Reliability and simulation of wireless real-time control networks

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NSF CPS: Science of Integration for Cyber Physical Systems

Annual Review Meeting

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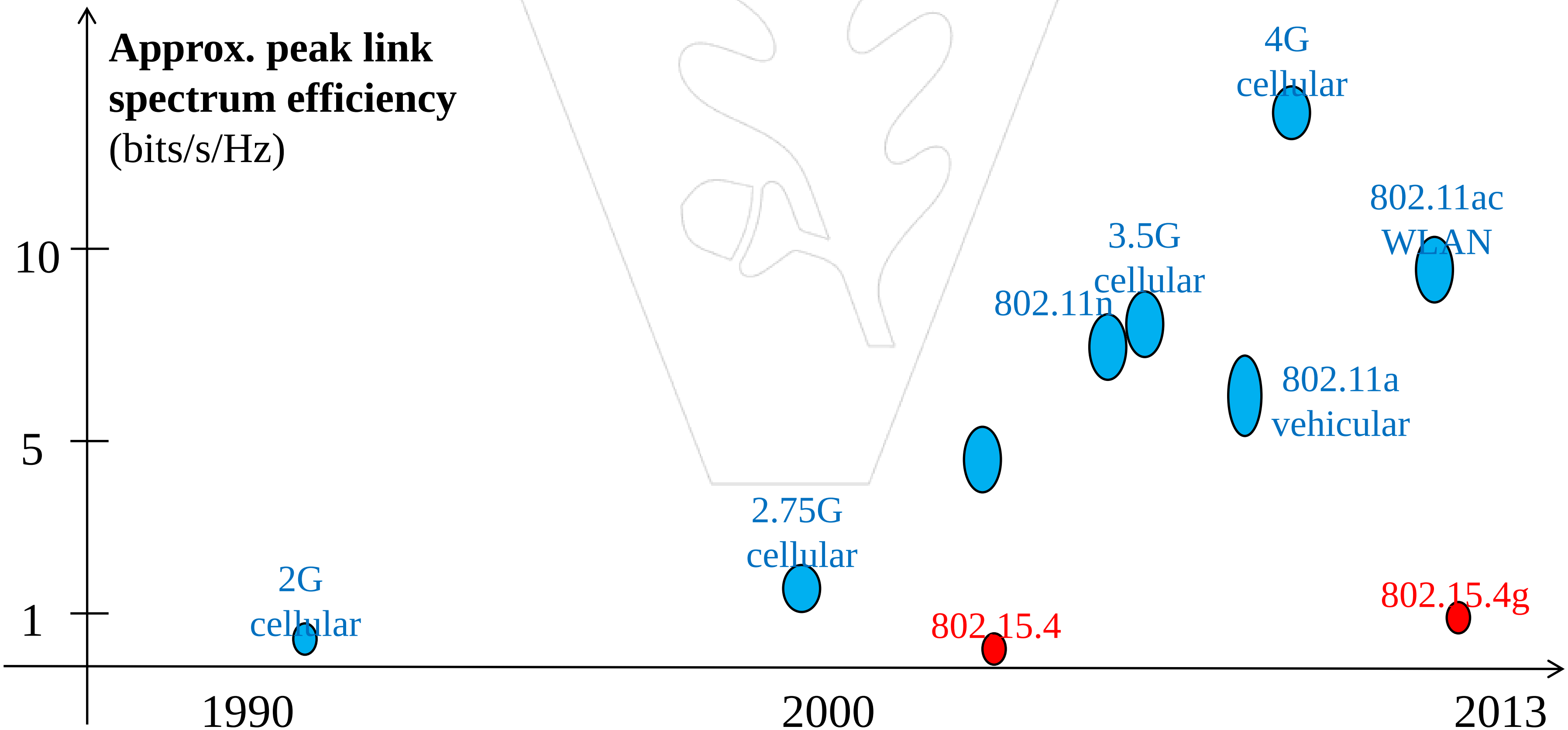
Outline

- Motivation
- Reliability analysis of wireless real-time networks
- Performance evaluation tool for wireless CPS
- Study of alternative physical layer technologies for WirelessHART-like networks
- Future work

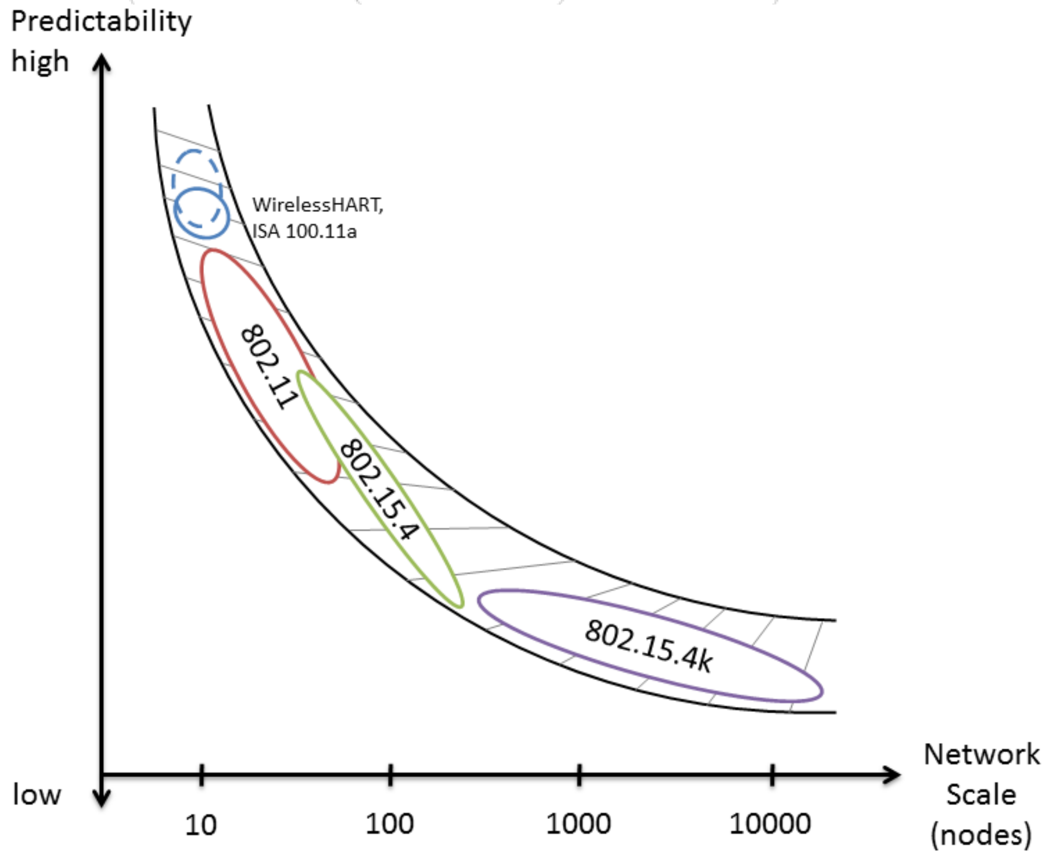
Challenges in industrial real-time networks

- Radio frequency spectrum is a scarce resource
  - Low-range WPAN PHYs vs. state-of-art (WLAN, cellular)
- Increasing gap in technology with non-adaptive LR-WPAN schemes
- New paradigms (e.g., dynamic spectrum access, better PHY designs) to allow for the required amount of radio spectrum



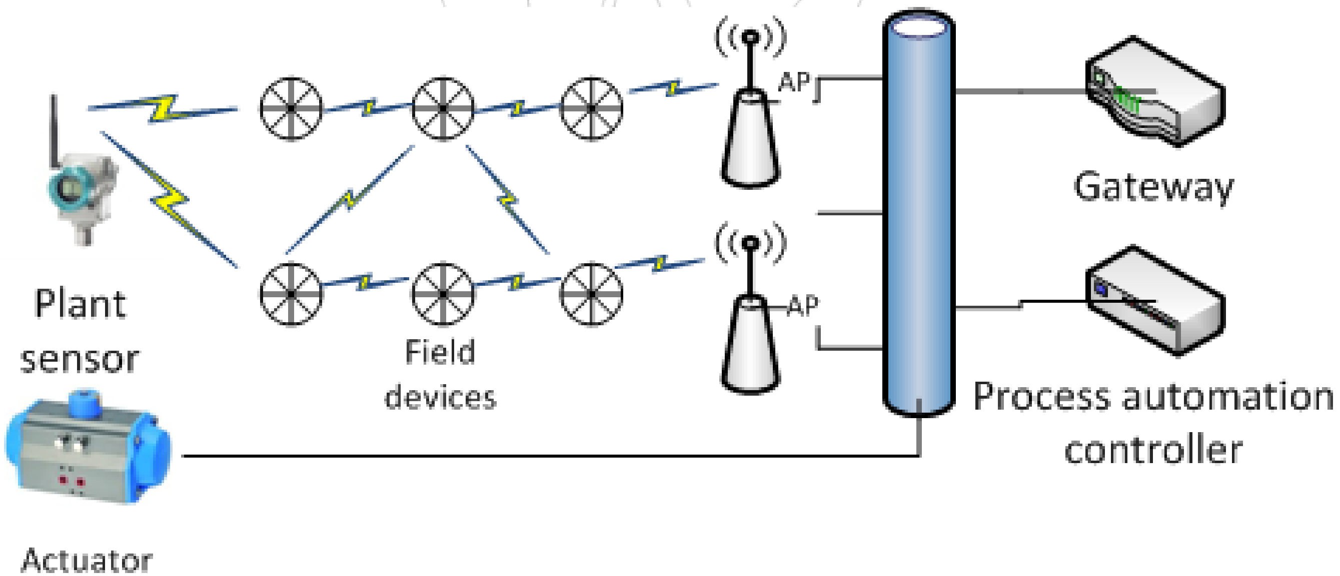
Motivation

- Science of Integration: requires predictability
  - Timing (deadlines)
  - Reliability (probability of successful packet delivery)



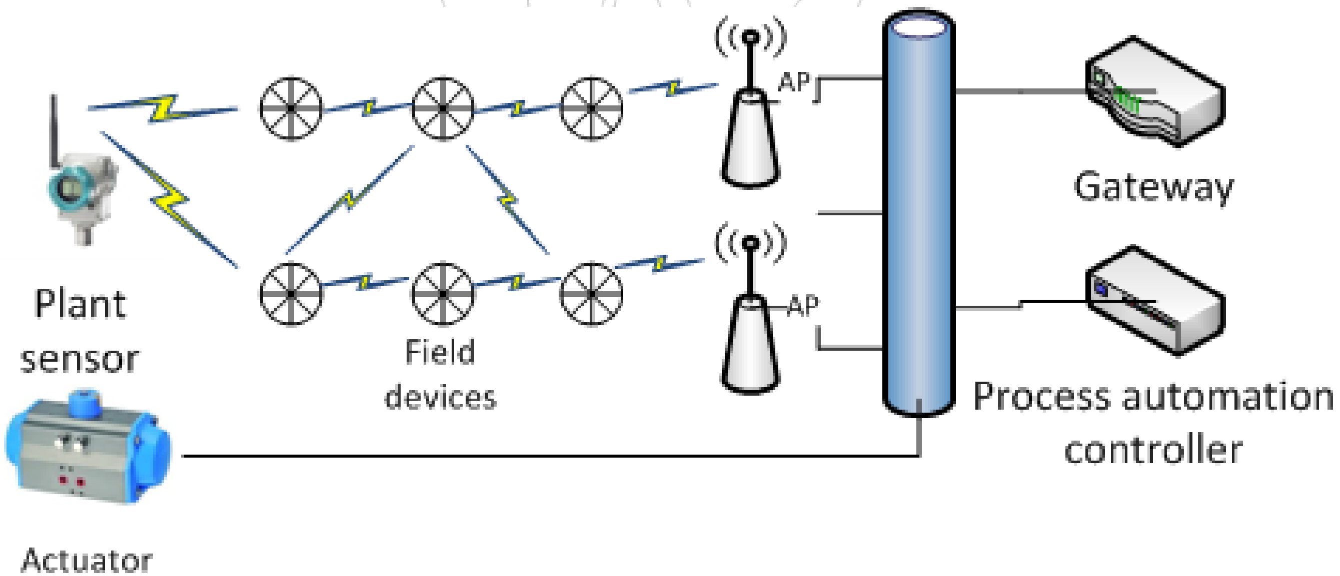
Motivation

- Go beyond treating the wireless network as „black box”
- Design goal: maximize the probability of successful packet transmission within a given deadline (reliability)
- Analyse reliability and delay with realistic environment models
  - Analytically
  - Using a realistic system simulation
- Incorporate physical layer realiability information into routing and scheduling



System under study

- Industrial mesh network for sensor (and actuator) applications
  - Examples: WirelessHART, ISA 100.11a
  - Centralized network management
    - Pre-planned graph routing
    - TDMA-like network scheduling with periodic superframe structure
  - Low-range wireless personal network physical layer (PHY)
    - Typically: IEEE 802.15.4



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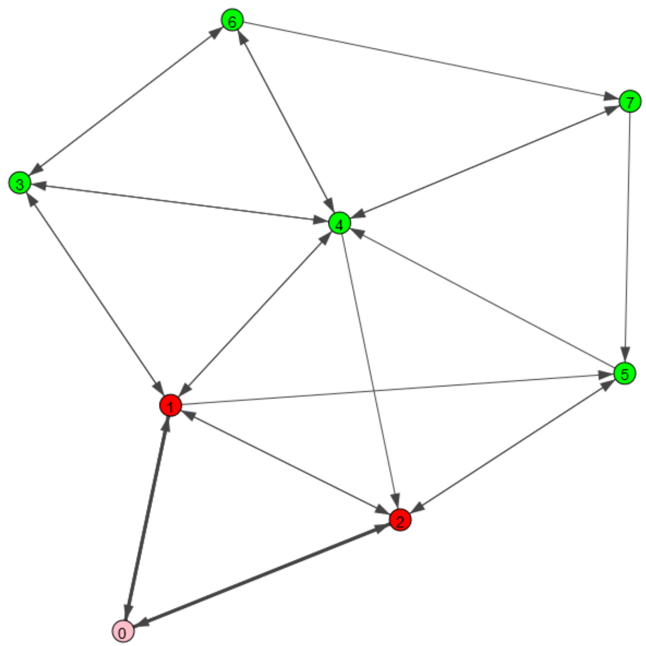
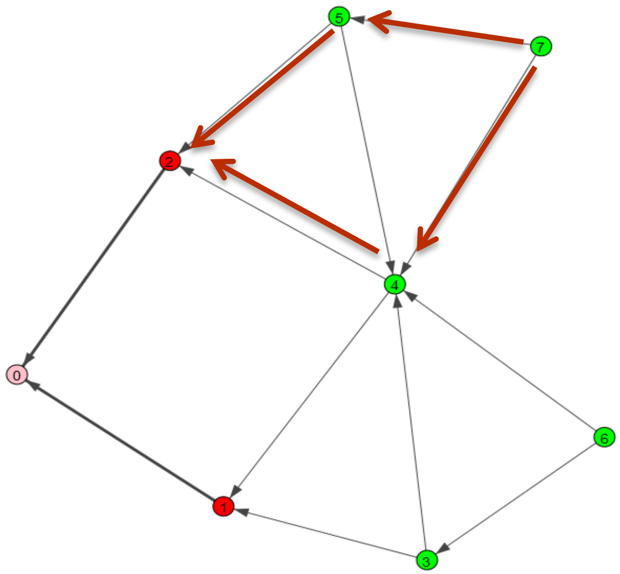
I. Reliability analysis

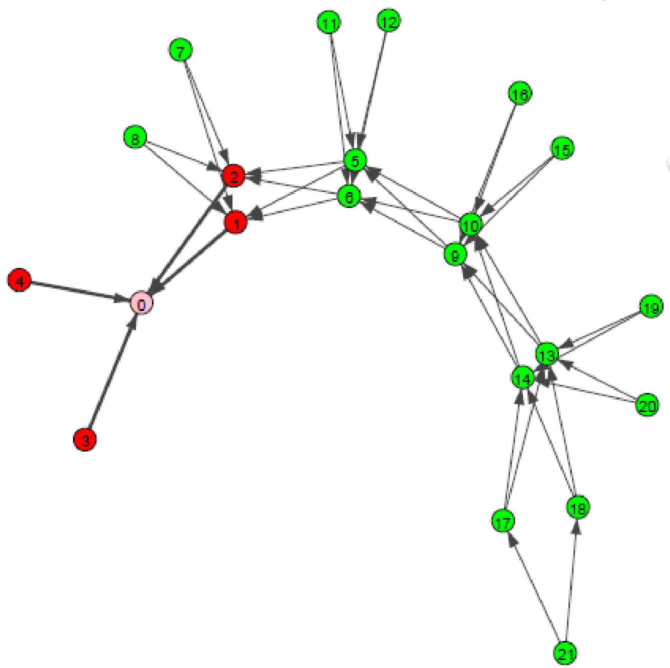
- Conventional routing approach:
  - Set up a connectivity graph
  - Choose (preferably) two independent routes using the two „best" links; allow for retransmission slots (overengineering)
- „Best" route: highest average „signal strength"? Lowest average packet error rate?

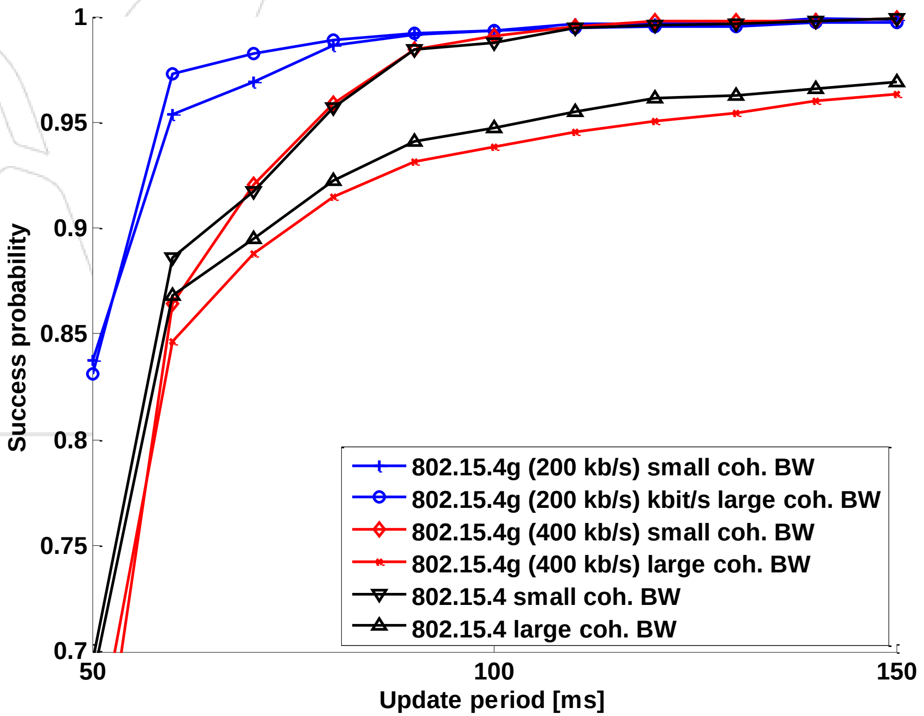




Reliability analysis

- End-to-end reliability is stochastic and highly dependent on environment and equipment characteristics
- The average packet error rate doesn't say all
- Average link strength tells even less





Reliability analysis

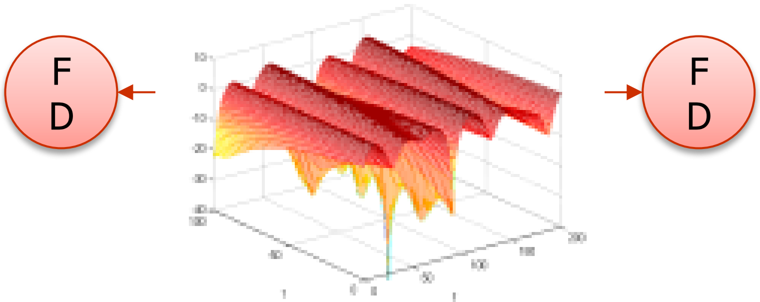
- TDMA-like conflict-free scheduling allows analytical reliability analysis
- Relies on the per-link outage probability

$$P_{\text{out}} = Pr[\text{SNR} < \eta]$$

- Outage is a practical measure
- Fading parameters can be estimated using physical layer measurements
- Derived results for known network layouts and randomly distributed nodes

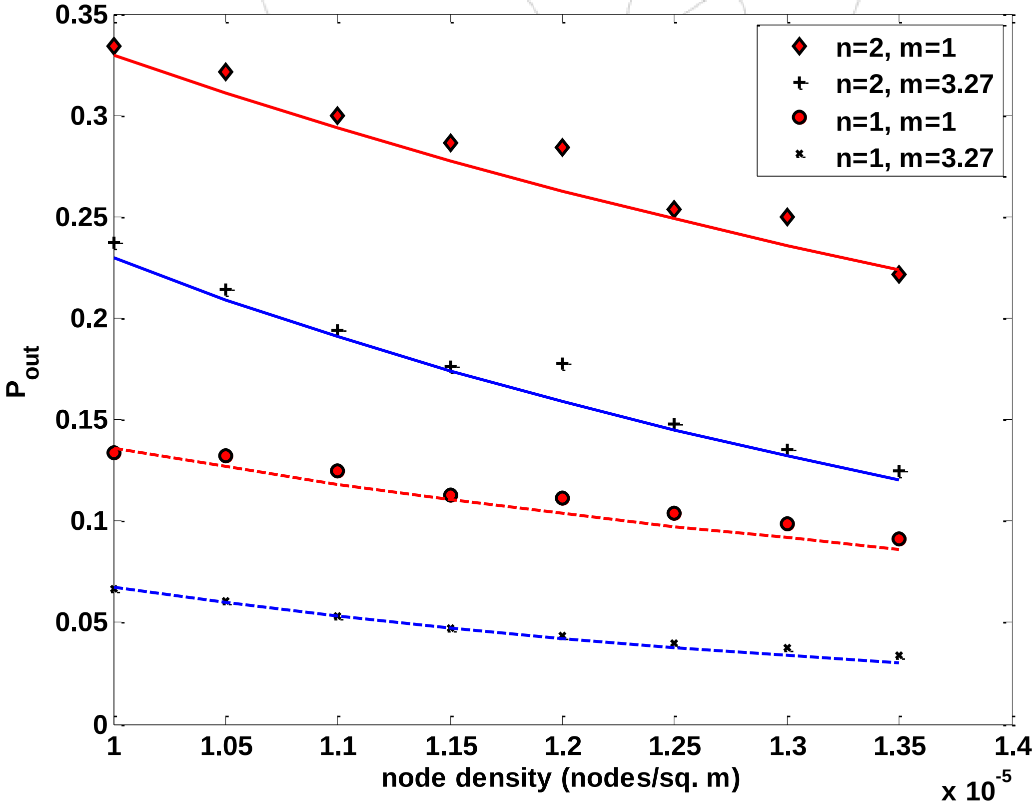
Realistic model of wireless propagation

- Nakagami-*m* channel
  - Describes a broad class of channel fading
  - *m* characterizes the „severity" of fading
    - m=1 reduces to Rayleigh fading
    - m>1 can be used to approximate Rice fading
- A distance-dependent path loss (for limiting cases of exponents 2 and 4 analytical results)



Per-link reliability

- Link outage probability versus node density with different fading „severity” (random layouts)
- To the *n*th nearest neighbor



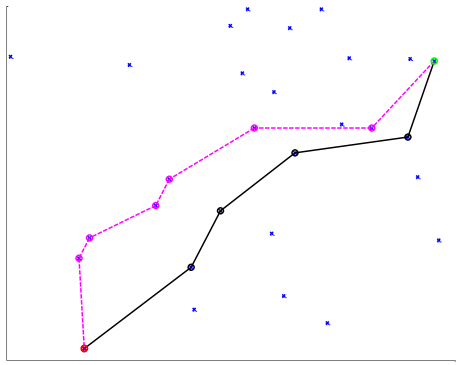
[ICCCN13]

From link to flow reliability

- Classical dynamic programming can be used to find the most reliable route within a given deadline from the per-link outages:

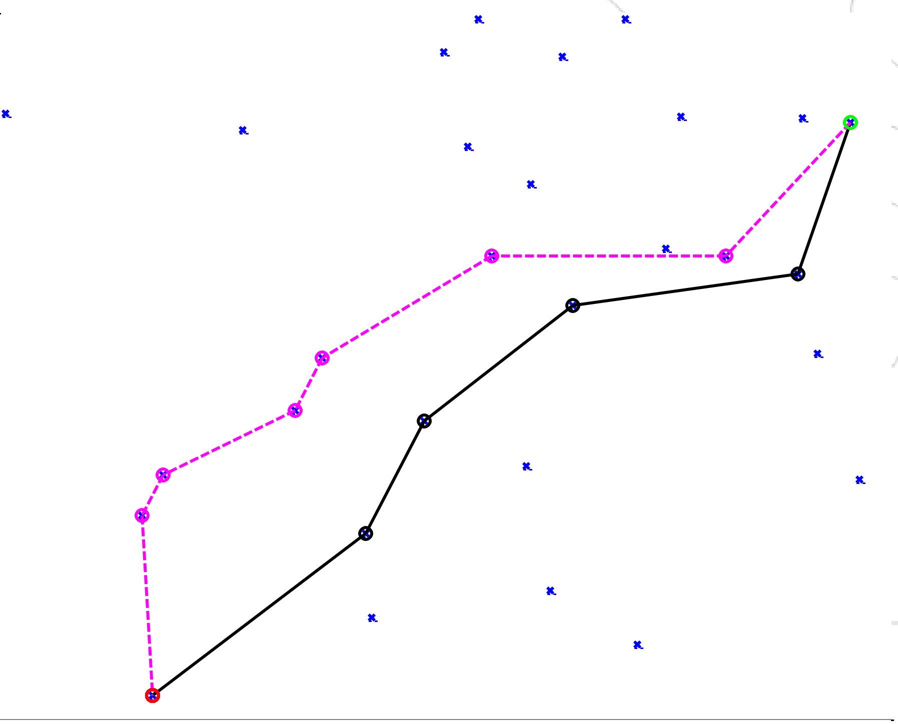
$$P_{\text{succ}} = \prod \left(1 - P_{\text{out},l}^{x_l}\right)$$

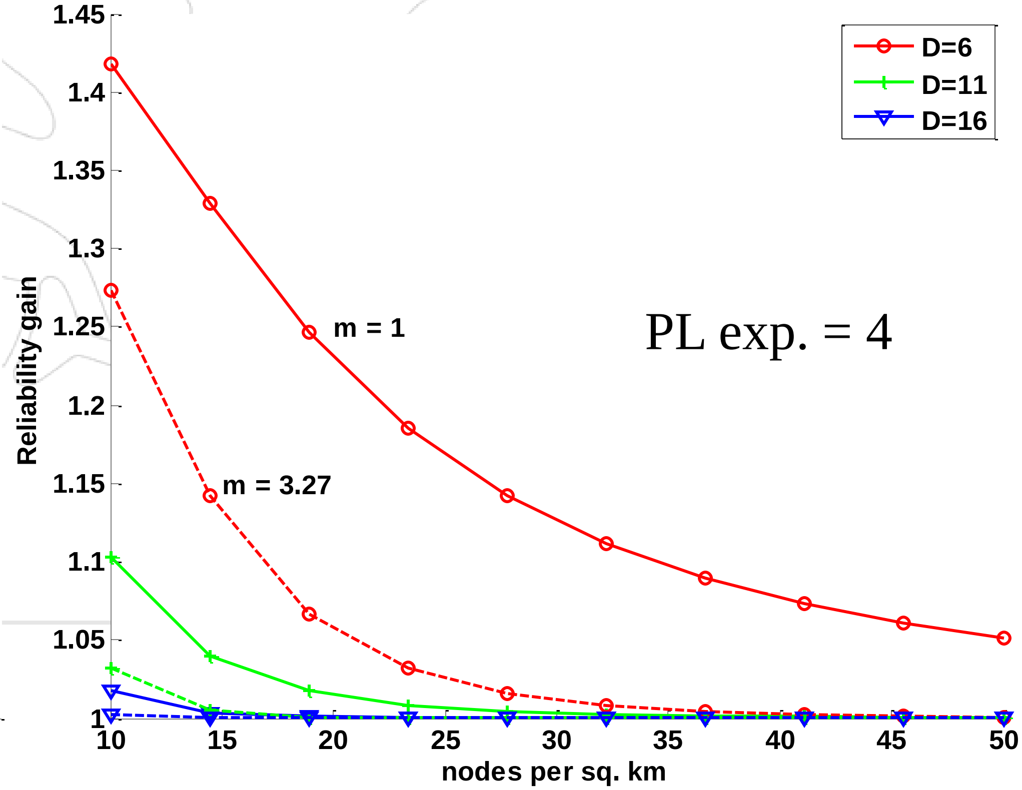
- Providing optimum redundant routes and optimum redundant link schedules is added complexity



Applications to routing

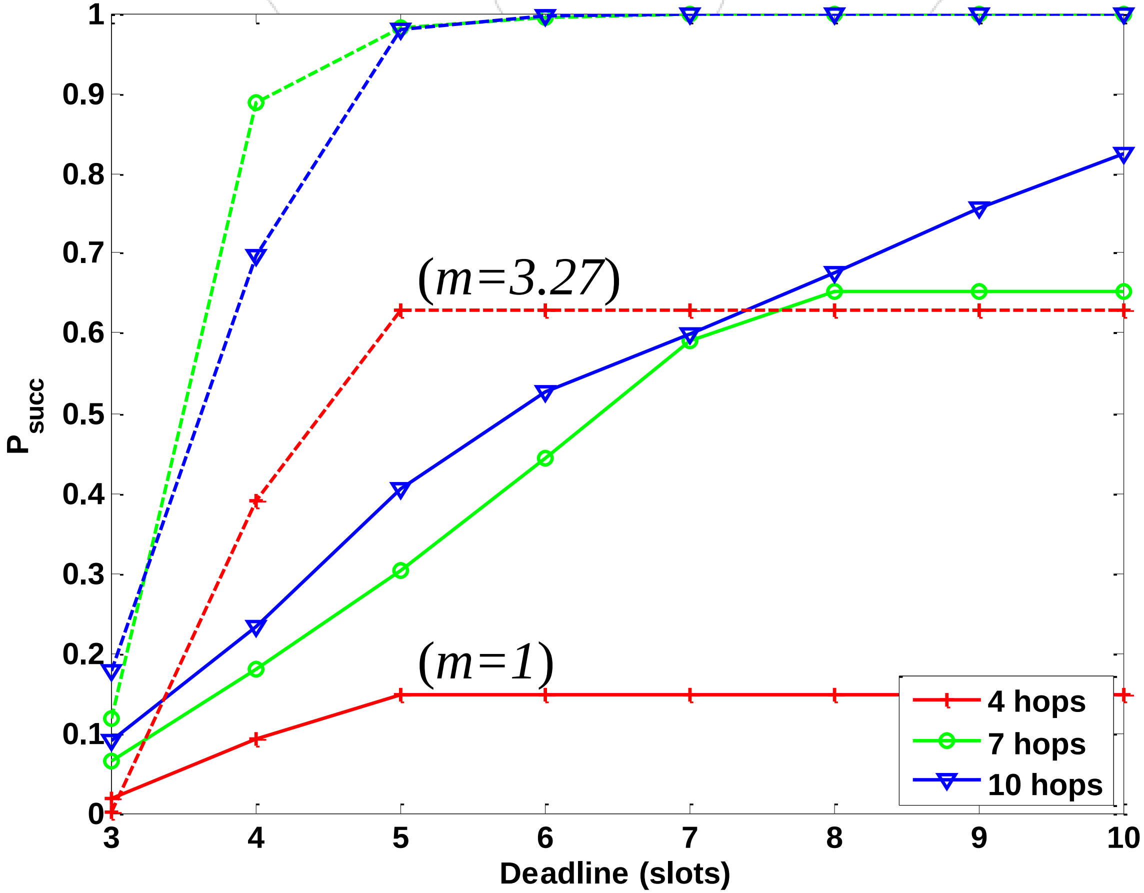
- Quantifying reliability gains from multipath next-hop routing in a random network





Node density vs. reliability vs. deadline

- Example: how many hops are optimum to bridge a given distance in a WirelessHART-like setting?
- (line network)



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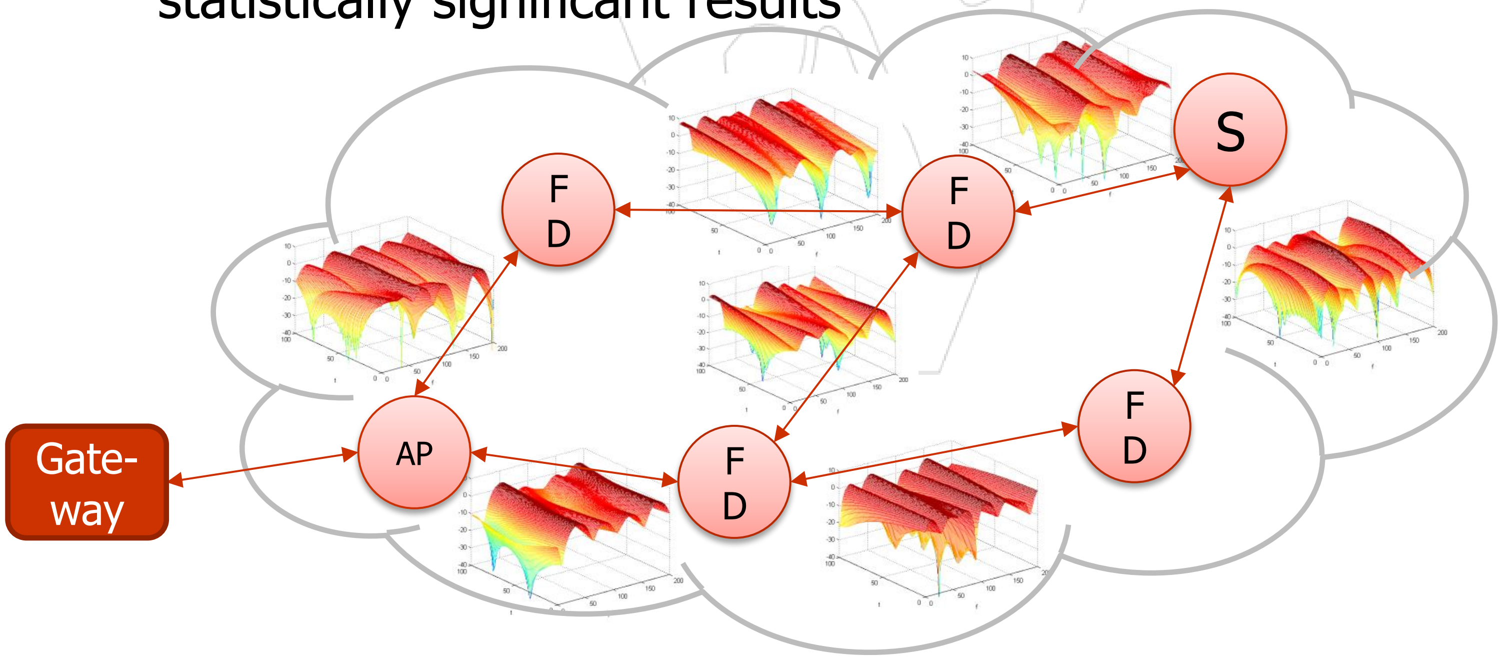
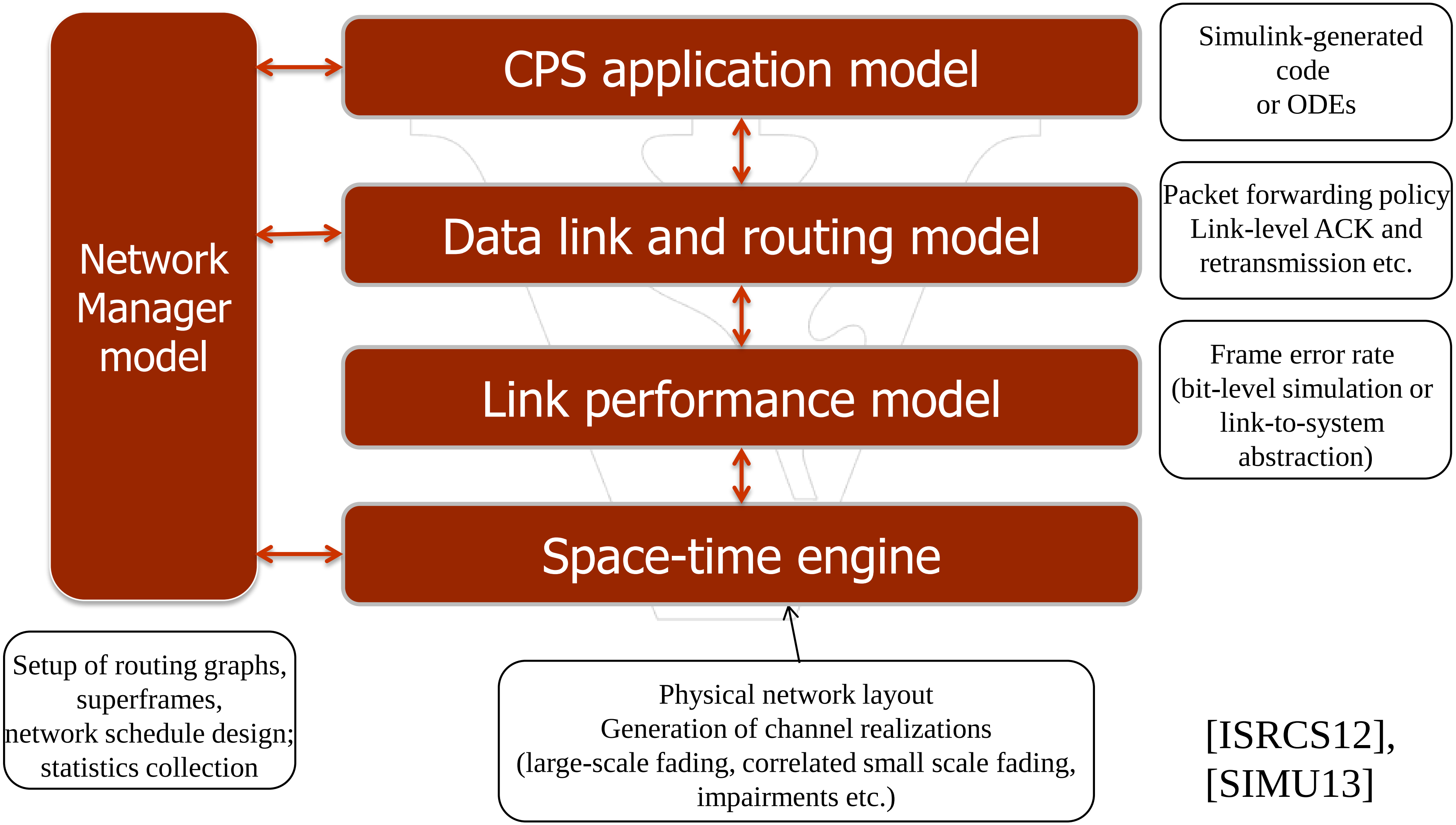
II. Performance evaluation of wireless CPS

- Need for accurate simulation models for real-time wireless mesh networks
- Reasonable wireless performance models
  - Realistic path loss, correlated fading processes, transceiver impairments, interference, ...
- More efficient simulation than TrueTime or Matlab+ns2
  - 100’s of independent Monte Carlo runs should be feasible to get statistically significant results



System-level simulation framework



[ISRCS12], [SIMU13]

Realistic channel model

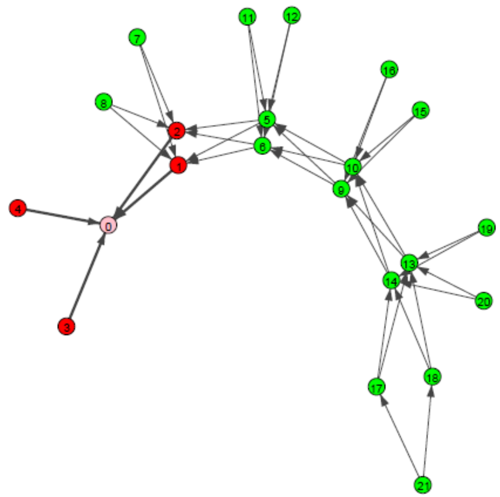
- Measurements of the industrial channel:
  - Strong line-of-sight component
  - 100 ms-scale coherence times
  - Low delay spread (-> high channel coherence bandwidth)
- Correlation might be adverse in the NCS application
  - WirelessHART uses channel hopping
  - „multi-frequency" channel model needed
- Computationally efficient multipath fading model with indenpendently parametrizable coherence time and coherence bandwidth

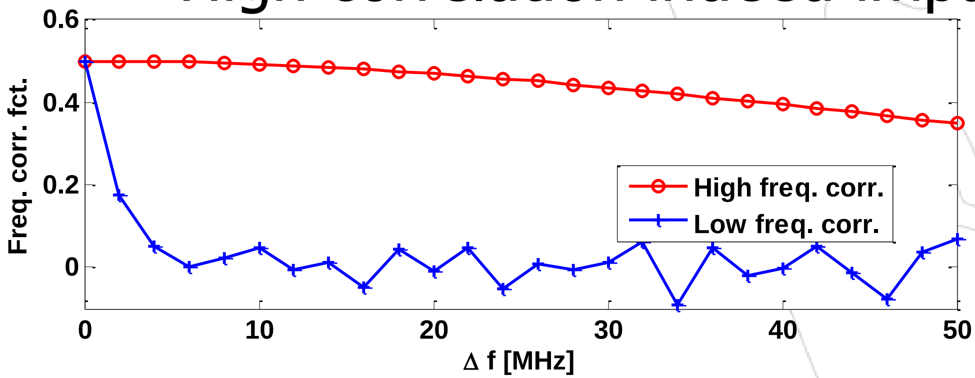
Realistic channel model

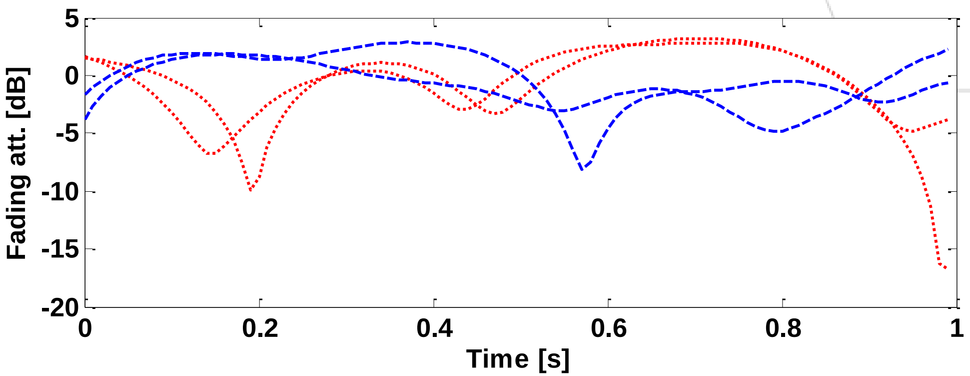
- Publish sensor measurement (5 hops)
- Probability of succesful delivery

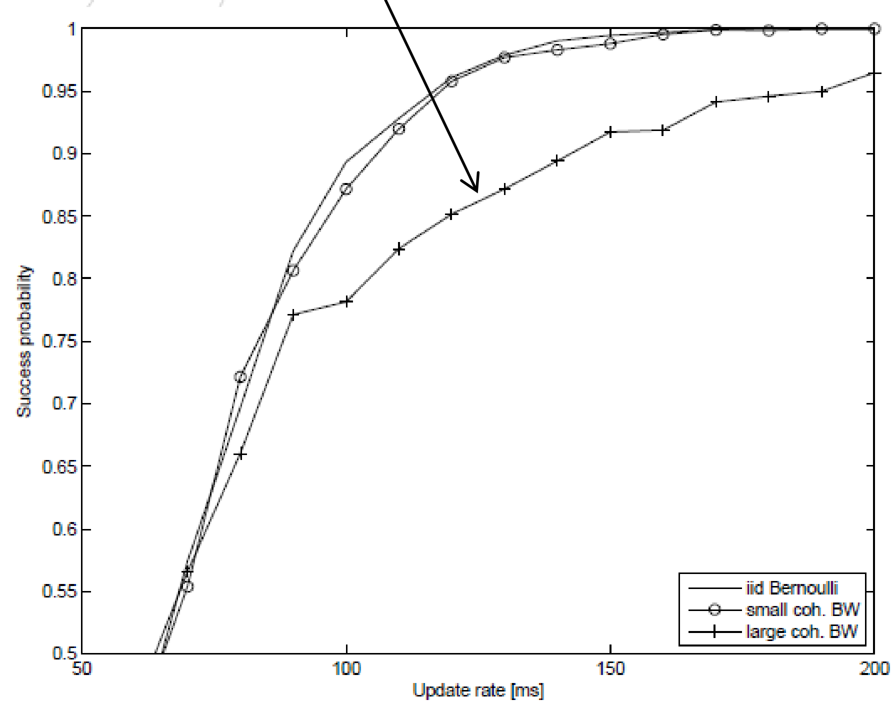
before the next measurement generated

- 10 ms time slots
- High correlation indeed impacts reliability





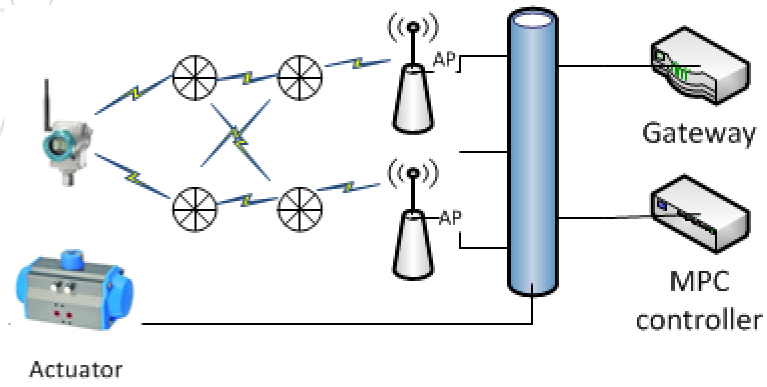




Case study: batch reactor with model-predictive controller

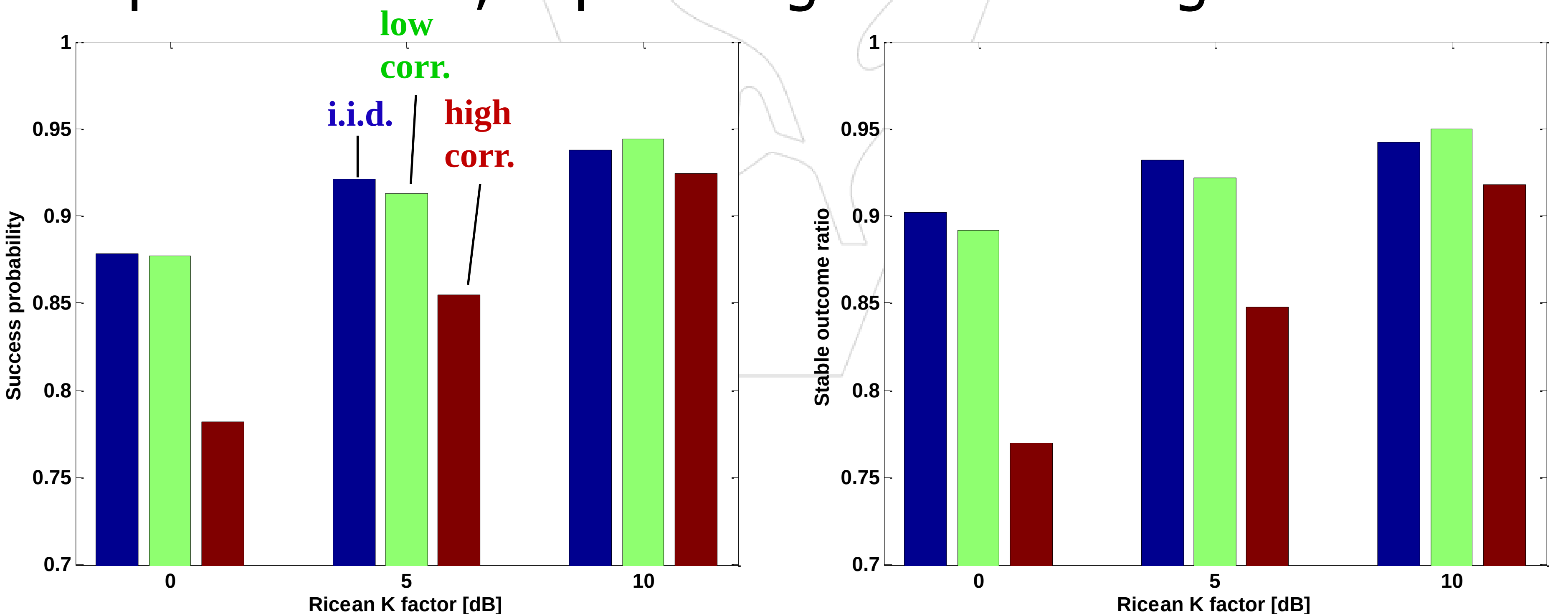
- Classic networked control system benchmark
- However, we assume a Model Predictive Controller (MPC)
  - Practical relevance
- 3-hop regular network layout
- Path loss, shadowing and our fading model
- Physical model:
  - Plant: ODE
  - Controller: Simulink-gen.

  C code



Case study: batch reactor with model-predictive controller

- Fixed deadline (6 time slots, 60 ms), metrics:
  - Successful delivery ratio
  - Probability of the step response remaining bounded
- The independent loss model overestimates performance, esp. for significant fading



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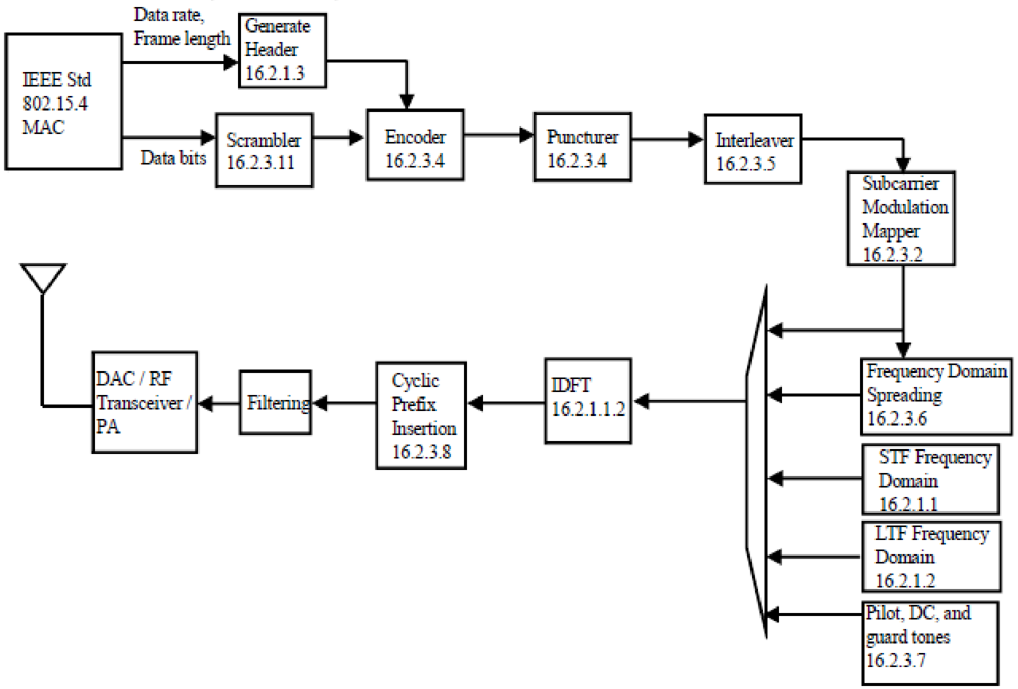
Case study: alternative PHY for WirelessHART

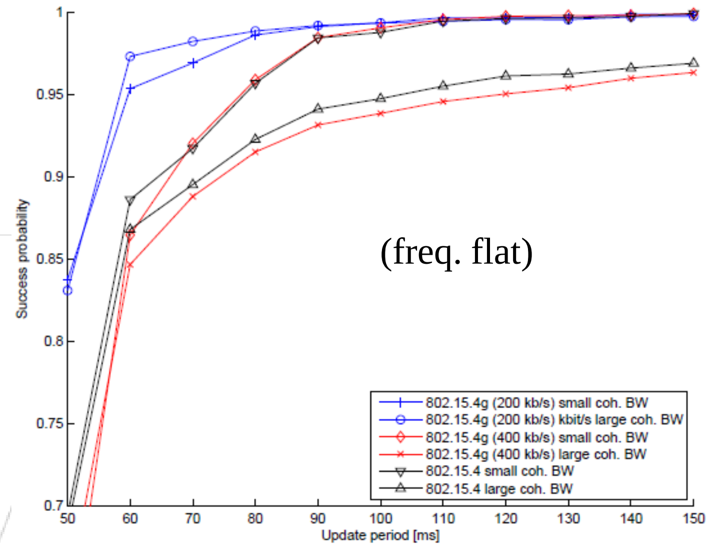
- The IEEE 802.15.4 physical layer in WirelessHART is spectrally inefficient
- Not robust under some typical channel conditions
- Alternative designs exist (802.11a) – hard to integrate
- IEEE 802.15.4g OFDM-based PHY as drop-in replacement for 802.15.4 in WirelessHART?

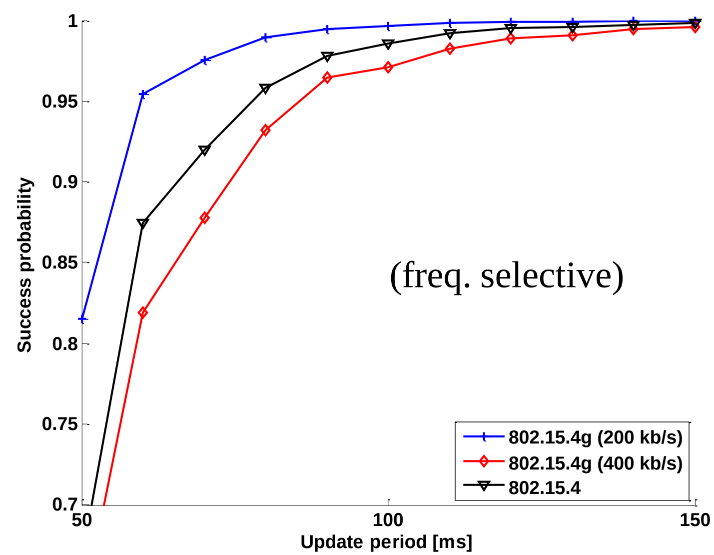
Parameter	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4
Nominal bandwidth (kHz)	1094	552	281	156
Channel spacing (kHz)	1200	800	400	200
DFT size	128	64	32	16
Active tones	104	52	26	14
# Pilot tones	8	4	2	2
# Data tones	96	48	24	12
MCS0 (kb/s) (BPSK rate 1/2 with 4x frequency repetition)	100	50	—	—
MCS1 (kb/s) (BPSK rate 1/2 with 2x frequency repetition)	200	100	50	—
MCS2 (kb/s) (QPSK rate 1/2 and 2x frequency repetition)	400	200	100	50
MCS3 (kb/s) (QPSK rate 1/2)	800	400	200	100
MCS4 (kb/s) (QPSK rate 3/4)	—	600	300	150
MCS5 (kb/s) (16-QAM rate 1/2)	—	800	400	200
MCS6 (kb/s) (16-QAM rate 3/4)	—	—	600	300



802.15.4g-based PHY

- Compares favorably, especially over frequency-selective channels
- Slow, flat fading is still bad
- Side note: can we beat 802.15.4 on highly correlated flat fading channels?
  - 802.15.4g is designed for highly selective channels (very long 24 us cyclic prefix)
  - Delay diversity will be able extract **frequency diversity** from appropriate 802.15.4g modes
  - Very well suited for 802.15.4g

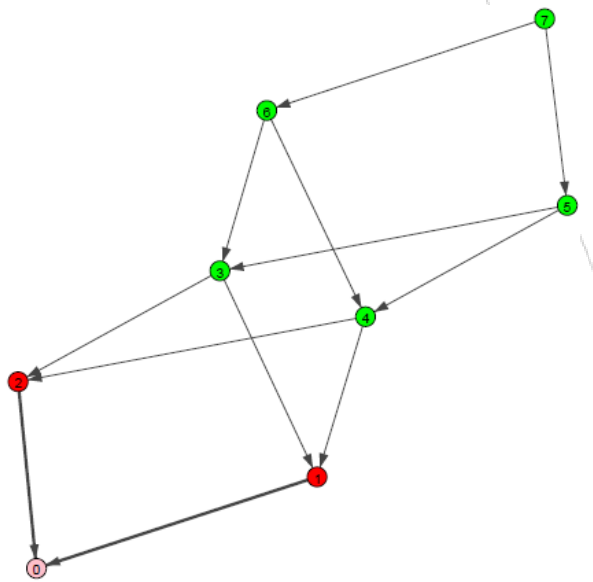


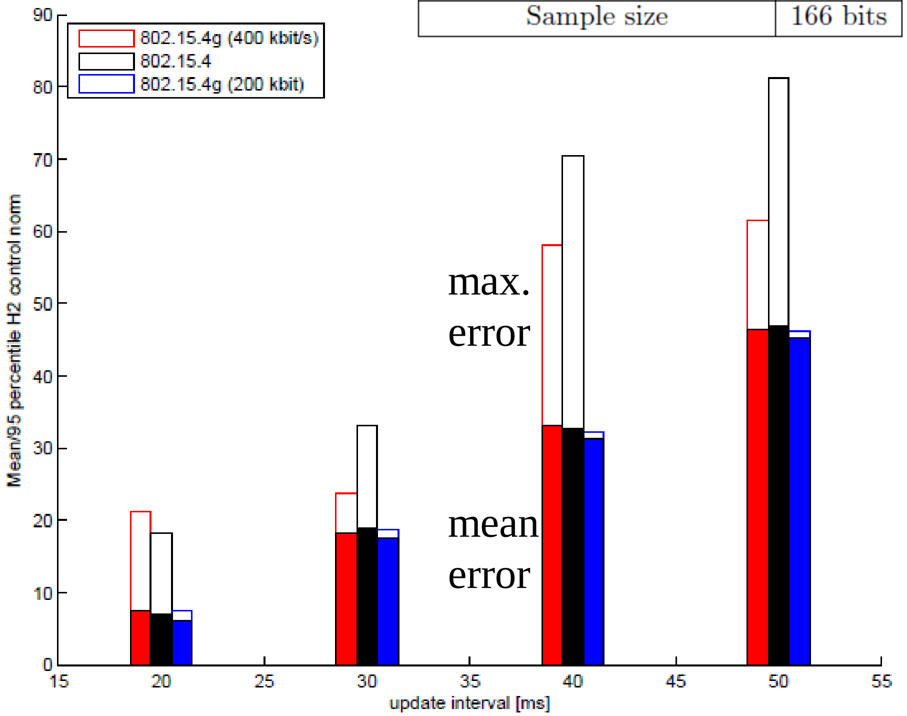


NCS example w/different PHYs

- Batch reactor Networked Control System benchmark with standard PI controller
- Sensor meas. through 3-hop uplink, wired actuator
- Quadratic error of step response over many realizations

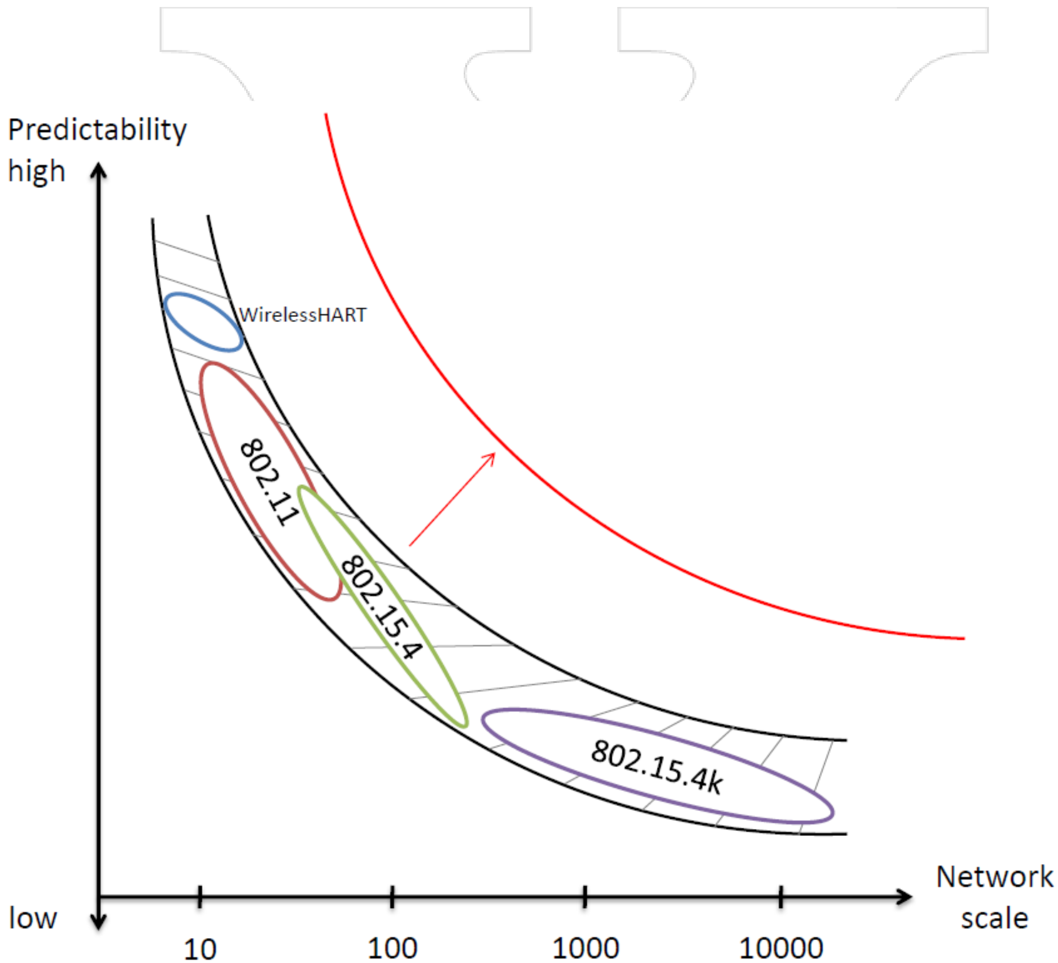
Reference distance d_0	15 m
Reference path loss $L_0(d_0)$	65 dB
Path loss exponent n	3.5
Ricean K factor	6 dB
Shadow fading σ_S	5 dB
Inter-node distance	80 m
Sample size	166 bits





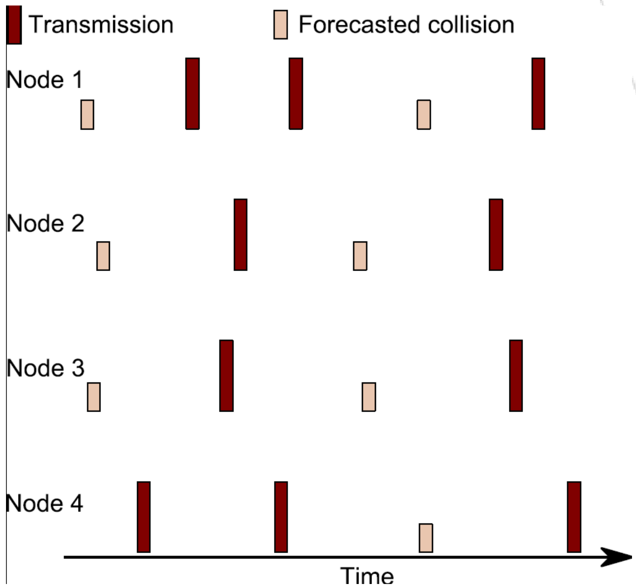
Future work

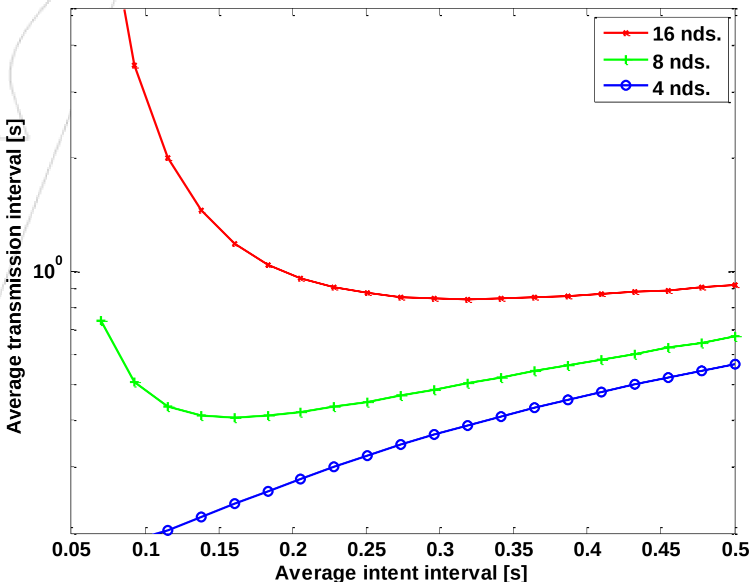
- General challenge: push the envelope of predictability vs. network size to the right



Future work

- Research into topology-independent low-power asynchronous MAC schemes
  - „Collision forecasting" based on pseudorandom sequences
  - Adaptable to traffic characteristics
  - Multi-channel operation





Conclusions

- Average link loss probabilities don't tell the whole story
  - Analytic treatment of reliability in wireless real-time networks is possible for rather simple scenarios
  - Overengineering could be reduced by incorporating physical layer data and using better tailored PHY designs
- Wireless real-time networks ought to become more complex in the future
  - Realistic system simulation to enable cross-layer integration

Thank you!