The Heathland Experiment
Results And Experiences

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Introduction

- Wireless sensor networks very active field
- But:
  - Number of theoretical publications >> number of deployments
  - Vast majority algorithms only simulated & not implemented on real sensor networks
  - Current simulation tools are not capable to completely represent sensor networks in harsh environment over long period of time
- Real deployments are indispensable!

Heathland Experiment

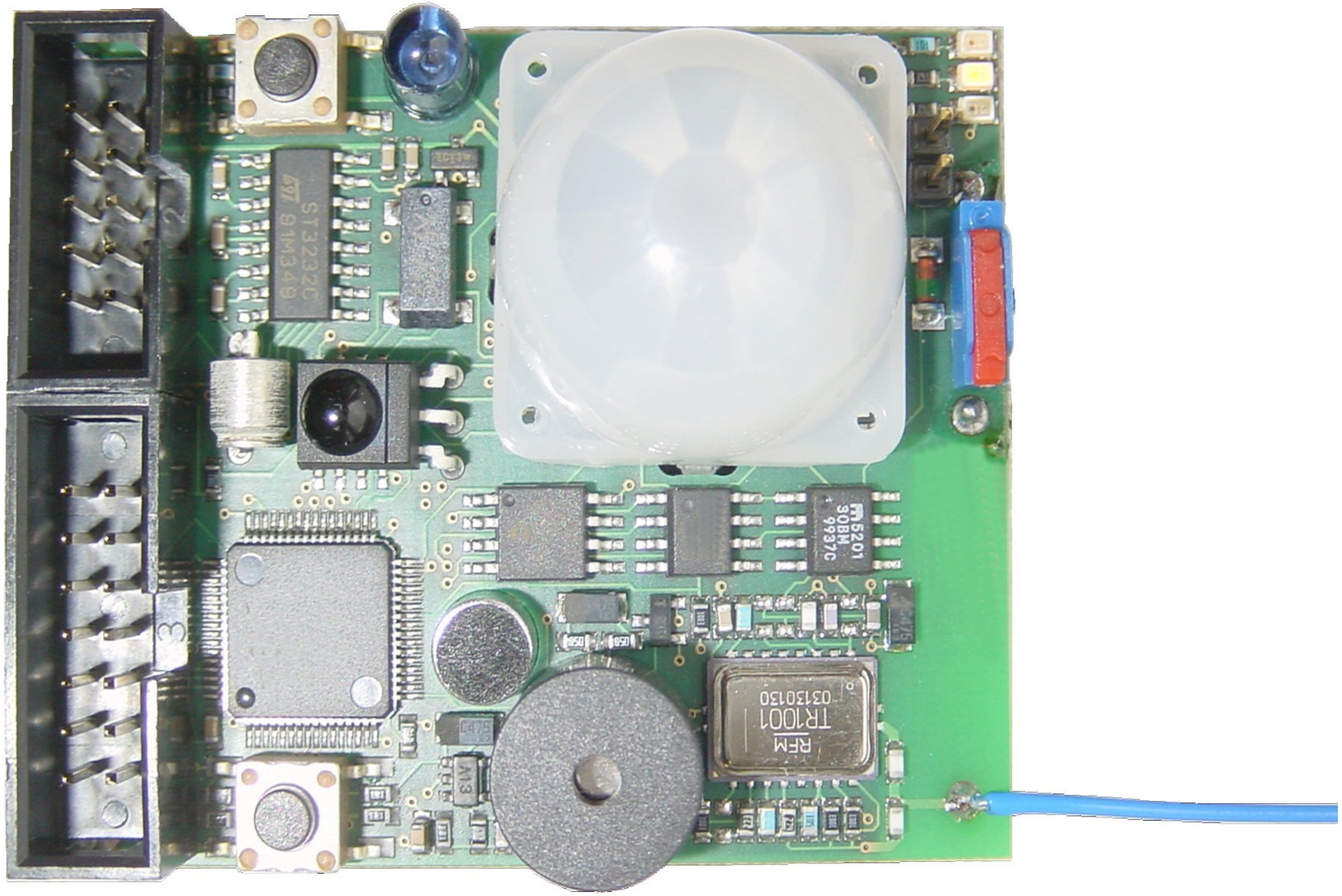
- Real deployment of a sensor network
- 24 nodes running for 2 weeks in March 2005
- Location: Heathlands of Northern Germany
- First outdoor long term usage of Embedded Sensor Board (ESB)
- Application ran without any human attention
- Objective:
  Reveal problems that can only be discovered through experience

Goals

- General radio performance (packet loss, packet errors)
- Constancy of transmission ranges
- Performance of our neighborhood protocol
- Communication in a multi-hop environment
- Dynamic adaption to changes of transmission ranges
- Test depth-first search implementation
- Increased expectation of life was not a goal

Platform: ESB Nodes

Source: www.scatterweb.net



Platform: ESB Nodes

- Texas Instruments micro controller MSP 430
- Transceiver TR1001, 868 MHz, 19.2 kbit/s
- RS232 serial interface
- Sensors: light, passive infrared, temperature, vibration, microphone
- Tunable radio transmit power
- 2KB RAM, 8 KB EEPROM
- Powered by 3 AA batteries
- Power consumption: 8 µA (sleep mode) up to 12 mA (all sensors on)

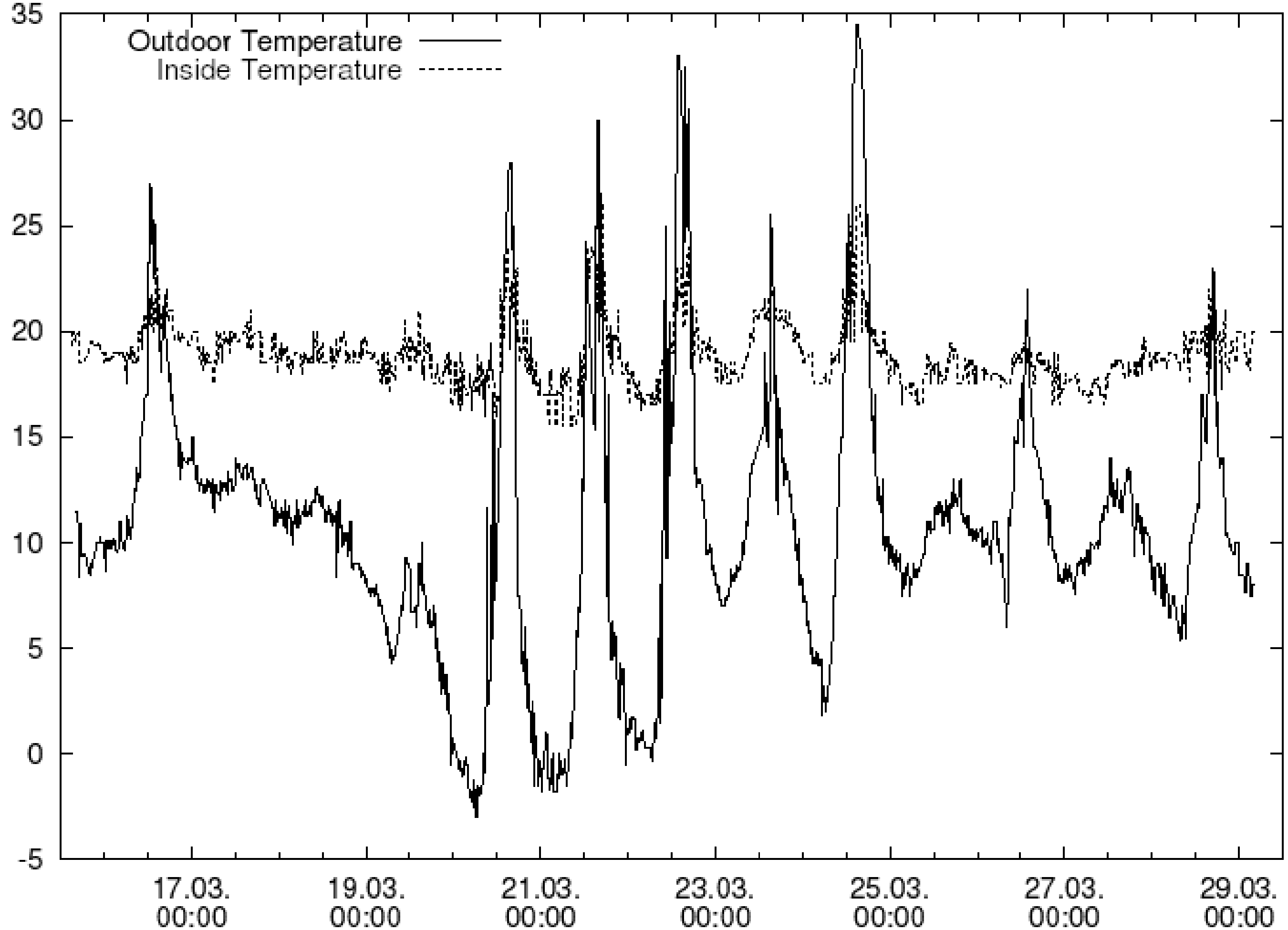
Packaging

Packaging

Packaging

Weather

Recorded Temperature



Application

- Sense & send: Sensors deployed in wide-ranging area take periodic readings & report to central repository
- Nodes periodically send readings from their 5 sensors to sink
- To account for topology changes, routing trees and neighbor relationships were recomputed regularly
- Scalable application
- Application could cope with node failures, deployment of new nodes, decreasing communication radii due to fading battery energy
- Multi-hop network

Application

Sense & Send Application

Depth-first Algorithm Routing

Wireless Neighborhood Exploration WNX

Radio Transmission Protocol Firmware

WNX

- Modified implementation of TND, the proactive neighbor discovery protocol of TBRPF (RFC 3684)
- Simple, agile yet stable
- Uni- & bidirectional links
- Each node records last 32 expected hellos from each neighbor
- Quality descriptor: weighted moving average
- Hellos associated with weights → Link-quality between 0 and 255
- Radio signal strength indicator, not included

WNX

- At most 8 neighbors per node
- It takes 30 sec to discover new bidirectional link / to purge lost link
- Small memory footprint : 152 Bytes per node
- Currently protocol is extended

Application

- Uncertainty in radio communication → time triggered scheme
- Activities are initiated by progression of globally synchronized time-base
- Due to clock drift between individual nodes, sink sends periodically its local time into network
- All nodes including the sink have the same code
- Simplified deployment process
- Sink node sent data over a standard serial port interface to a PC (about 6MB per day)

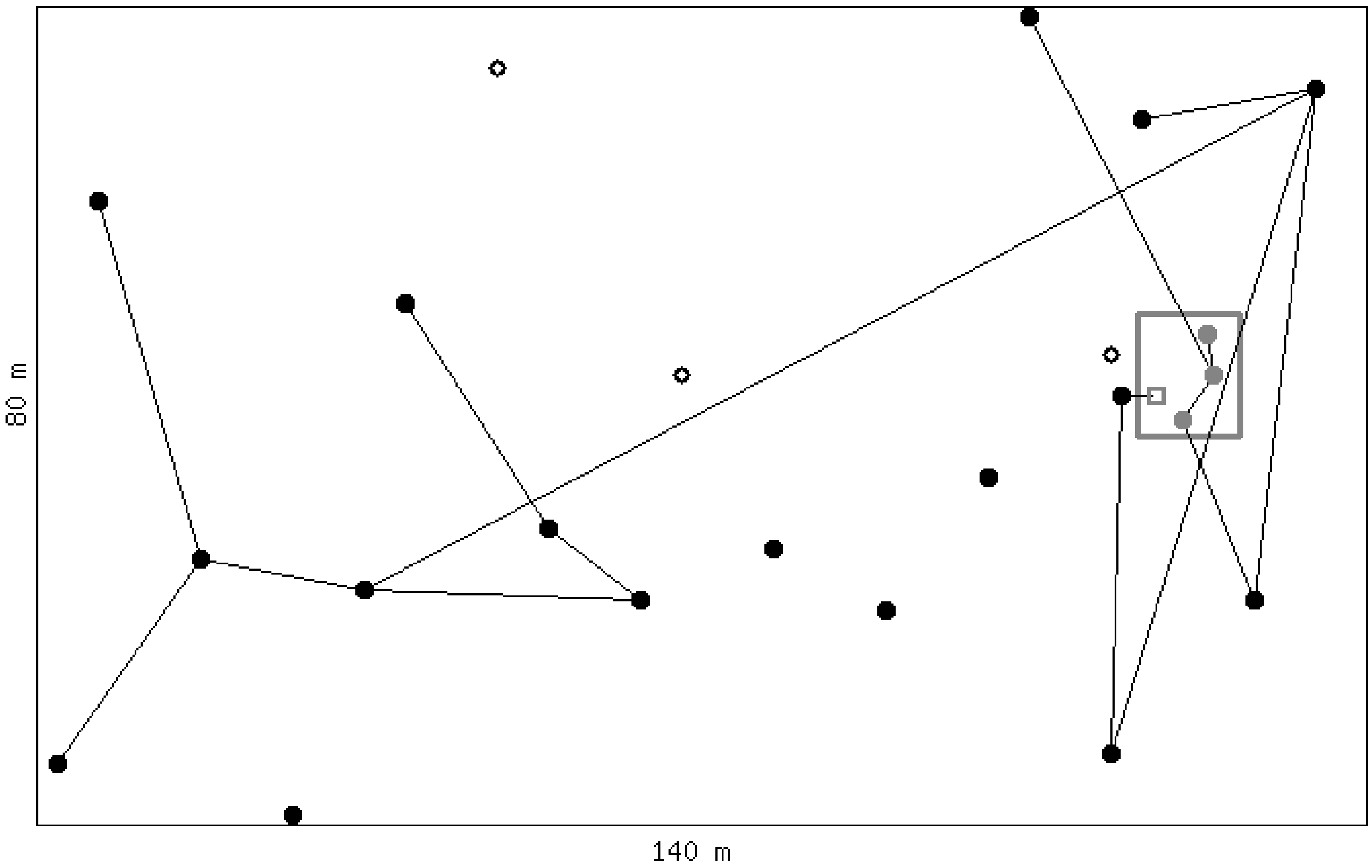
At start of every clock hour:

Time	Action	Result
0	Reset	Resets state of node
1	Start WNX	Nodes send Hello packets, compute link qualities and determine bidirectional links
9	Suspend WNX	List of bidirectional links with link quality
12	Start DFS	Depth-first search tree
14	Start measurements	Leaf nodes turn off radio, inner nodes turn off sensors In intervals of 10 minutes: - leaf nodes turn on radio - all nodes send measured data & link states to sink - the sink sends its local time to all nodes in tree - leaf nodes turn off radio

Application

- To reduce interferences, send time of leaf nodes randomly distributed in interval
- Every packet includes:
  - time-stamp with respect to local clock
  - remaining battery energy
  - number of packets received and sent
  - number of packet transmission retries
  - information about clock drift
- Packet size between 70 and 80 Bytes

Deployment



Territory

Deployment

Deployment

Deployment

Deployment

Deployment

Configuration

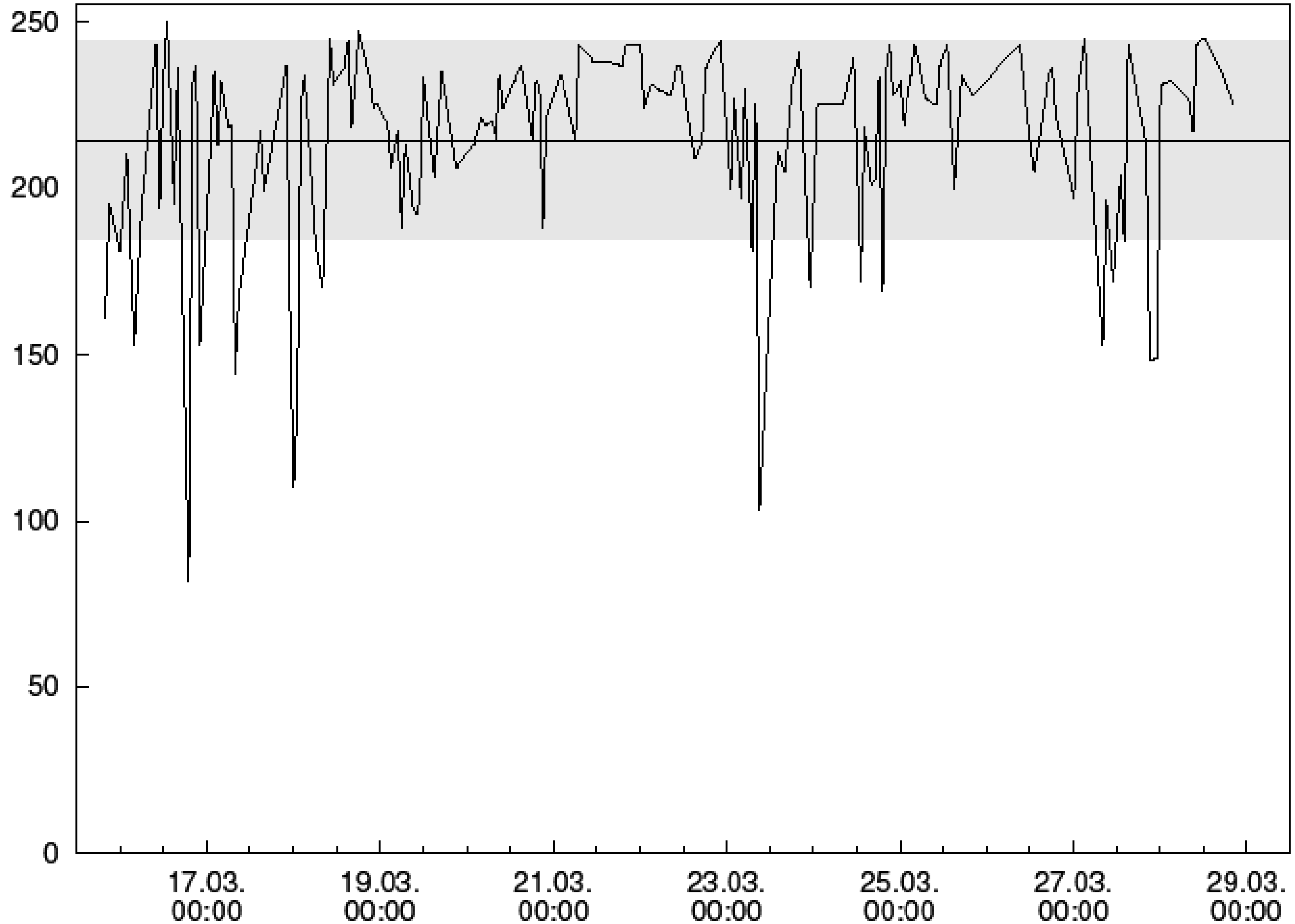
Radio Link Features

- Asymmetrical links: Connectivity from node A to node B might differ significantly from B to A
- Non-isotropical connectivity: connectivity need not be same in all directions (at same distance)
- Non-monotonic distance decay: Nodes geographically far away from source may get better connectivity than geographically closer nodes
- Link asymmetries may be caused by differences in hardware calibration
- Communication gray zones: Data messages cannot be exchanged although the HELLO messages indicate neighbor reachability

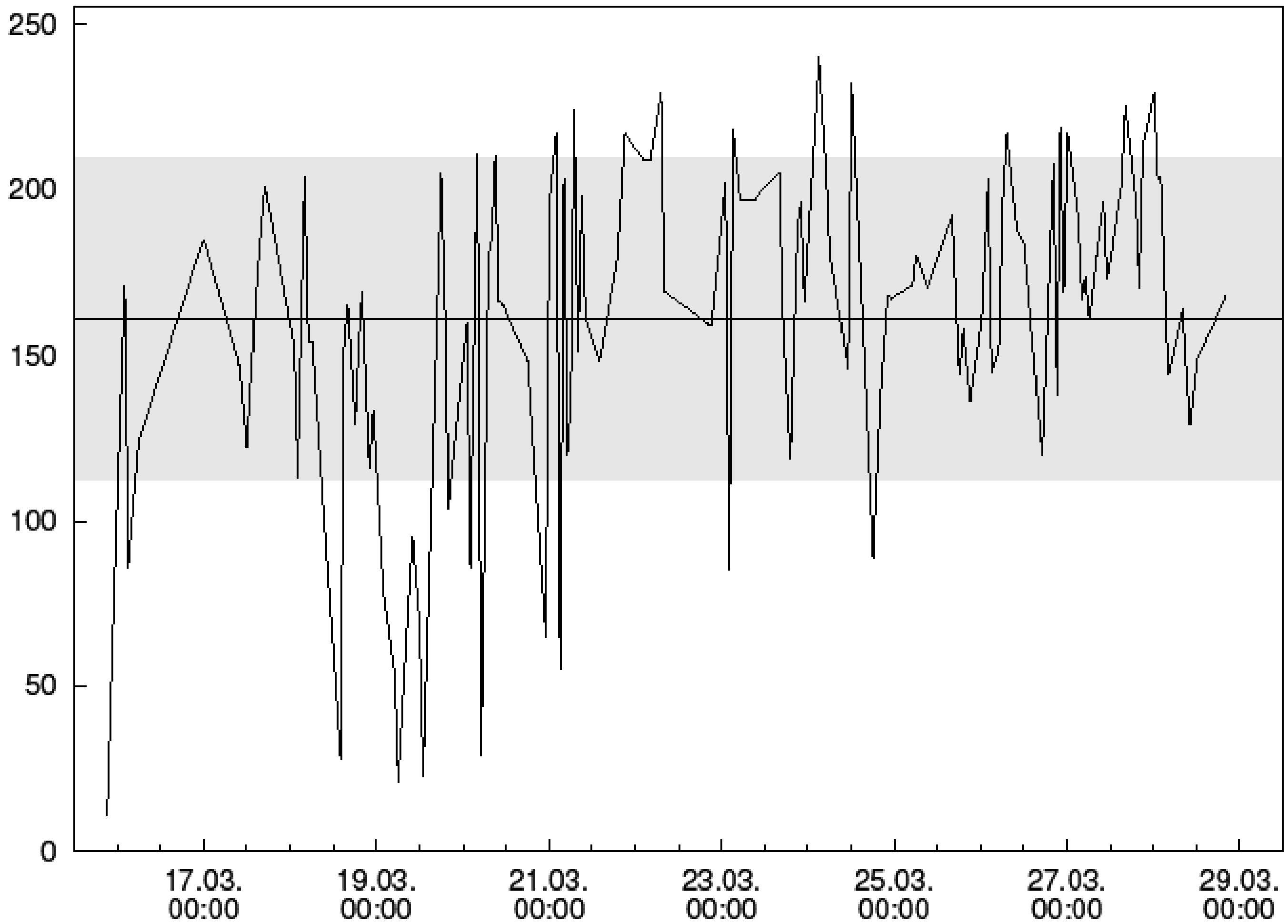
Analysis

- Altogether 24 nodes were used
- 3 nodes did not send significant amount of data after the first day (reasons are unknown)
- Remaining 21 nodes
- Out of the 210 different pairs of nodes, 45 appeared as links in a search tree
- Quality of these links varied considerably

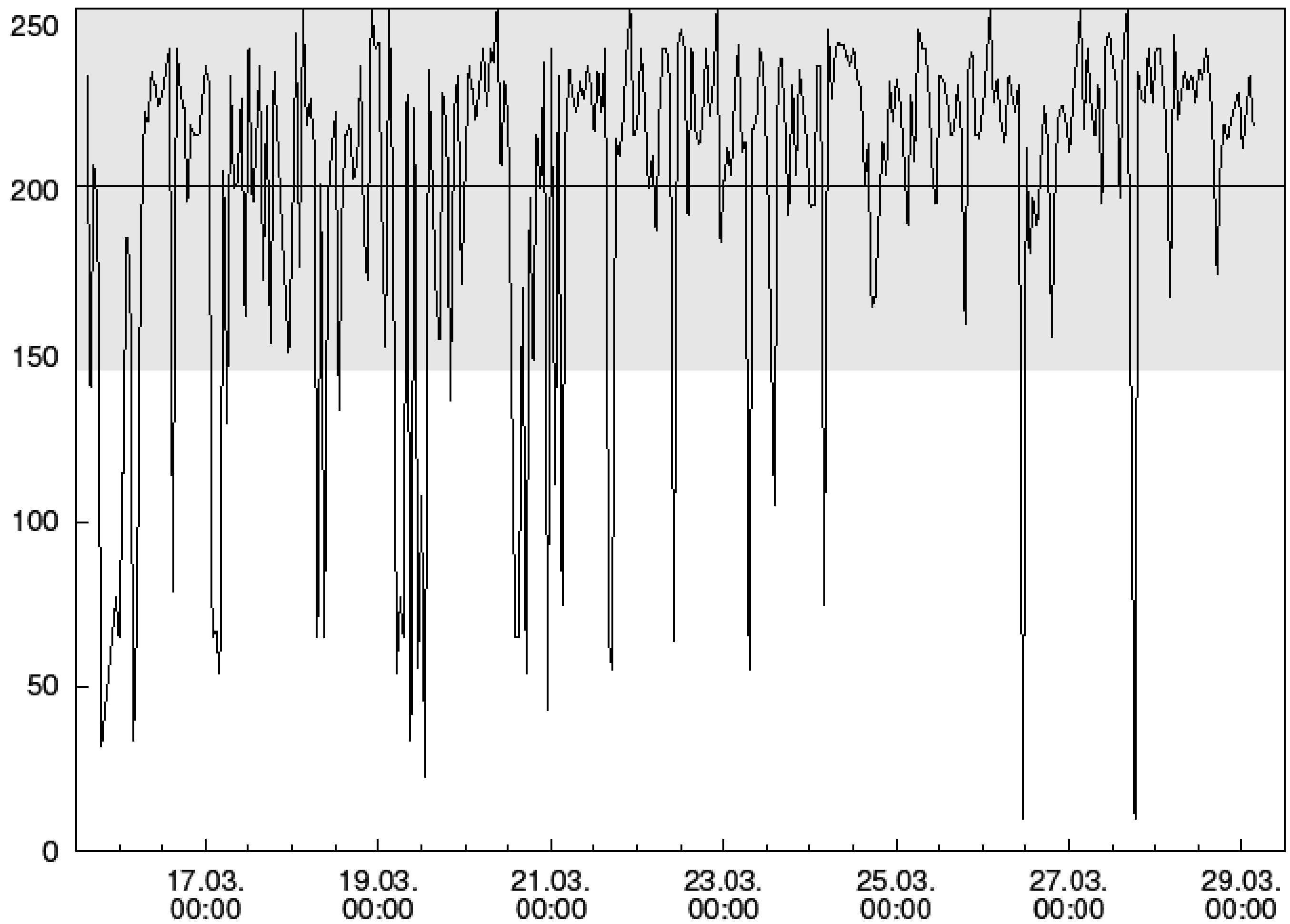
2 Indoor Nodes



2 Outdoor Nodes

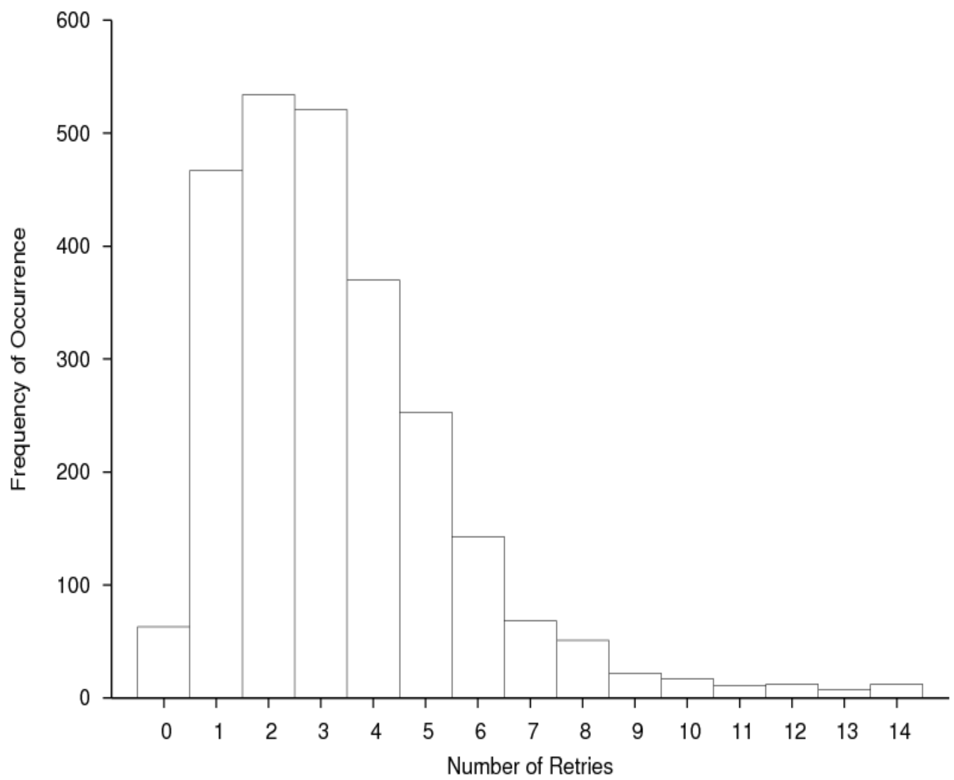


2 Outdoor Nodes



Retries in Unicast Transmission Scheme

- 15 retransmissions
- Maximal latency: 1143 ms, not including waiting time for channel access
- Observed latencies up to 3 s
- ~ 50% of all unicasts were successful
- Average number of retries: 3.89 → limit was too high
- Gnawali et al. max. 3 retries

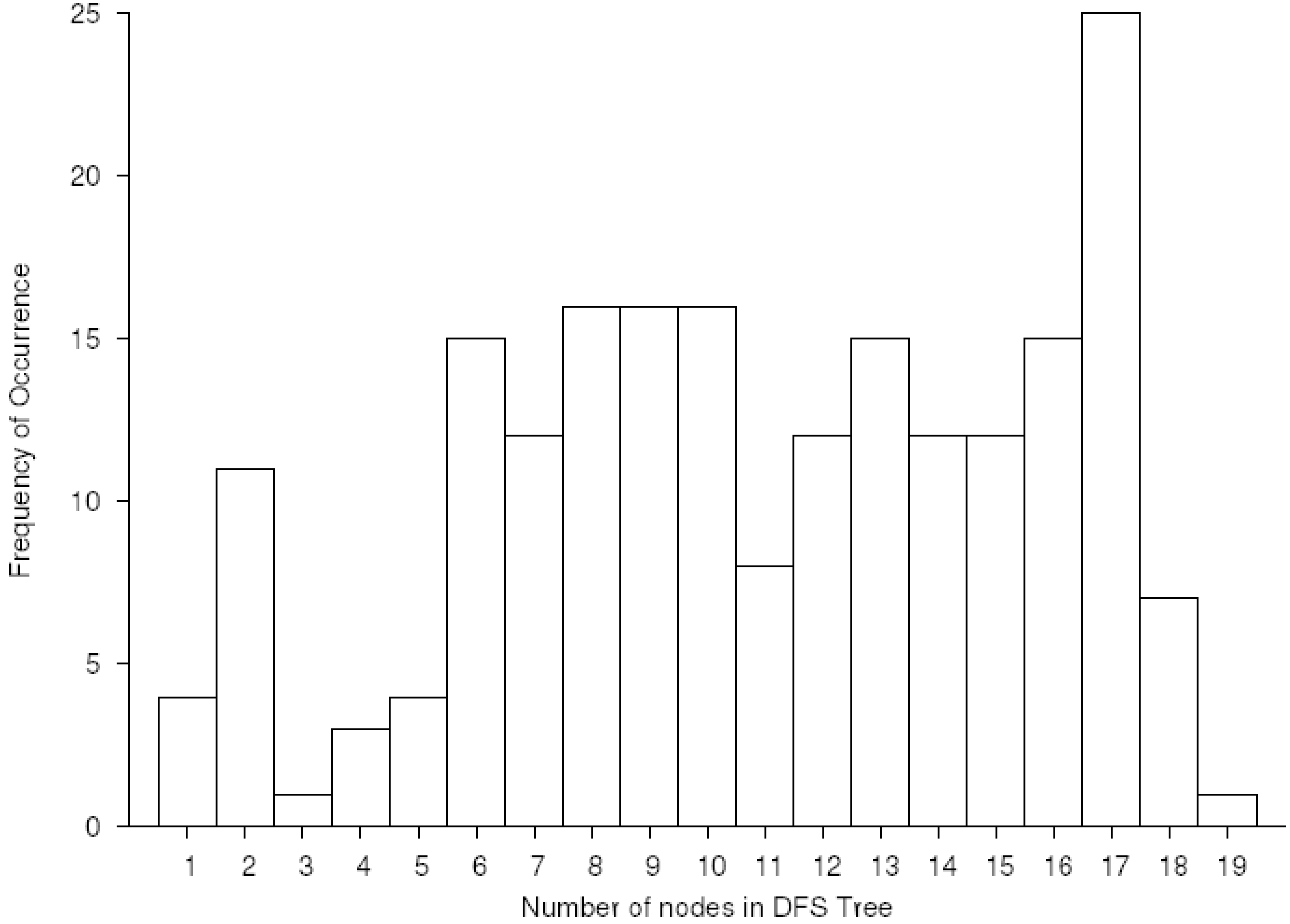


Lower value → less congestion & better overall success rate?

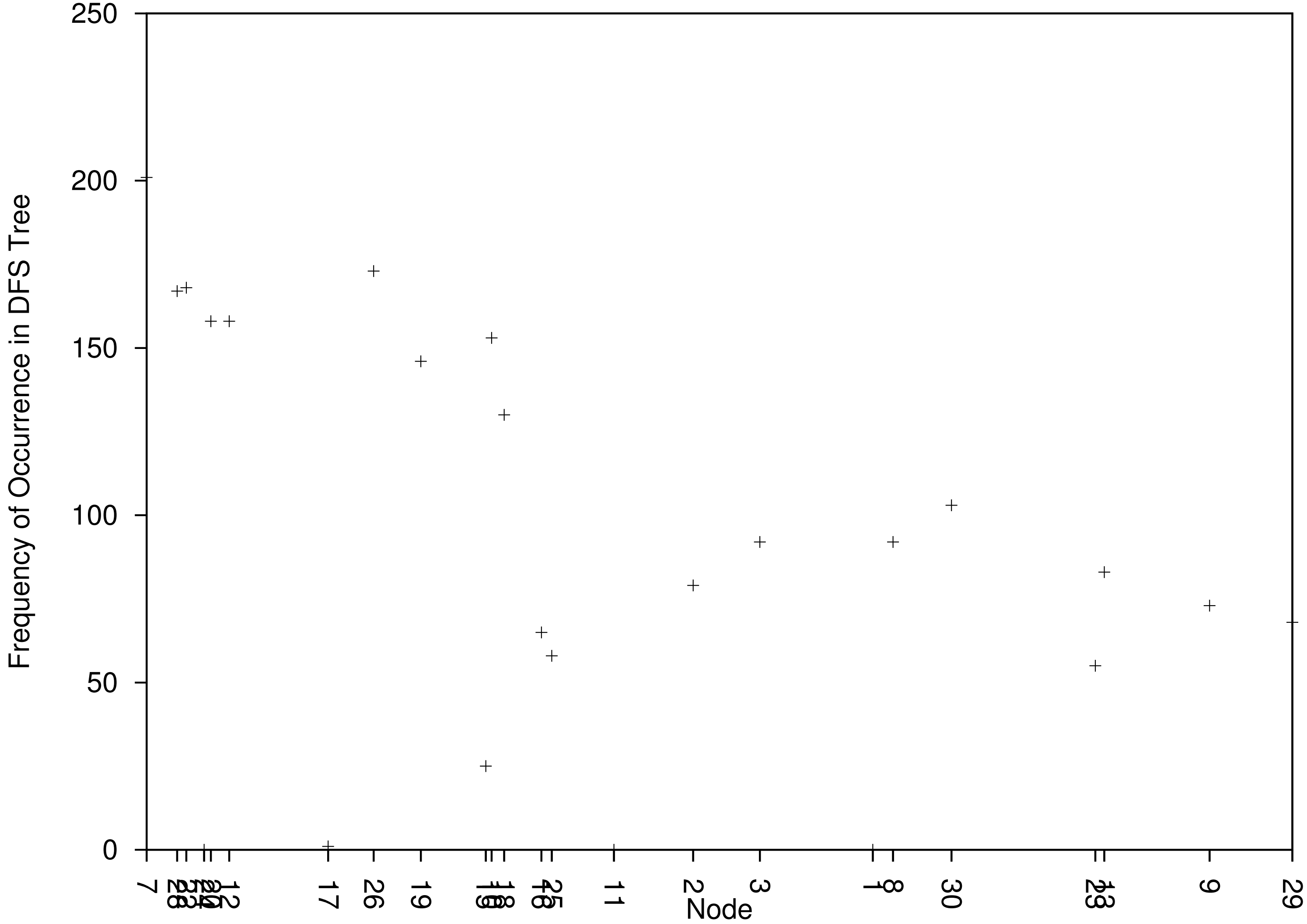
Depth-First Algorithm

- Sink started distributed depth-first search 317 times in 2 weeks (~22.5 per day)
- Links were chosen in descending quality order
- Search successfully terminated in 205 of these cases
- Successful depth-first does not visit all nodes of network
- Largest tree: 19 nodes (~ 90% of active nodes)
- More than 50% of all successfully built trees included more than 50% of nodes

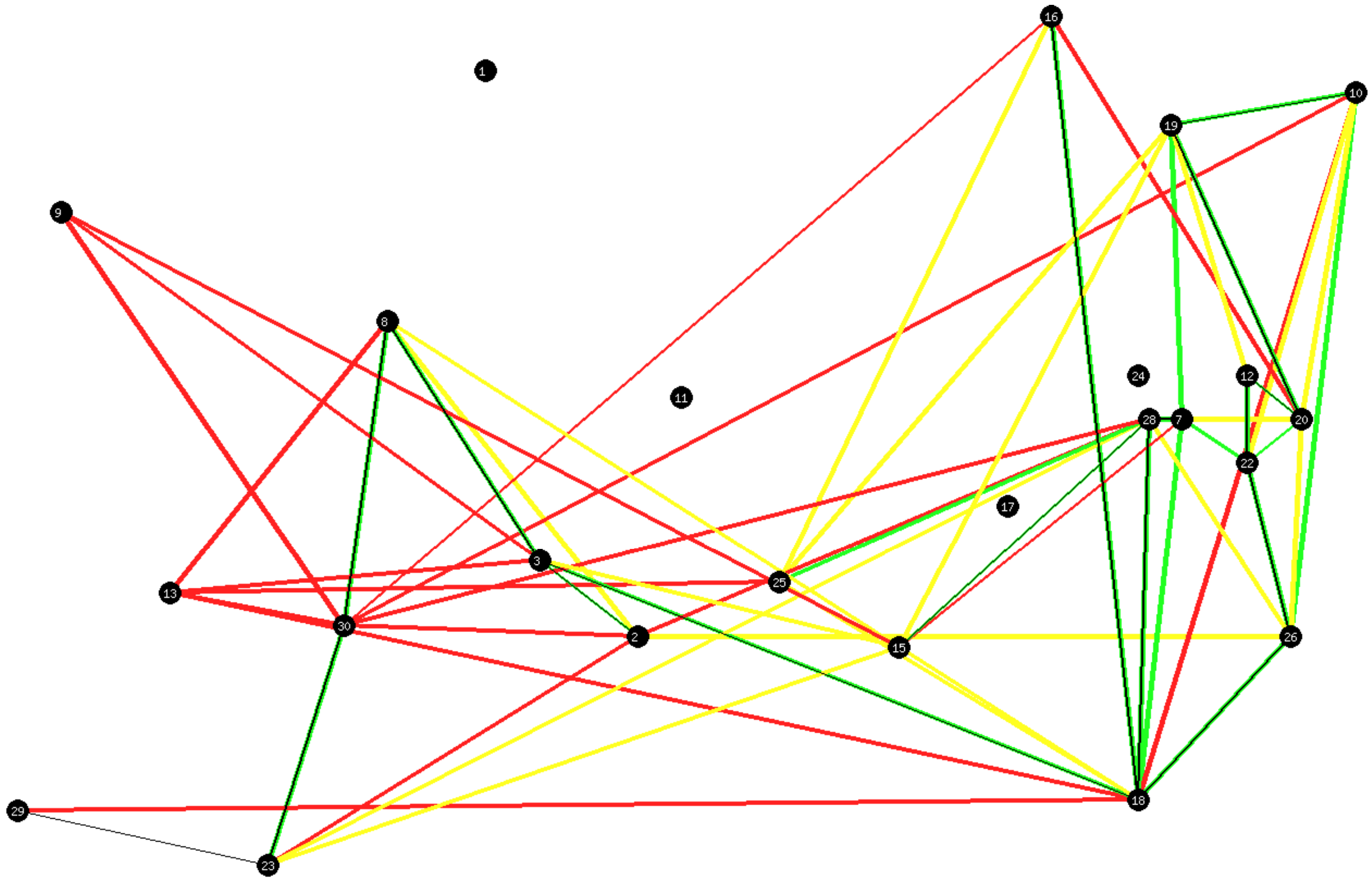
Depth-First Algorithm



Occurrences of Nodes in DFS Trees



Changing Link Quality



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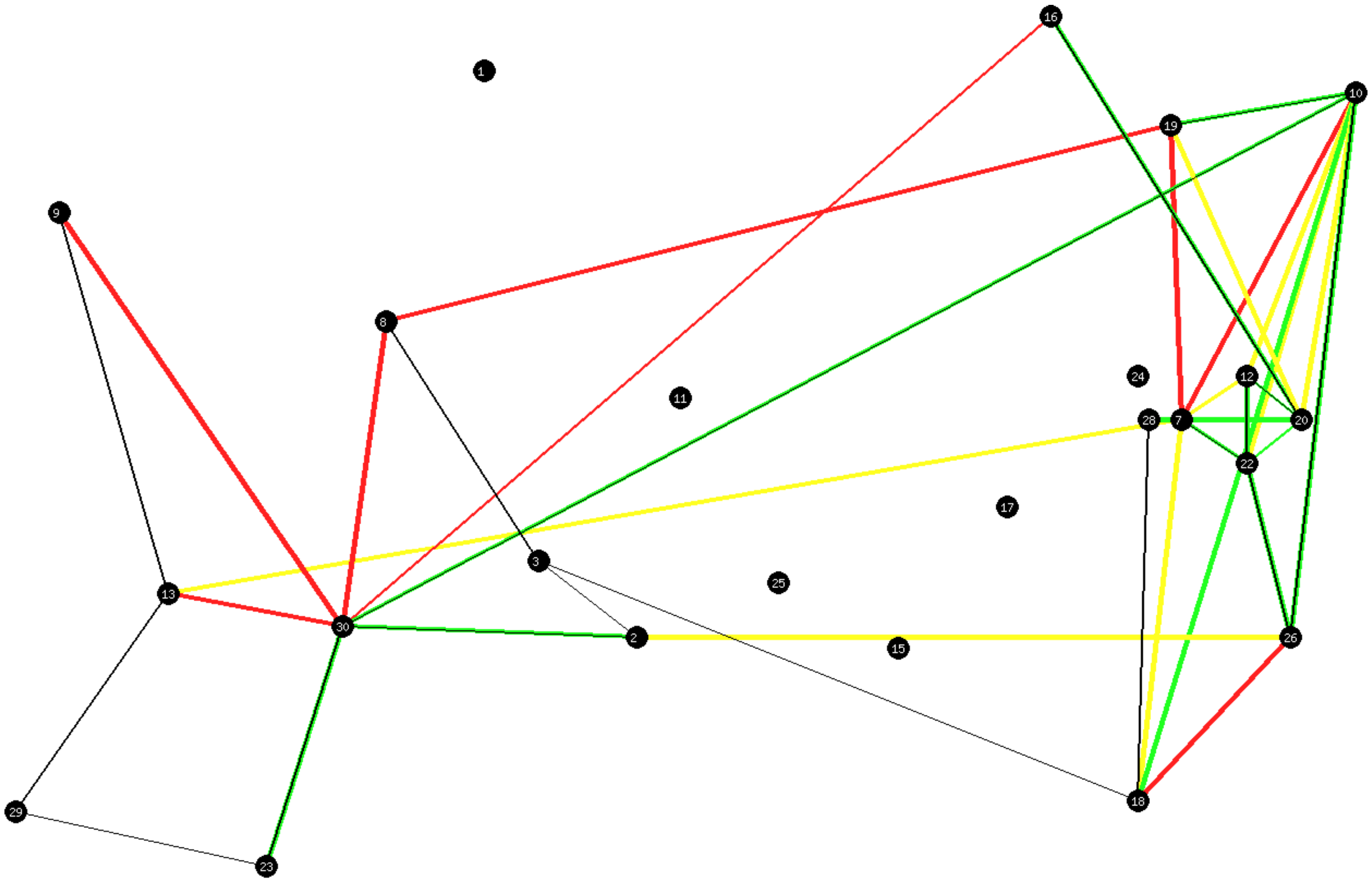

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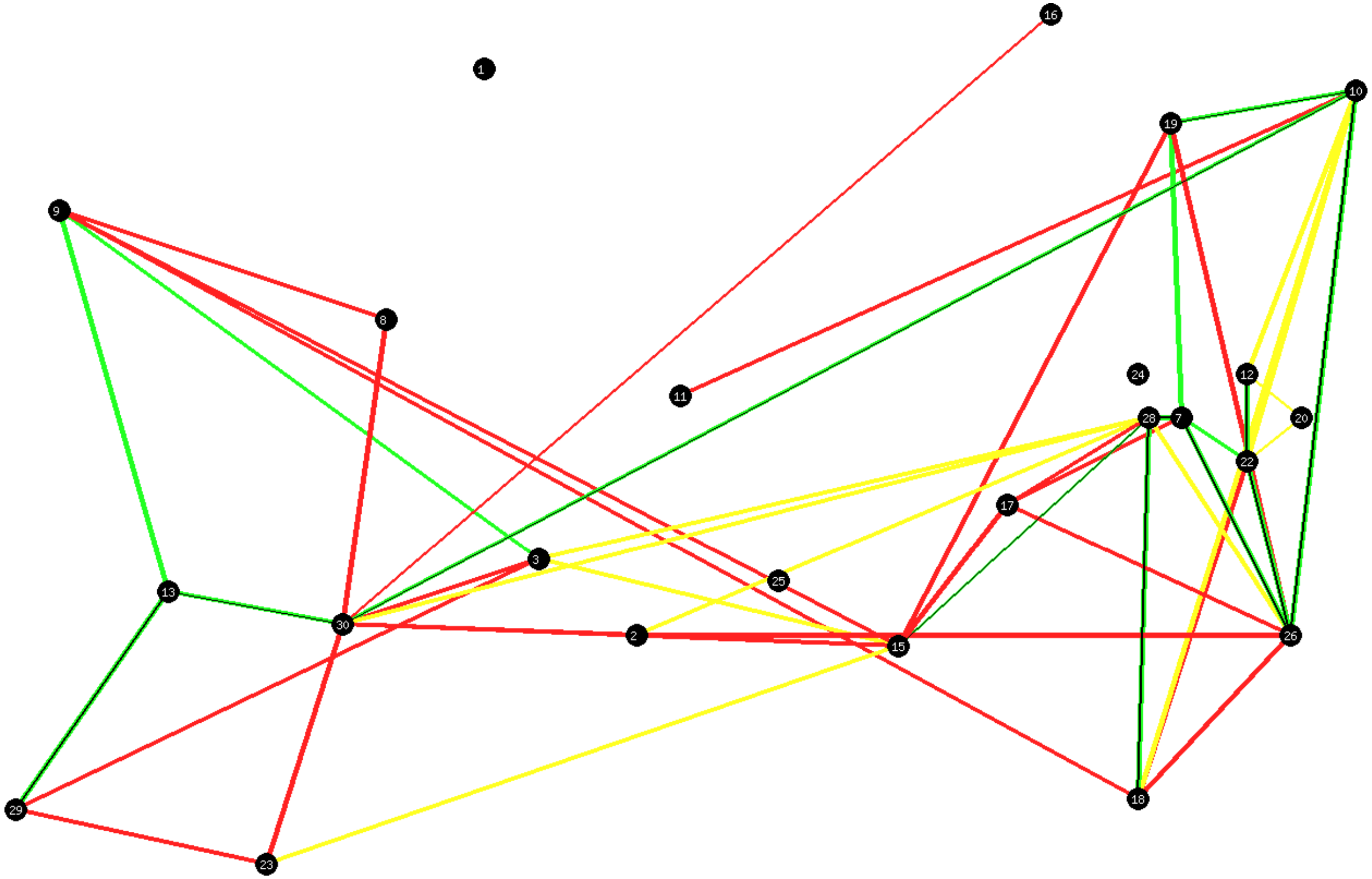

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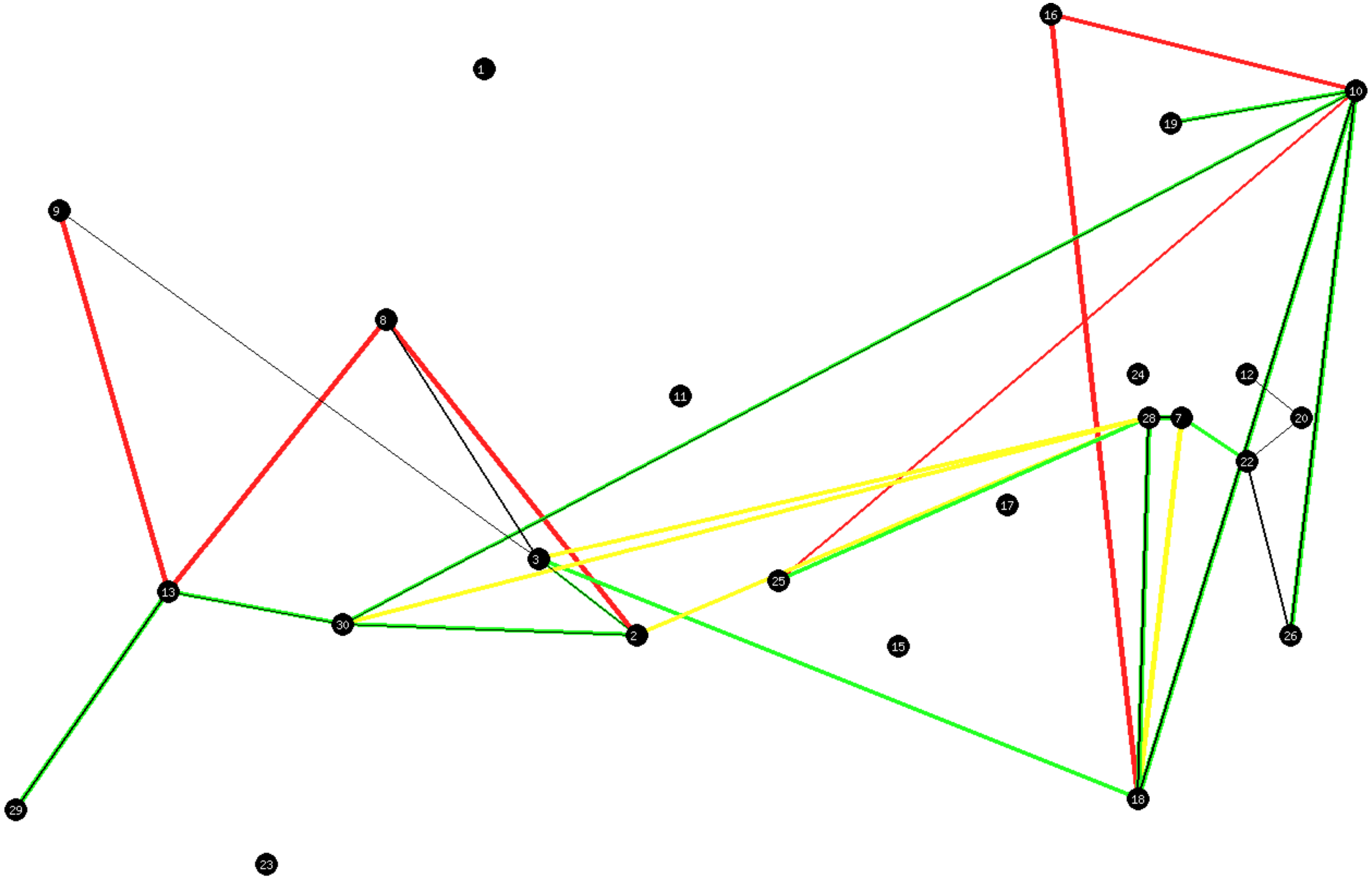

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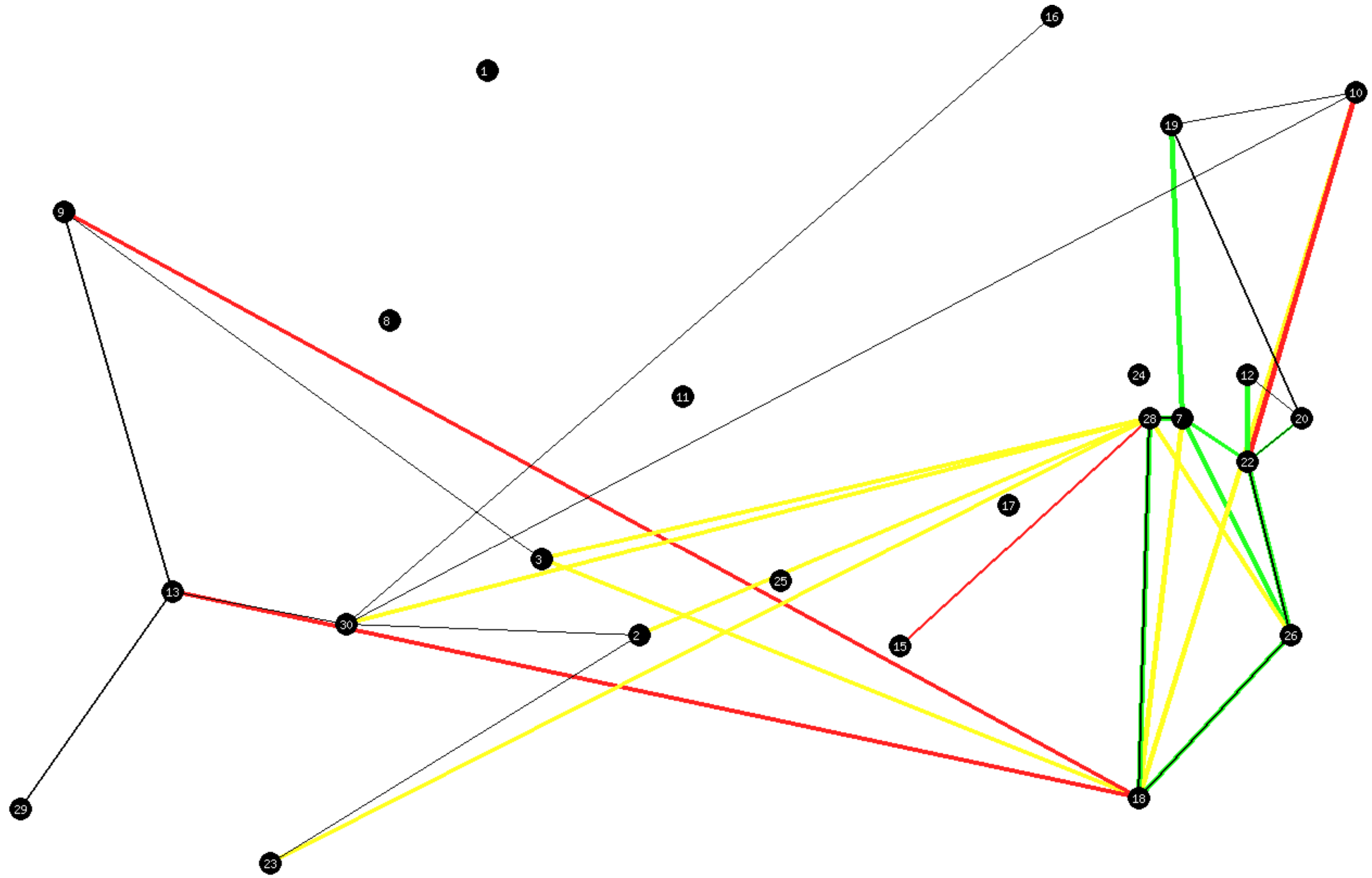


Depth First Trees

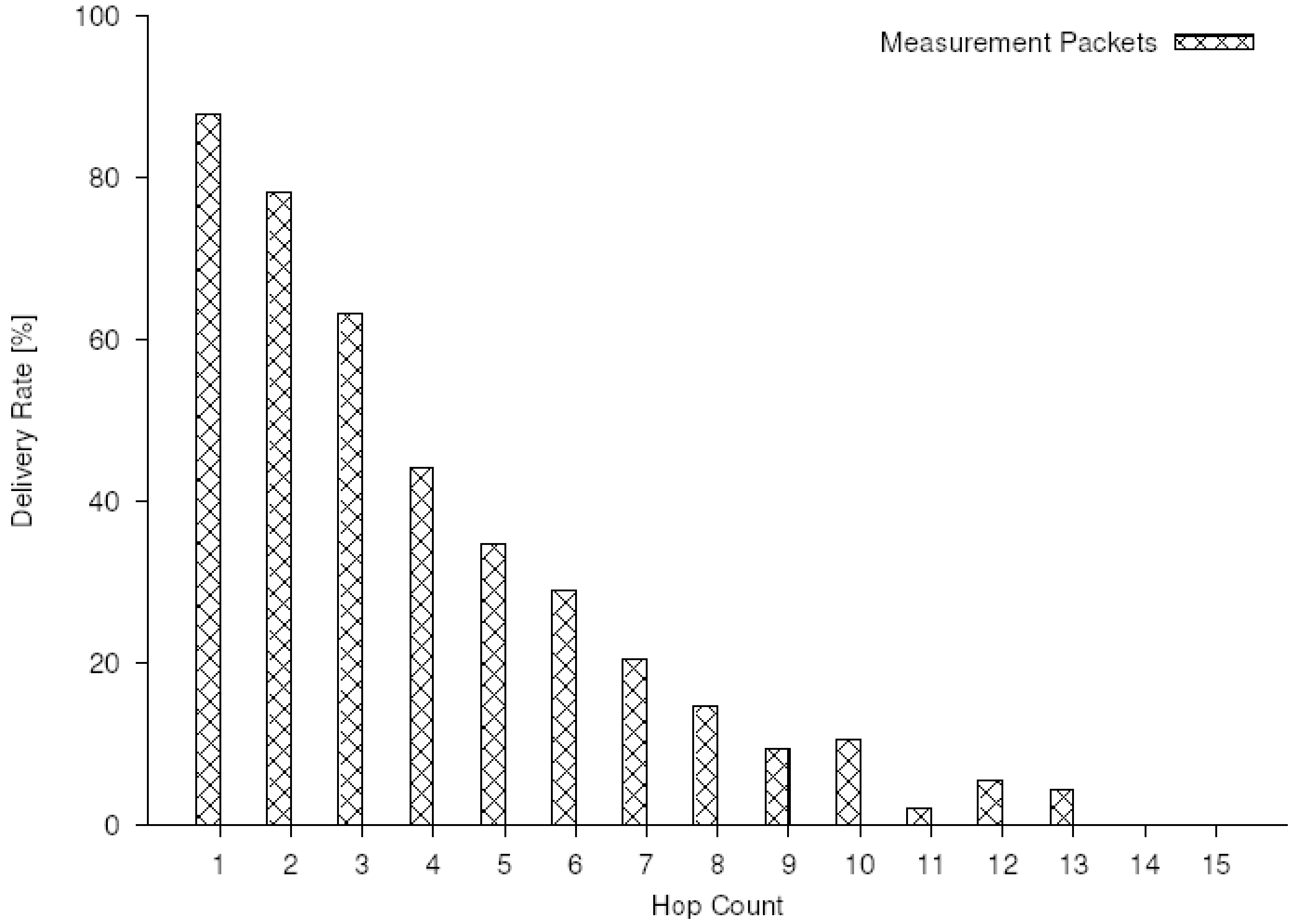
List of each node's successors is relatively stable over time

Node \ Nbs.	26	12	20	22	18	10	19	16	30
22	88	70	98						
26				55	7	72			
20		86		15			37	37	
10	41				26		82		71

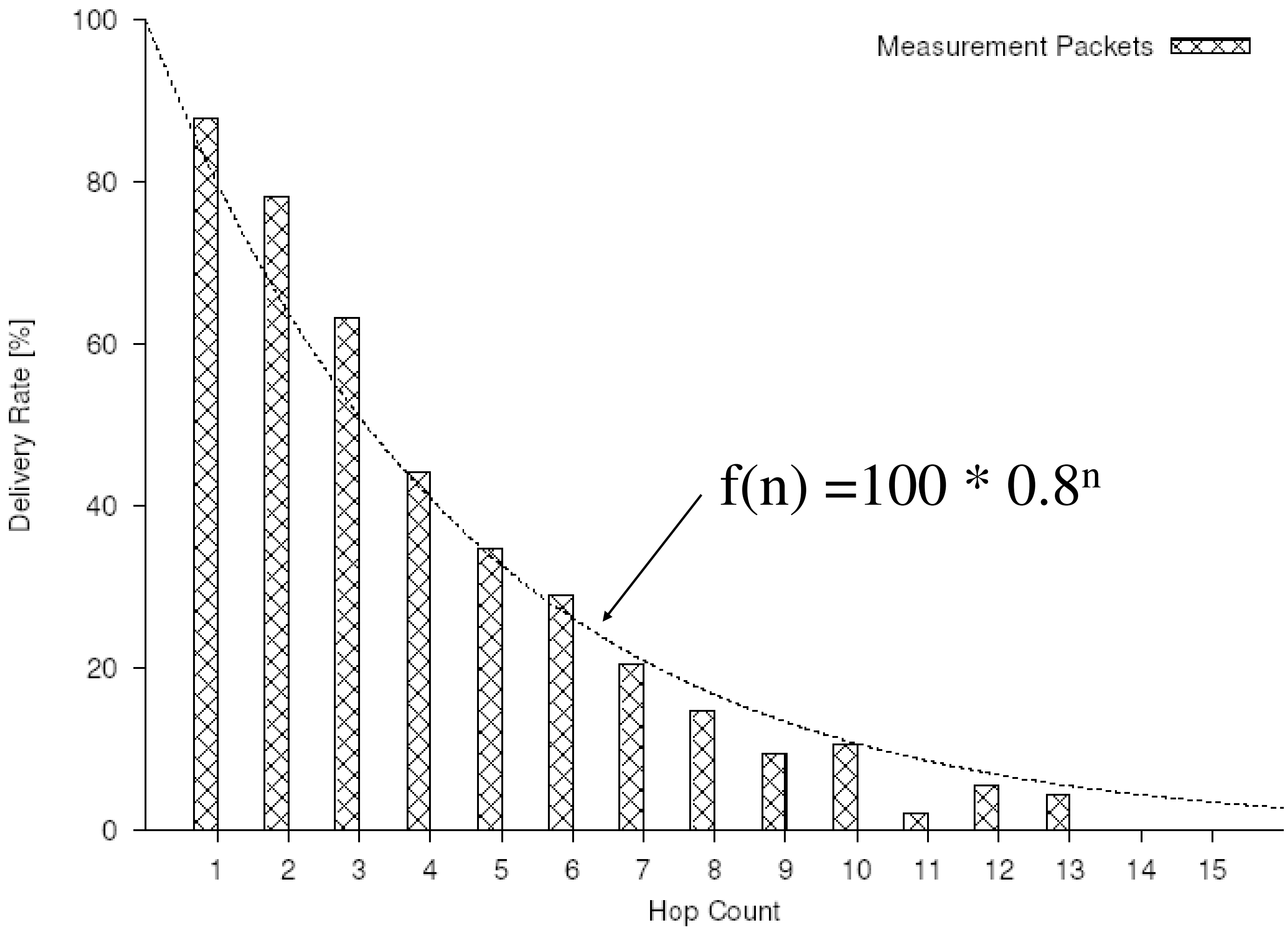
Routing

- DFS tree using for routing towards sink
- Success rate drops approximately exponentially with the depth d
- Transmission success of neighborhood packets exhibits a different run of the curve
- Size of a measurement packet ~ 70 bytes including packet header
- Neighborhood list packets 10% larger
- But significantly lower success rate

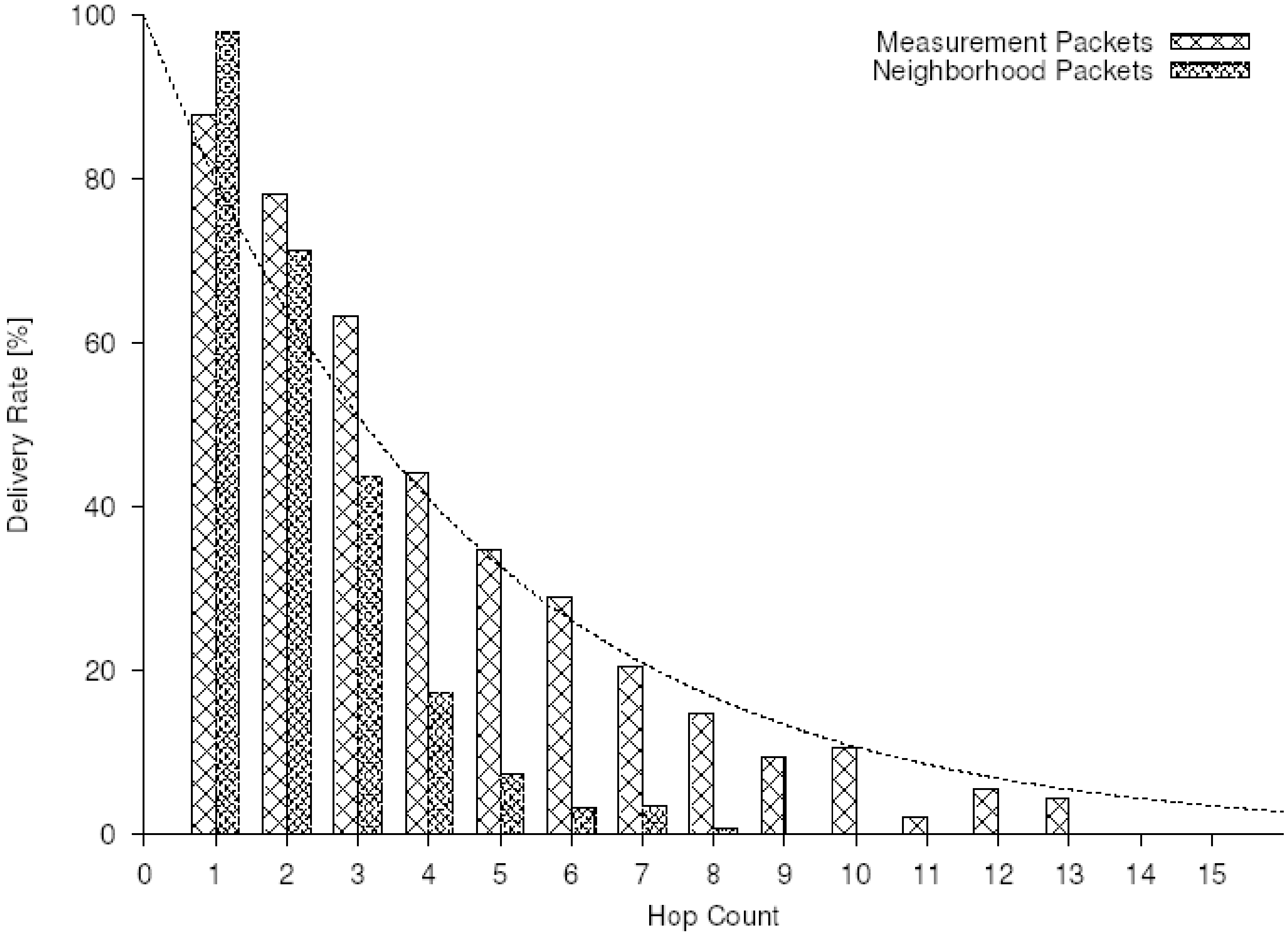
Success Rate



Success Rate



Success Rate



Reason

- Main reason:
  - probably not larger packet size
  - but is related to congestion
- Neighborhood packets were sent t seconds after measurement packets, t randomly chosen between 0 and15
- Due to retransmission of packets this time difference became very small after a few hops
- Reason for lower success rates of neighborhood packets for higher hop counts

Conclusion

- Lessons learned
  - Timing of actions very important to avoid congestion
  - Retransmission policy
  - Application has to deal with duplicate packets (lost ACKs)
  - High energy consumption for real time clock access
- We faced problems with the firmware implementation (e.g. reset of clock)
- Software installation procedure does not scale
- Unit disc graph model not appropriate
- Depth-first search implementation is robust and fault-tolerant
- Real deployments are a must to evaluate algorithms
- Careful planning: What data is needed, where and when to store it