

# Embedded Internet and the Internet of Things

## WS 12/13

### 9. Testbeds and Experimentation

Prof. Dr. Mesut Güneş  
Distributed, embedded Systems (DES)  
Institute of Computer Science  
Freie Universität Berlin

# Overview

---

- Motivation
- Testbed architectures
- Historical review of testbeds
- The "Testbed in the box" problem
- Experiment lifecycle
- The DES approach
- Analysis of experiments

---

# Motivation

# Motivation

---

- Plenty of applications and protocols proposed
  - Performance evaluation mostly analytical or simulative
    - Reported performance do not hold in real world
    - Integration and interfaces required for real applications
    - Design and implementation patterns needed
  - Experiment environments (testbeds) required
    - Research and development mix up
    - Real HW/SW interaction
    - Experiments on real HW/SW
    - System software
  - Experiments on testbed shall support analytical and simulative models
- > New challenges with experimentally-driven research

151 papers presented at MobiHoc (2000-2005)

- 114 of 151 (75.5%) are simulation-based papers
- 34 of 114 (29.8%) did not state simulator used
- 98 of 112 (87.5%) did not include confidence intervals
- 106 of 114 (93%) did not address initialization bias
- ...

*MANET Simulation Studies: The Incredibles, ACM's Mobile Computing and Communications Review, 9(4):50-61, 2005.*

“ ... there are a number of ways in which you can go about doing network system performance analysis. In order of **increasing ugliness**, they are as follows:

- 1) Conduct a mathematical analysis which yields explicit performance expressions.
- 2) Conduct a mathematical analysis which yields an algorithmic or numerical evaluation procedure.
- 3) Write and run a simulation.
- 4) Build the system and then measure its performance!

”

*Leonard Kleinrock, On the modeling and analysis of computer networks, Proc. IEEE, 1993*

# Challenges of a testbed

---

- What is a testbed?



Not satisfying, since unrealistic

- WSN/IoT consist of high number of nodes
- Typical WSN protocols cannot be evaluated

- Specific challenges

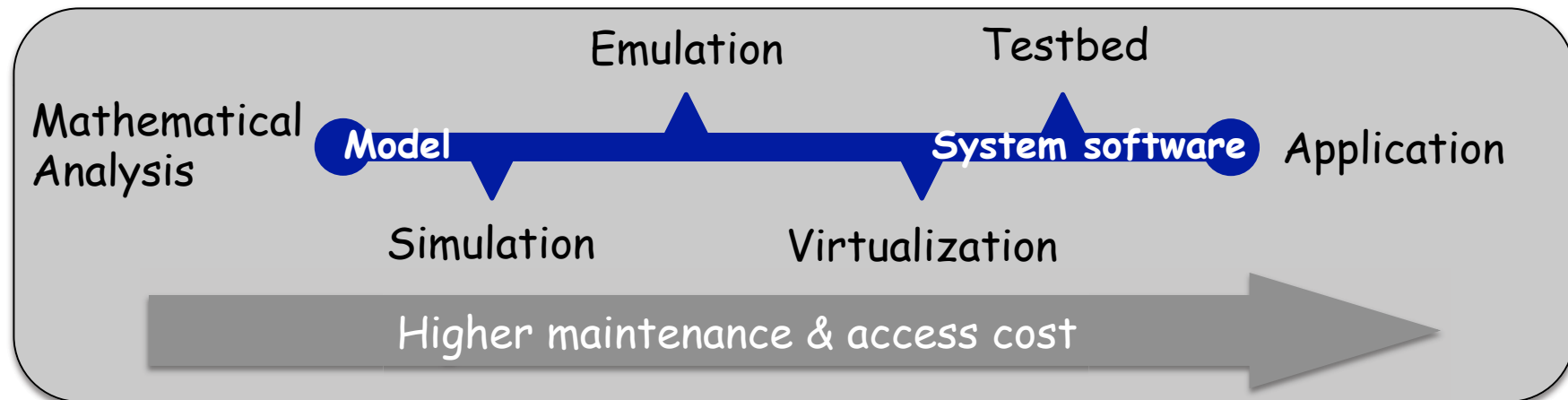
- High number of nodes
- Influence of network environment
- Side effects, e.g., collecting of results during experiment runtime may influence results

---

# Testbed architectures

# Testbed architectures

- Study environments (for wireless networks)
  - Different degrees of realism
  - Researcher adapts to the facility of choice



- **Trend: From simulations to testbeds!**

# Testbed architectures

---

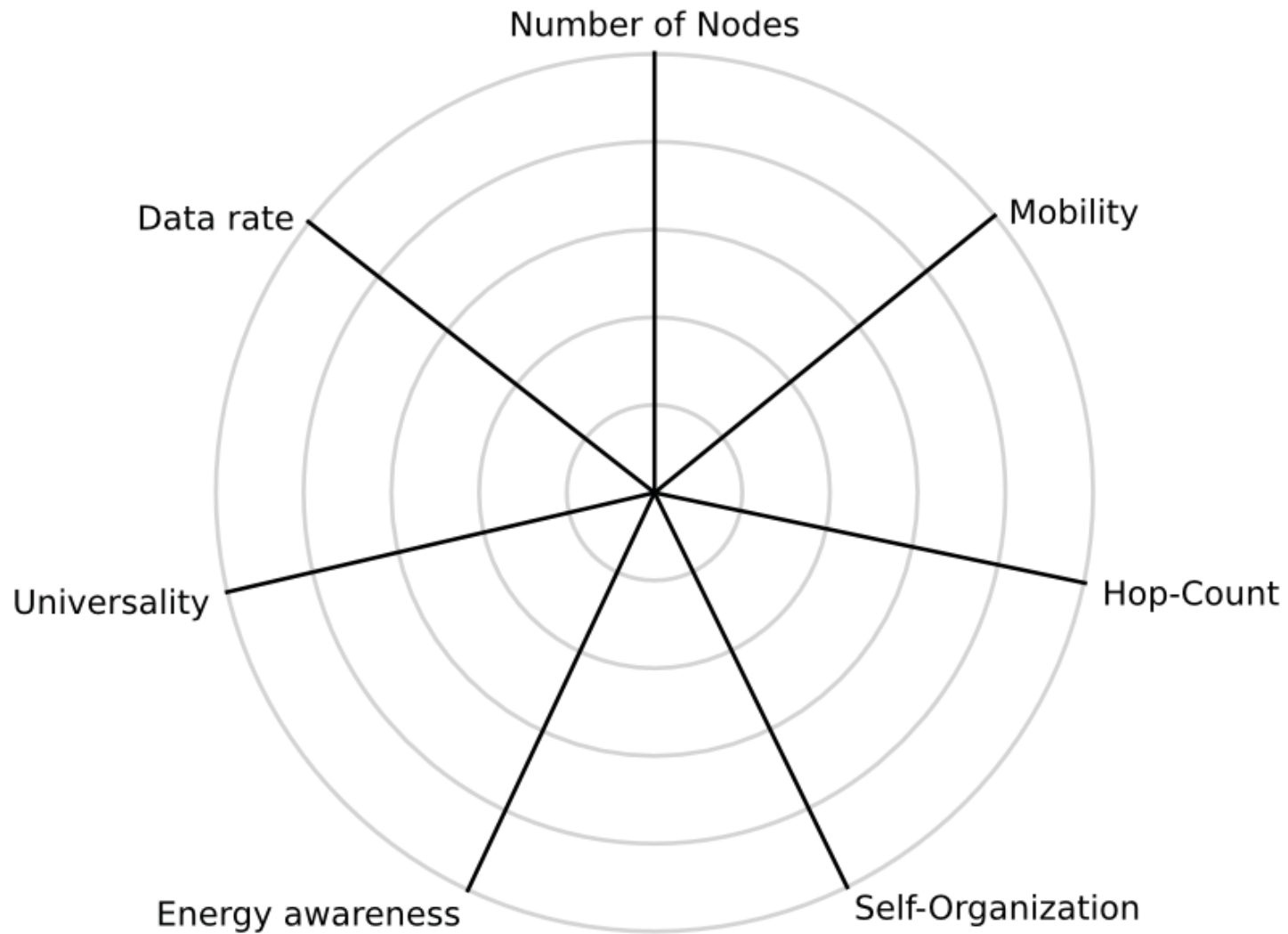
- Differences between testbed and productive network?
  - Location/Environment: Interference, Signal loss, ...
  - Topology
  - Platform (HW/SW)
  - Infrastructure: Testbed specific HW + management

-> Even a testbed is not always the same. It may change over time, e.g., day of week, number of people, open/close doors, etc.

# Testbed architectures

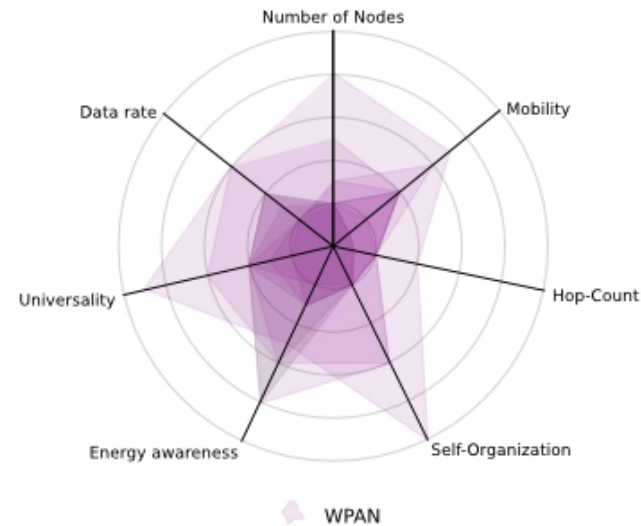
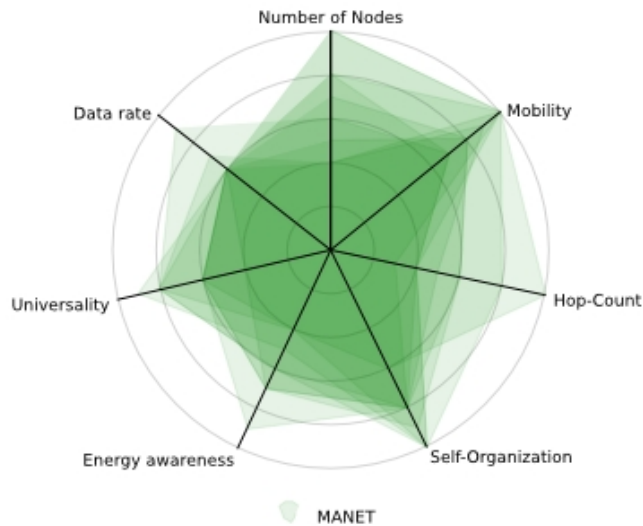
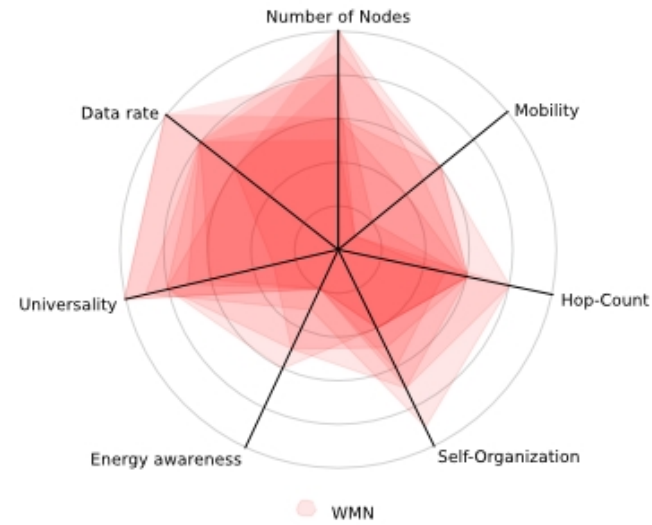
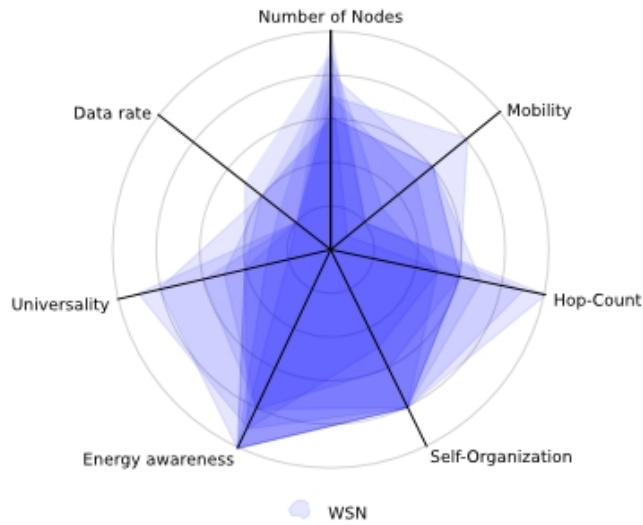
## Characteristics of Wireless Networks

---



# Testbed architectures

## Characteristics of Wireless Networks



# Study Environments

---

- **Applicability:** Degree of transferability of the results, conclusions, and the study environment into the real world.
- **Repeatability:** Rates how straightforward the repetition of a given experiment in that study environment is.
- **Controllability:** Assesses the degree of control the researcher has over the study environment as well as the studied subject.
- **Maintainability:** Describes the effort to maintain the evaluation environment.
- **Scenario creation:** Describes the flexibility in creating different experiment scenarios.
- **Scalability:** Assesses the feasibility of large scale experiments with respect to the number of nodes in the network, the experiment duration, and the number of network connections during the experiment.
- **Duration:** Describes the experiment time.
- **Cost:** Evaluates the cost of experiments.

# Study Environments: Characteristics

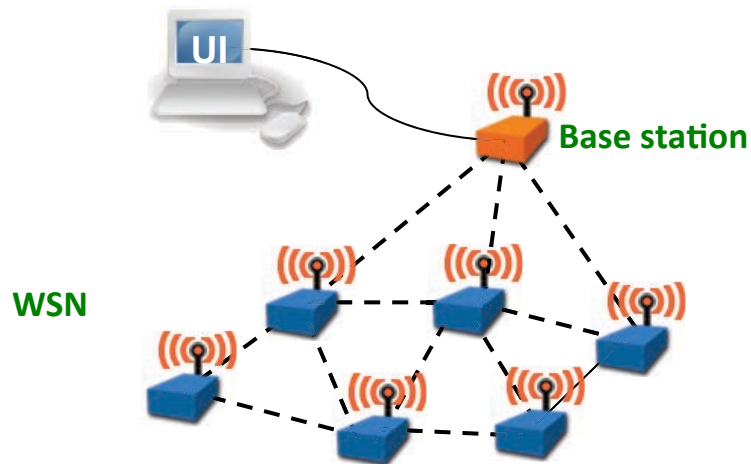
Characteristic	Environments				
	Theoretical Analysis	Simulation	Emulation	Virtualization	Testbed
Applicability	—	low	middle	high	high
Repeatability	—	high	low	low	low
Controllability	—	high	middle	middle	low
Maintainability	—	low	middle	middle	high
Scenario creation	—	simple	middle	middle	hard
Scalability	—	high	middle	middle	low
Duration	—	variable	realtime	realtime	realtime
Cost	—	low	middle	middle	high

# Study Environments: Support of Network Layers

Layer (ISO/OSI)	Environments				
	Theoretical Analysis	Simulation	Emulation	Virtualization	Testbed
Application	—	low	high	high	high
Transport	—	low/high	middle	high	high
Network	—	low	middle	high	high
Data Link	—	high	middle	middle	high
Physical	—	high/low	middle	low	high

## 2-Tier

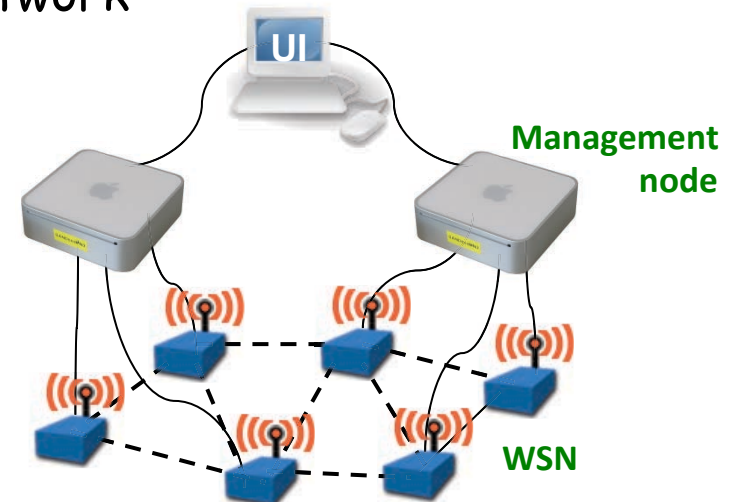
- Experiment data and management data are transmitted over same medium
- Experiment data is stored in the nodes



Suitable for simple/short experiments

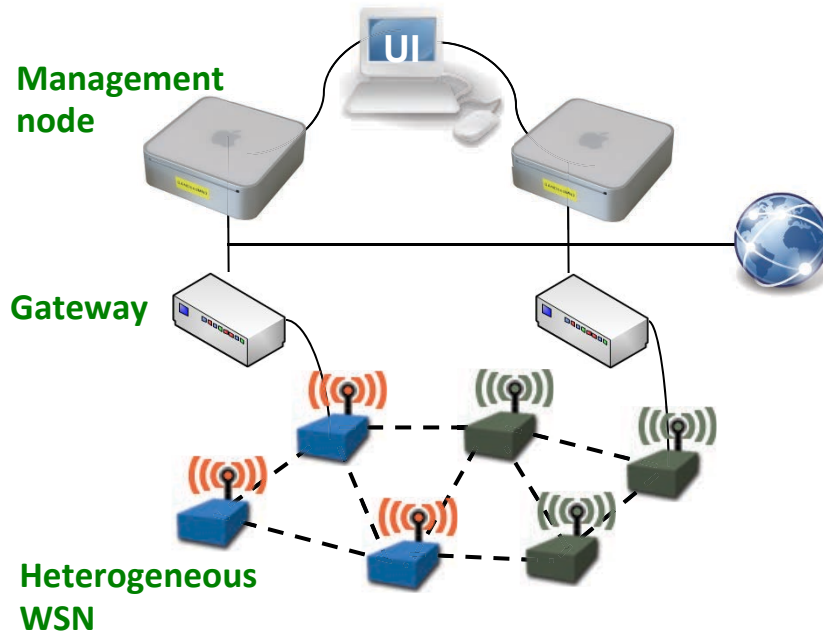
## 3-Tier

- Separate medium for experiment data and management data
  - Complex, but more flexible management
  - Additional HW for management required
- Management data is transmitted over separate "management network"



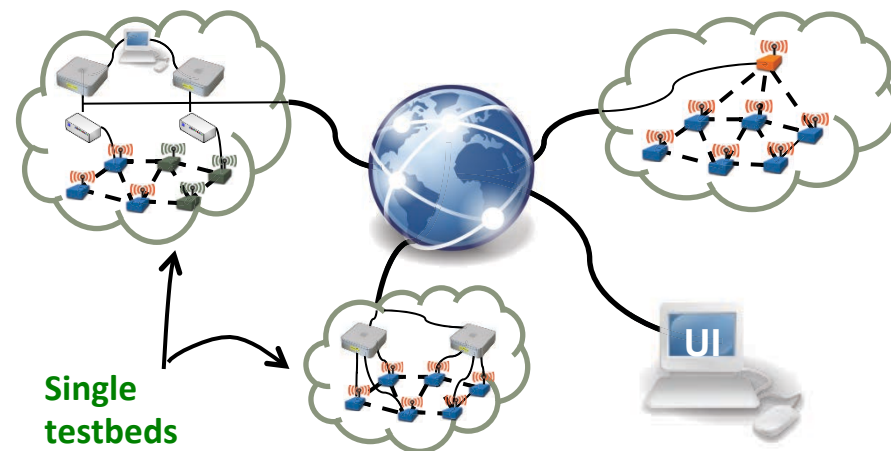
## 4-Tier

- Testbed can communicate to other networks via a bridge/gateway
  - Complex management
- Often heterogeneous HW in testbed



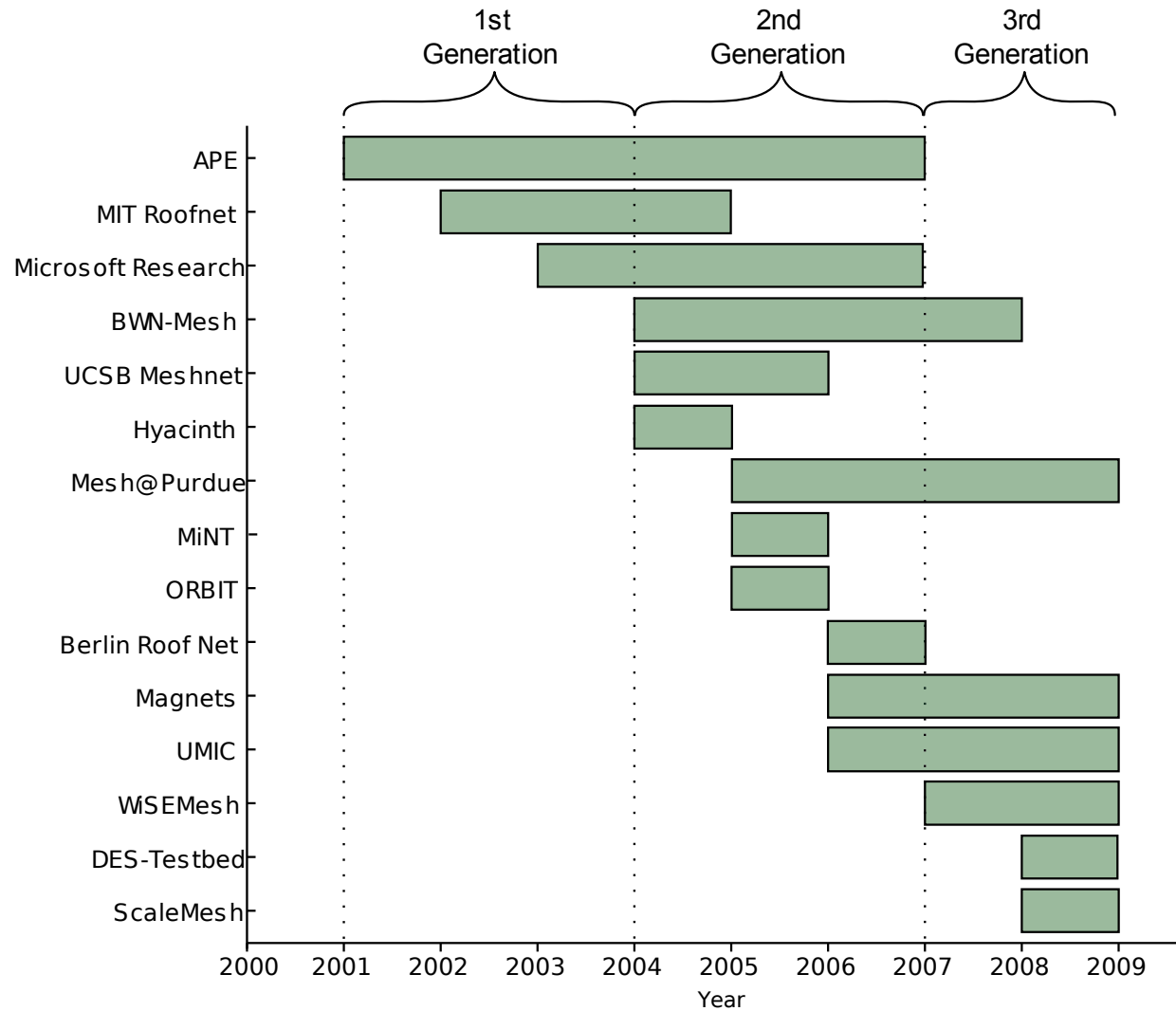
## Testbed federation

- Connecting of multiple testbeds with different architectures over the Internet -> Federation
- Unified management -> Interfaces for different approaches required
- Heterogeneous HW



# Historical review of testbeds

# Historical review of testbeds



# Historical review of testbeds

Project	Nodes	Radio	OS	Routing		Mobility	Internet
				Layer	Protocols		
APE	??	a/b/g	Linux	IP	AODV-UU, Mad-hoc AODV, OLSR, LUNAR, TORA, DSR	x	-
BWM-Mesh	15	b/g	??	??	??	-	-
Carleton Univ.	??	a/b/g	$\mu$ CLinux	IP	QoS enhanced OLSR	-	-
DES-Mesh	100	b/g	Linux	IP	# $\geq$ 10	-	-
Hyacinth	9	a	Windows XP	??	??	-	-
MP	32	a/b/g	Linux	IP	AODV, OLSR	-	x
Microsoft Research	23	a/b/g	Windows CE	MAC	LQSR	-	-
MiNT	12	a/b/g	Linux	IP	??	x	-
MIT Roofnet	50	b/g	Linux	IP	Srcr	-	x
Berlin Roof Net	??	b/g	Linux	IP	??	-	x
ORBIT	64	a/b/g	Linux	IP	??	-	-
Meshnet	25	a/b/g	Linux	IP	AODV	-	-
UMIC-Mesh	51	a/b/g	Linux	IP	DYMO, OLSR	-	-
WiSEMesh	56	b/g	Linux	IP	OLSR	-	x

# Historical review of testbeds

Project	Nodes	Hardware	OS	Routing	Mobility
Casino Lab	52, 26	Tmote Sky, Tmote Connect	??	??	–
DES-WSN	2×100	MSB-A2	Contiki	??	–
DSN	2×30	BTnode, Tmote, TinyNode, A80, ...	BTnut	AODV	–
ExScal .	1000, 200	XSM, XSS	TinyOS	LGR	–
Kansei	2×210, 50, 5	XSM, XSS, Trio	??	??	x
MoteLab	190	Tmote Sky	TinyOS	??	–
Tutornet	104, 13	Tmote Sky, MicaZ, Stargate	TinyOS	??	–
TWIST	200	eyesIFX, Telos, NSLU2	TinyOS	??	–
Great Duck Island	147	Mica	TinyOS		–
Skomer Island	10	MSB-430, MSB-H	ScatterWeb	MicroMesh	–
ZebraNet	7	ZebraNet node	??	??	x
Redwood macroscope	27	Mica2Dot	TinyOS	MintRoute	–
Univ. of W. Australia	??	Mica2	TinyOS	??	x
Edgar Mine	10	??	??	??	–
Volcano	16	TMote Sky	TinyOS	MintRoute	–
GlacsWeb	8	unnamed custom product	??	single hop	–
PermaSensorGIS	??	??	??	??	–
heathland experiment	5	ESB	ScatterWeb	??	–

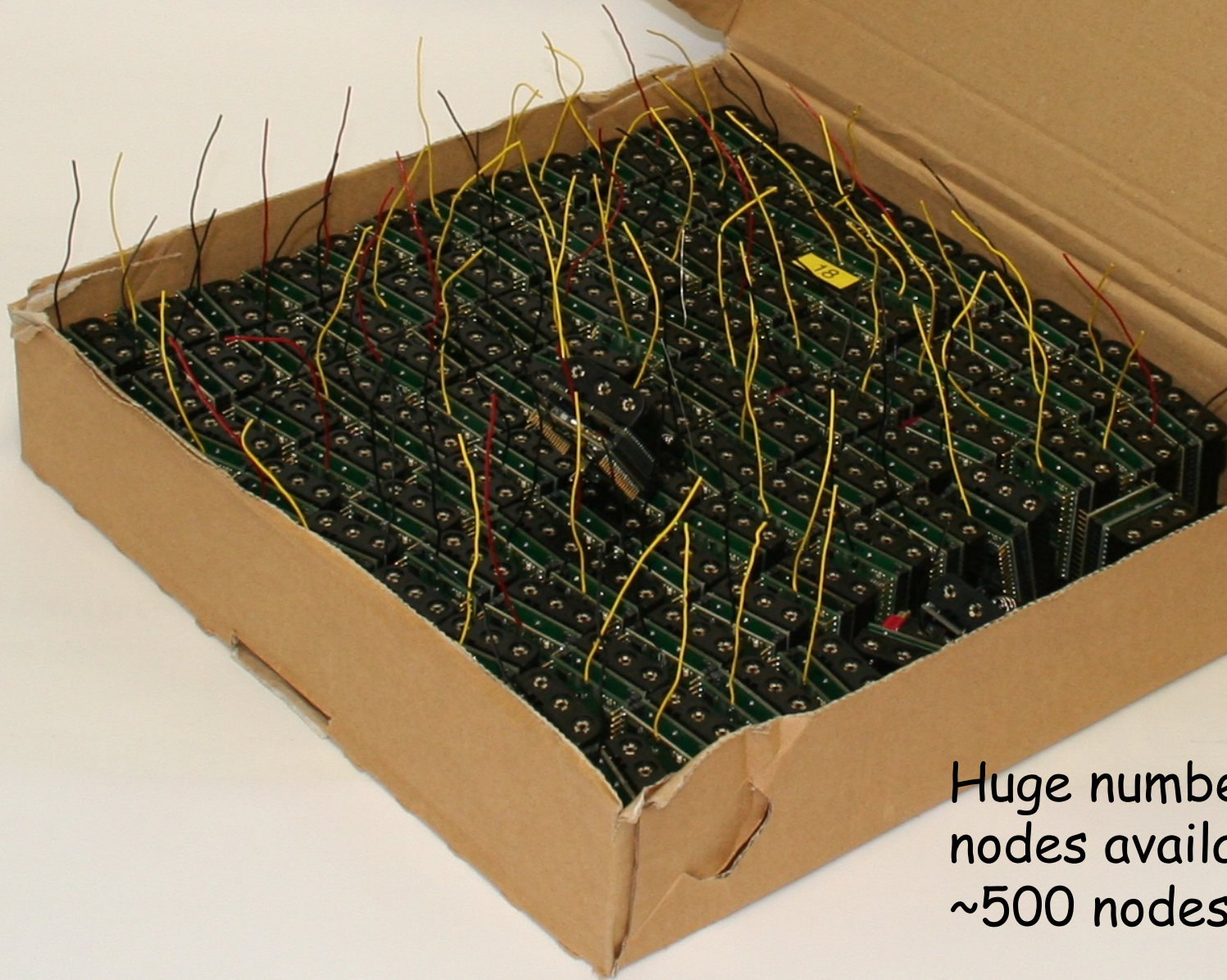
---

## The “Testbed in the box” Problem or why we need a persistent testbed?

# Available hardware

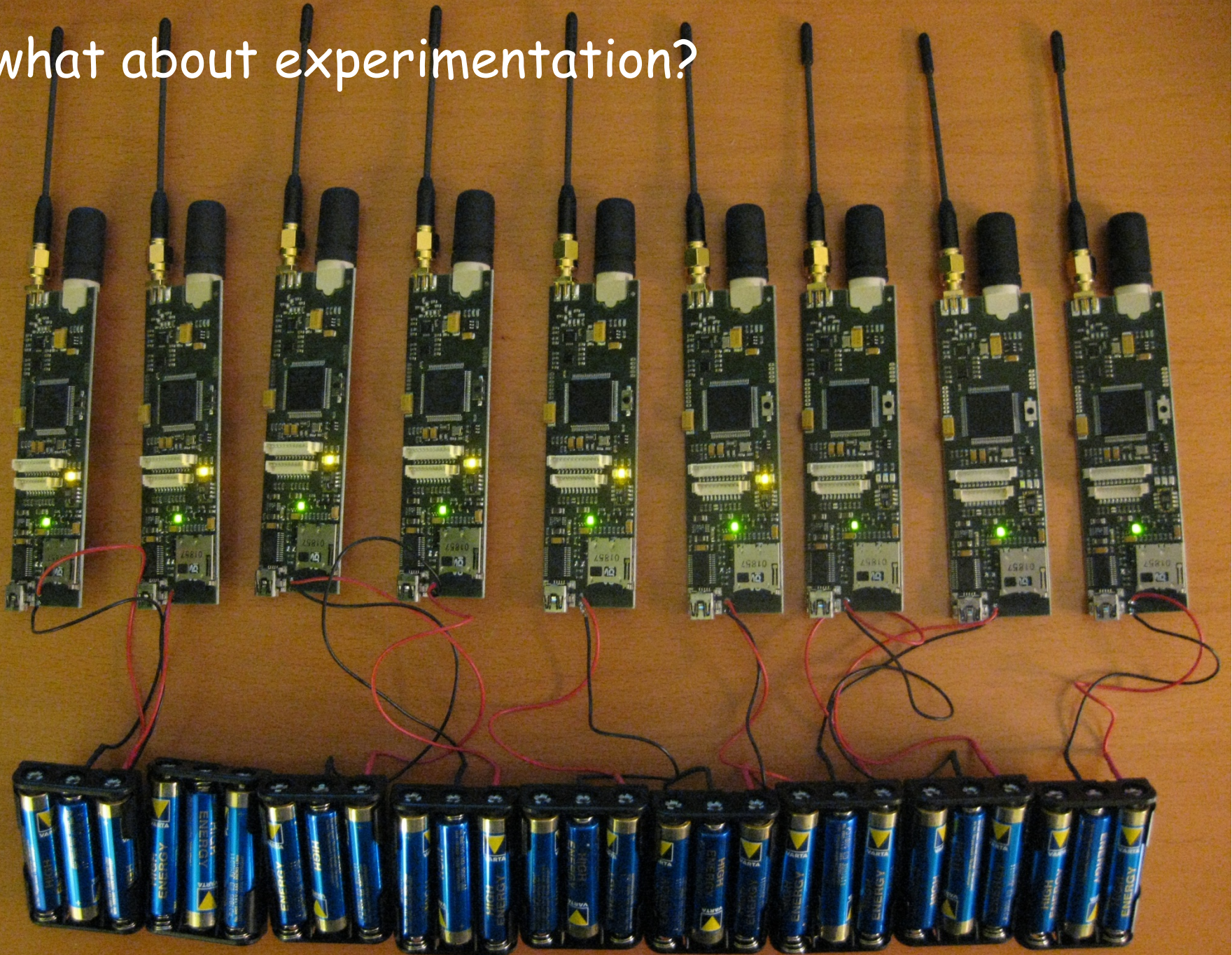


Testbed in the box ...

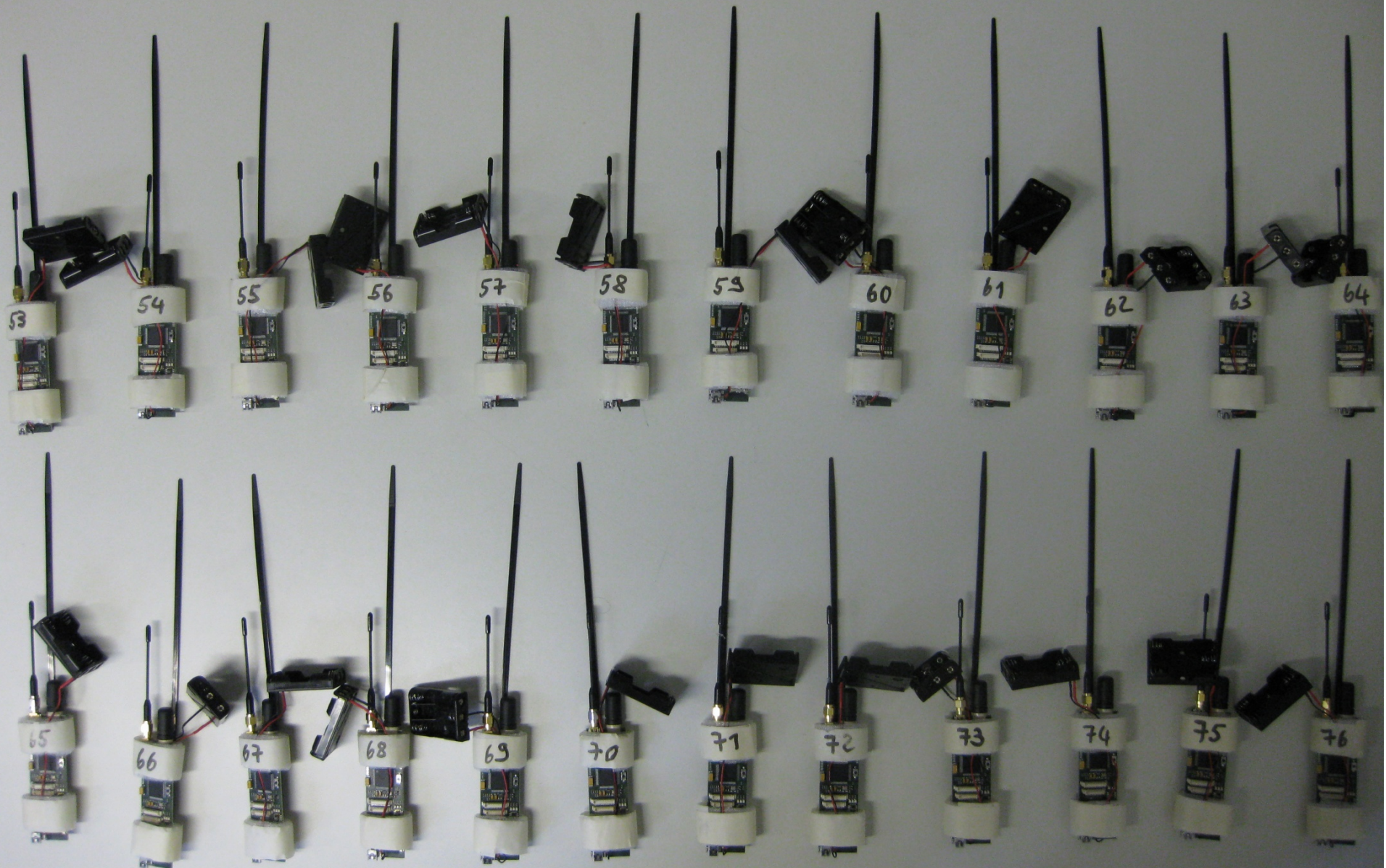


Huge number of  
nodes available  
~500 nodes, but ...

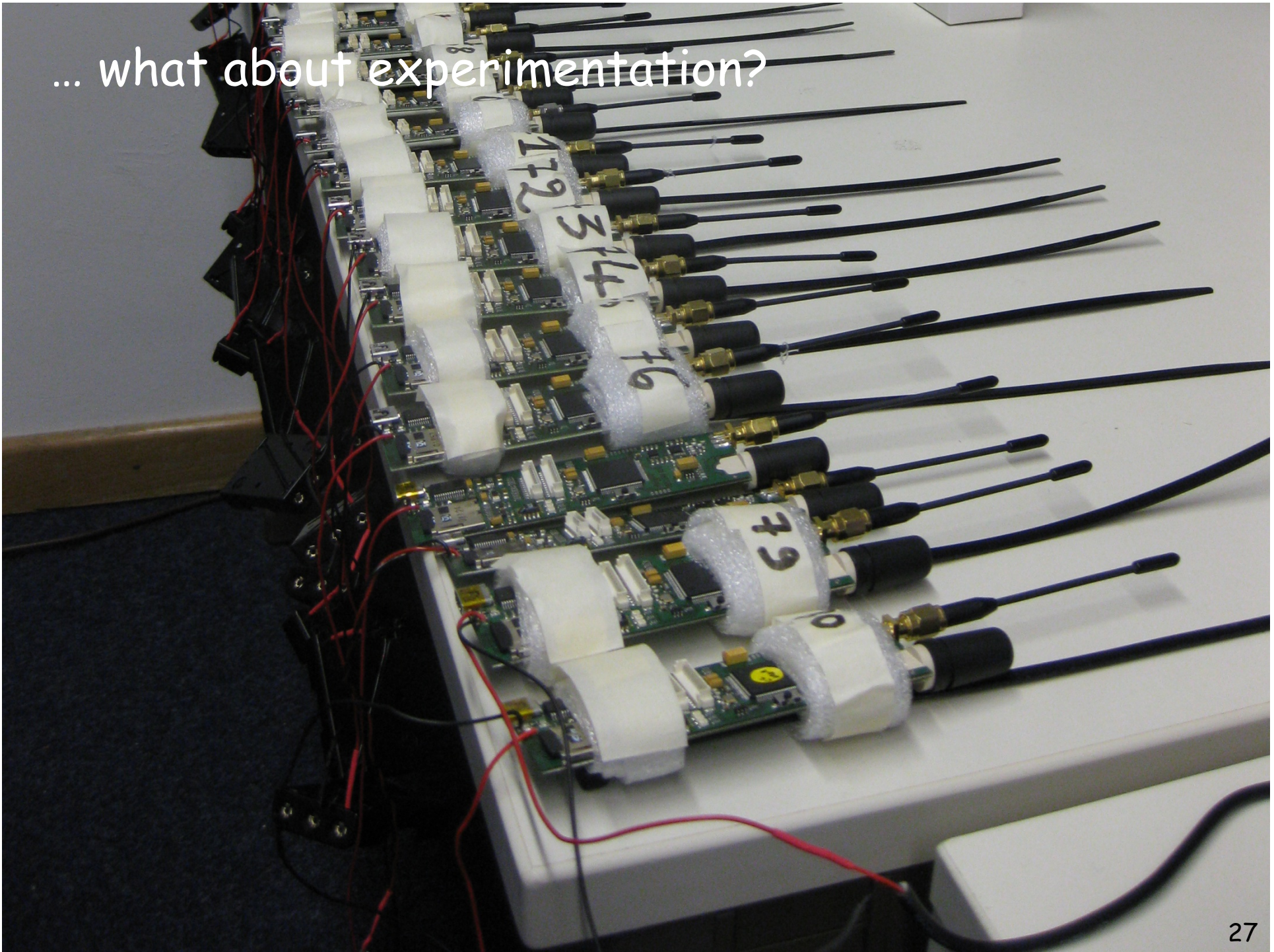
... what about experimentation?



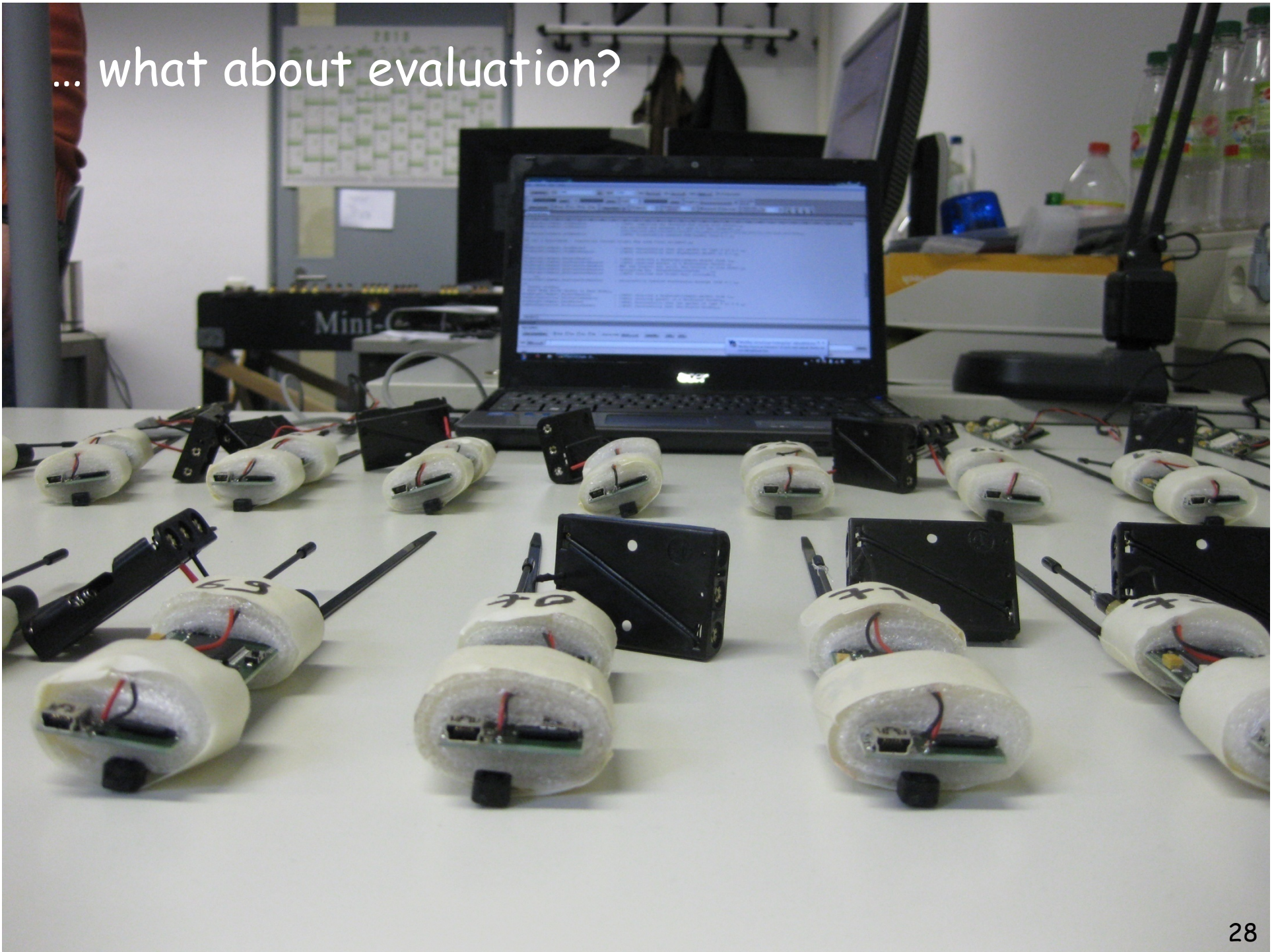
... what about experimentation?



... what about experimentation?



... what about evaluation?



# Experiment lifecycle and the Scientific workflow

# The scientific method

---

- Scientific method

“Principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through **observation** and **experiment**, and the formulation and testing of hypotheses.”

*Merriam-Webster Online Dictionary*

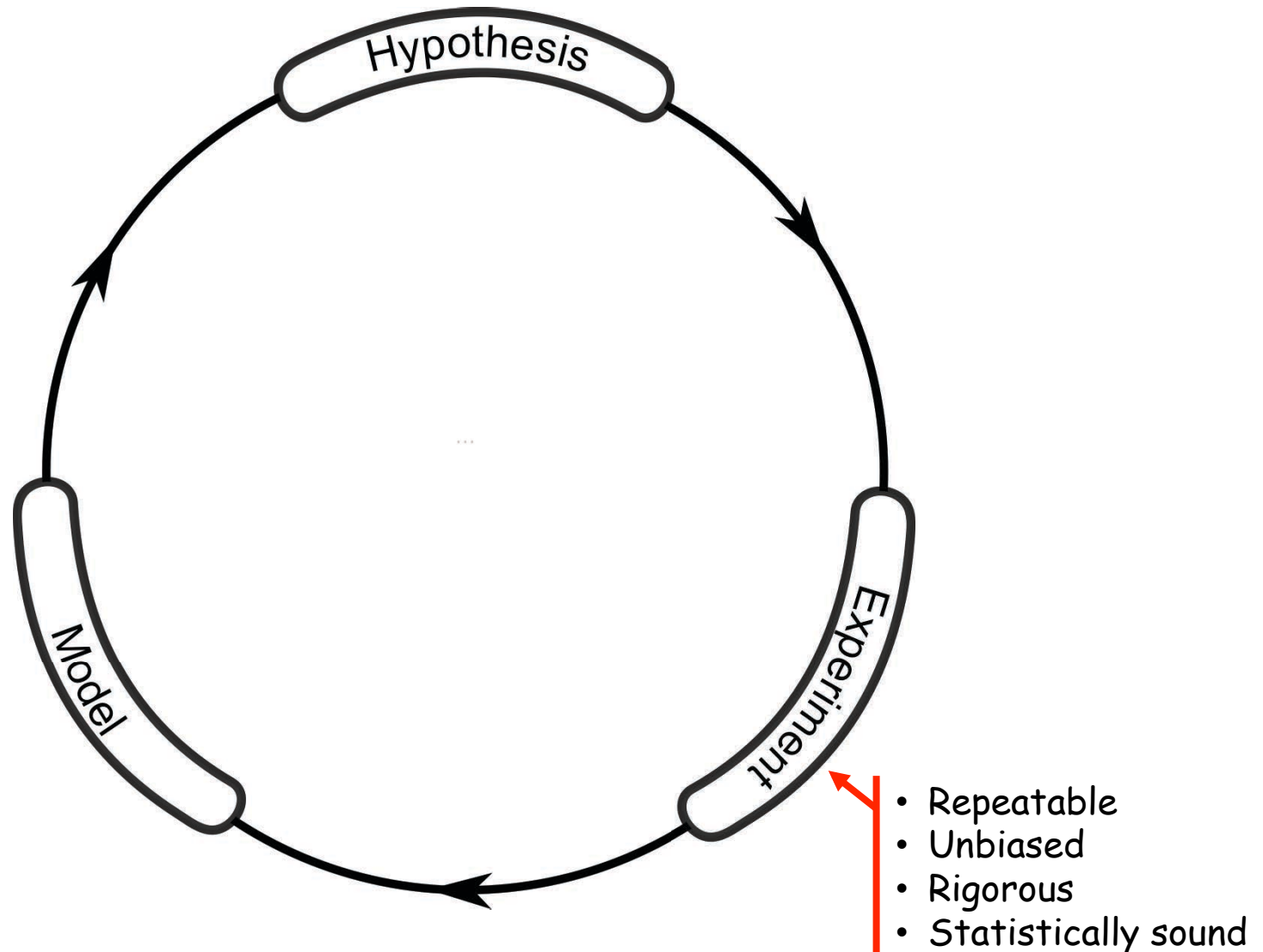
- Experiment

“An operation or **procedure** carried out **under controlled conditions** in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law.”

*Merriam-Webster Online Dictionary*

# Scientific method

---



# Criteria for sound experimentation

---

- **Repeatable**

The reported results should be reproducible by other researchers. This requires a detailed description of the experiment setup, study environment, and results.

- **Unbiased**

The results should reflect a general idea of the subject of the study and should not be specific to an experiment.

- **Rigorous**

The experiment setup must reflect the true character of the subject to study.

- **Statistically sound**

The analysis of the experiment results must be based on mathematical methods.

# Experimentation: Manual experimentation

---

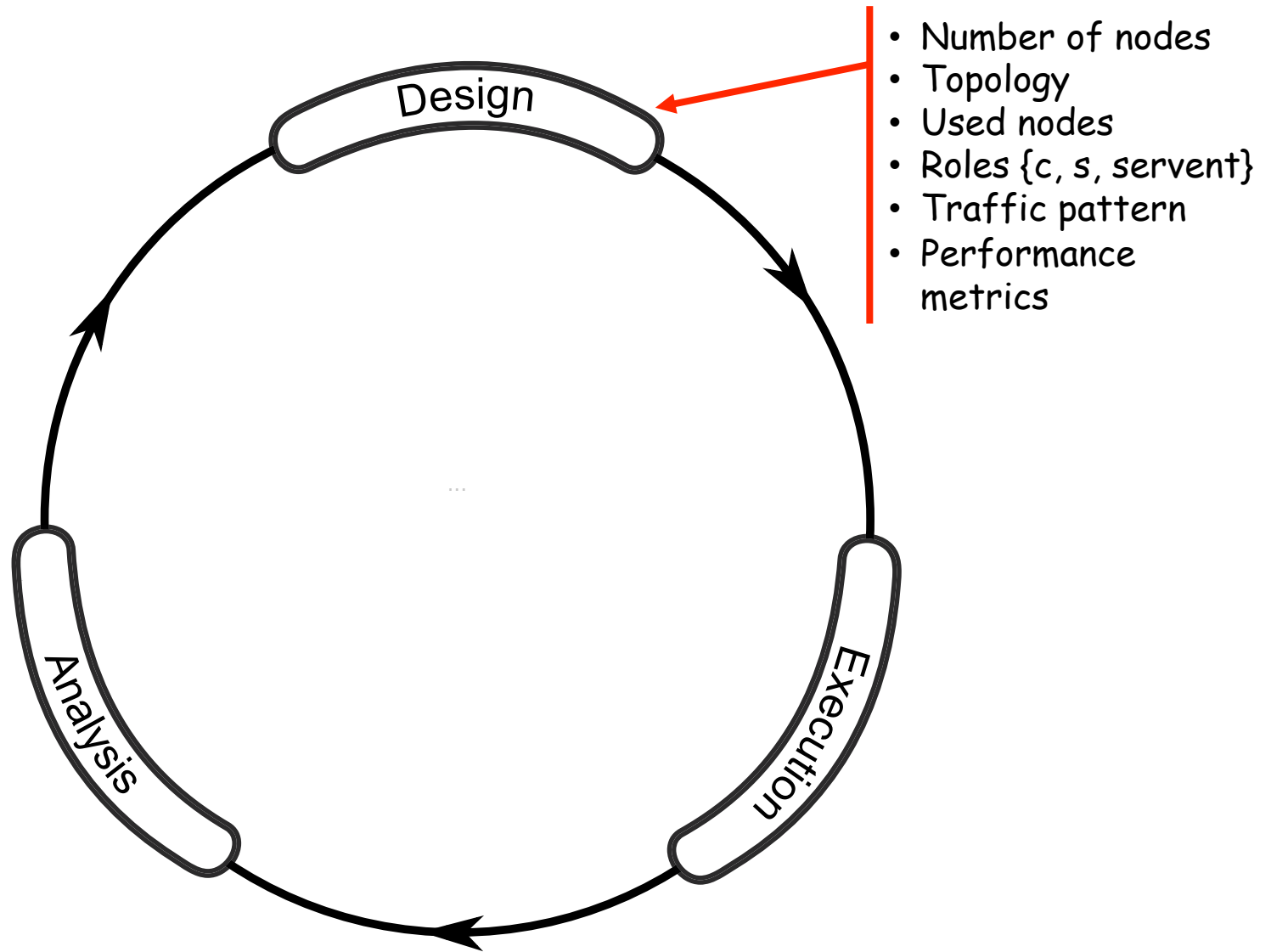
- The basic scientific method of experimentation
  - Design
  - Execution
  - Analysis
- Manual experimentation
  - Labor intensive
  - Many pitfalls in design/configuration
  - Replication of experiments
  - Criteria for sound experimentation/evaluation



 **Need for an automatic experimentation framework**

# Lifecycle of an experiment

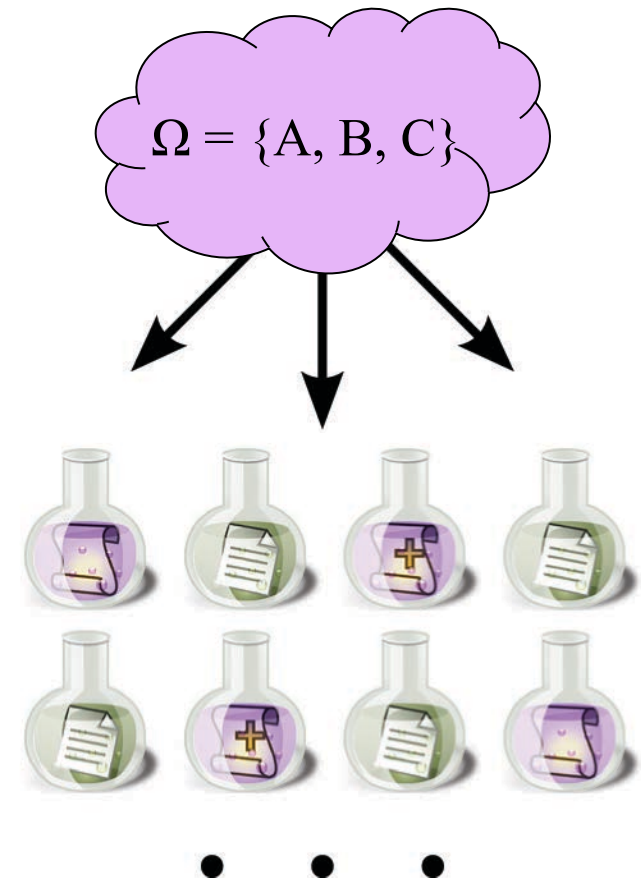
---



# Scientific sound experimentation

- Reliable results require a sound experiment design

- Use random topologies
- What about the parameter spaces?
  - Parameter space  $\Omega = \{A, B, C\}$
  - with  $|A|=5, |B|=3, |C|=7$
  - $|\Omega| = 5 \times 3 \times 7 = 105$
- Replication of experiments
  - Worst case 10 replications  $\blacktriangleright$  1050 runs
  - Average case 30 replications  $\blacktriangleright$  3150 runs



- Challenges and pitfalls

- How do you configure the nodes?
- How do you assure a reliable timing?
- How do you process the results?
- ...

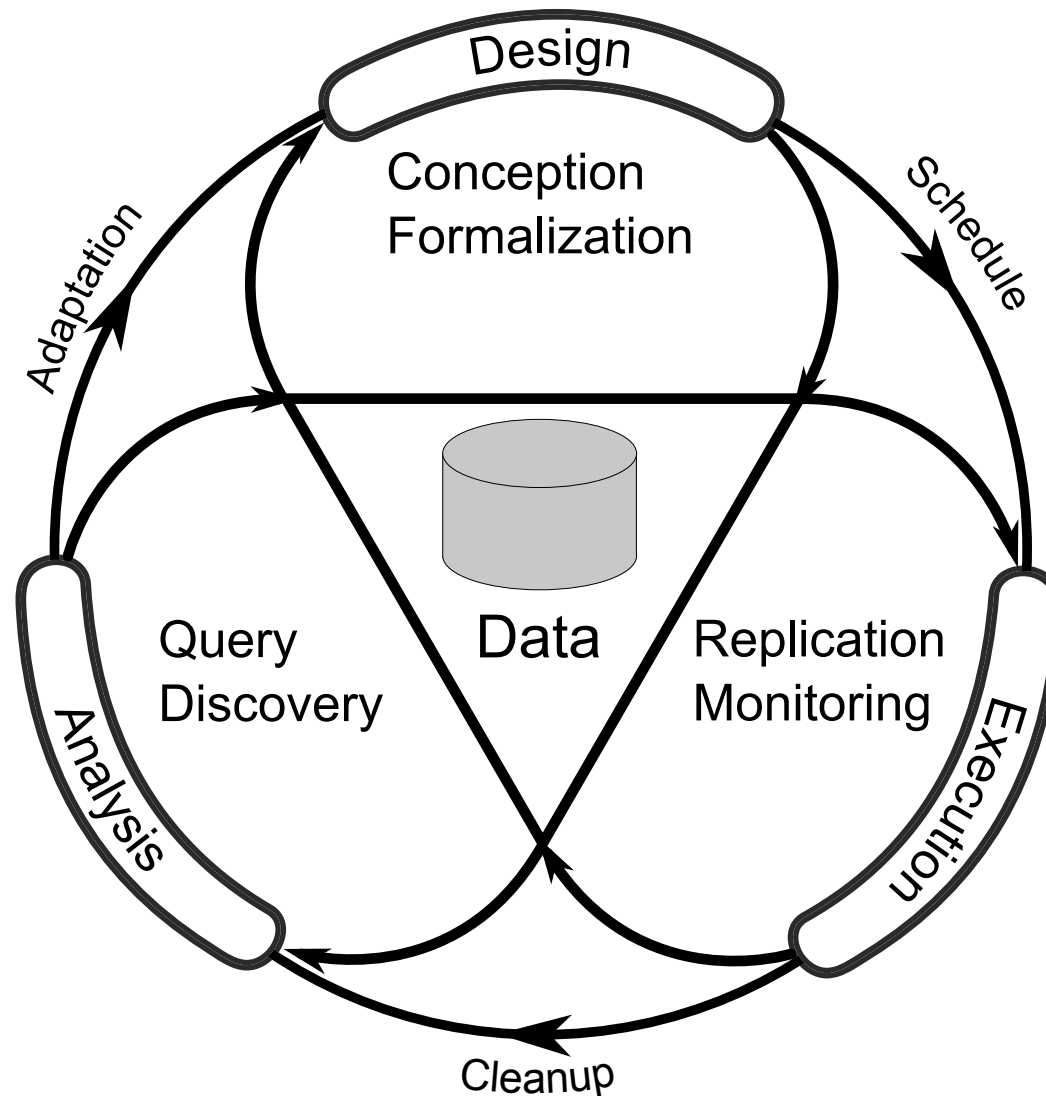
# Requirements on the scientific workflow

---

- **Formalization:** Formal experiment description language, i.e., capable to define start and end states.
- **Scheduling:** Support of automated experiment run.
- **Replications:** Individual and independent repetition of experiments.
- **Monitoring:** Recording the state of the experiment system independent from the measurements.
- **Cleanup system:** Put the experiment system in a defined system before and after an experiment.
- **Query and Discovery:** Cognitive process of knowledge discovery and structural relationships. Computation of statistically sound performance metrics.
- **Adaptation:** The formal description of the experiment can be put in relationship to the obtained performance results.

# Scientific workflow

---

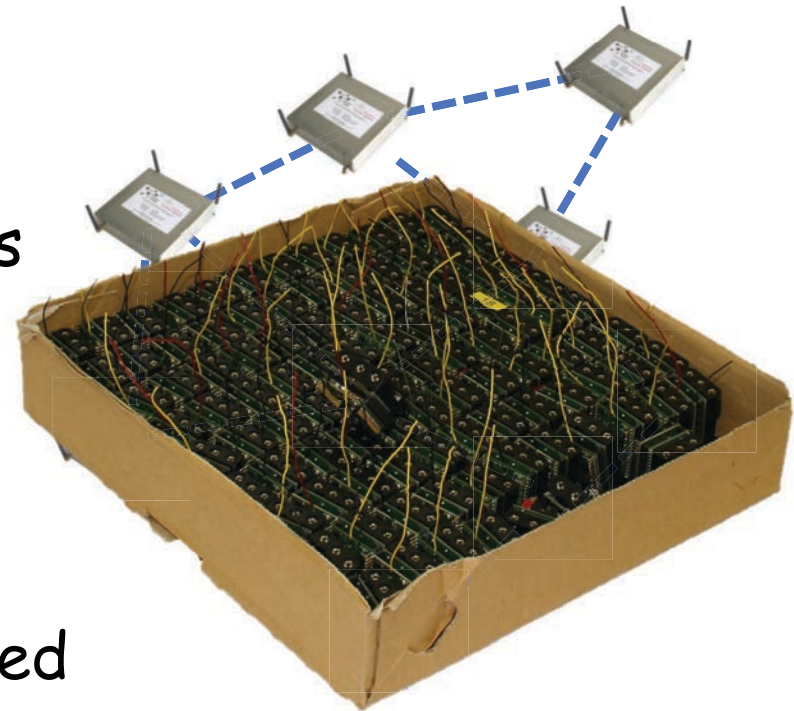


# The DES approach

# DES-Testbed

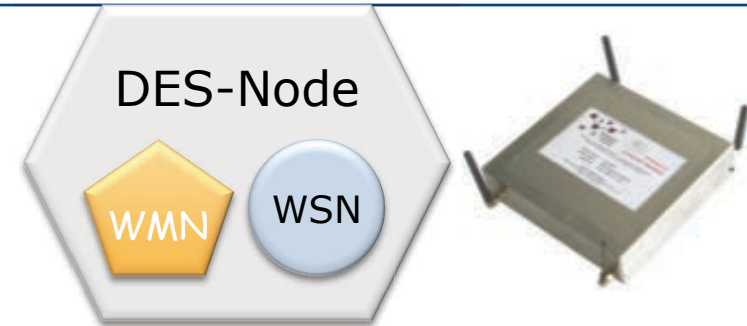
---

- Testbed of the CST research group with focus on ...
  - transformation of theoretical approaches into real systems
  - interaction and integration of networking technologies
  - improving models, e.g., for simulations
- Weakness of current approaches
  - Testbed in the box
  - Short experiment run times
  - Experimentation methodology
- Important aspect @ DES-Testbed
  - Long-term studies



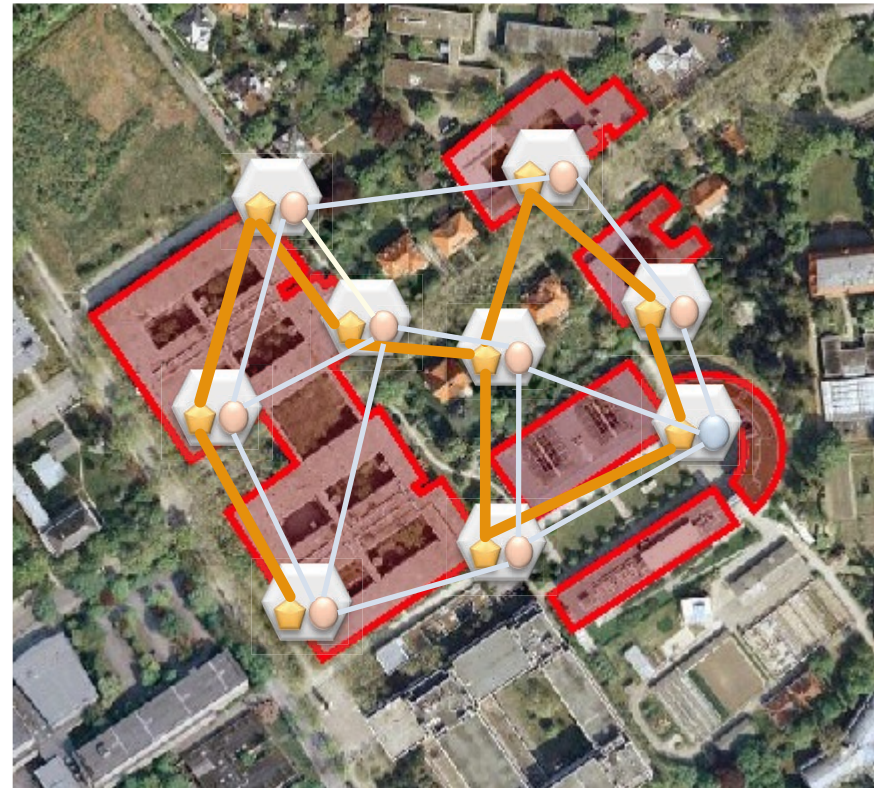
# DES-Testbed: Overview

- Distributed Embedded Systems (DES)

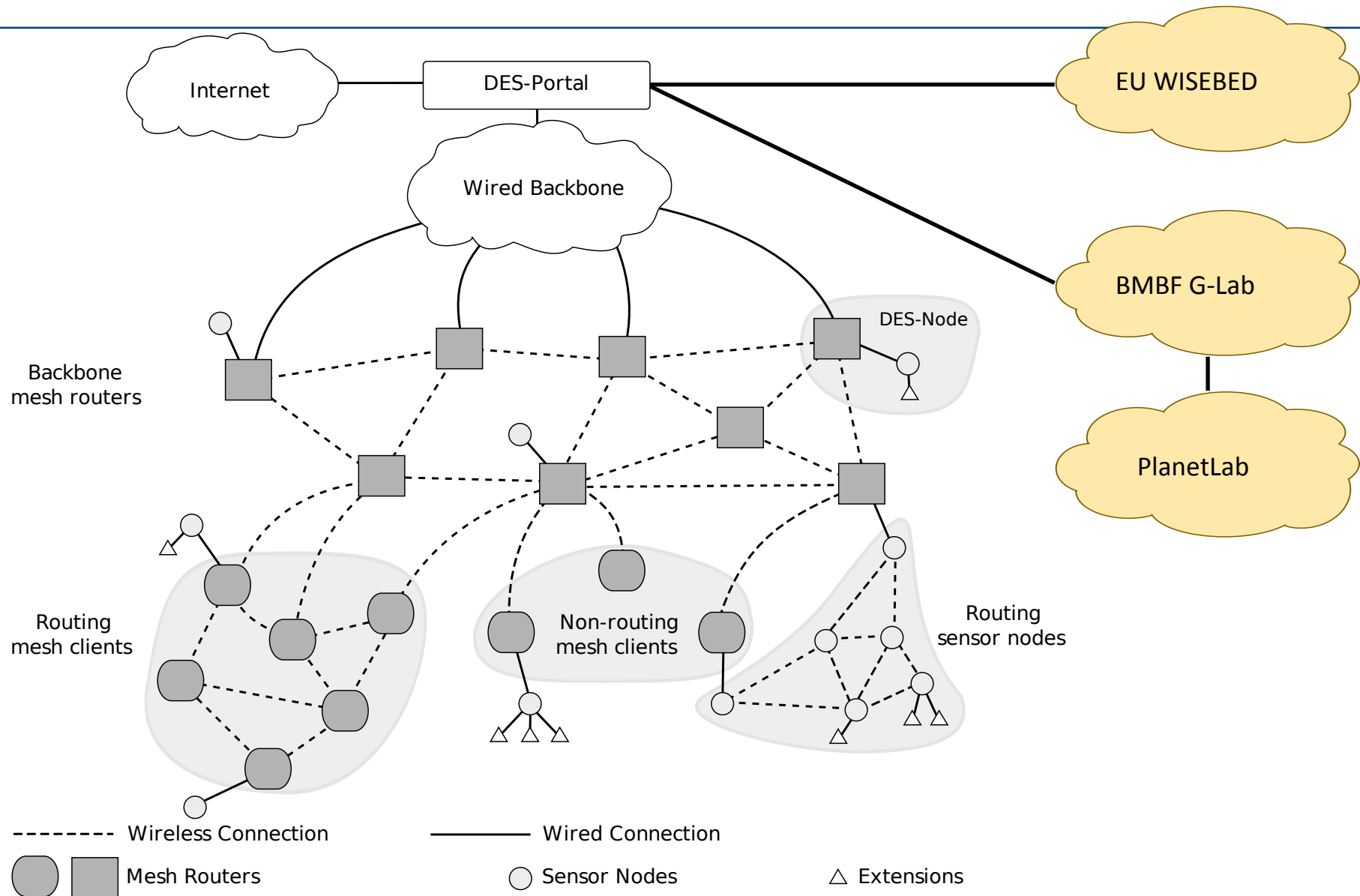


- Properties of the DES-Testbed

- Persistent testbed
- >100 hybrid nodes
- Spanning  $\geq 3$  buildings
- Wireless mesh nodes
- Wireless sensor nodes
- Indoor nodes
- Outdoor nodes
- Mobile nodes
- Wired connection to a server
- Collocated to university WLAN

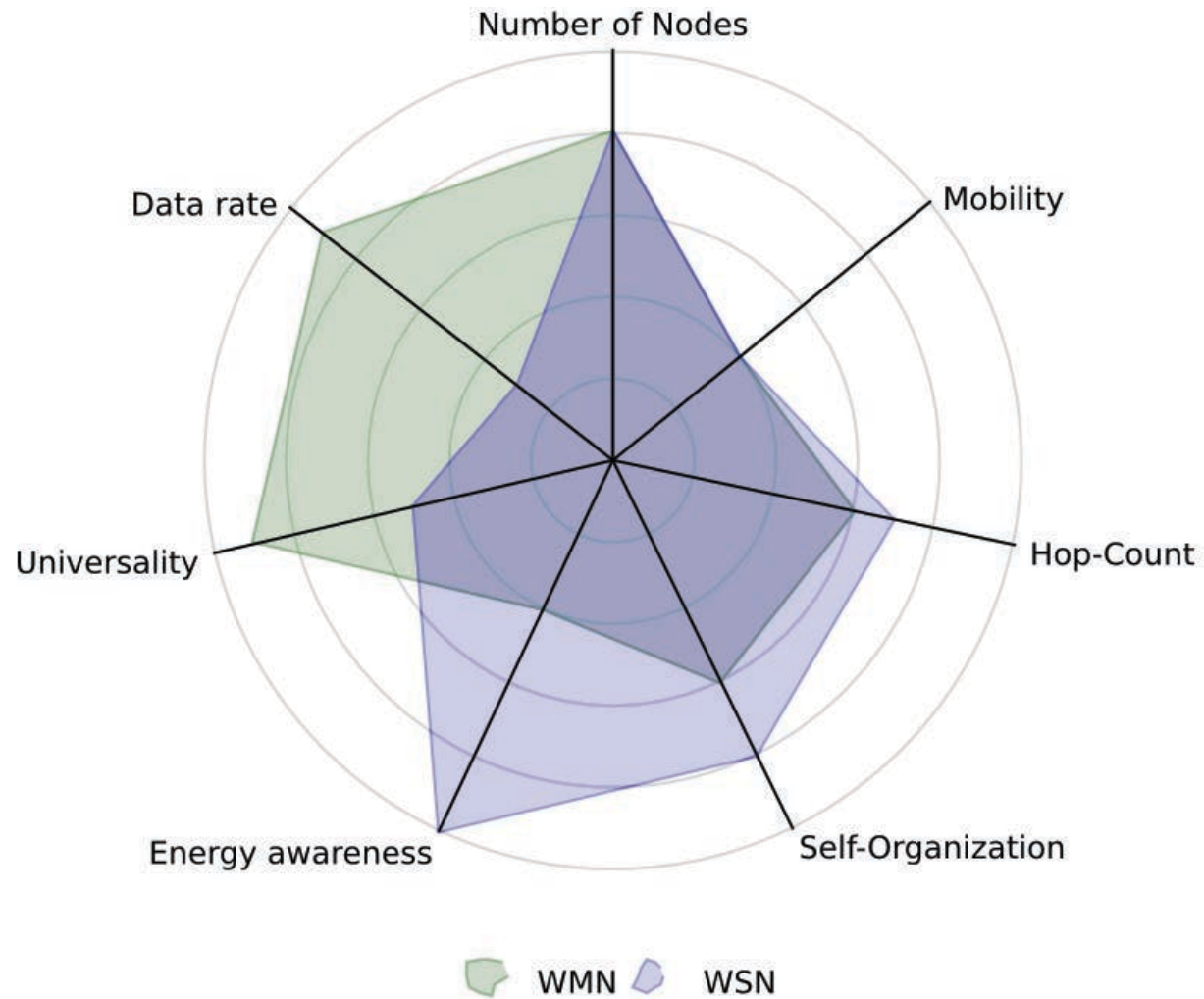


# DES-Testbed: Architecture

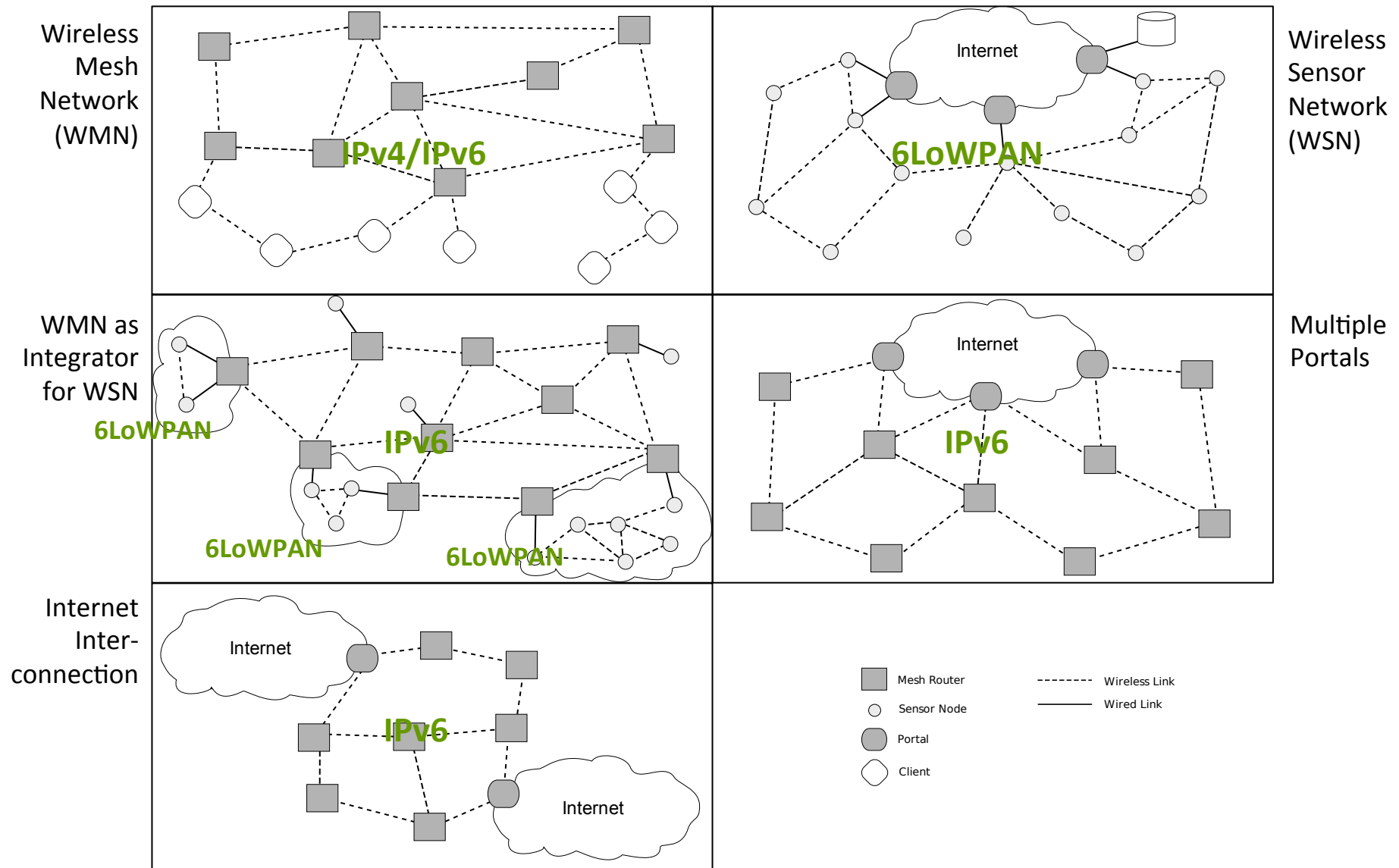


# DES-Testbed: Characteristics

---



# DES-Testbed: Network configurations



# DES-Testbed: DES-Node

- Wireless mesh node
  - PC Engines Alix2c2
  - 500 MHz AMD Geode LX800
  - 256 MB DDR DRAM
  - 2 Ethernet Ports
    - Via VT6105M
  - 2 miniPCI slots
  - dual USB 2.0 port
  - CompactFlash socket
  - Customized enclosure
  - Debian Linux
  - 3 wireless interfaces
  - IEEE 802.11a,b,g



# DES-Testbed: DES-Node

- **Wireless sensor node (MSB-A2)**

- **LPC-2387 ARM7**

- 98 kB RAM
- 512 kB Flash

- **Chipcon CC1100**

- 10dBm
- ISM band at 868-870 MHz

- Data rate  $\leq 500$  kbps

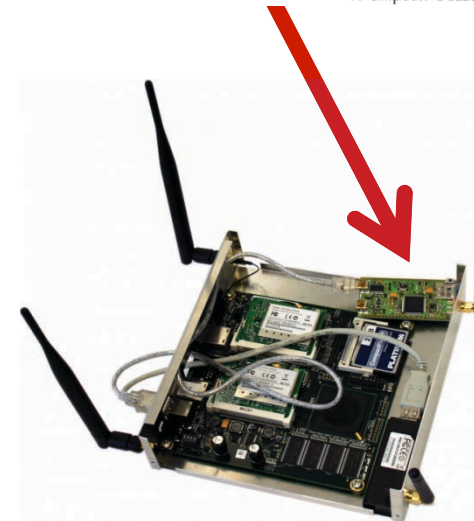
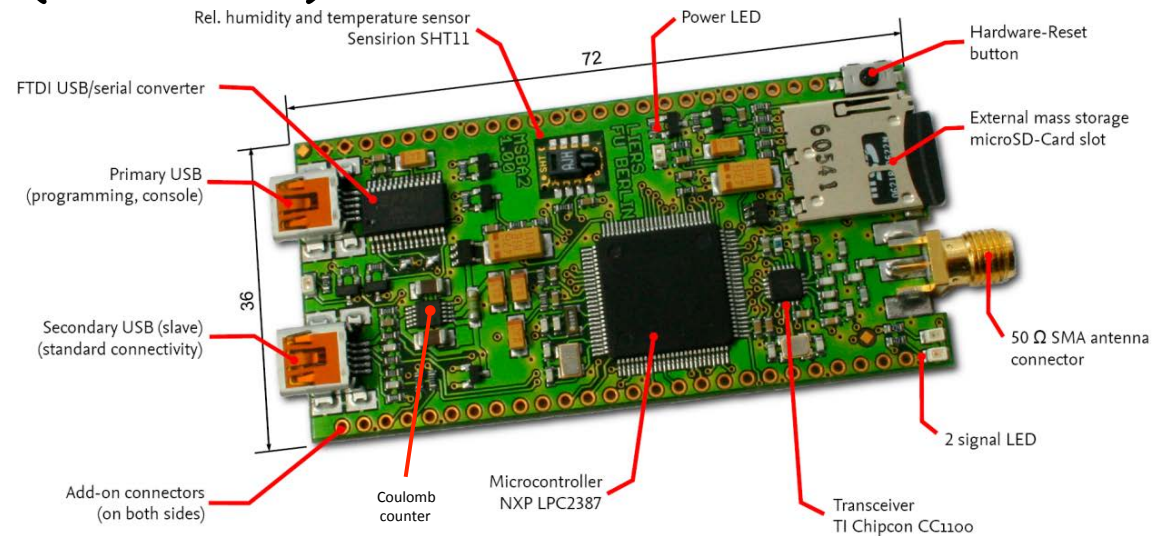
- **Coulomb counter for battery depletion measurement**

- **GPIO pins**

- **mini USB 2.0 port**

- **microSD-card socket**

- **Micro kernel operating system**



# DES-Testbed: DES-Node

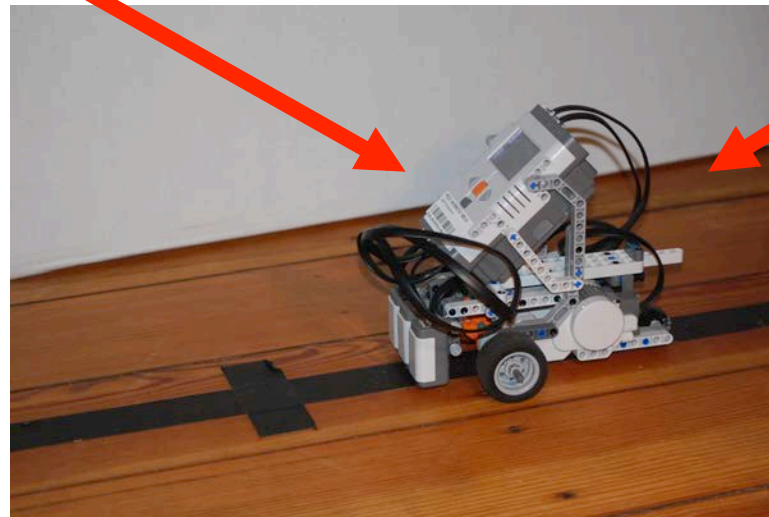
## Mobile WMN-node

Android based smartphone



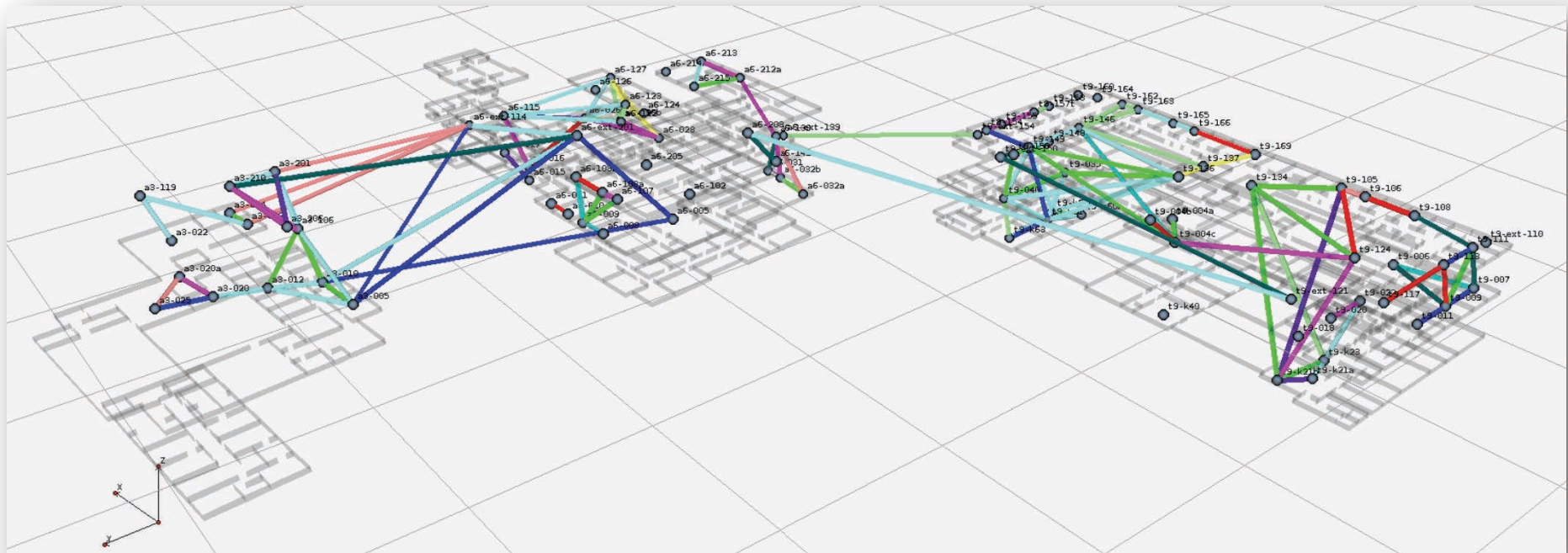
## Mobile WSN-node

- TI ez430-Chronos
- Compatible to Chipcon CC1100
- Sensors: Temperature, 3-axis accelerometer, pressure, battery voltage



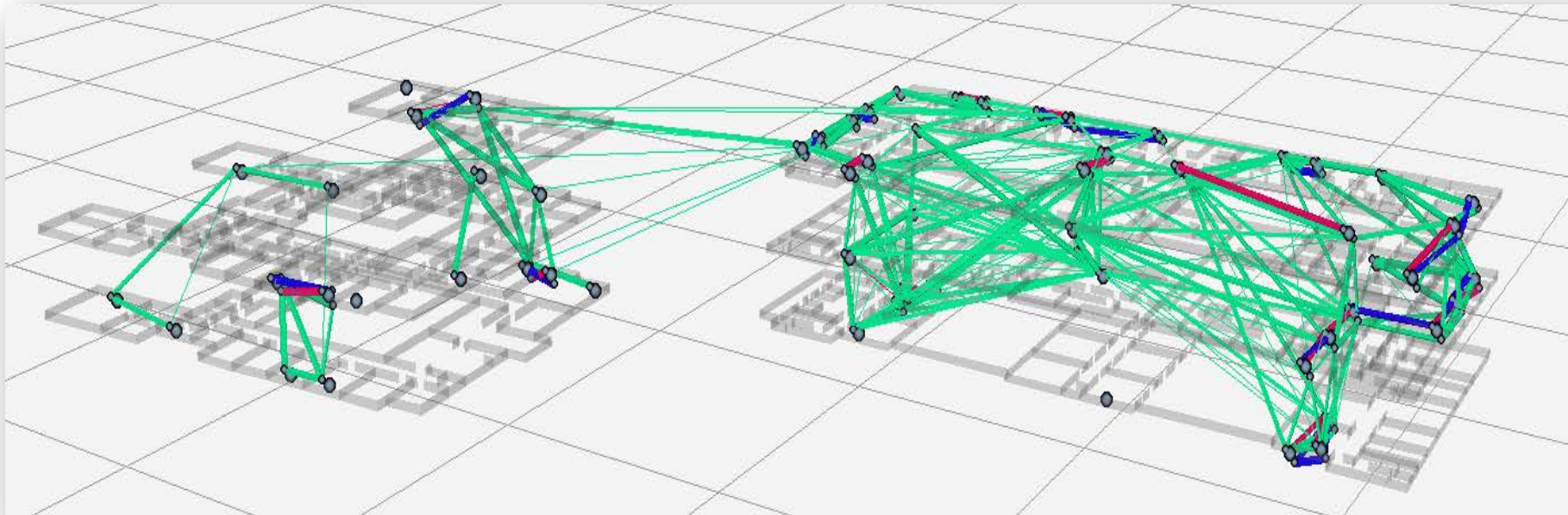
Mobile robot to carry devices: Lego Mindstorm NXT

# DES-Testbed: DES-Vis

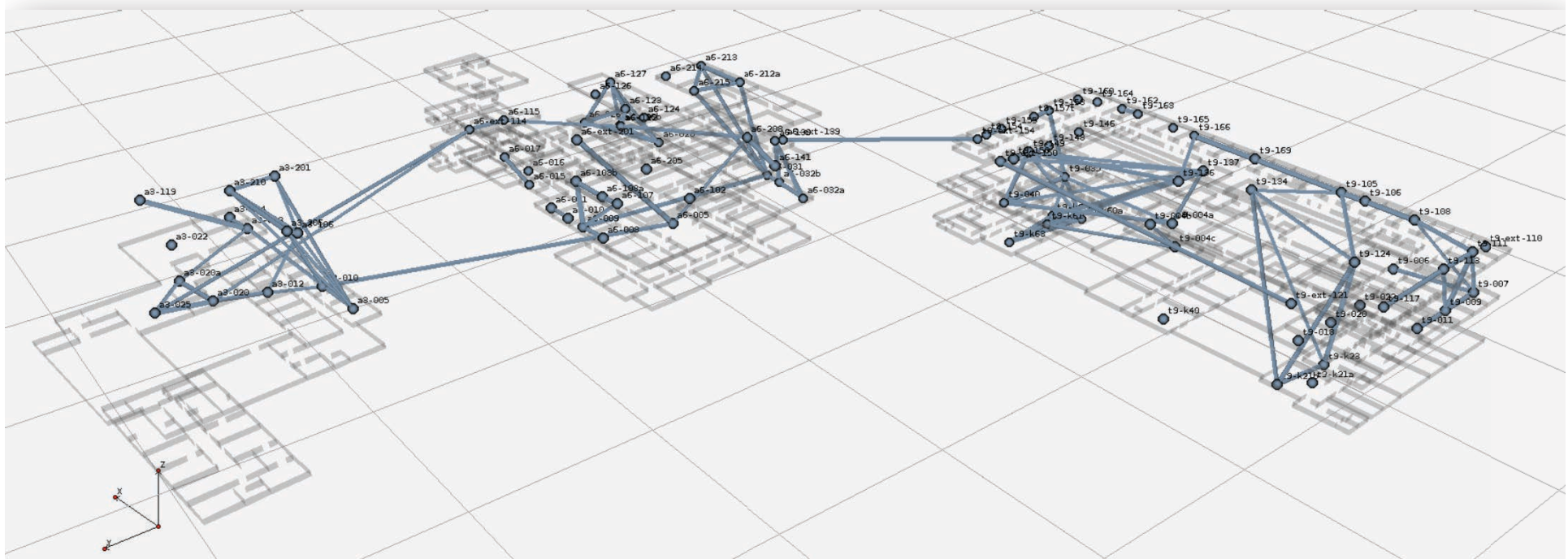


# DES-Testbed: DES-Vis

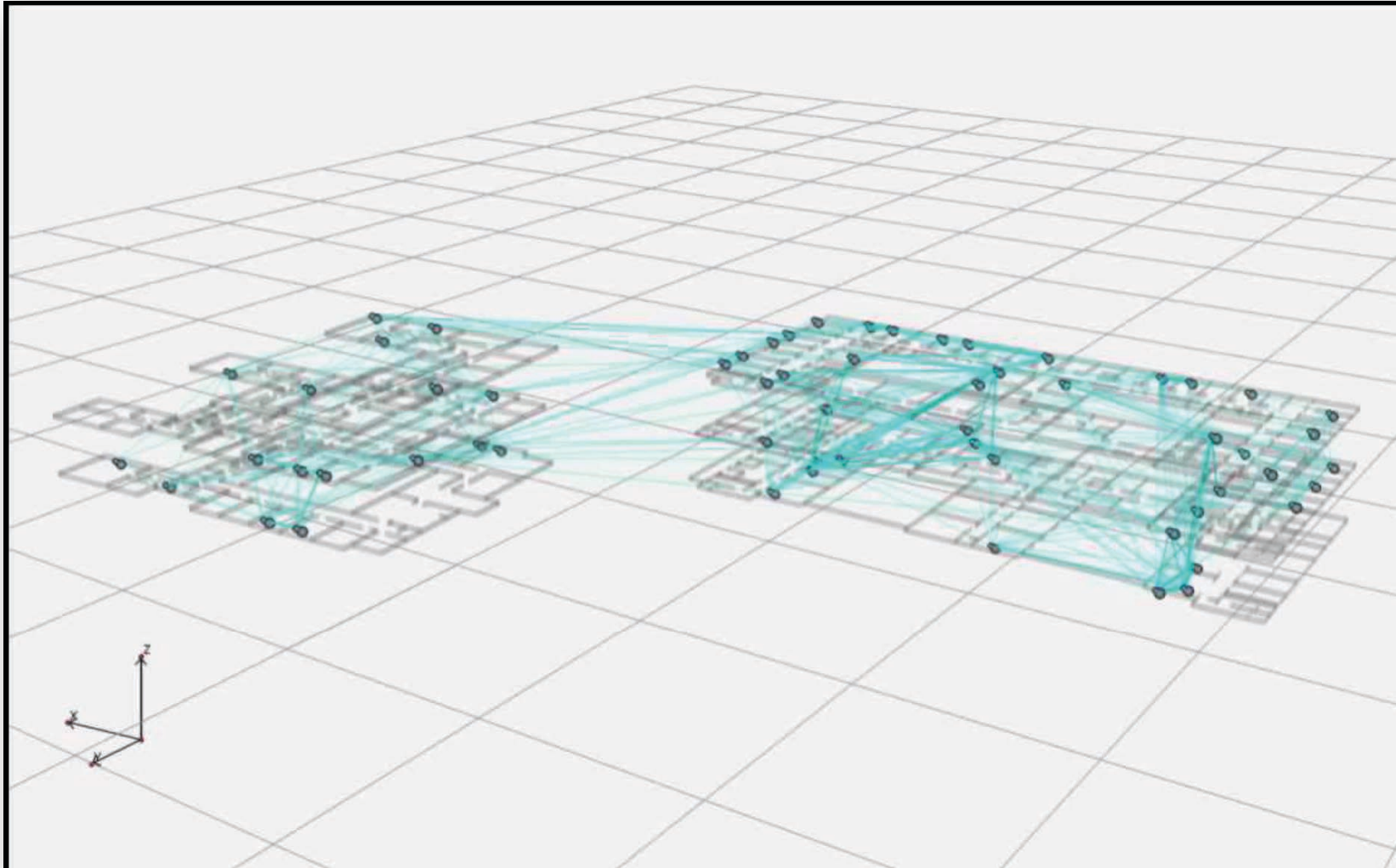
---



# DES-Testbed: DES-Vis



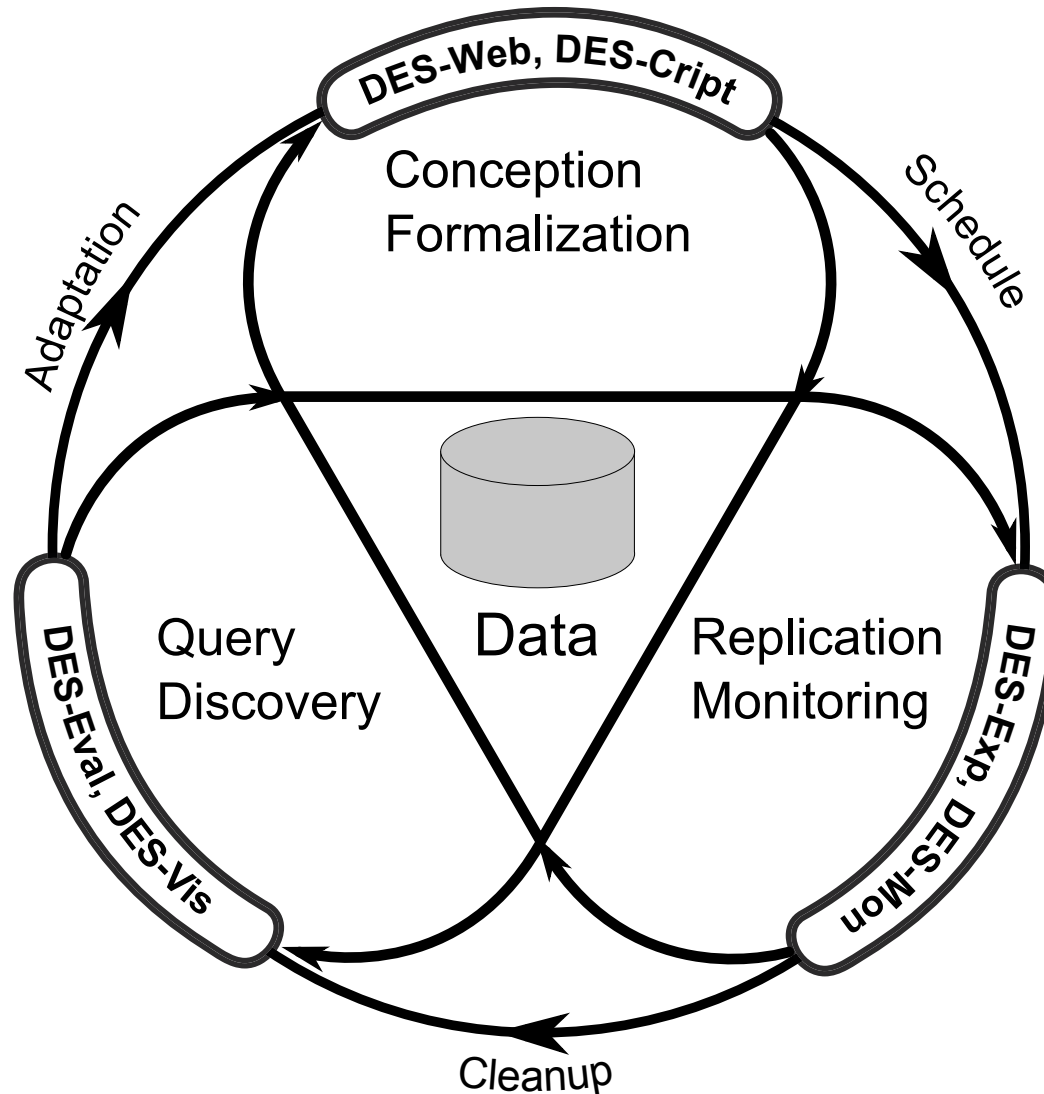
# DES-Testbed: DES-Vis (Animation)



Color = Channel, Line thickness = Quality of channel

# Scientific workflow in the DES-Testbed

---

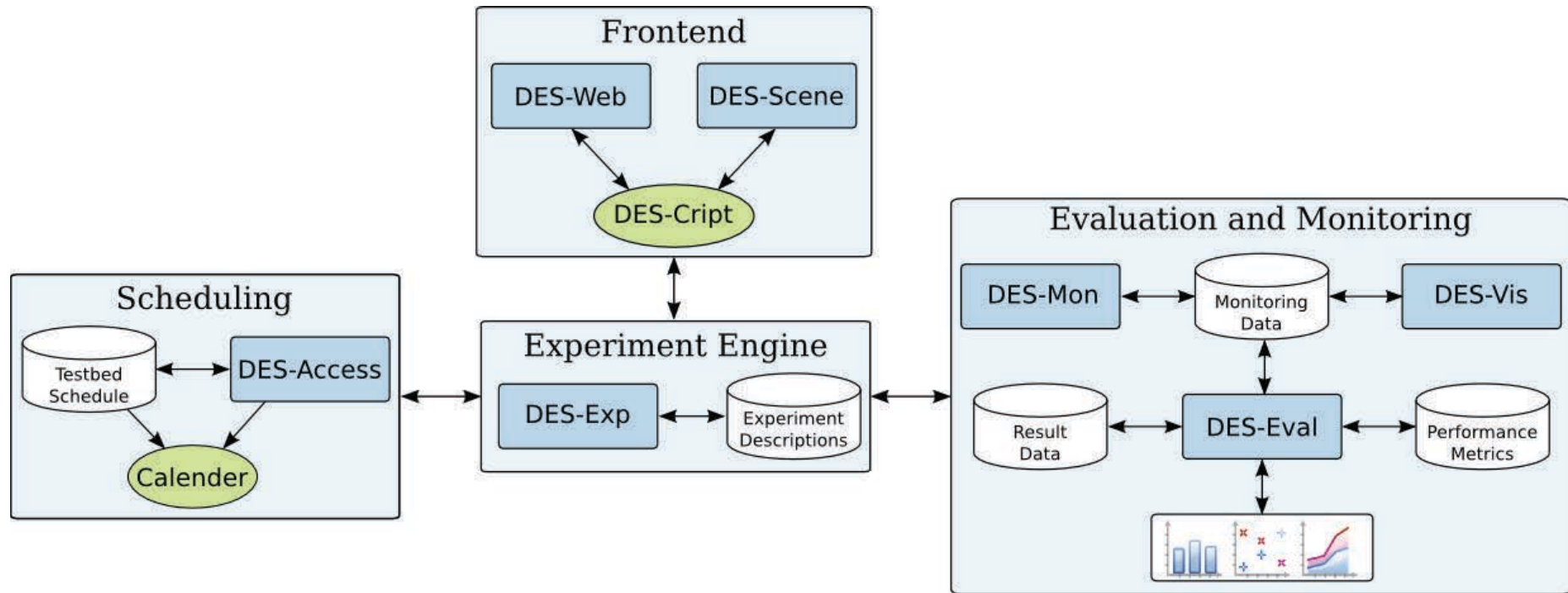


# Scientific workflow in the DES-Testbed

---

- Requirements for automated experimentation
  - Workflow for experimentation
  - Experiment description and definition
  - Automated scheduling and running
  - Time based running of experiments
  - No or minimum load on the testbed nodes
  - Support of testbed nodes without Ethernet connection
  - Web based user interface
  - Evaluation and preparation of results
- Approach: **DES-TBMS**
  - DES-Testbed Management System

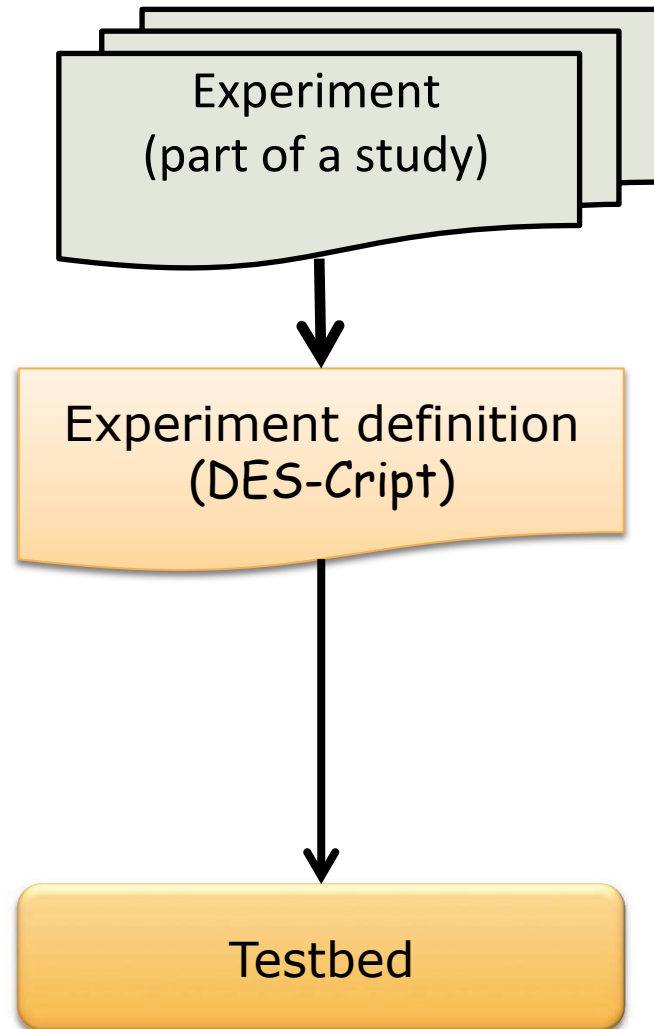
# Scientific workflow in the DES-Testbed



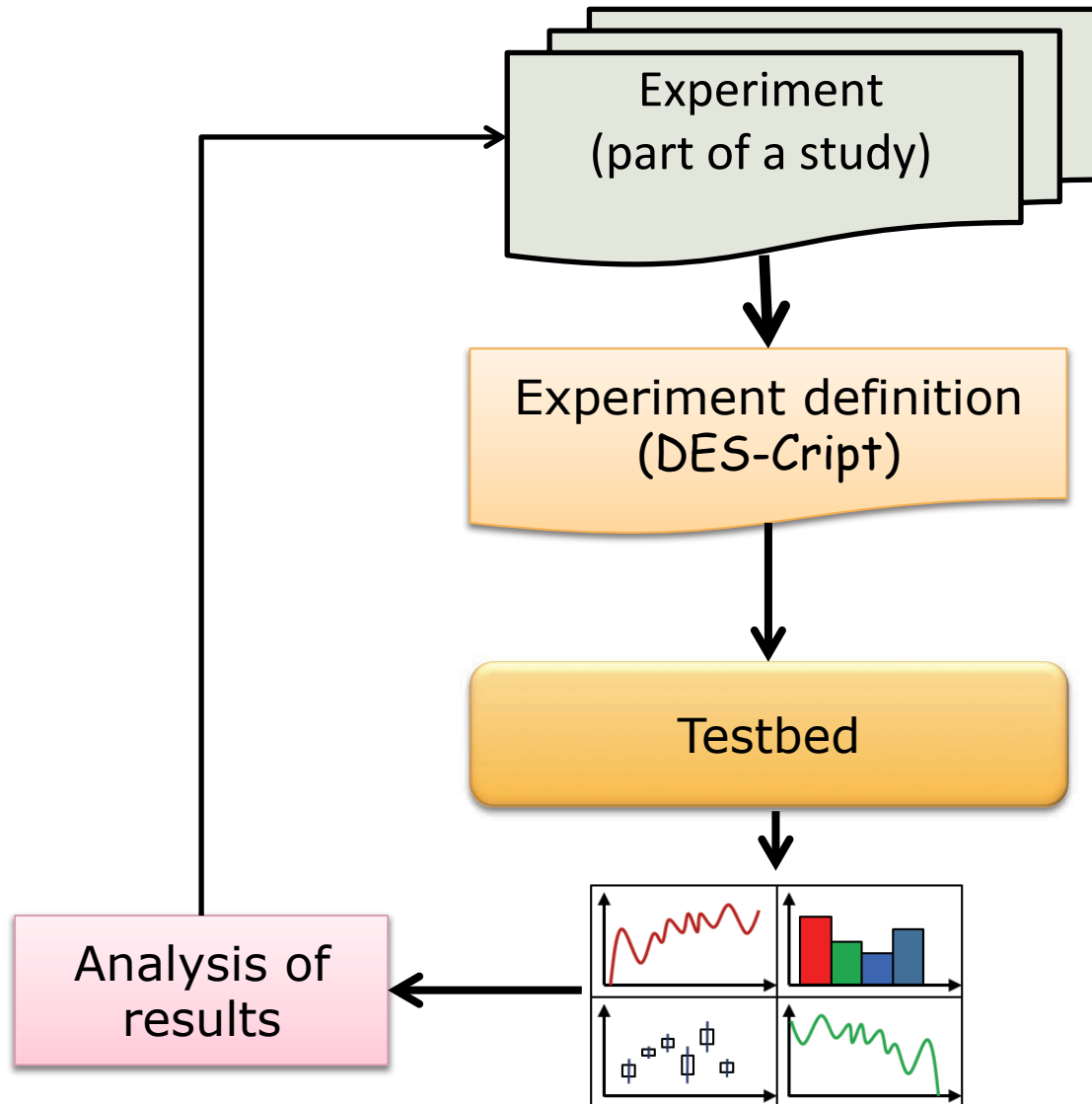
- DES-TBMS: Testbed Management System
  - Matches experiment workflow
  - Modular architecture

# DES-Framework

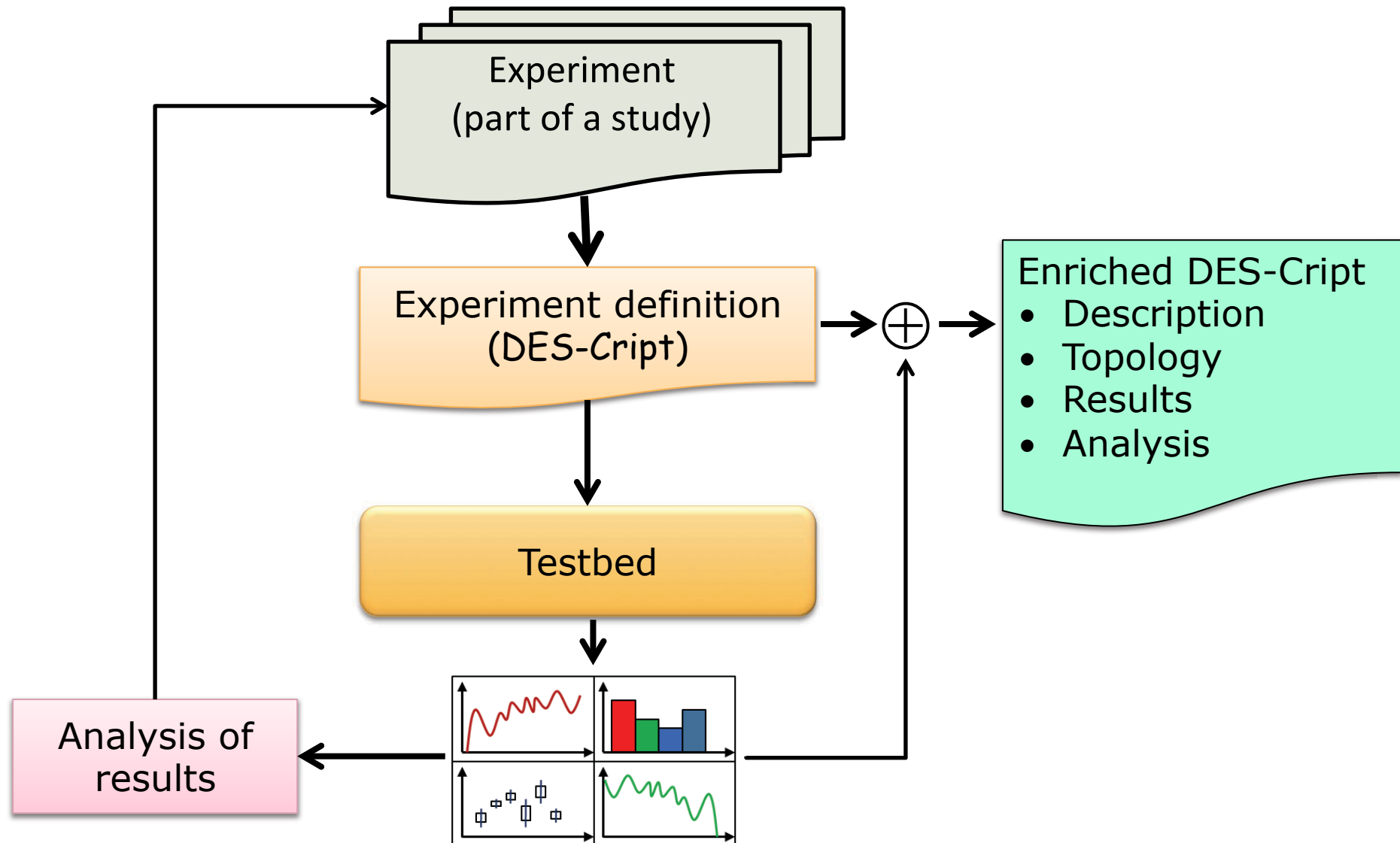
---



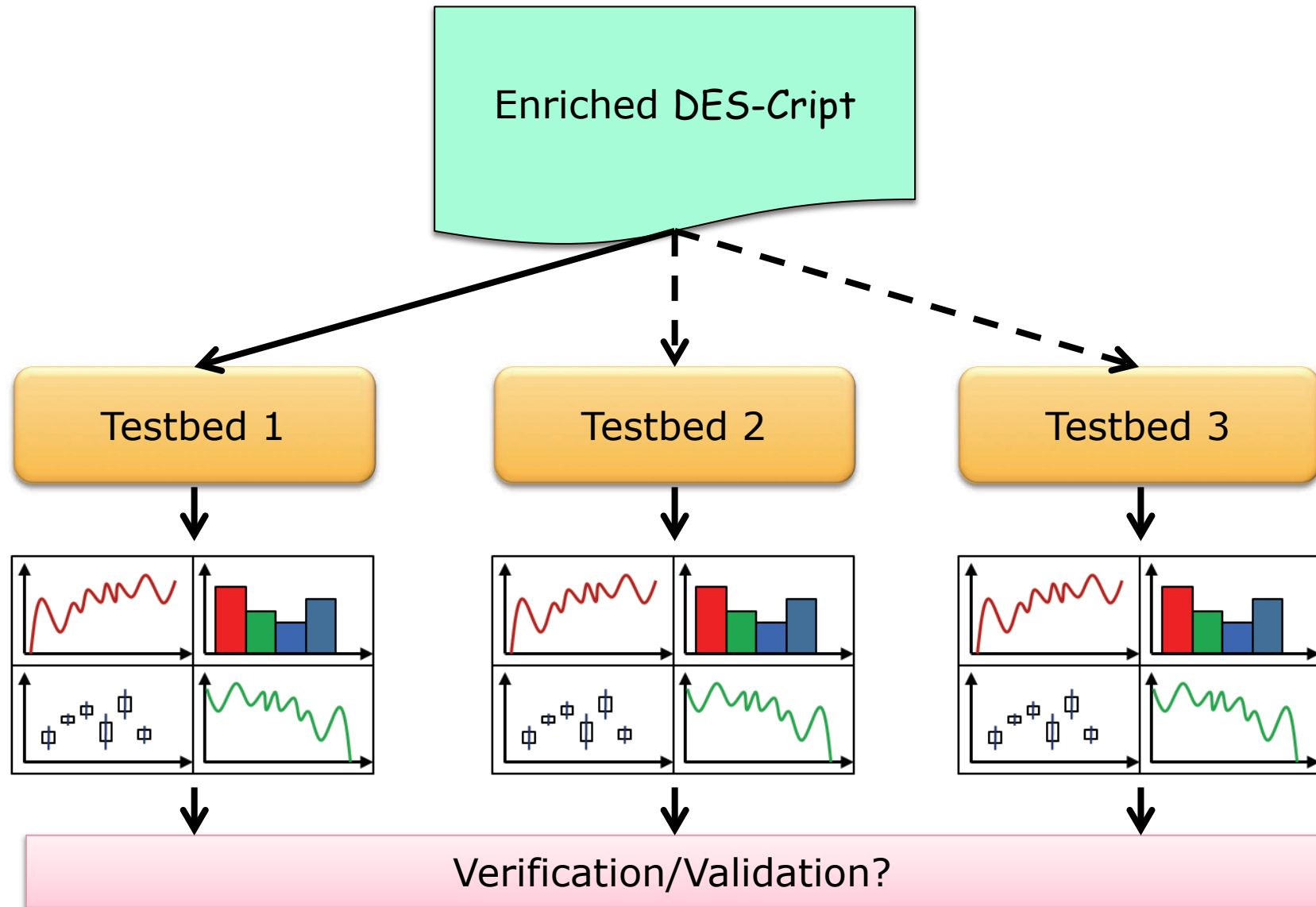
# DES-Framework



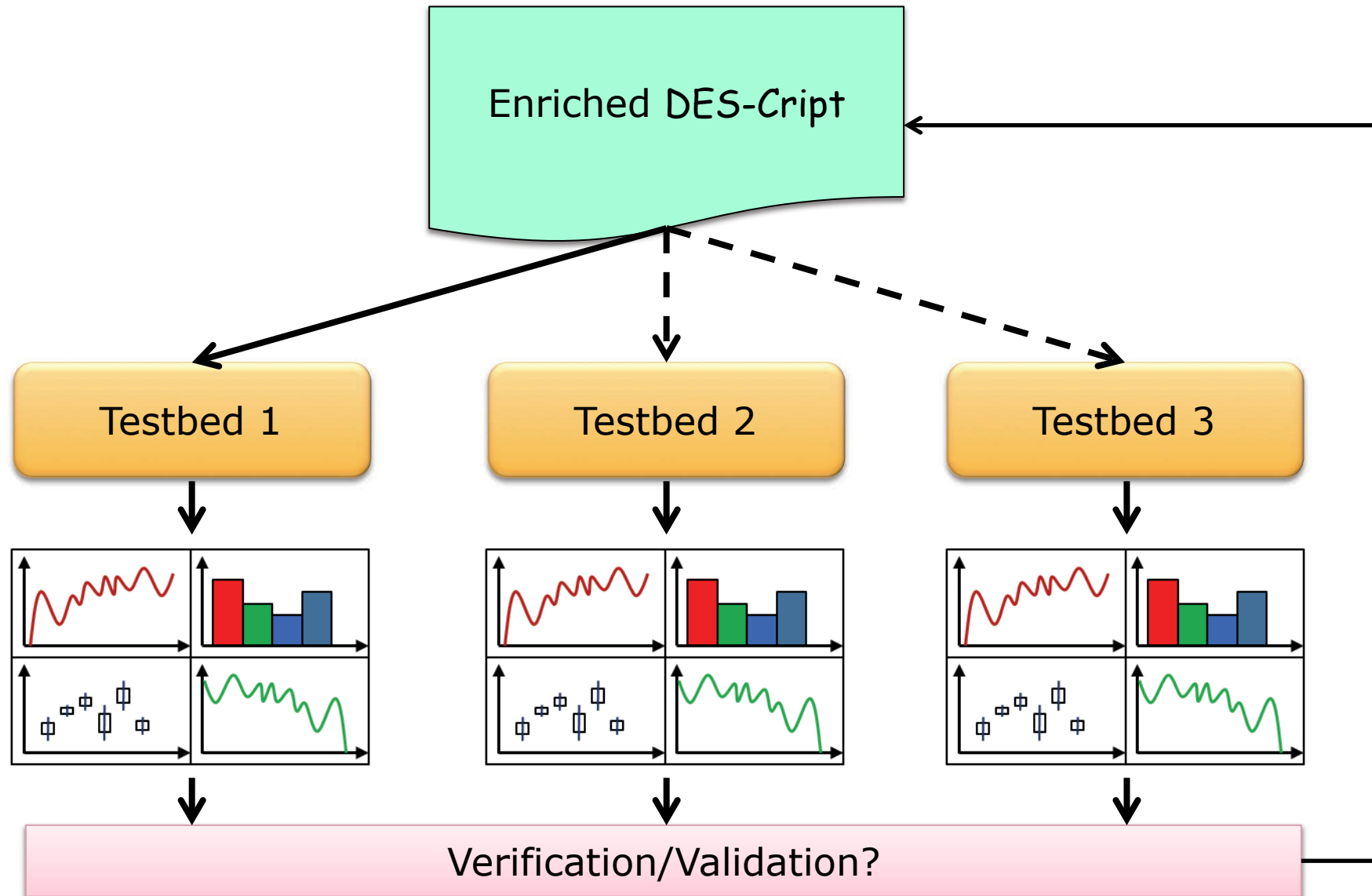
# DES-Framework



# DES-Framework



# DES-Framework



# Experiment Design: DES-Cript

- Domain specific language for networking experiments
  - XML-based
  - Holistic description
  - Automated execution
- Simplifies
  - Replications
  - Modifications
  - Communication among experimenters
- Structure
  - <general>
  - <init>
  - <actions>

```
<experiment>
  <general>
    <name>...</name>
    <start_time>...</start_time>
    <owner>...</owner>
    <description>...</description>
    <iterations>...</iterations>
    <groups>
      <group name="groupname" role="Server">
        <members>...</members>
      </group>
    </groups>
    ...
  </general>
  <init>
    <action id="0">
      ...
    </action>
    ...
  </init>
  <actions>
    <variables>
      ...
    </variables>
    <action_block id="1">
      <action id="1">
        <group>...</group>
        <command>...</command>
        <start_time>...</start_time>
        <duration>...</duration>
      </action>
      ...
    </action_block>
    ...
  </actions>
</experiment>
```

# Experiment Design: DES-Cript

```
<experiment>
  <general>
    <name>Simple TCP flow with iperf</name>
    <start_time>2009-09-11 20:00:00</start_time>
    <iterations>30</iterations>
    ...
    <groups>
      <group name="Receiver-TCP" role="Server">
        <members><node id="t9-150"></node></members>
      </group>
      <group name="Sender-TCP" role="Client">
        <members><node id="t9-155"></node></members>
      </group>
    </groups>
  </general>
  <actions>
    <action_block id="1" execution_mode="1">
      <action id="1">
        <group>Receiver-TCP</group>
        <command>iperf -s</command>
        <start_time>0</start_time>
        <duration>330</duration>
        <evaluation_script>iperf.py</evaluation_script>
      </action>
    </action_block>
    <action_block id="2" execution_mode="1">
      <action id="1">
        <group>Sender-TCP</group>
        <command>iperf -c t9-150-wlan0 -t300</command>
        <start_time>10</start_time>
        <duration>330</duration>
        <evaluation_script>iperf.py</evaluation_script>
      </action>
    </action_block>
    ...
  </actions>
</experiment>
```

Actions can be executed in three modes:

- Sequential
- Parallel
- Time based

# Experiment Design: DES-Cript

---

- Experiment Actions

- Heart of the experiment
- Related to node group

- Execution modes

- Sequential
- Time-based

- ActionParameters

- Impact of parameters
- Packet size, channel, ..

- Different types

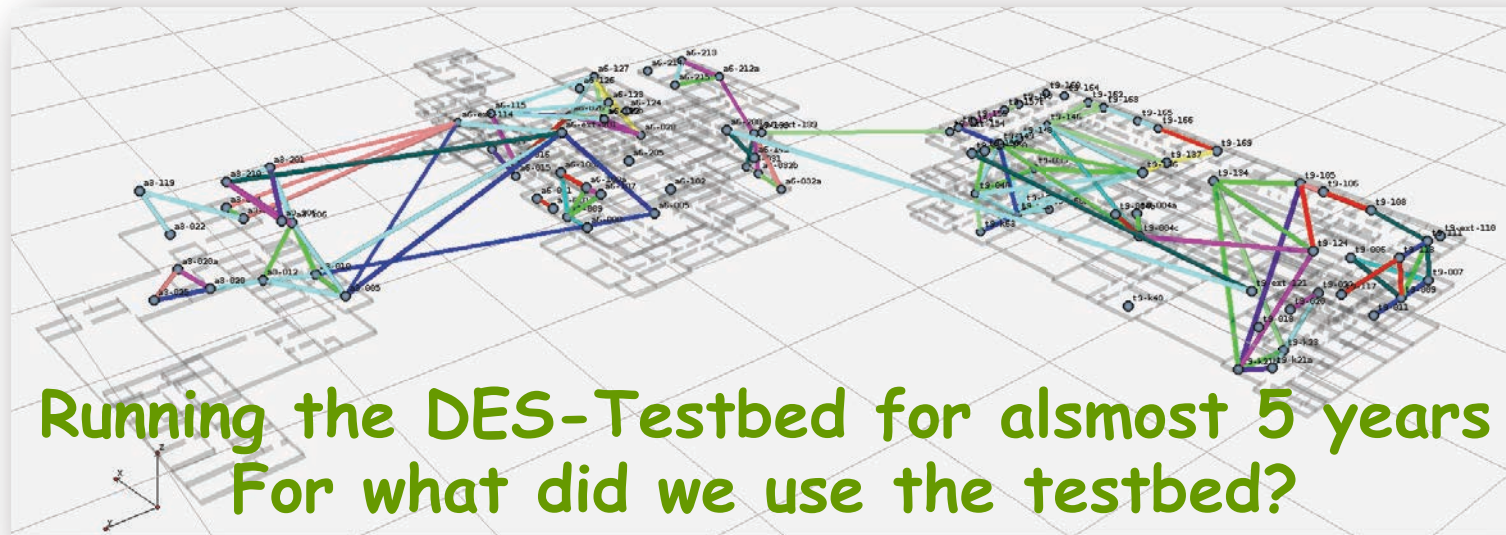
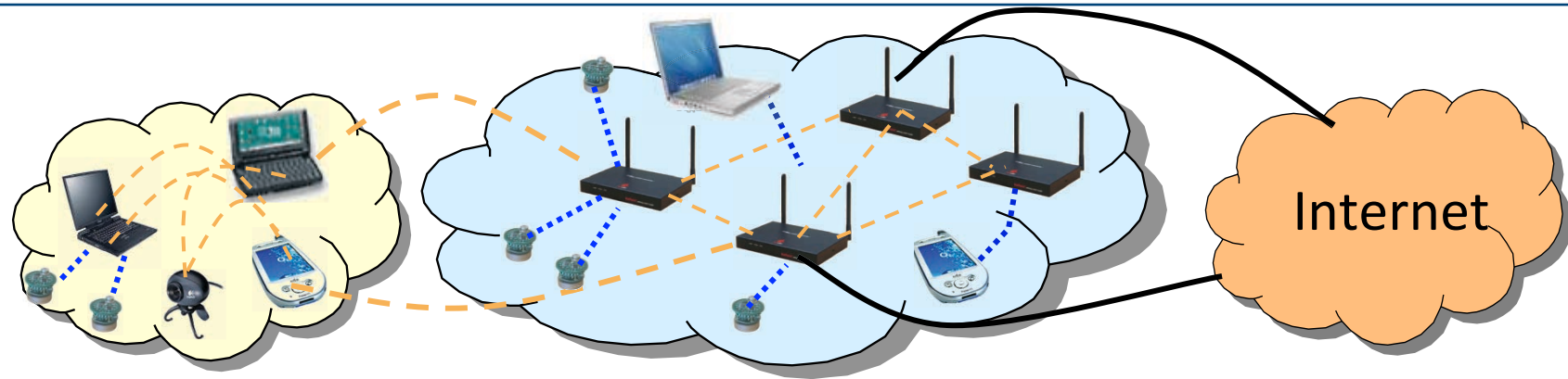
- Set, Integer, Real
- Range and step

```
<actions>
  <action_block id="1" execution_mode="1">
    <action id="1">
      <group>Receiver-TCP</group>
      <command>iperf -s</command>
      <start_time>0</start_time>
      <duration>30</duration>
    </action>
    ...
  </action_block>
  ...
</actions>
```

```
<actions>
  <variables>
    <variable name="ch">
      <type>SET</type>
      <values>1,3,5,7,9,11,13</values>
    </variable>
    ...
  </variables>
  ...
</actions>
```

# Analysis of experiments

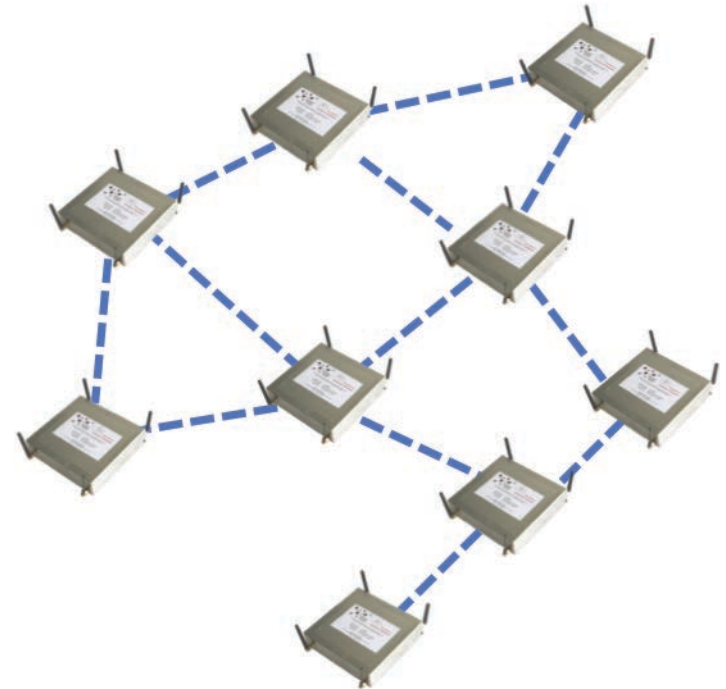
# Analysis of experiments



# What can be experimented?

---

- In fact, everything that runs on
  - Unix/Linux machine
  - MSB-A2
- Particularly
  - Routing (DES-SERT)
    - AODV, OLSR, ARA, BATMAN, NAMTAB, Gossip
  - Localization and Location based services
    - Anchor-free and Anchor-based
  - Channel assignment
    - Distributed and centralized
  - Service placement
    - DNS, Certification authority
  - Security and PKI
  - MAC
  - Transport layer (TCP, DCCP, SCTP)
  - Applications: Audio, Video, Bulk transfer, etc.
- Special configurations for the integration of networks
  - Wireless mesh networks (WMN)
  - Wireless sensor networks (WSN)
  - Integrated heterogeneous wireless networks



# Analysis of experiments

---



FIRE Engineering Workshop, 6-7.11.12  
Ghent, Belgium

Motto: FIRE is real. Let's use it!

# Analysis of experiments

---

- Experiments run in 2010 and 2011
- Testbed ~ Tool for research
- How to measure usefulness? -> Metrics?
  - Scientific output
  - Cost
  - User perception (usability)
  - Flexibility
  - Quantitative
  - Qualitative

# Scientific output

---

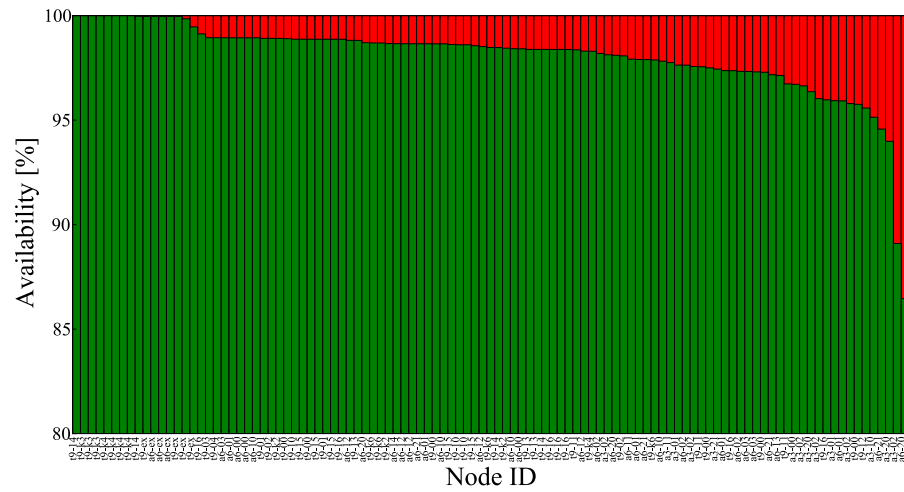
Projects that used the testbed	6
Number of theses (B.Sc., M.Sc., etc.)	32
Total number of publications	25
- Conference papers	15
- Workshop papers	5
- Journal articles	3
- Technical reports	2

Scientific output based on the DES-Testbed during the years 2010 and 2011.

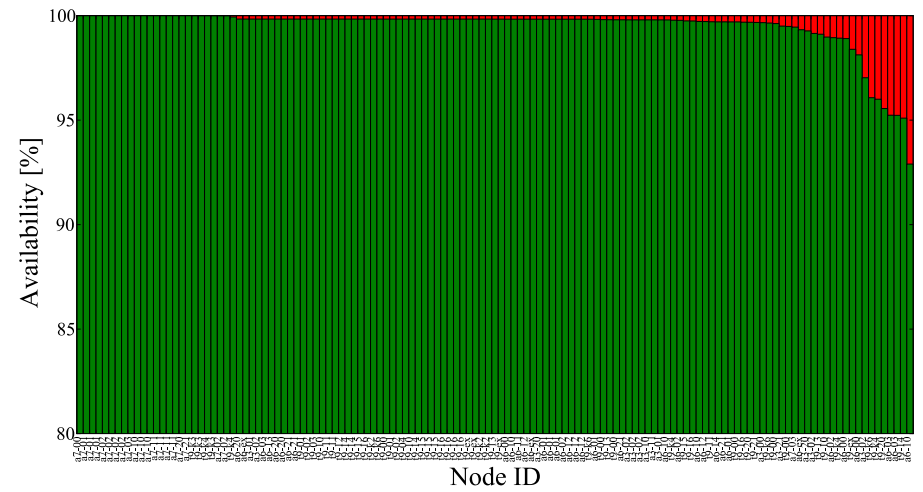
# Availability of the nodes

---

2010

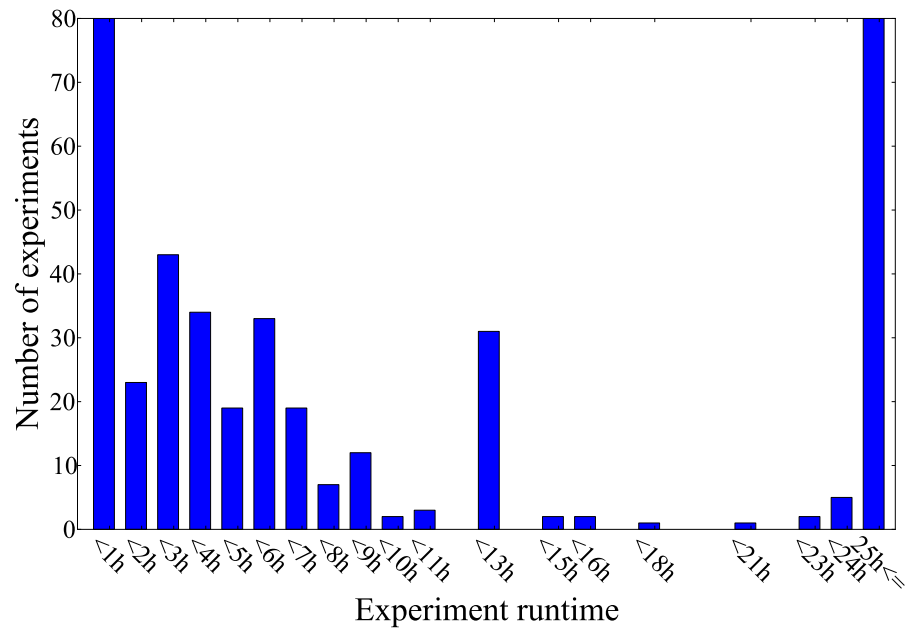


2011

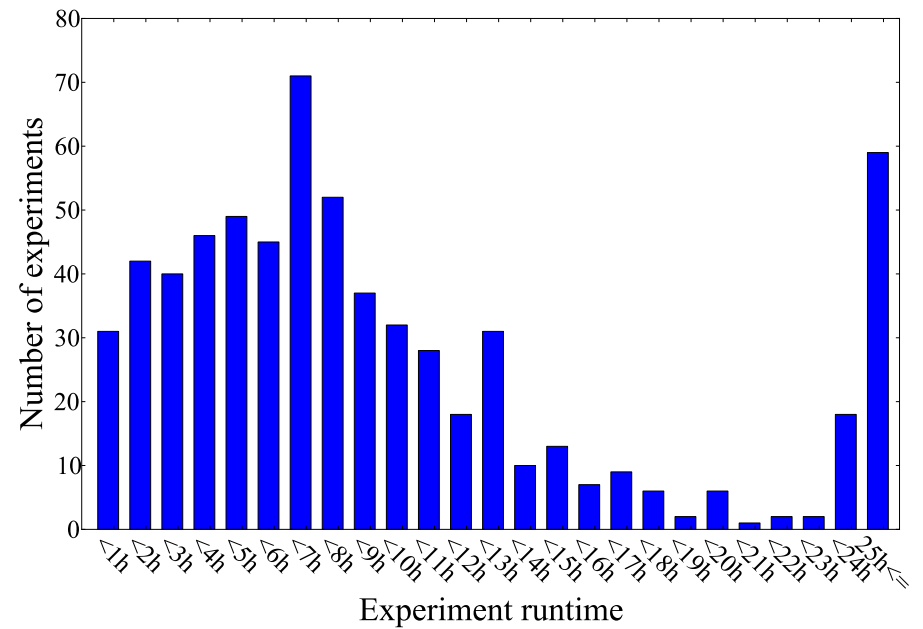


# Experiment runtime

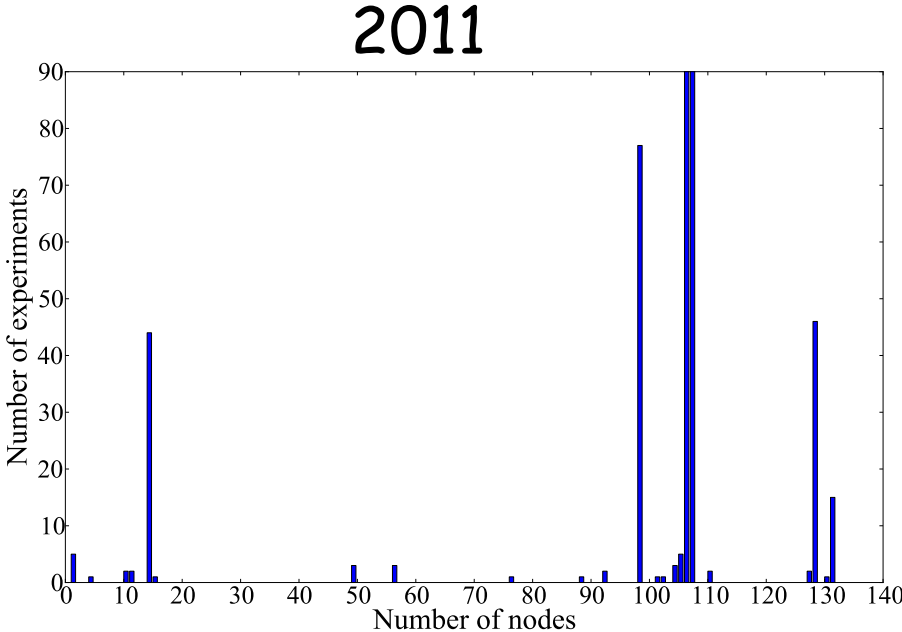
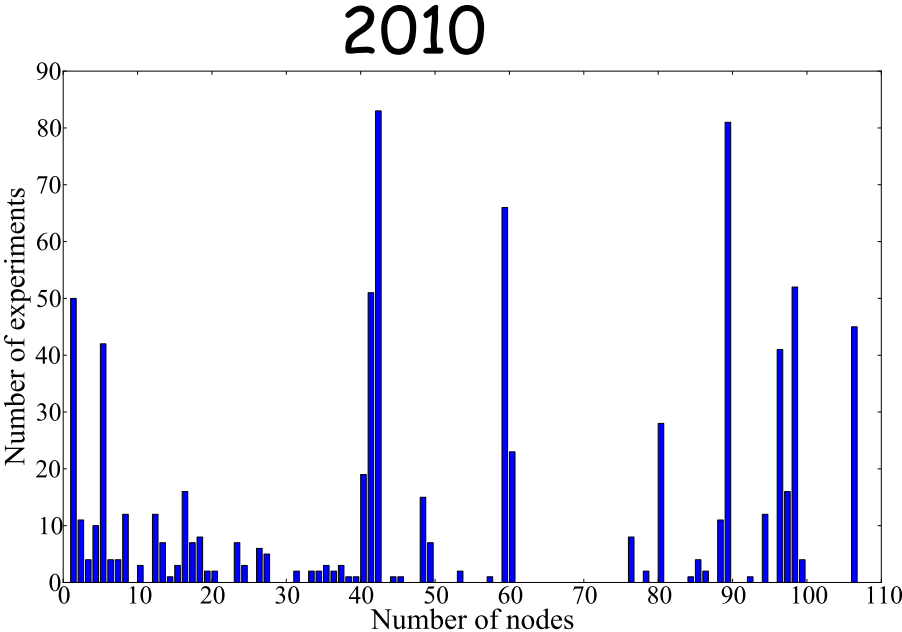
2010



2011



# Nodes per experiment



# Users of the testbed

---

	<u>2010</u>	<u>2011</u>
Number of users	20	30
Internal users	18	26
- Students	12	20
- PhDs	6	6
External users	2	4

The experimenters of the DES-Testbed distinguished between internal and external users.

# Summary of the experiments

---

	2010	2011
Average uptime of nodes [%]	98	99.5
Number of experiments	407	661
Max runtime of experiments [h]	132	875
Average runtime of experiments [h]	8	11
Max number of nodes in experiments	106	131
Average number of nodes in experiments	55	99
Number of users	20	30
Average number of experiments per user	39	22

Summary of the performed experiments in 2010 and 2011.

# Topics of experiments

---

Topic	2010		2011	
	Count	Time [h]	Count	Time [h]
Application Layer	10	20	70	721
Channel Assignment	54	329	83	1116
Localization	25	368	0	0
MAC	28	124	3	29
Mobility	22	41	102	557
Routing	75	451	362	4067
Security	0	0	12	85
Service Placement	6	72	0	0
Tracking	12	58	0	0
Transport Layer	0	0	18	216
WSN*	66	276	78	598

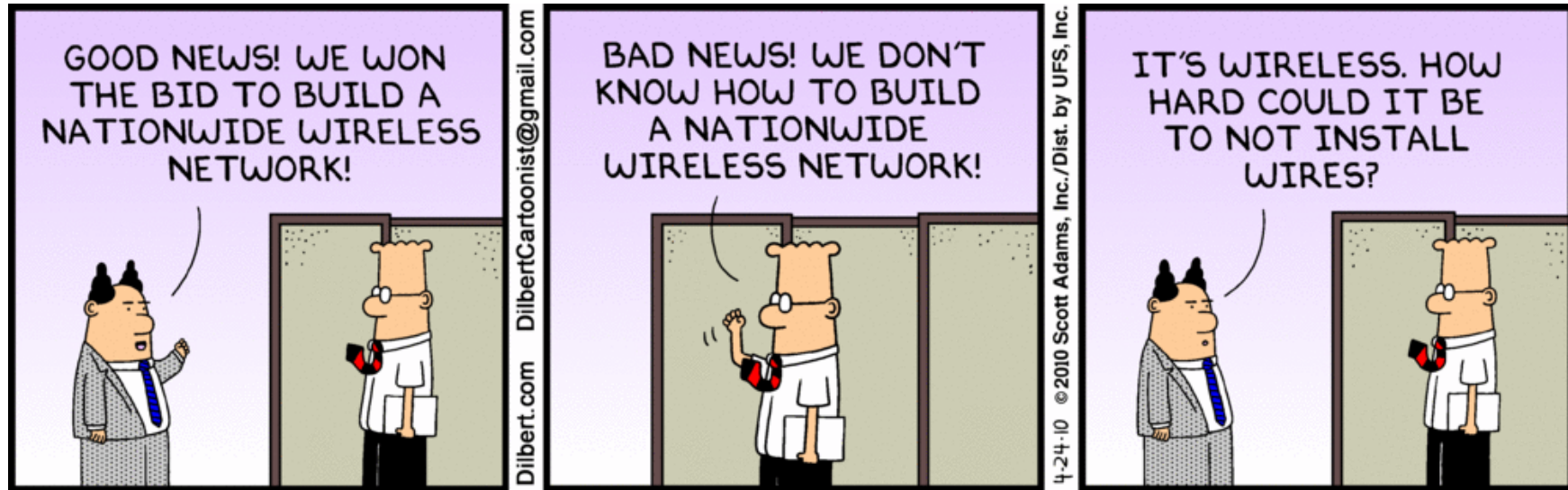
---

# Summary

# Summary

---

- Most performance evaluation is done with simulation
  - Results do not hold in reality
  - Interaction and integration into “real” Internet
- Problems running a testbed for research
  - No standards
  - Most of the work is done by PhD and MSc students
  - High learning curve
- From scientific perspective
  - a holistic understanding of the experiment lifecycle is required
  - researcher needs a scientific workflow tool
  - “research results” take “little” longer



Thank you very much for your attention!

Good luck in the exam.

# Literature

---

- [Kurkowski] Stuart Kurkowski, Tracy Camp, and Michael Colagrosso, "[MANET simulation studies: the incredibles](#)", SIGMOBILE Mob. Comput. Commun. Rev. 9, 4 (October 2005), 50-61. DOI=10.1145/1096166.1096174  
<http://doi.acm.org/10.1145/1096166.1096174>
- [Kleinrock] Kleinrock, L., "[On the modeling and analysis of computer networks](#)" Proceedings of the IEEE , vol.81, no.8, pp.1179-1191, Aug 1993, doi: 10.1109/5.236194
- [Günes08a] Günes, M., B. Blywis, and F. Juraschek, "[Concept and Design of the Hybrid Distributed Embedded Systems Testbed](#)", no. TR-B-08-10: Freie Universität Berlin, 2008.
- [Günes08b] Günes, M., B. Blywis, F. Juraschek, and P. Schmidt, "[Practical Issues of Implementing a Hybrid Multi-NIC Wireless Mesh-Network](#)", no. TR-B-08-11: Freie Universität Berlin, 2008.
- [Blywis] Blywis, B., M. Günes, F. Juraschek, J. Schiller, "[Trends, Advances, and Challenges in Testbed-based Wireless Mesh Network Research](#)", ACM/Springer Mobile Networks and Applications (MONET), February, 2010
- [Günes10] Günes, M., F. Juraschek, and B. Blywis, "[An Experiment Description Language for Wireless Network Research](#)", Journal of Internet Technology (JIT), Special Issue for Mobile Internet, vol. 11, no. 4, 07/2010
- [Günes12] Günes, M., F. Juraschek, and B. Blywis, "[Exploring the Experiments of a FIRE Testbed](#)", FIRE Engineering Workshop, Ghent, Belgium, 2012.

# Literature

---

[SANDBed] Hergenröder, Horneber, "Towards a Generic Management Model for Wireless Sensor Network Testbeds", INSS 2010: 7th International Conference on Networked Sensing Systems.

[WSNTB] Sheu, Chang, Sun, Hu, "WSNTB: A testbed for heterogeneous wireless sensor networks", First IEEE International Conference on Ubi-Media Computing, 2008

[des-testbed] <http://www.des-testbed.net>

[wisebed] <http://wisebed.eu>

[rwglab] <http://www.rwglab.de>