed WSN,SF telemetry system
Data sources: WSN, internal sensors, onboard camera, external signals (GPS, telemetry system with Doopler effect analyses)
WSN Nodes: temperature, pressure, fuel flows, accelerations, other

Slimming of Ariane 5. Problem to solve!



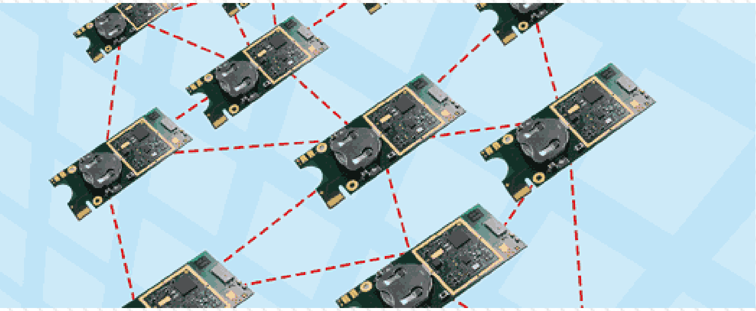
- 600 – 800 sensors are used for miscellaneous measurements
- 70 % of avionic mass are cables
- 10000 € is an approximate delivery cost of 1 kg of payload to the orbit

How can we save some money ?

Leave the cables on the earth !

Use a Wireless Sensor Network !

Use Energy Harvesting !



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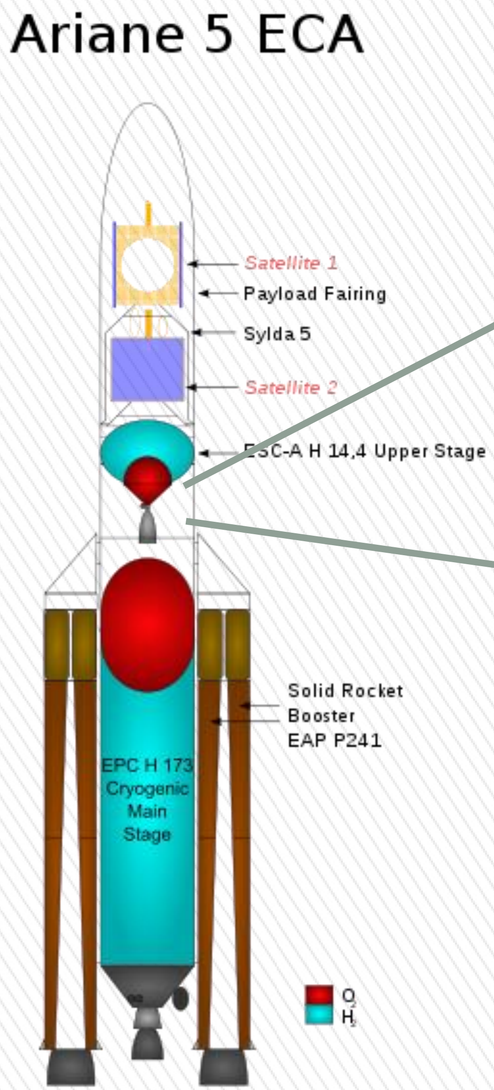
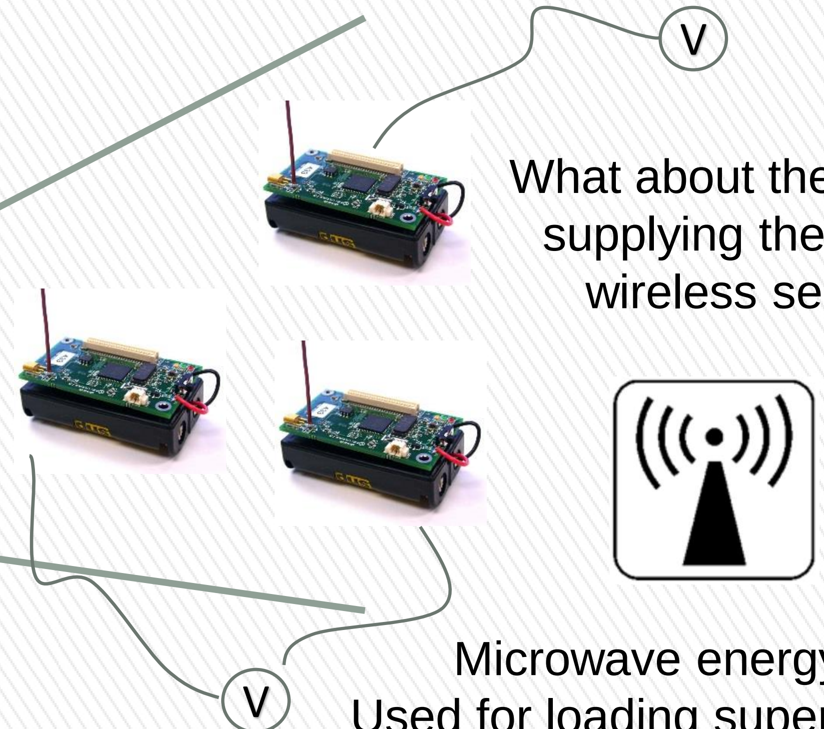
Slimming of Ariane 5. Problem to solve!





What about the cables for supplying the power to wireless sensors ?

Microwave energy pomp
Used for loading super capacitors or batteries of WSN Nodes

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Wireless Sensor Network on Ariane 5

4 main types of sensors used in Ariane 5:

- specialized analog applications - 1000 measurements per second
- gyros, accelerometers - 100 measurements per second
- pressure gauges, flowmeters - 10 measurements per second
- temperature - 1 measurement per second

The output data from each measurement (16 bits) **must** be transferred to the mission control.

Task is not easy because it needs to ensure:

- extreme reliability
- very high efficiency and throughput of sensors
- minimum network time delay between the measurement and transmission to the ground station

Crucial question: What network topology needs to be used ?

Graph theory will provide the answer

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Wireless Sensor Networks - applications

WSN characteristics:

- Power consumption constraints for nodes using batteries or energy harvesting (vibration/microwave energy)
- Ability to cope with node failures
- Mobility of nodes
- Communication failures
- Heterogeneity of nodes
- Scalability to large scale of deployment
- Ability to withstand harsh environmental conditions
- Ease of use
- Cross-layer design

WSN applications:

- Area monitoring
- Health care monitoring
- Air pollution monitoring
- Forest fire detection
- Landslide detection
- Water quality monitoring
- Natural disaster prevention
- Machine health monitoring
- Data logging
- Water/Waste water monitoring
- Structural Health Monitoring
- **Measurements of critical parameters in flying vehicles**

cost

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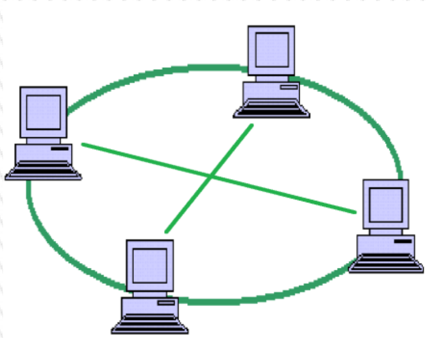
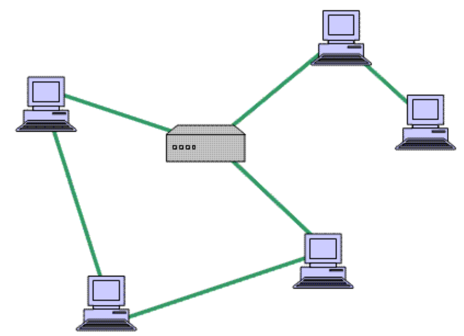
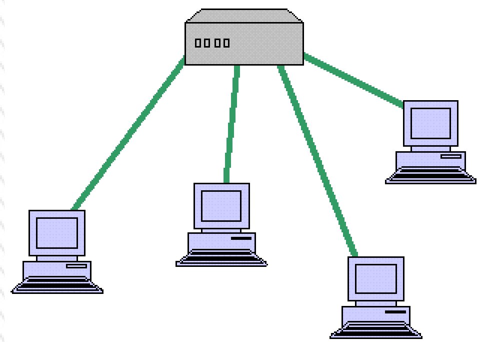
Basic network topologies





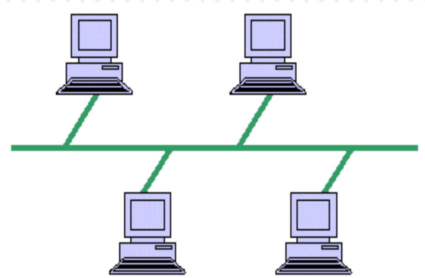


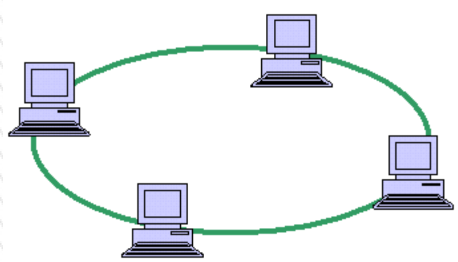
Fully connected
(each of nodes connected to each other)

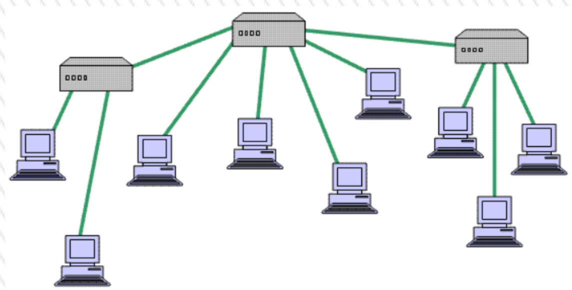
$\frac{n(n-1)}{2}$ connections

Mesh
(partially connected)

Star
(each node to central hub)







Common bus
(common transmission medium)

Ring
(each node = signal repeater)

Tree
(based on hierarchy of nodes)

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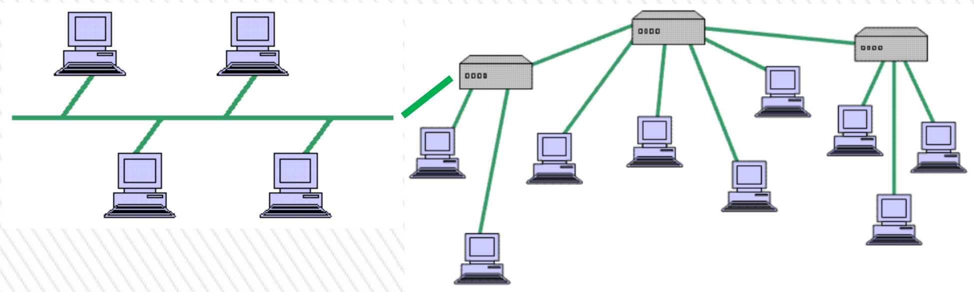
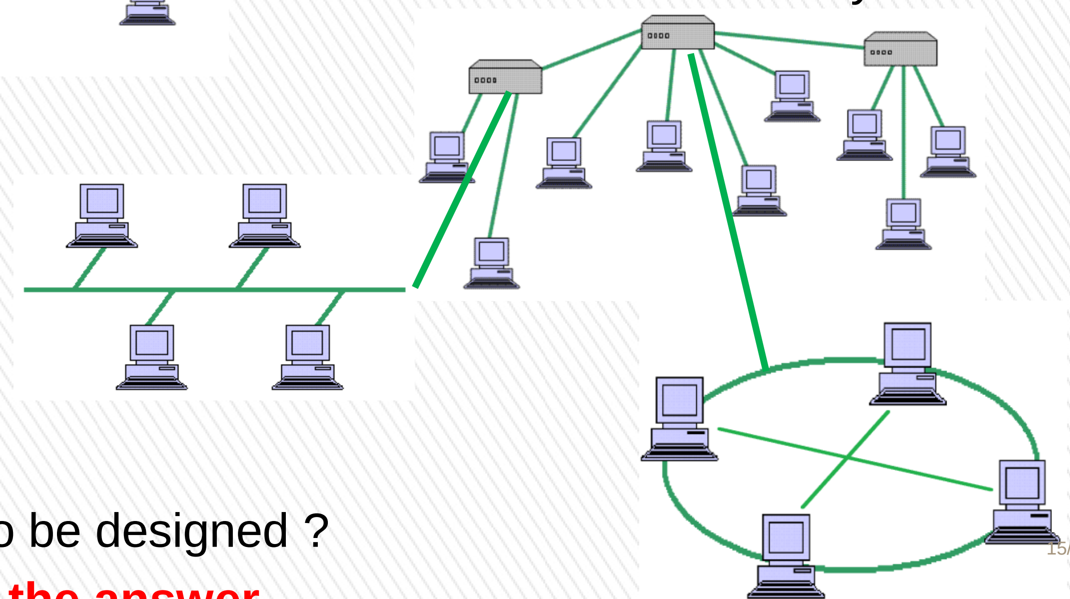
Network topologies in the real world

In a real situation, a hybrid topology – a combination of two or more different basic topologies – is used.



Common bus + Tree

Common bus + Tree + Fully connected



How network topology needs to be designed ?

Graph theory will provide the answer

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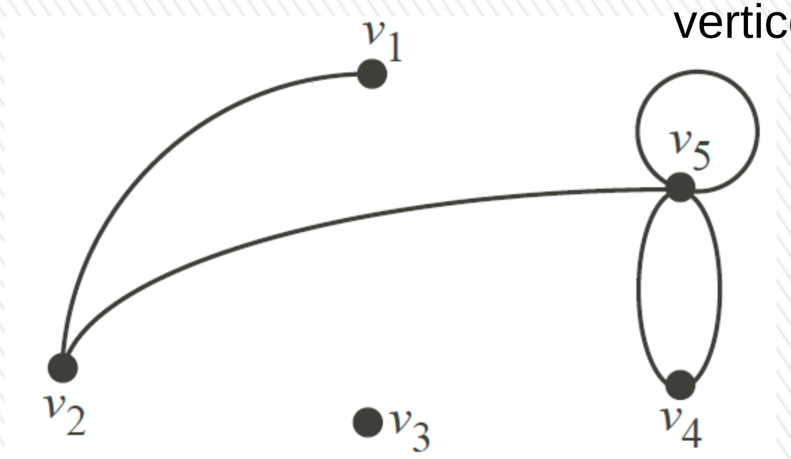
Introduction to graph theory

What is a graph?

Conceptually, a *graph* is formed by set of *vertices V* and *edges E* connecting the vertices.

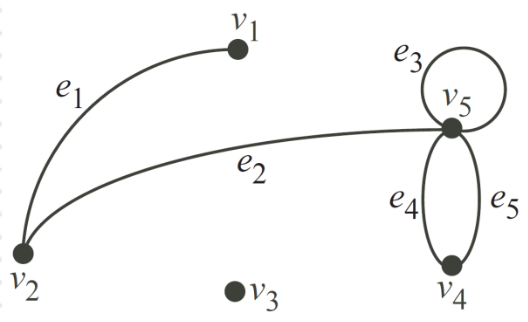


$$G = (V, E)$$

In our case, a vertice represent a wireless sensor and an edge transmission link between two wireless sensors.

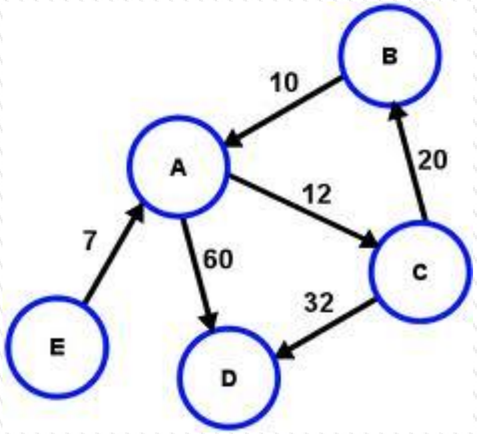
We have $V = \{v_1, \ldots, v_5\}$ *for the vertices and* $E = \{(v_1, v_2), (v_2, v_5), (v_5, v_5), (v_5, v_4), (v_5, v_4)\}$ *for the edges.*

Graph theory – main definitions



$$V = \{v_1, \ldots, v_5\}$$

$$E = \{e_1, \ldots, e_5\}$$



- The two vertices u and v are *end vertices* of the edge (u, v).
- Edges that have the same end vertices are *parallel*.
- An edge of the form (v, v) is a *loop*.
- A graph is *simple* if it has no parallel edges or loops.
- A graph with no edges (i.e. E is empty) is *empty*.
- A graph with no vertices (i.e. V and E are empty) is a *null graph*.
- A graph with only one vertex is *trivial*.
- Edges are *adjacent* if they share a common end vertex.
- A directed graph is a graph, where the edges have a direction associated with them. Opposite – an undirected graph.
- The *degree* of the vertex v, written as d(v), is the number of edges with v as an end vertex.
- By convention, we count a loop twice and parallel edges contribute separately.
- A weighted graph associates a label (weight or cost) with every edge in the graph.

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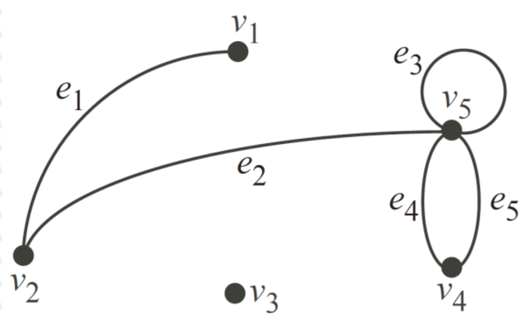
Graph theory



$$V = \{v_1, \ldots, v_5\}$$

$$E = \{e_1, \ldots, e_5\}$$

The graph $G = (V, E)$, *where* $V = \{v_1, \ldots, v_n\}$ *and* $E = \{e_1, \ldots, e_m\}$, *satisfies*

$$\sum_{i=1}^{n} d(v_i) = 2m.$$

Corollary. *Every graph has an even number of vertices of odd degree.*

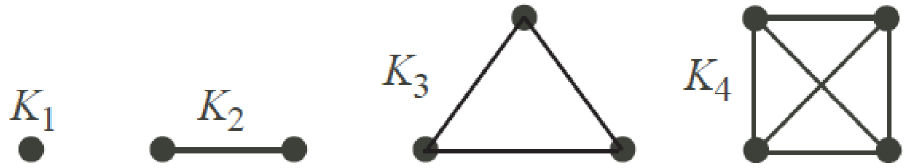
Proof. If the vertices $v_1, \ldots, v_k$ have odd degrees and the vertices $v_{k+1}, \ldots, v_n$ have even degrees

$$d(v_1) + \cdots + d(v_k) = 2m - d(v_{k+1}) - \cdots - d(v_n)$$

is even. Therefore, k is even. □

Graph theory

A simple graph that contains every possible edge between all the vertices is called a *complete graph*. A complete graph with n vertices is denoted as K_n. The first four complete graphs are given as examples:

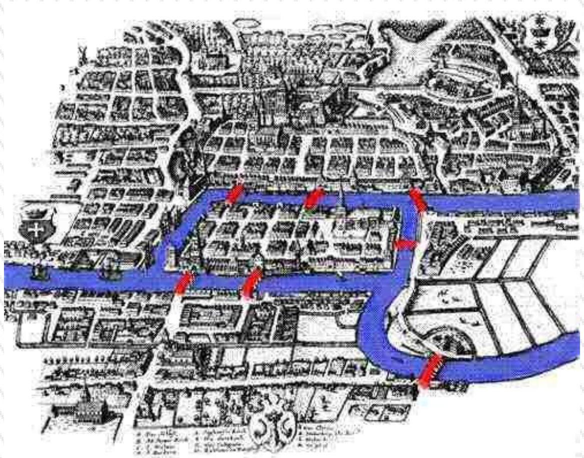


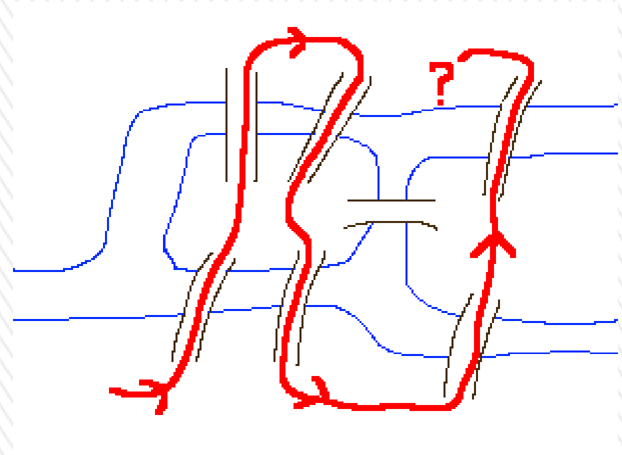
The graph $G_1 = (V_1, E_1)$ is a *subgraph* of $G_2 = (V_2, E_2)$ if

1. $V_1 \subseteq V_2$ and
2. Every edge of G_1 is also an edge of G_2.

A complete graph = representation of a fully connected network topology

Example 1. Seven Bridges of Königsberg





The problem was to find a walk through the city that would cross each bridge once and only once and come back to the starting point. Is it possible in Königsberg ?

NO !

Leonhard Euler in 1735 has given the answer and laid the foundations of graph theory and prefigured the idea of topology

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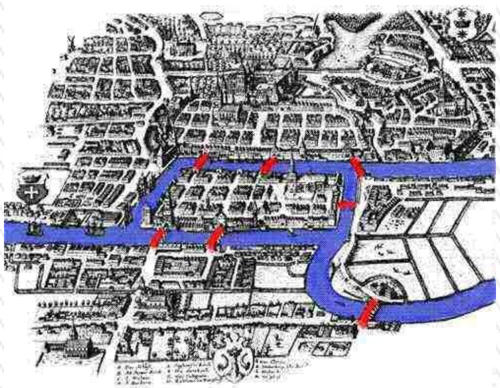
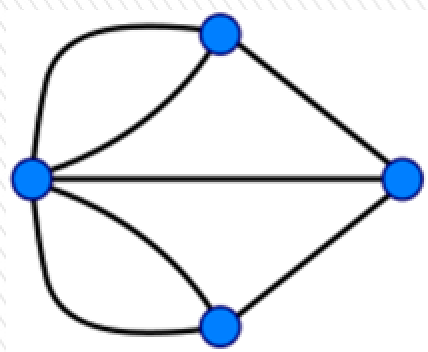
Example 1. Seven Bridges of Königsberg

Königsberg bridge problem is considered to be the first theorem of graph theory

Euler abstracted the bridges into *edges* and pieces of land into *nodes* of a *graph*.



An Eulerian trail (or Eulerian path) is a trail in a graph which visits every edge exactly once

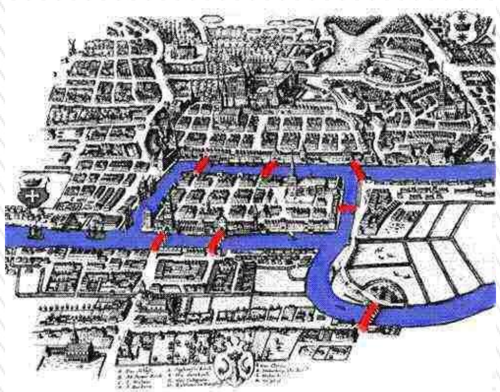


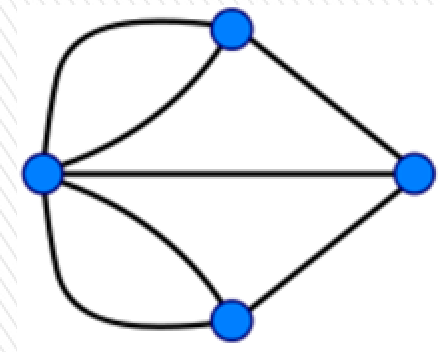
Eulerian cycle is an Eulerian trail which starts and ends on the same vertex

Why is it impossible to find in Königsberg a walk through the city that would cross each bridge once and only once (the so called Euler walk)?

Graph theory will provide the answer

Example 1. Seven Bridges of Königsberg





Graph

Euler abstracted the bridges into *edges* and pieces of land into *nodes* of a *graph*.

The rules of the graph theory state that:

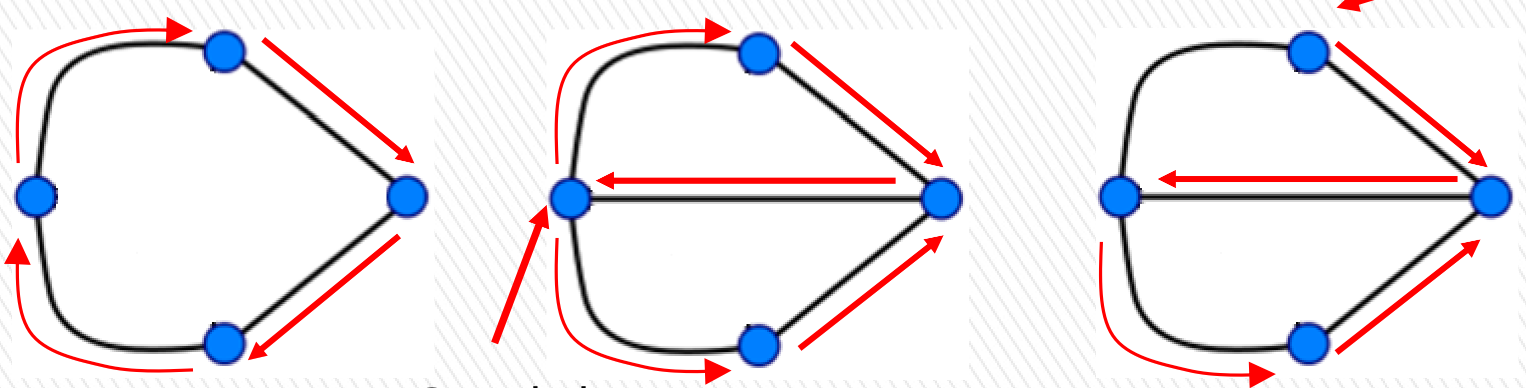
- The sum of degrees of the vertices of a graph is even
- Every graph has an even number of odd degree vertices
- **If the number of odd vertices is greater than 2 no Euler walk exists**
- If the number of odd vertices is 2, Euler walk exist starting at either of the odd vertices
- With no odd vertices, Euler walk can start at an arbitrary vertex

Example 1. Seven Bridges of Königsberg

Eulerian Cycle

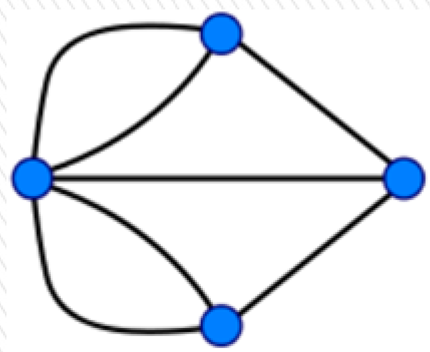
Eulerian path (walk)

Start is here



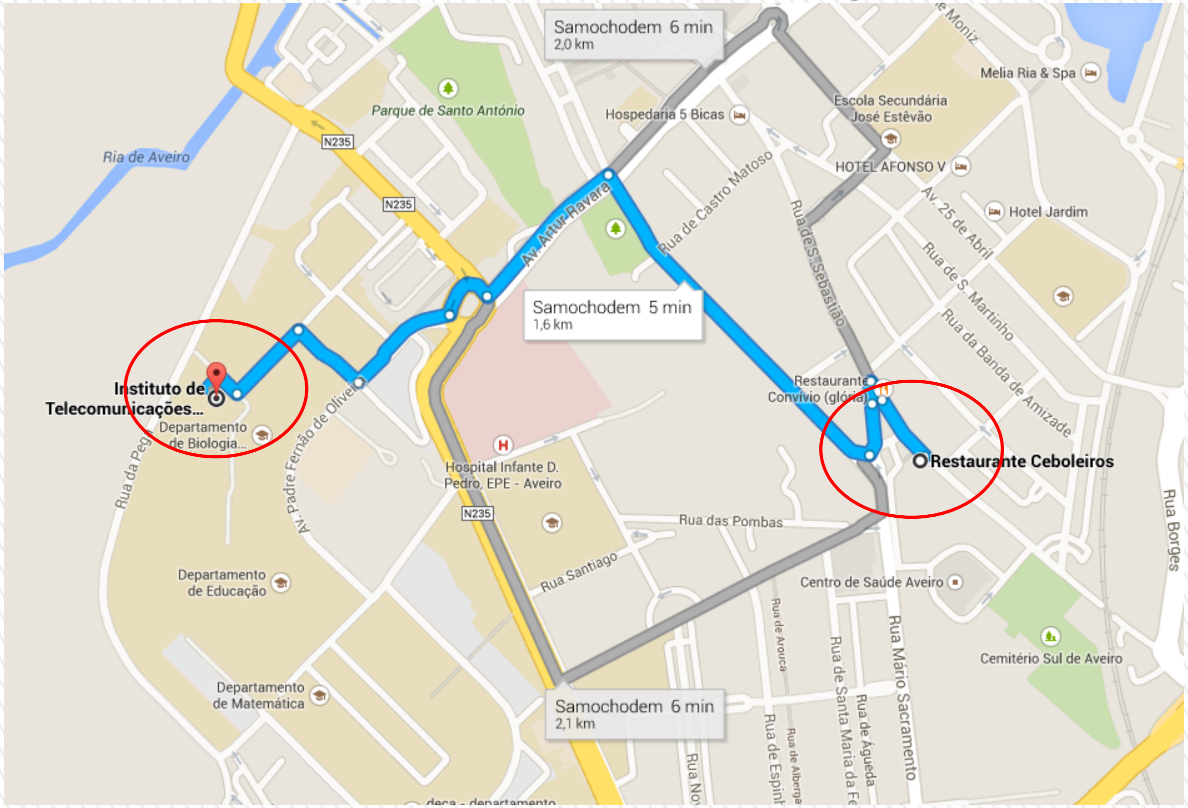
Start is here

Graph of Bridges of Königsberg



Example 2. Finding an optimal way on the map

Crossing = Vertex, Streets = Edges



Which way is optimal ?

What does it mean optimal ? Shortest ? Fastest ? Safest ?

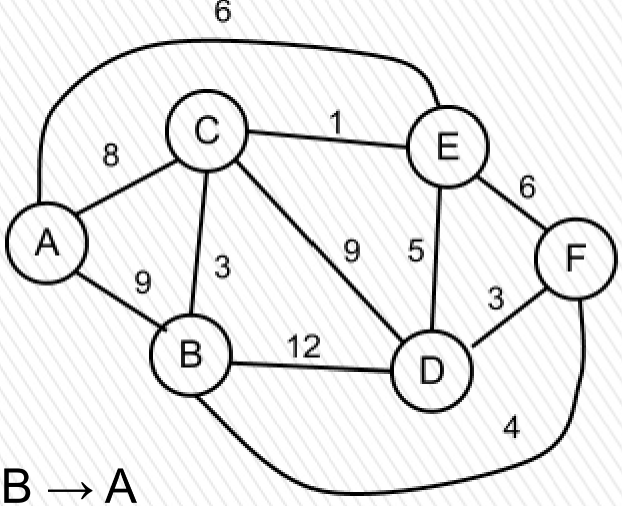
Graph theory will provide the answer

Example 3. Travelling salesman problem

17 Cities !

What is the shortest possible route that visits each city exactly once and returns to the origin city?

Graph representation



Possible solutions:

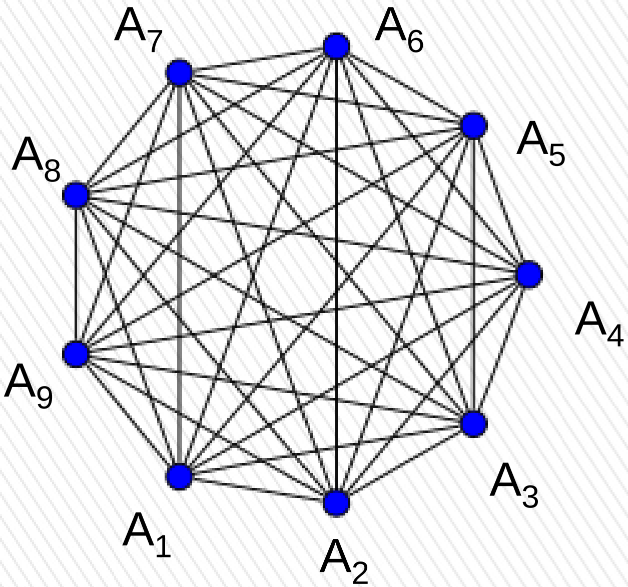
A→C →E →F →D →B → A
8 + 1+ 6 + 3 + 12+ 9 = 39

E→F →D →C →B →A → E
6 + 3 + 9 + 3 + 9 + 6 = 36

Brutal force algorithm:
Check all combinations and choose the best one.

Graph theory will provide the answer

Example 3. Travelling salesman problem



$\{A_9, A_1, A_2, \ldots, A_9\}$

$\{A_9, A_1, A_3, \ldots, A_9\}$

$\{A_9, A_1, A_4, \ldots, A_9\}$

$\{A_9, A_1, A_5, \ldots, A_9\}$

$\{A_9, A_1, A_6, \ldots, A_9\}$

$\{A_9, A_1, A_7, \ldots, A_9\}$

$\vdots$

$\{A_9, A_8, A_7, \ldots, A_1\}$

20160 combinations

Assuming 1 million combinations per second can be calculated, we get

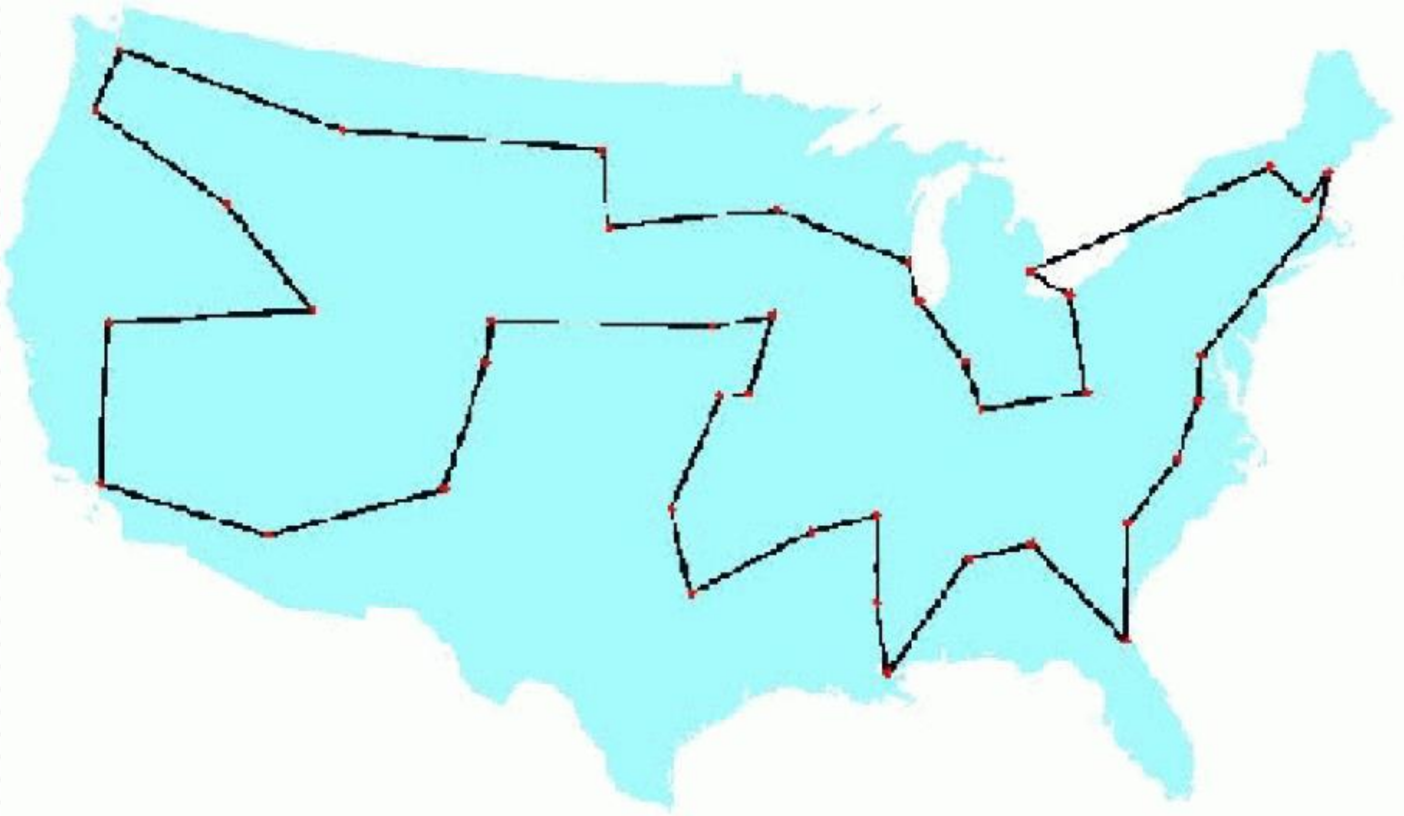
n=9 $\frac{(n-1)!}{2} = 20160$ combinations t=0.02 sec.

n=17 $\frac{(n-1)!}{2} = 1.046139494*10^{13}$ t=121 days

n=20 $\frac{(n-1)!}{2} = 6.082255020*10^{16}$ t=1928 years

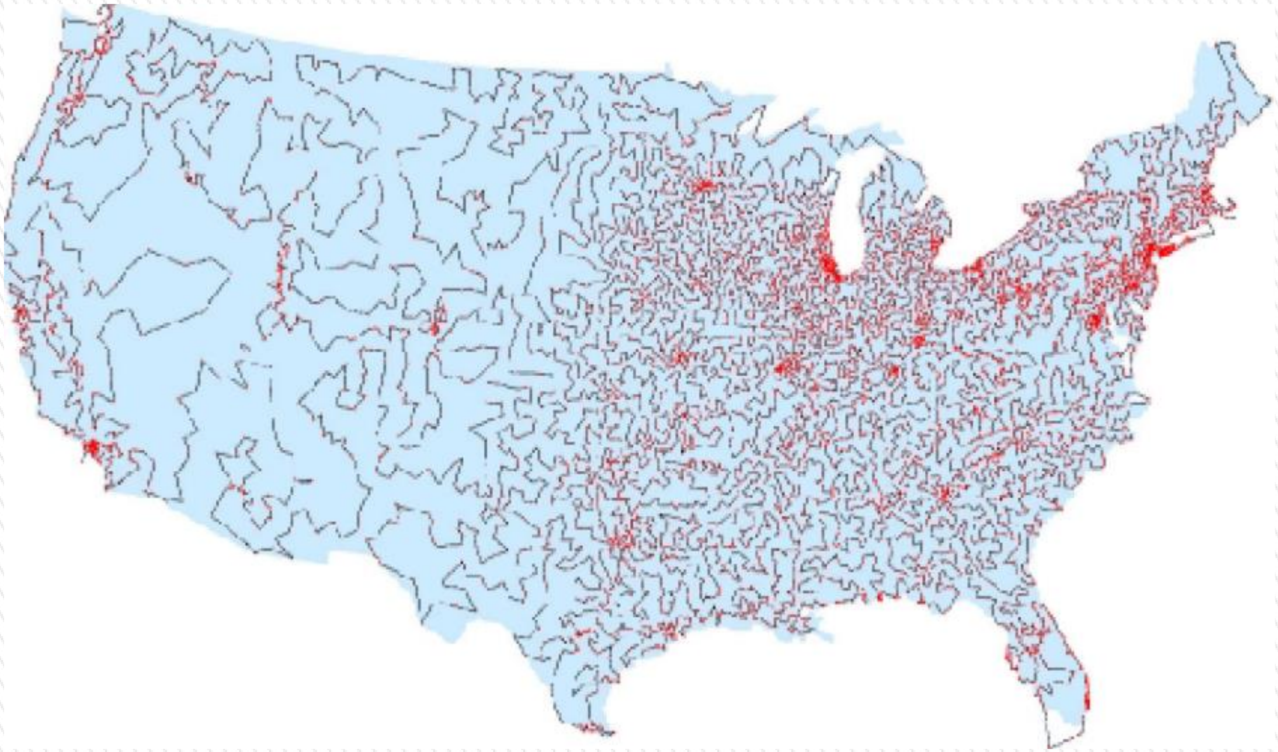
Example 3. Travelling salesman problem

In 1954 George Dantzig, Ray Fulkerson i Selmer Johnson presented solution of TSP for 49 cities of USA

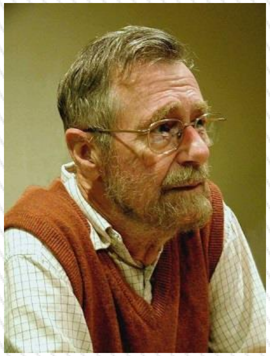


Example 3. Travelling salesman problem

In 1998 the solution of TSP for 13549 cities of USA has been published



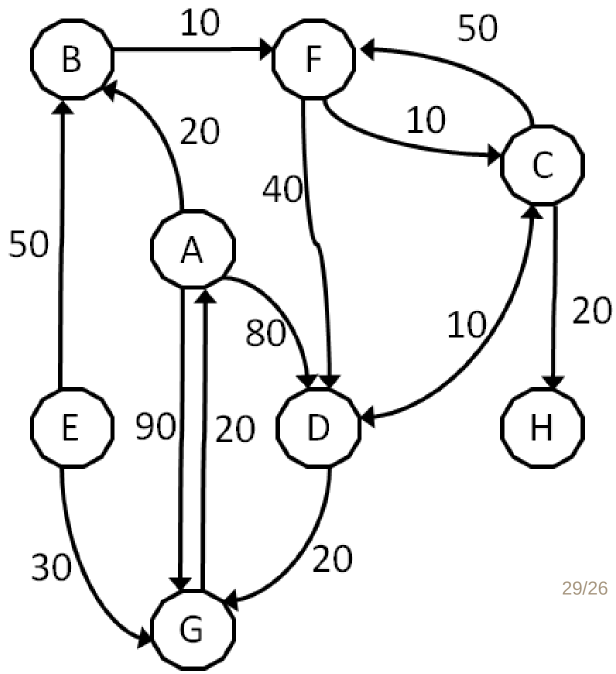
Graph theory – Dijkstra's Algorithm



Single-Source Shortest Path Problem (Dijkstra's Algorithm - 1959)

The problem of finding shortest paths from a source vertex v to all other vertices in the graph.

- Weighted graph G = (E,V)
- Source vertex s Є V to all vertices v Є V
- Both directed and undirected graphs
- All edges must have non-negative weights
- Graph must be connected

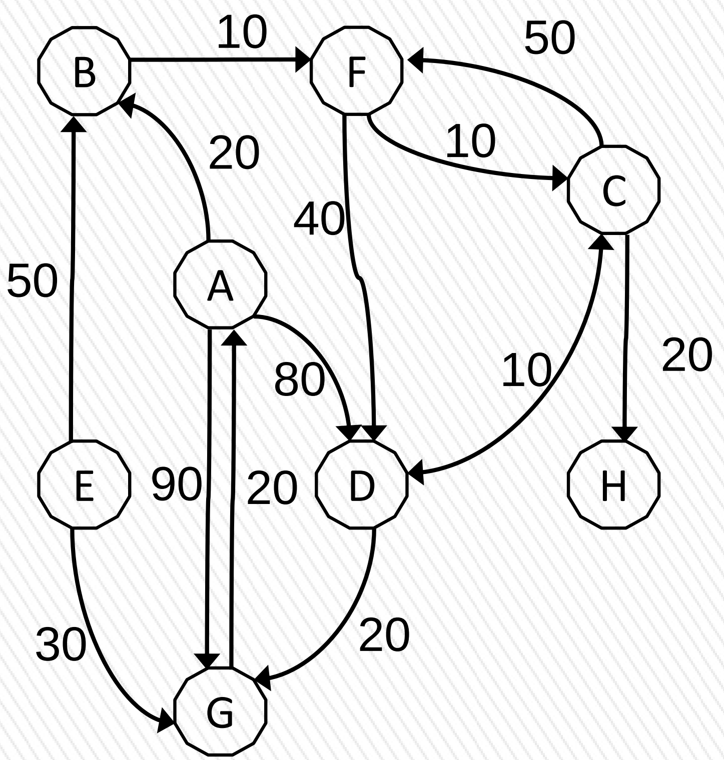


Computational complexity $O(V^2)$

Graph theory - Dijkstra Algorithm

```
dist[s] ←0                                 (distance to source vertex is zero)
for  all v ∈ V–{s}
      do  dist[v] ←∞                       (set all other distances to infinity)
S←∅                                        (S, the set of visited vertices is initially empty)
Q←V                                        (Q, the queue initially contains all vertices)
while Q ≠∅                                 (while the queue is not empty)
do   u ← mindistance(Q,dist)               (select the element of Q with the min. distance)
     S←S ∪ {u}                             (add u to list of visited vertices)
     for all v ∈ neighbors[u]
          do  if   dist[v] > dist[u] + w(u, v)          (if new shortest path found)
                   then      d[v] ←d[u] + w(u, v)       (set new value of shortest path)
                                                        (if desired, add traceback code)
return dist
```

Graph theory – Dijkstra's Algorithm



If A is the source vertex.
What are the shortest paths to vertices:
B, C, D, E, F ,G ,H ?

	A →	B	C	D	E	F	G	H
1								
2								
3								
4								
5								
6								
7								

Return back to WSN for Ariane 5

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Data transfer limit 250 kbits/sec. = 31.25 kBytes/sec.

Module name	NXP JN516X	Telit NE51-2.4	Microchip MRF24J40
Power Supply [V]	2-3.6	2-3.6	2.4-3.6
Data rate [bps]	250k	250k	250k
RX Sensitivity [dBm]	-95	-97	-95
TX Pout [dBm]	up to +2.5	up to +4.5	up to 0
Programmable Pout [dBm]	-30 to +2	N/A	-35 to 0
Power cons. on RX mode [mA]	23	26	19
Power cons. on TX mode [mA]	20	35	23
Sleep time mode [mA]	0.6	2	2
Wake up time [ms]	1.2	N/A	N/A

Each sensor can work in one of 8 frequency channels (only one can be used at a time!)

Return back to WSN for Ariane 5

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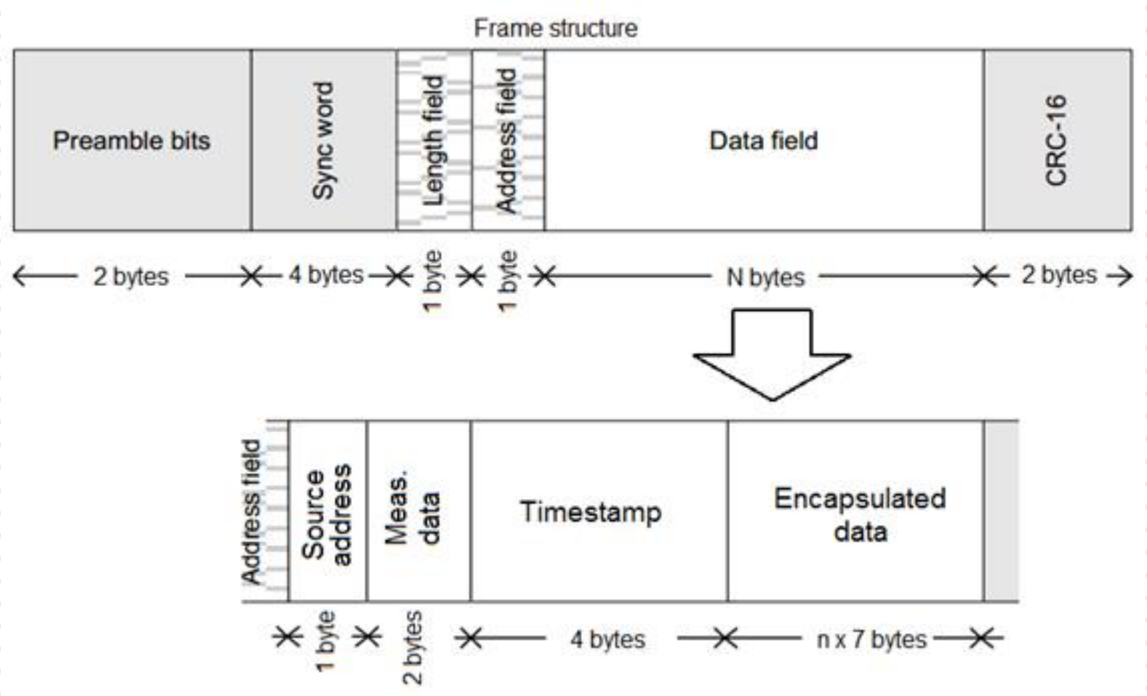
WSN frame



Data = time stamp (32 bits) + measurement data (16 bits)

Assuming 1000 measurements of 2 bytes per second. We need 27 bits to stamp measurement data taken during 24 hours. Conclusion: time stamp 32 bits = 4 bytes.

Conclusion: To send even single measurement of **2** bytes, the total data transfer equals = 2 + 4 + 1 + 1 + 1+ 4 + **2** + 2 = 17 bytes

Return back to WSN for Ariane 5

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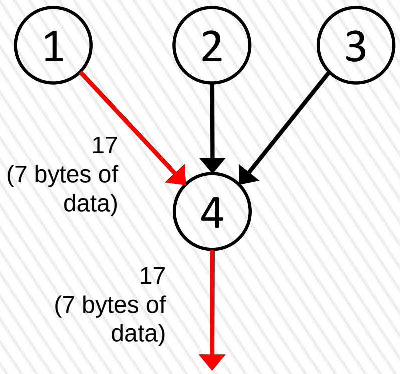
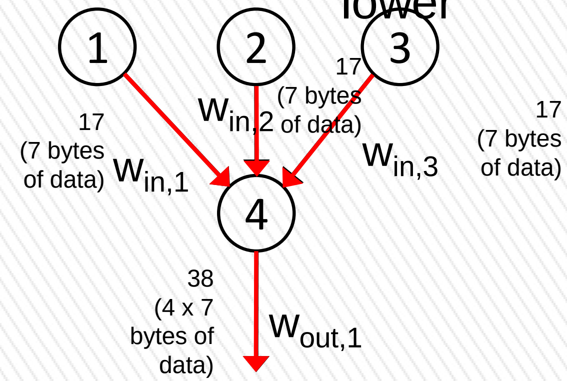
First scenario. Data are resend immediately after receiving



Second scenario. Data are collected from all nodes in layer above and then send out lower

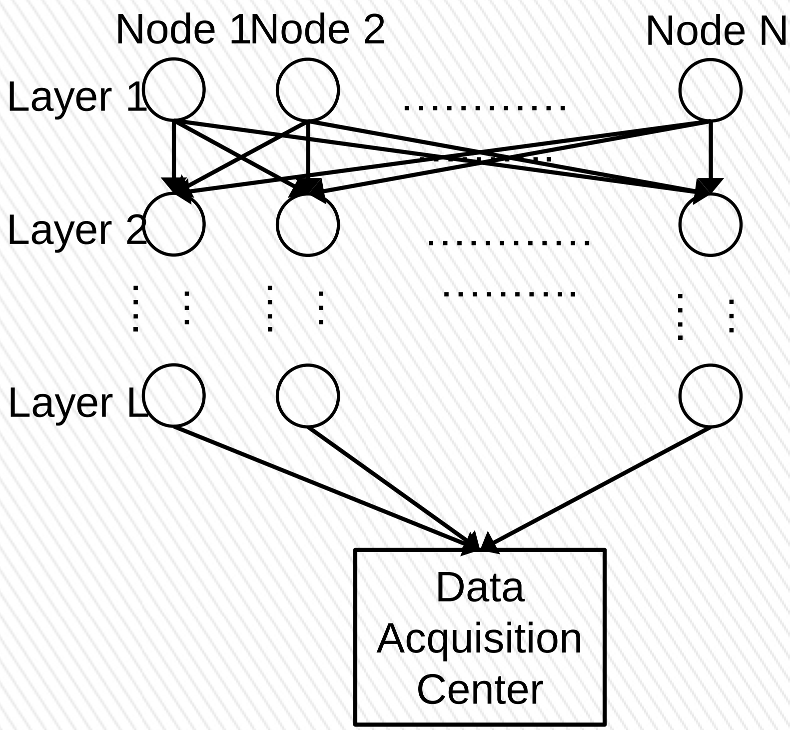


Weights of edges represent data transfer

The maximum data transfer rate is determined as a sum of input data rate and output data rate:

$$\varepsilon(v_i) = \sum_j w_{in,j} + \sum_k w_{out,k} < 250 \text{ kbps}$$

Data rate calculation for a partially connected (layer) topology



Total no. of nodes L*N

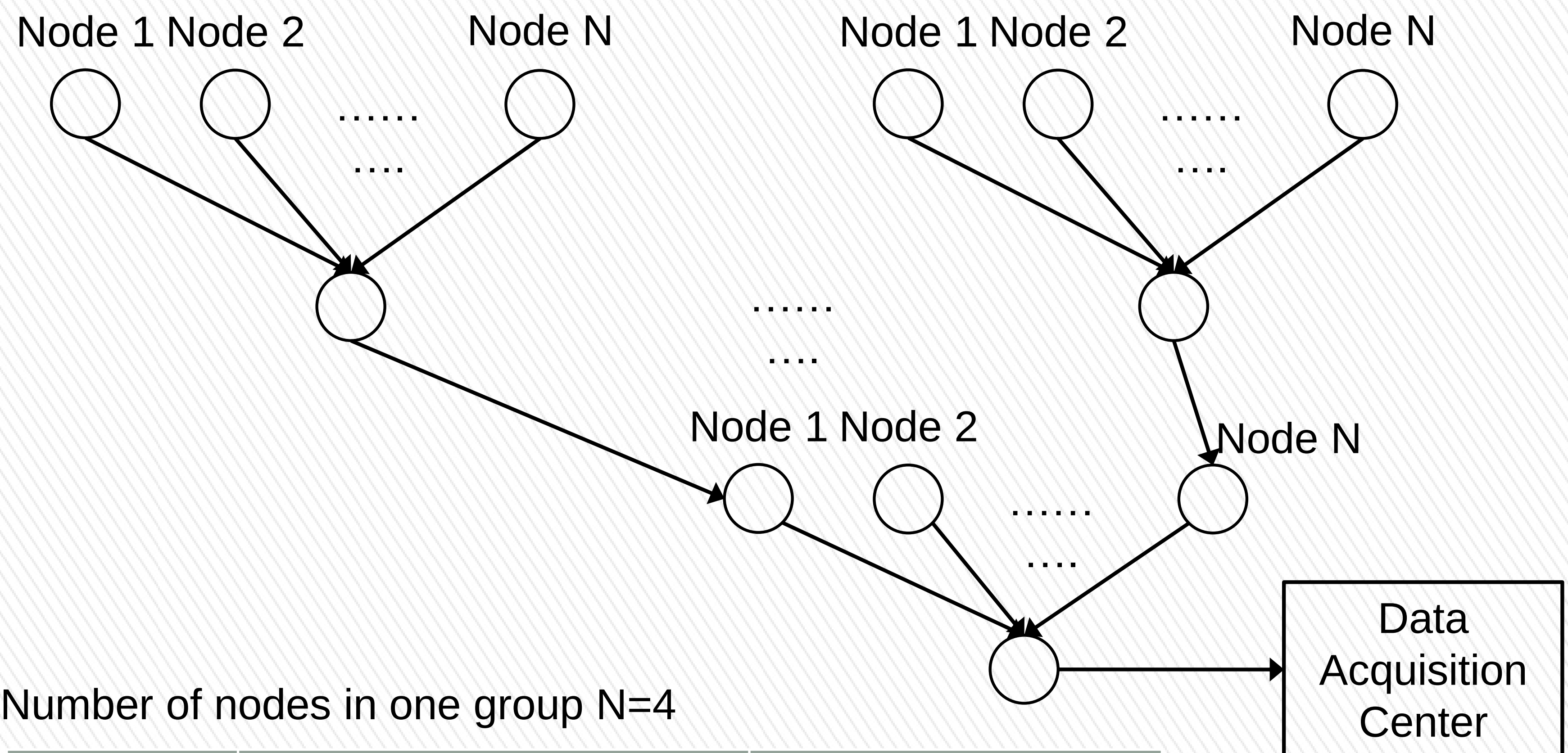
N = 5

Layer number (L)	Data transfer [Byte]			Data rate threshold (total number of nodes)
	Input	Output	Sum	
1	0	17	17	
2	85	52	137	Gyr – 100 sps (10)
3	260	227	487	
4	1135	1102	2237	Press – 10sps (20)
5	5510	5477	10987	Temp – 1 sps (25)
6	27385	27352	54737	

Maximum node throughput = 31.25 kBps!

Data rate calculation for a tree topology

SpaceForest
innovative solutions



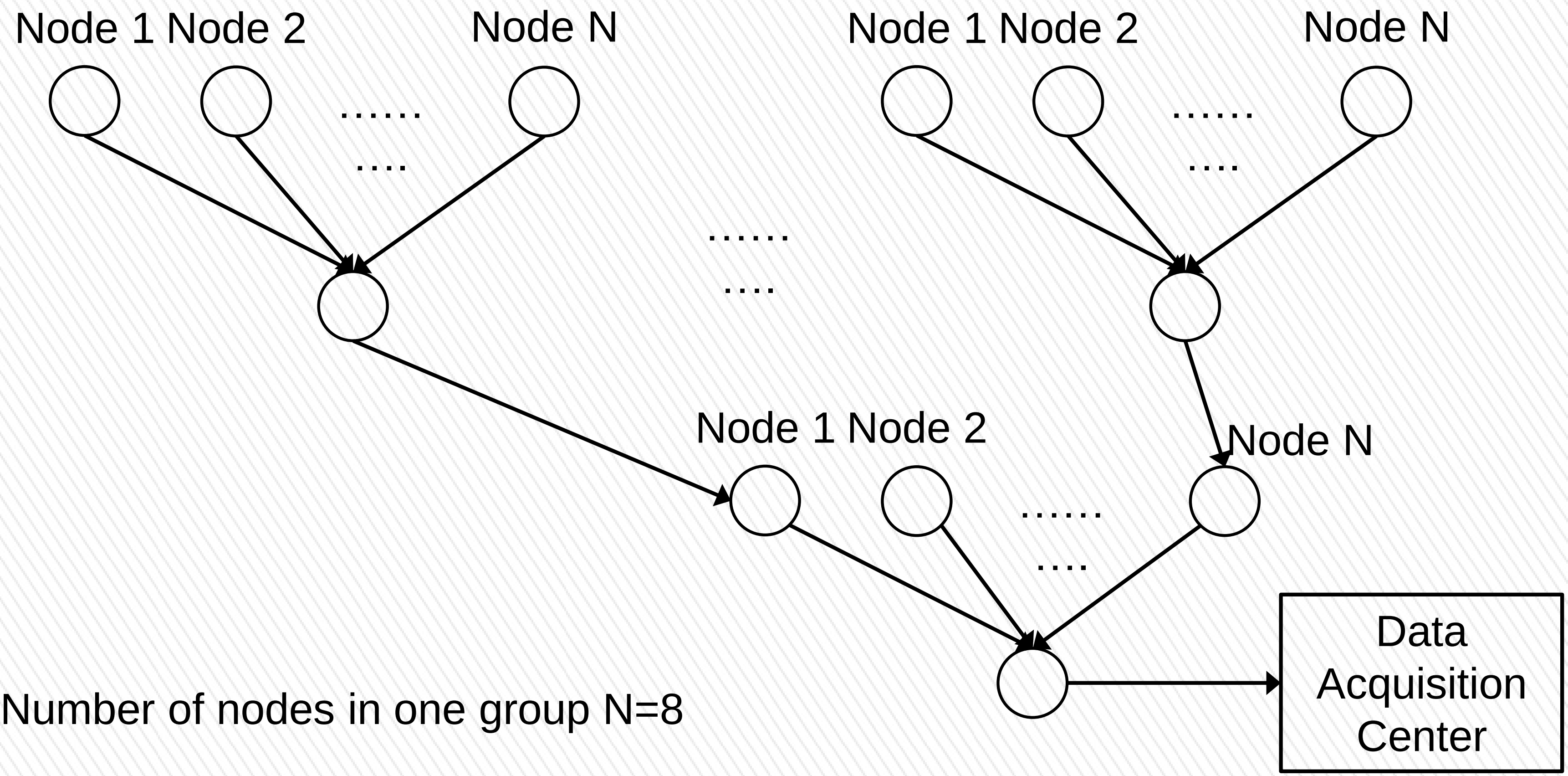
Number of nodes in one group N=4

Layer number (L)	Node Throughput [Bps]			Data rate threshold (total number of nodes)
	Input	Output	Sum	
1	0	17	17	
2	68	45	113	Gyr – 100 sps (5)
3	180	157	337	
4	628	605	1233	Press – 10sps (85)
5	2420	2397	4817	
6	9588	9565	19153	Temp – 1 sps (1365)
7	38260	38237	76497	

Maximum node throughput = 31.25 kBps!

Data rate calculation for a tree topology

SpaceForest innovative solutions



Number of nodes in one group N=8

Layer number (L)	Node Throughput [Bps]			Data rate threshold (total number of nodes)
	Input	Output	Sum	
1	0	17	17	
2	136	73	209	Gyr – 100 sps (9)
3	584	521	1105	Press – 10sps (73)
4	4168	4105	8273	Temp – 1 sps (585)
5	32840	32777	65617	
6	262216	262153	524369	

Maximum node throughput = 31.25 kBps!

Return back to WSN for Ariane 5

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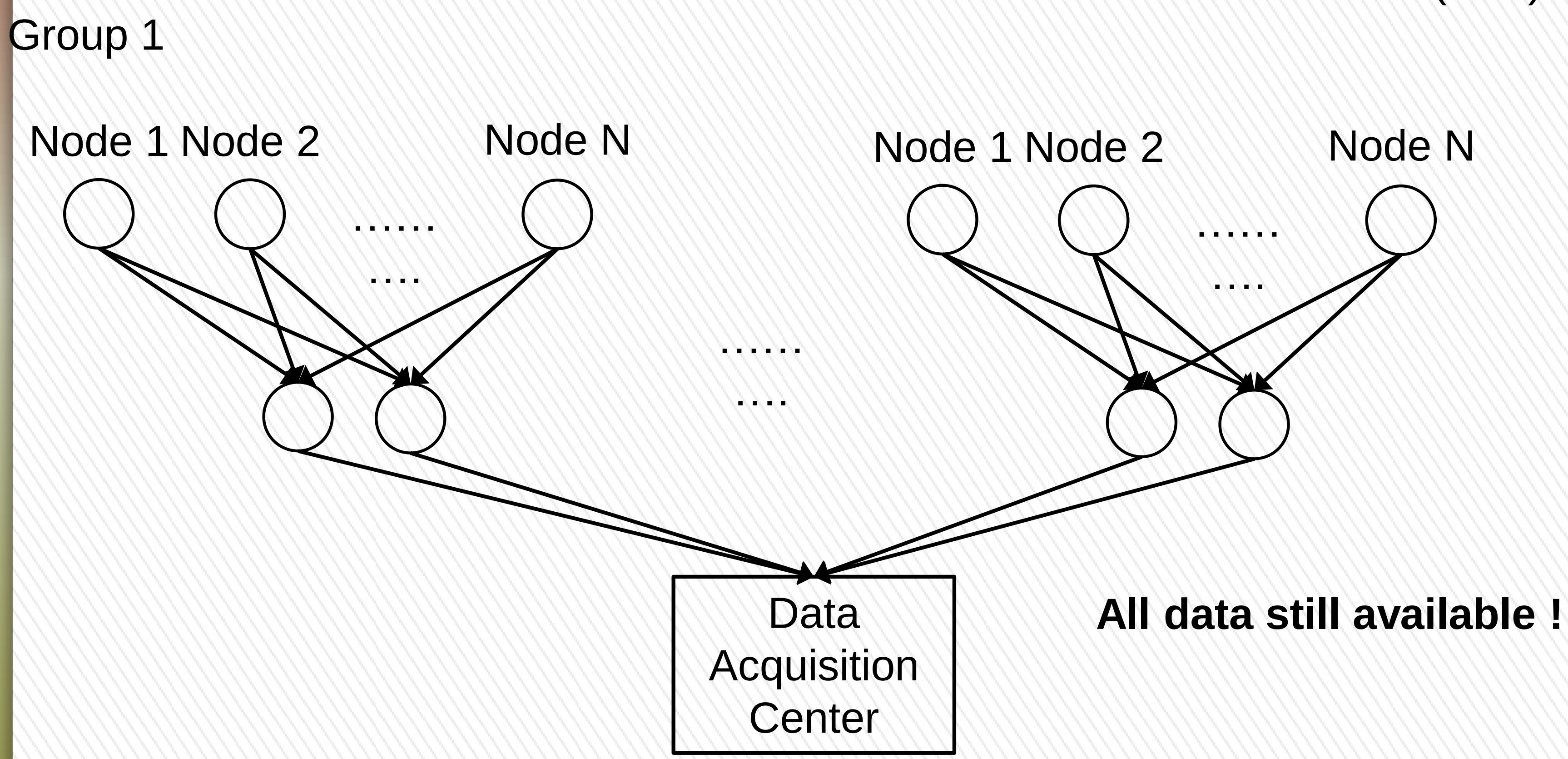
innovative solutions

Topology with redundant nodes

Total no. of nodes G*(N+2)



All data still available !

Return back to WSN for Ariane 5

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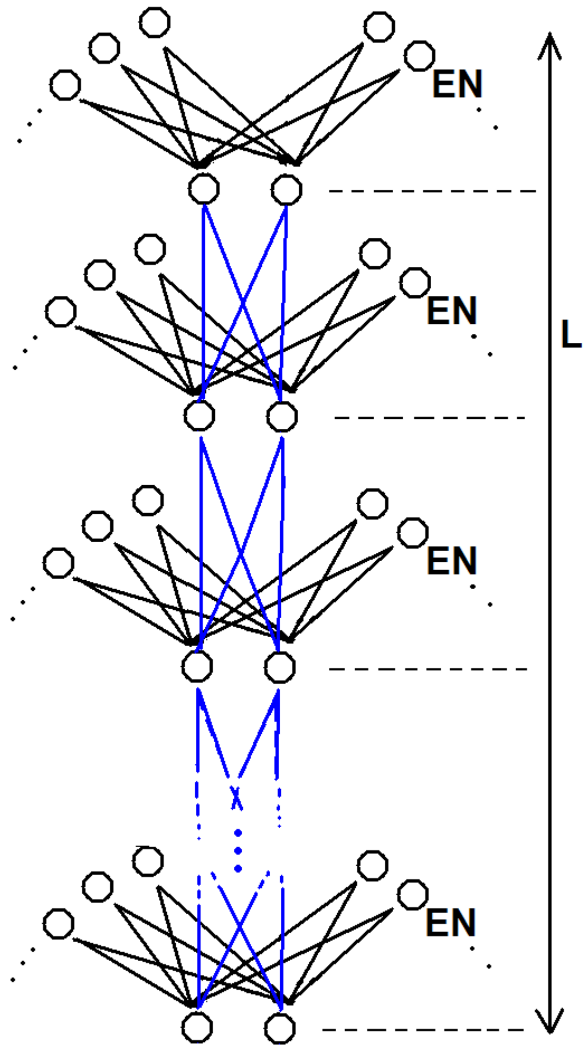
innovative solutions

Topology with redundant nodes (EN = 5)



Layer number (L)	Node Throughput [Bps]			Data rate threshold (total number of nodes)
	Input	Output	Sum	
1	0	17	17	
2	85	45	130	Gyr – 100 sps (10)
3	175	80	255	
..	..	..	..	
35	1295	1200	2495	Press – 10sps (175)
36	1330	1235	2565	
..	..	..	..	
356	12530	12435	24965	Temp – 1sps (1780)
357	12565	12470	25035	

Maximum node throughput = 31.25 kBps!

Example of WSN optimization

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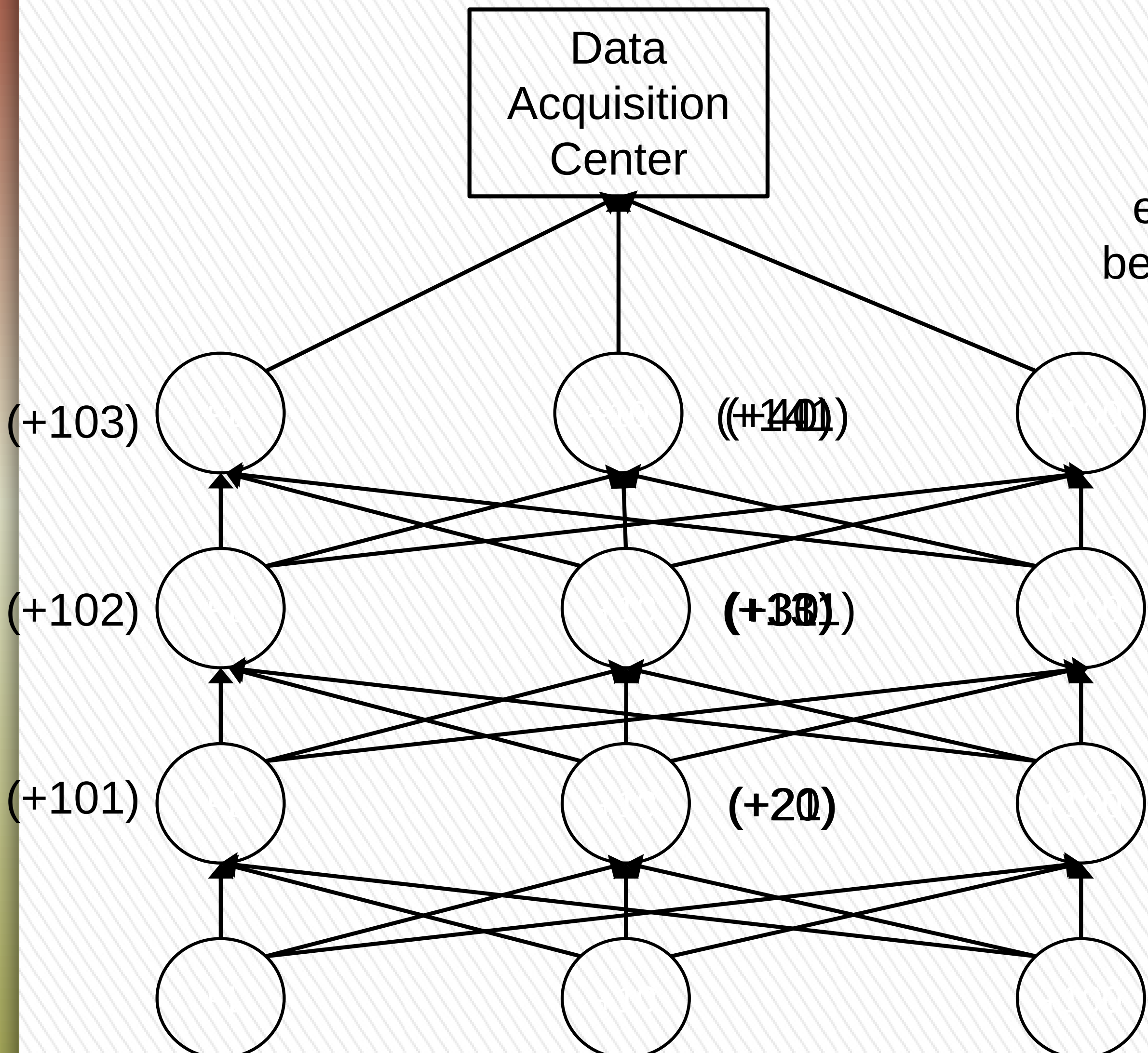
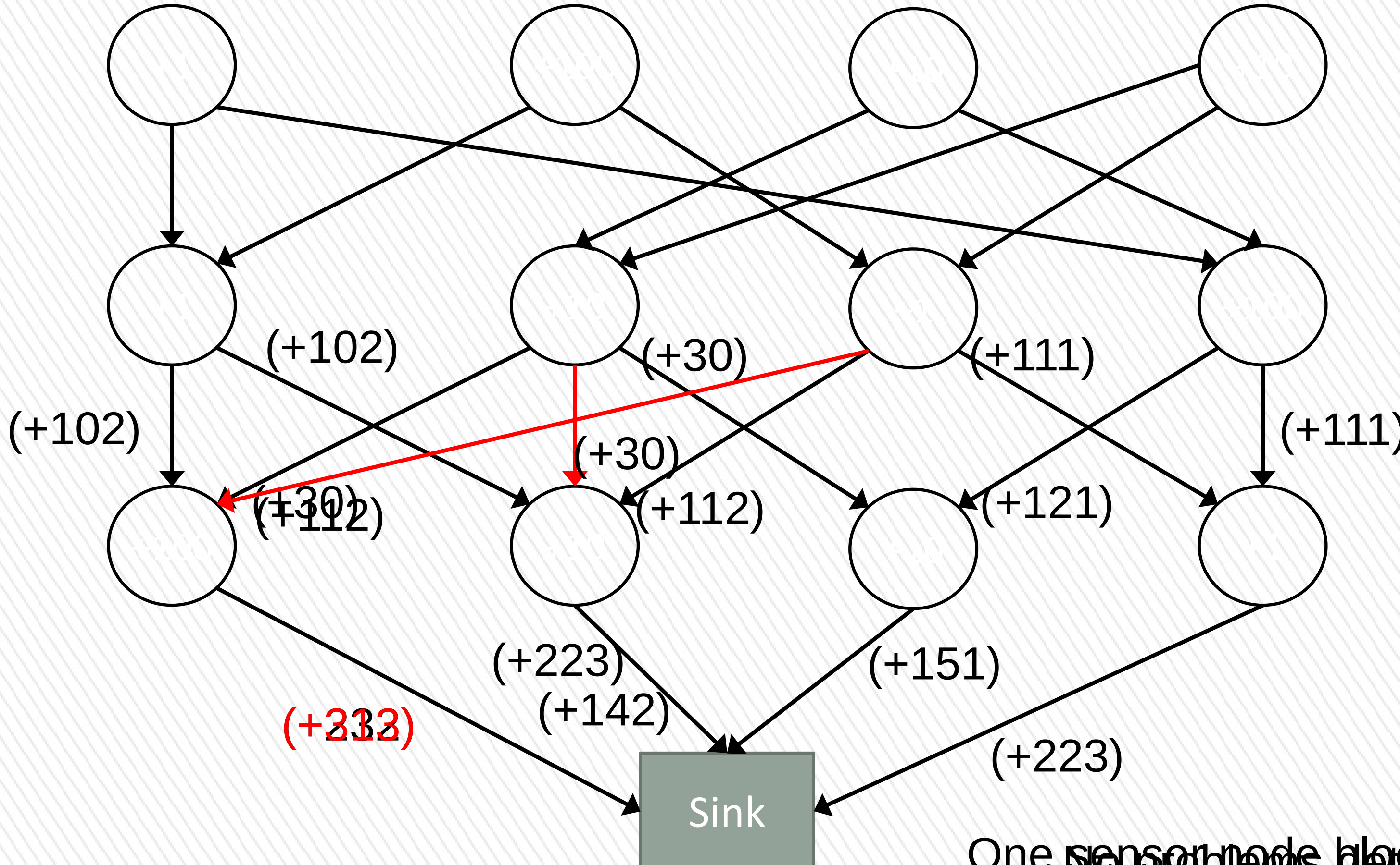


Result:
Spanning tree – a graph enabling unamigous connection between two nodes (here directed)

Famous algorithm for finding the minimum spanning tree (lowest overall edge length):
- Borůvka algorithm

Example of WSN optimization



One sensor node blocked – redundancy lost!

No problems detected!

Maximum bit rate limited to 250 kbps

Problem to solve!

Given are:
- Nodes of the network
- Their physical location
- Sensor parameters
  - Maximal sensor throughput
  - Number of frequency channels
  - Number of measurements per second

We are looking for:
- an appropriate optimization algorithm
- an appropriate optimization cost function for minimization during optimization, example:

$$c_i = h\left(\frac{\varepsilon(v_i)}{T} - 1\right) \qquad C = \sum_i c_i$$

C → 0 for an optimal solution

h( ) – Heaveside function

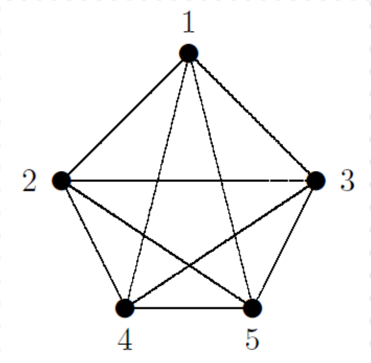
$\varepsilon(v_i) = \sum_j w_{in,j} + \sum_k w_{out,k}$ < T=250 kbps

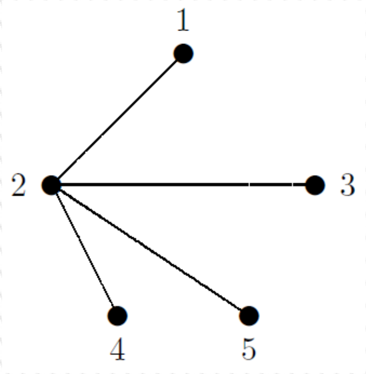
Result:
An optimal Wireless Sensor Network topology.

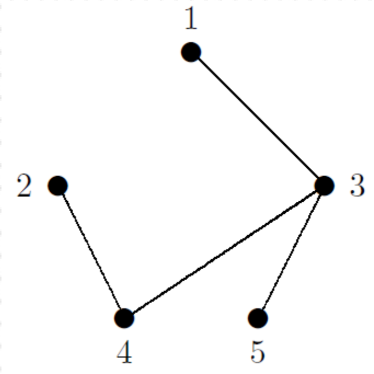
Different approach – spanning trees

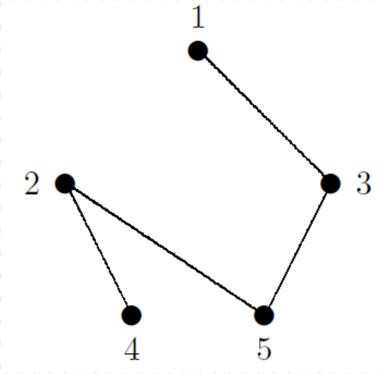
What is spanning tree ?

For a given K_5 complete graph we have 5^3=125 spanning trees









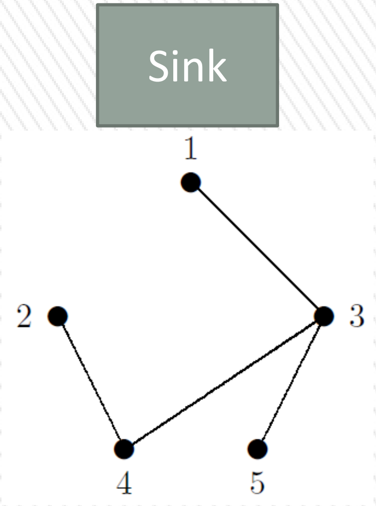
Different approach – spanning trees

Advantages:

- Not redundant network connections -> less susceptible to overloading,

Disadvantages:

- Not redundant network connections -> nor reliable



Different approach – spanning trees

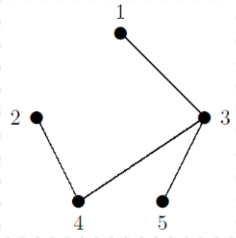
In general for a given complete graph K_n
We have n^{n-2} spanning trees

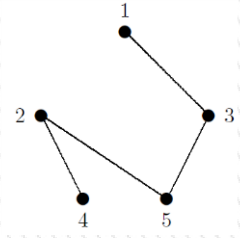
But in our case we have about *n*=800 wireless network nodes (graph vertices)

This gives 800^{798} spanning trees

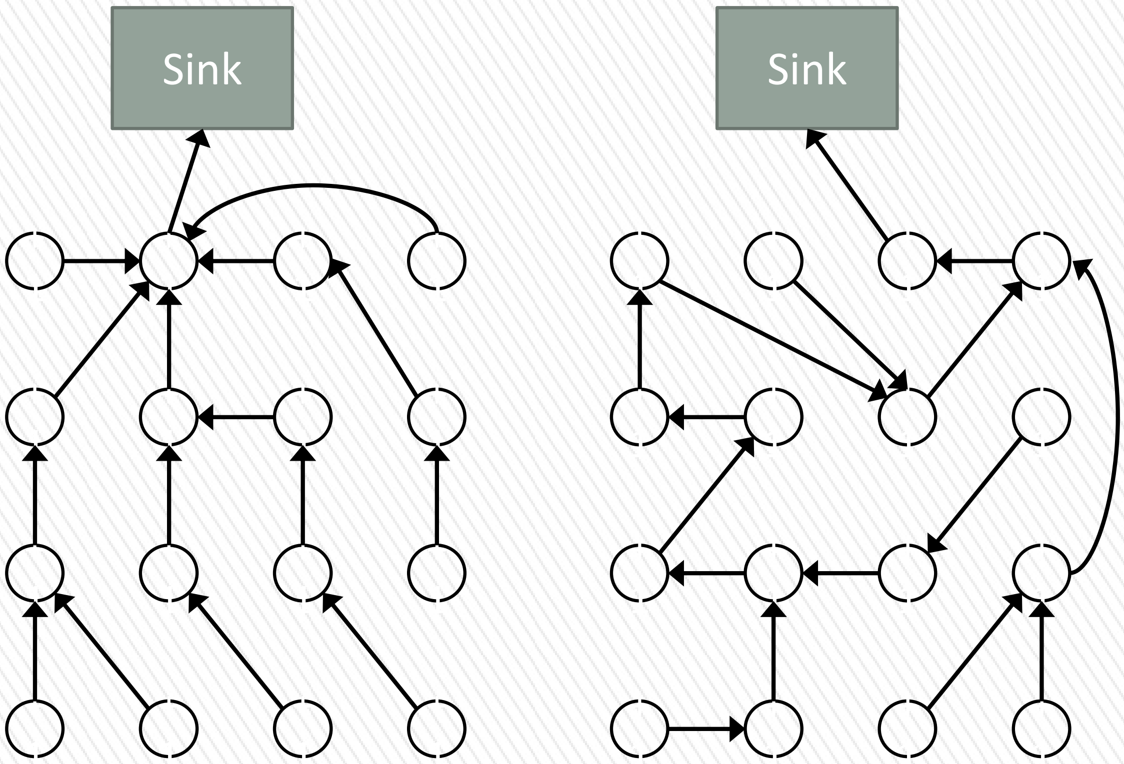
How to find them ?

$$K_n \rightarrow 800^{798}$$



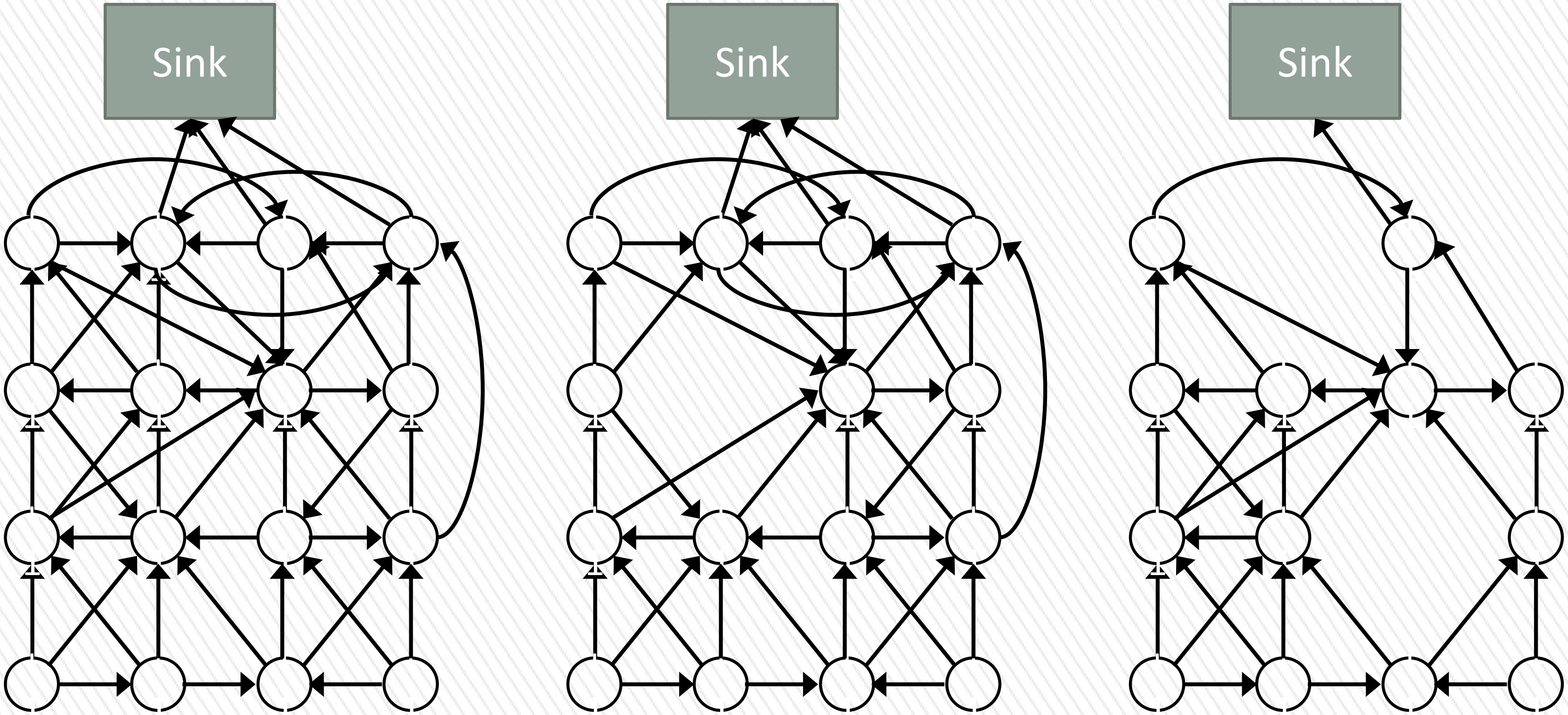


Different approach – spanning trees



In general we have 16^{14} spanning trees

Different approach – spanning trees



Even if some of nodes are broken data are transmitted form the other nodes

Different approach – spanning trees

Algorithm:

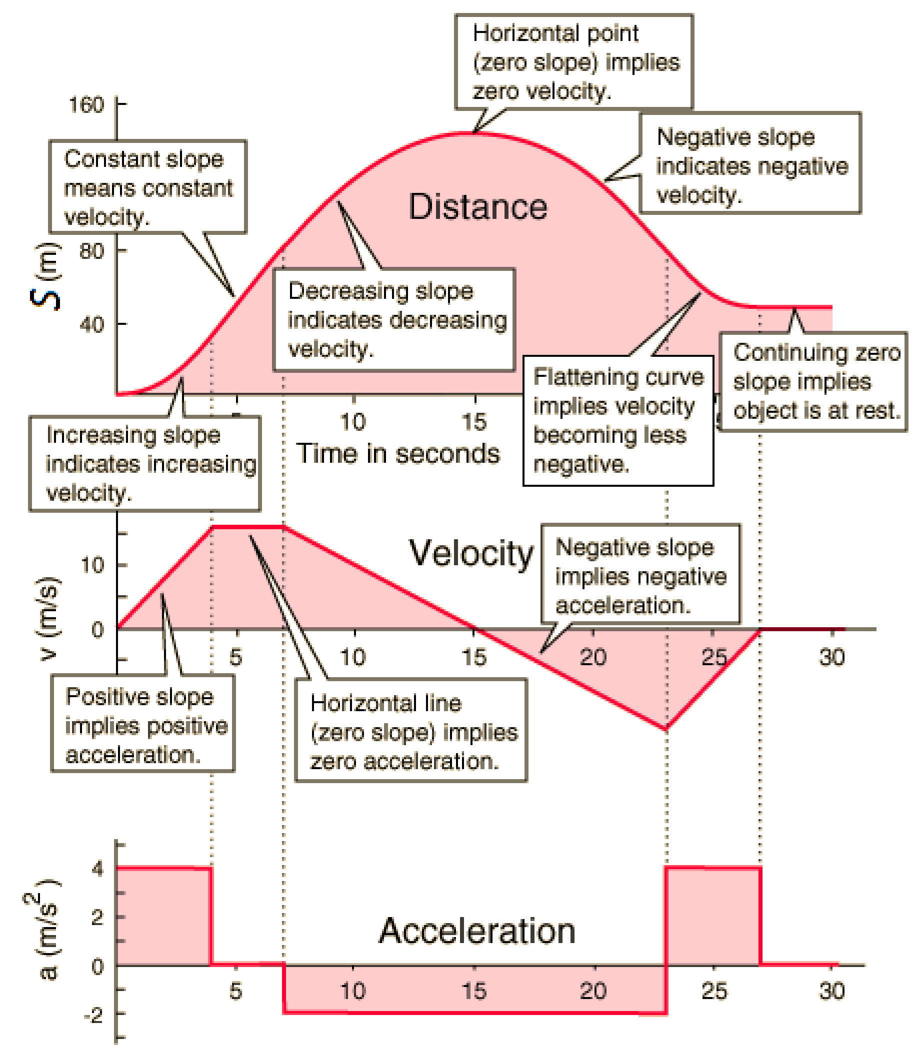
- For a given set of WSN nodes generate T spanning trees such that phisical distance between nodes allows to transfer data between them,
- To each node assign its primary spanning tree,
- Direct the edges of each spanning tree in direct to the sink,
- Any time the node transmits its own measurement data, the transmission goes to all nodes in all its spanning trees,
- Any time the node retransmits measurement data of the other nodes, the transmission goes to the node in its primary spanning trees,

Do we have more time ?

SpaceForest
innovative solutions

Development of a method for calculating the velocity and position of the flying objects using measurements of acceleration

General concept



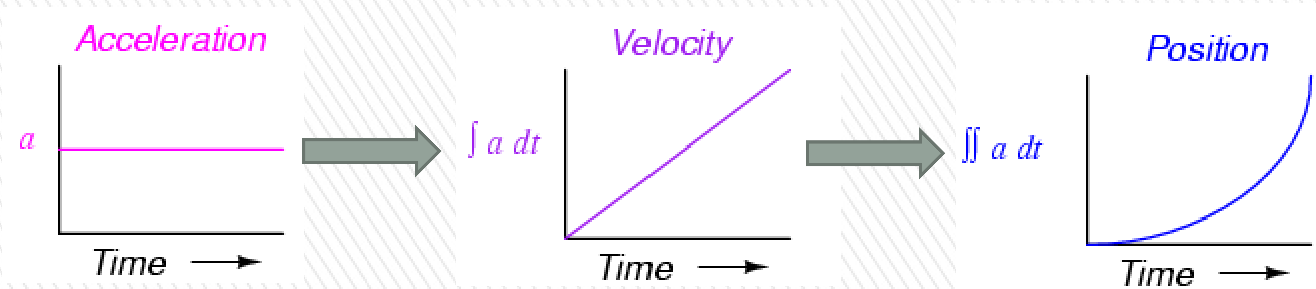
$$v(t) = \frac{dS(t)}{dt}$$

Velocity is defined as the rate of change of position with respect to time

$$a(t) = \frac{dv(t)}{dt} = \frac{d^2S(t)}{dt^2}$$

Acceleration is defined as the derivative of the velocity

General concept



$$a(t) = \frac{dv(t)}{dt} = \frac{d^2S(t)}{dt^2}$$

$$v(t) = \frac{dS(t)}{dt}$$

For move in 3D space we have to consider acceleration in 3 directions

$$\vec{a}(t) = a_x(t)\vec{i}_x + a_y(t)\vec{i}_y + a_z(t)\vec{i}_z$$

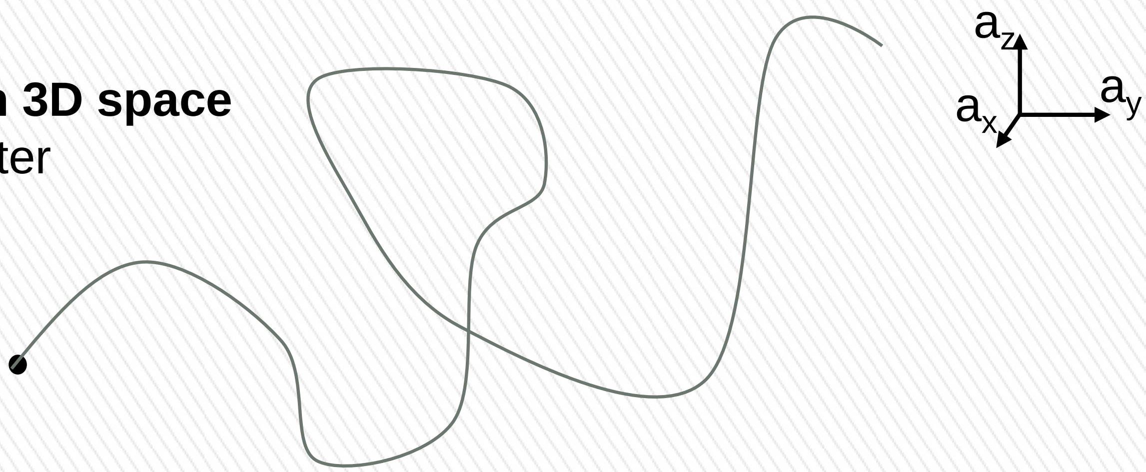
$a_x(t)$ $\qquad v_x(t) = \int_0^t a_x(\tau)\, d\tau \qquad s_x(t) = \int_0^t v_x(\tau)\, d\tau = \iint_0^t a_x(\tau) d\tau^2$

$a_y(t)$ $\qquad v_y(t) = \int_0^t a_y(\tau)\, d\tau \qquad s_y(t) = \int_0^t v_y(\tau)\, d\tau = \iint_0^t a_y(\tau) d\tau^2$

$a_x(t)$ $\qquad v_z(t) = \int_0^t a_z(\tau)\, d\tau \qquad s_z(t) = \int_0^t v_z(\tau)\, d\tau = \iint_0^t a_z(\tau) d\tau^2$

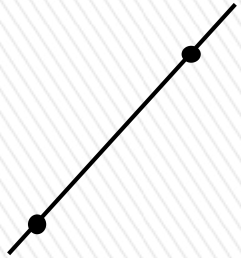
How many accelerometers and where ?

0-dimentional object in 3D space
– 1 accelerometer



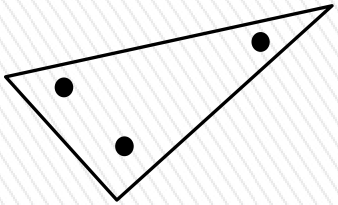
1-dimentional object in 3D space
– 2 accelerometers

Object can rotate !

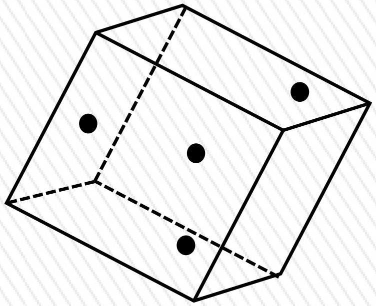


How many accelerometers and where ?

2-dimentional object in 3D space
– 3 accelerometers lying not on the straight line



3-dimentional object in 3D space
– Rocket ! – 4 accelerometers ? And maybe 3 are enough ?



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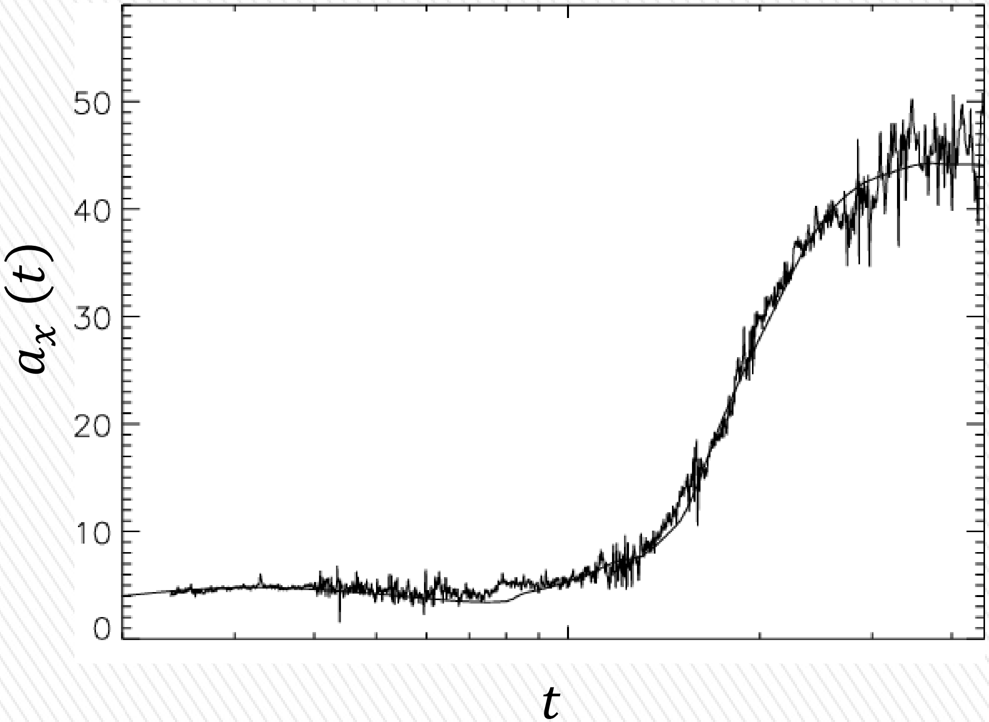


Sources of errors:

- accelerometer noise,
- rocket motor vibrations,
- air drag

$$S_x\ (t) = \iint_0^t [a_x\ (\tau) + n_x\ (\tau)] d\tau^2$$

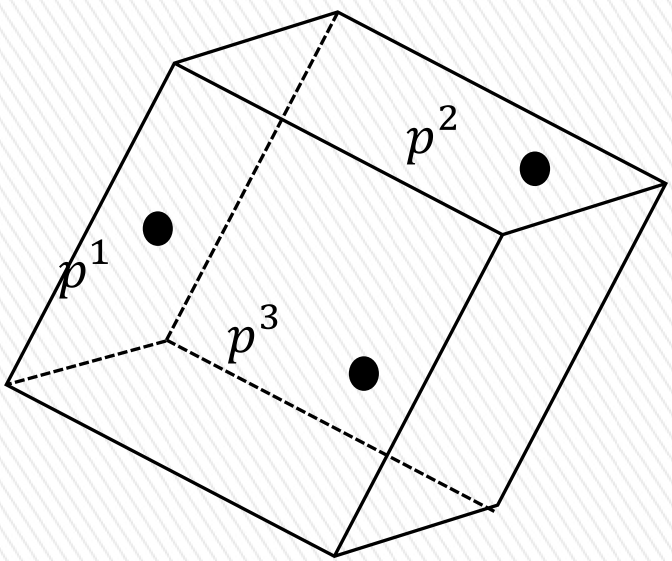
If mean value of $n(t)$ is not equal to zero, the error will cumulate in time *t*

Measurement errors and method of their minimization

$$S_x^i(t) = \iint_0^t \left[a_x^i(\tau) + n_x^i(\tau)\right] d\tau^2 \quad i = 1,2,3$$

$$S_y^i(t) = \iint_0^t \left[a_y^i(\tau) + n_y^i(\tau)\right] d\tau^2 \quad i = 1,2,3$$

$$S_z^i(t) = \iint_0^t \left[a_z^i(\tau) + n_z^i(\tau)\right] d\tau^2 \quad i = 1,2,3$$



$$\begin{matrix} p^1\,(S_x^1, S_y^1, S_z^1) \\ p^2\,(S_x^2, S_y^2, S_z^2) \\ p^3\,(S_x^3, S_y^3, S_z^3) \end{matrix} \left\{ \begin{matrix} \|p^1 - p^2\| = d^{12} \\ \|p^2 - p^3\| = d^{23} \\ \|p^1 - p^3\| = d^{13} \end{matrix} \right.$$

How $n(t)$ functions look like ???

$n_x^i(t), n_y^i(t), n_z^i(t)$?, $i = 1,2,3$

Conclusions

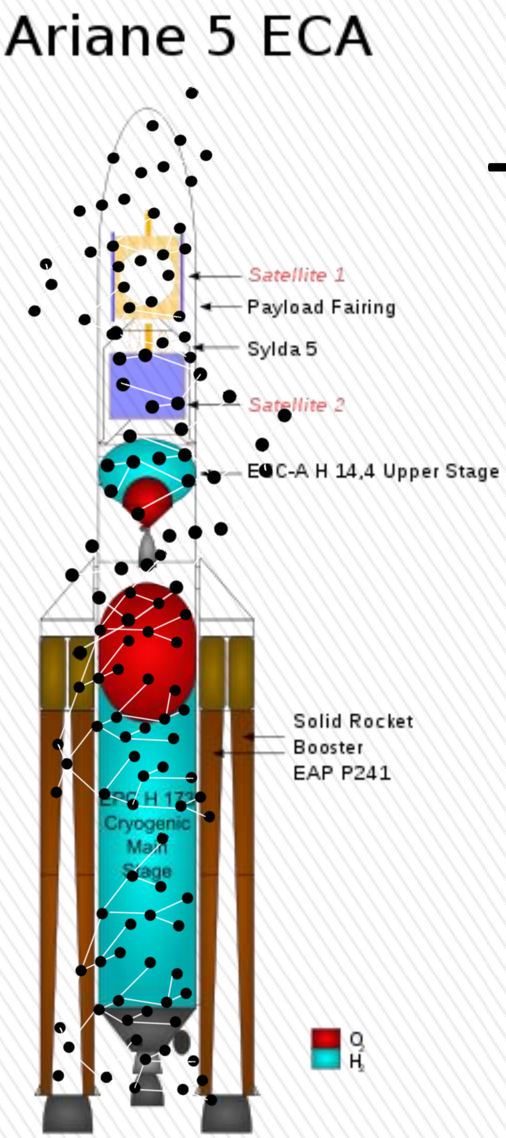
A Wireless Sensor Network needs to be used to decrease the mass of the Ariane 5 rocket.

To find an optimal WSN, an optimization algorithm must be created, which would take the following optimization parameters into account

- number of sensors
- available data throughput of each sensor
- number of data created in time unit by each sensor
- data priority
- network redundancy
- physical distance between sensors and wave propagation conditions

Knowing these parameters and using graph theory algorithms, an adequate optimization cost function (shortest path for the most important sensors, optimal transmission bit rate for each node) can be built and an optimal solution (network topology) can be found.

After successfully completed tests, the proposed solution can become a potential solution for different networking problems, including sensor network in Ariane 5.



Thank you for attention