Bozheng Pang and His Story of Bluetooth Low Energy

Bozheng Pang

Chair of Distributed and Networked Systems, TU Dresden, Germany

bozheng.pang@tu-dresden.de

(Department of Computer Science, KU Leuven, Belgium)

(bozheng.pang@kuleuven.be)

Bozheng Pang

- First name: Bozheng

- Surname: Pang

- From: Xi'an (terracotta army), China

- Hobbies:

  - Foodie (What is for dinner 😋?)

  - Traveler (Travel everywhere by working everywhere)

  - Daydreamer (When will I win a Nobel prize 😋?)

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Bozheng Pang

- Education:
  - Bachelor: China University of Mining and Technology, China 🇨🇳

    (09.2013 ~ 07.2017)

  - Master: Nanyang Technological University, Singapore 🇸🇬

    (09.2017 ~ 09.2018)

  - PhD: KU Leuven, Belgium 🇧🇪

    (03.2019 ~ 04.2023)

- Work:
  - Postdoc: KU Leuven, Belgium 🇧🇪

    (04.2023 ~ 02.2024)

  - Postdoc: TU Dresden, Germany DE

  - (03.2024 ~ present)

Research on Bluetooth Low Energy

Bluetooth Low Energy

Performance Analysis and Optimization

in Environments with Interference

- Interference for Bluetooth Low Energy (BLE)
  - Other protocols (Wi-Fi)
  - Same protocol (BLE)

- How to **improve** BLE performance under Wi-Fi interference?
- How to **quantify** BLE performance under other BLE devices?

Research on Bluetooth Low Energy

BLE vs Wi-Fi

- RQ1: How to **improve** BLE performance under Wi-Fi interference?
  - RO1.1: Characterization
  - **RO1.2: Improvement**
  - RO1.3: Analysis (of improvement)

BLE vs BLE

- RQ2: How to **quantify** BLE performance under other BLE devices?
  - RO2.1: Characterization
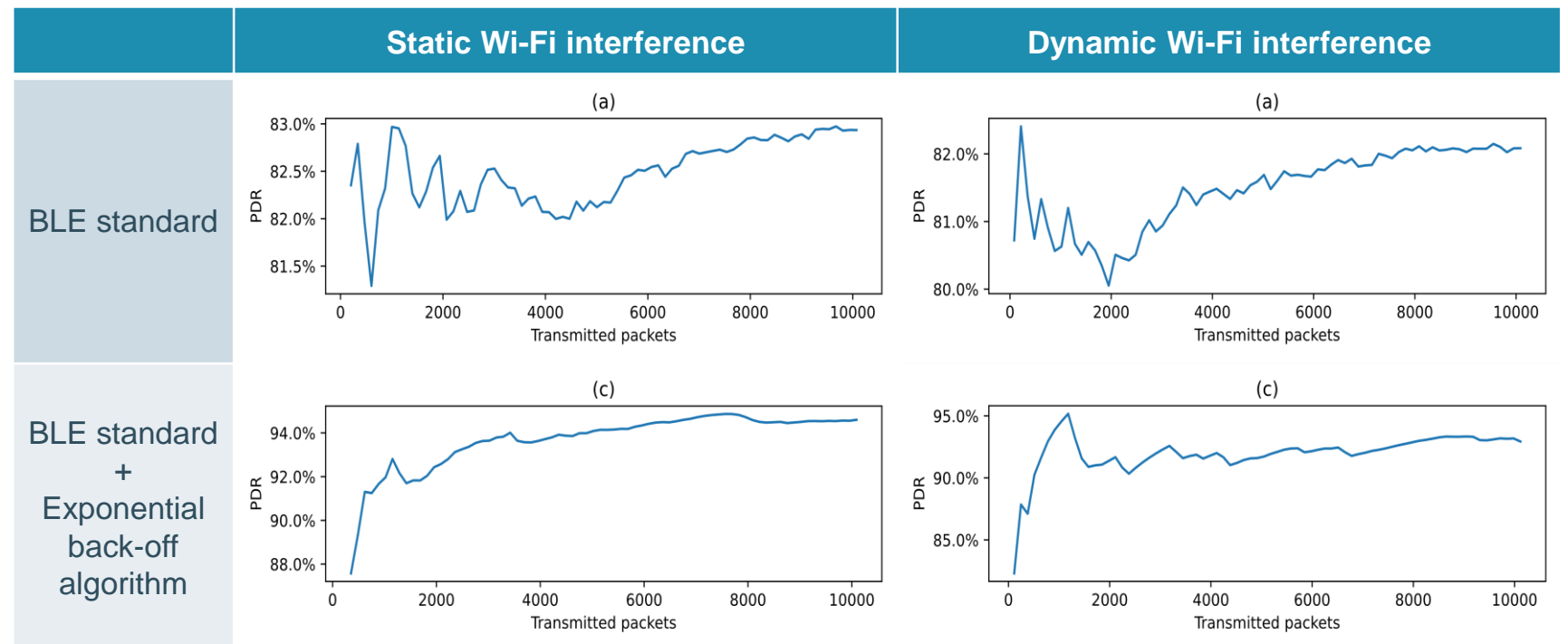 - RO2.2: Simulation
  - **RO2.3: Quantification**

RQ1: BLE vs Wi-Fi
RO1.2: Improvement

- **Exponential back-off algorithm based**

	Static Wi-Fi interference	Dynamic Wi-Fi interference
Interference on a channel?		
↓		
Blacklist the channel for connection intervals		
BLE standard	(a)	(a)
BLE standard + Exponential back-off algorithm	(c)	(c)

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RQ1:　　BLE vs Wi-Fi
RO1.2:　Improvement

- **Improved channel selection algorithm (CSA)**

- Change the logic of BLE CSAs
  - Blacklisting and whitelisting

    👇

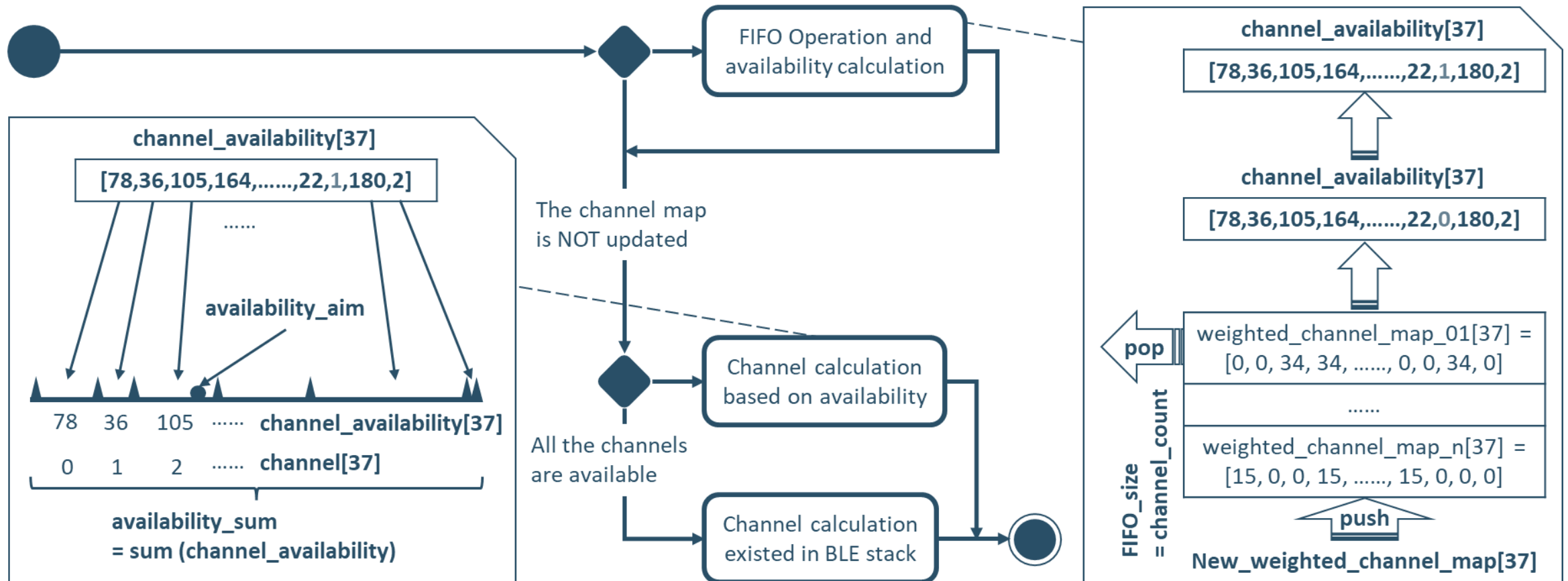 - Channel availability

- True / False 　　　　　　👉　　　　　0% **or** 100%
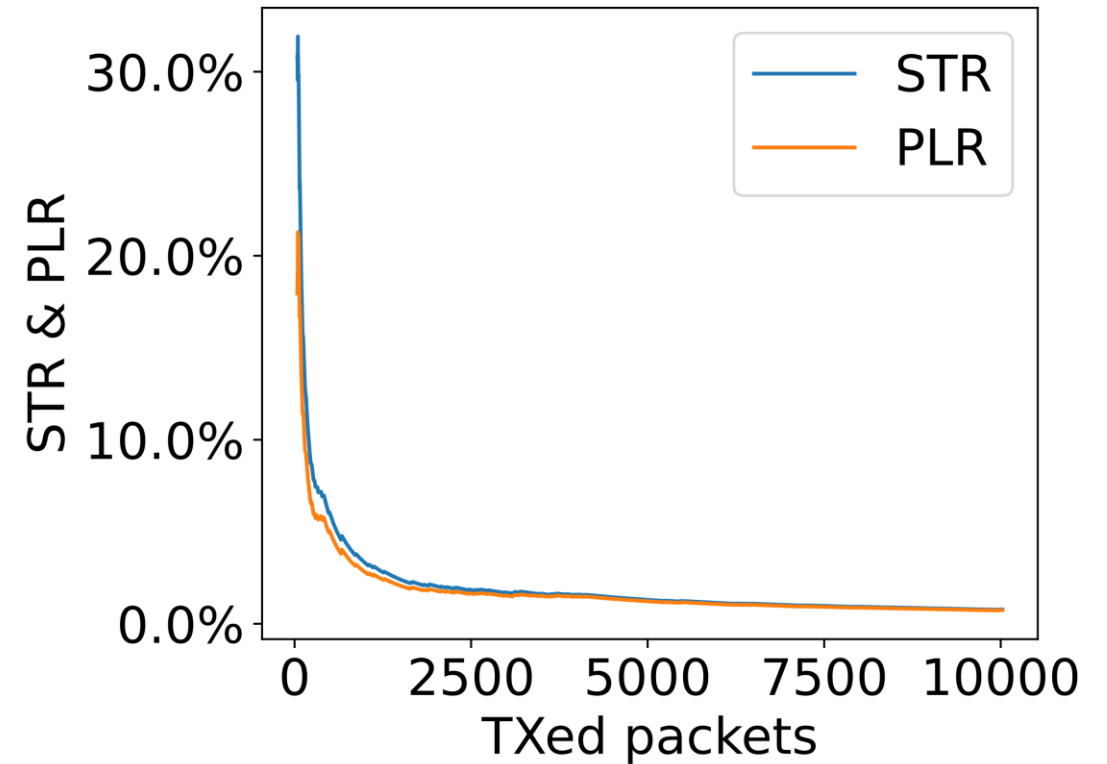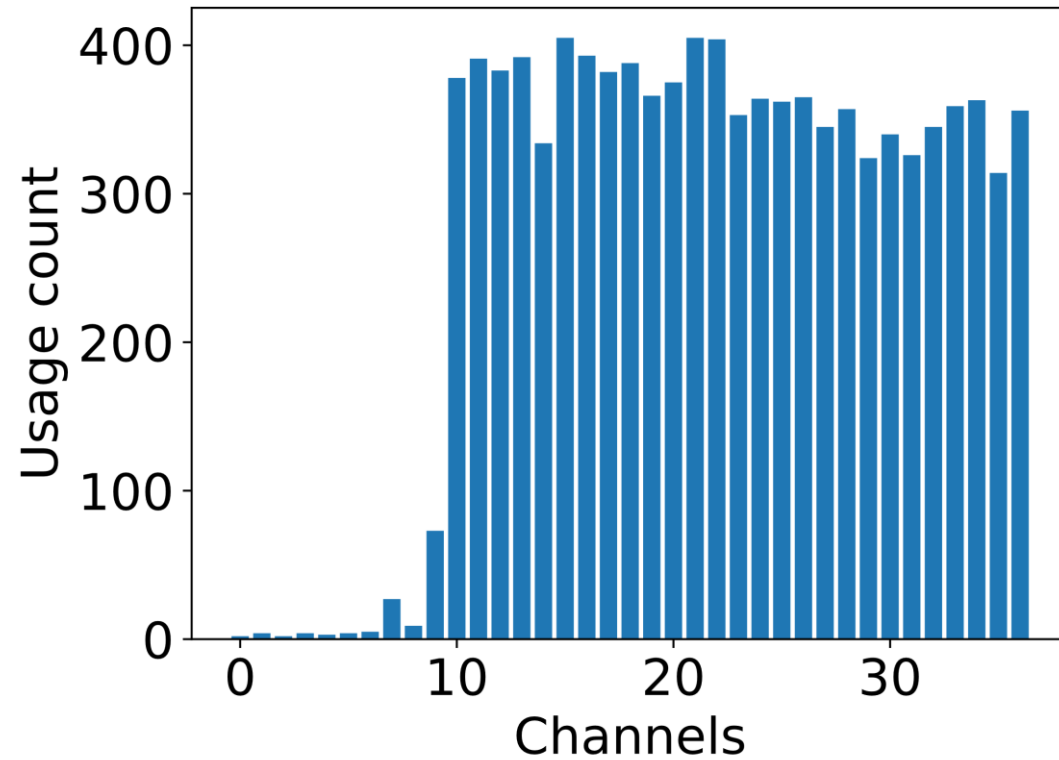
- Availability / Probability 　👉　　　　　0% **to** 100%

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RQ1: BLE vs Wi-Fi
RO1.2: Improvement

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RQ1: BLE vs Wi-Fi
RO1.2: Improvement

PANG, B., T'Jonck, K., Claeys, T., Pissoort, D., Hallez, H., Boydens, J. (2021). Bluetooth Low Energy Interference Awareness Scheme and Improved Channel Selection Algorithm for Connection Robustness. *Sensors*, *21* (7), Art.No. 2257. doi: 10.3390/s21072257

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BLE vs BLE

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RQ2:   BLE vs BLE
RO2.3: Quantification

- Too many parameters inside BLE communication
  - Most / All impact BLE performance
  - Simulations / Experiments can be time-wasting

- How can the time be saved?

- A mathematical model
  - Explain / Quantify the impact of BLE parameters on the performance

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RQ2: BLE vs BLE
RO2.3: Quantification

- A mathematical model for BLE reliability

- An equation to quantify reliability of a BLE connection
  - Quantify 👉 calculate ≠ trend
  - Inputs
    - Various parameters
  - Output
    - Reliability

$$P_{TF} = (1 - (1 - \boxed{BER_V})^{2 \cdot L_V})$$
$$\cdot \min(1, \frac{\boxed{m} \cdot (\boxed{\overline{PT_V}} + \boxed{IFS}) + \boxed{n} \cdot (\boxed{\overline{PT_D}} + IFS)}{\boxed{CI_D}})$$
$$\cdot (1 - \max(0, n \cdot \frac{IFS - \overline{PT_V}}{n \cdot (\overline{PT_D} + IFS) - IFS})^m)$$

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RQ2: BLE vs BLE
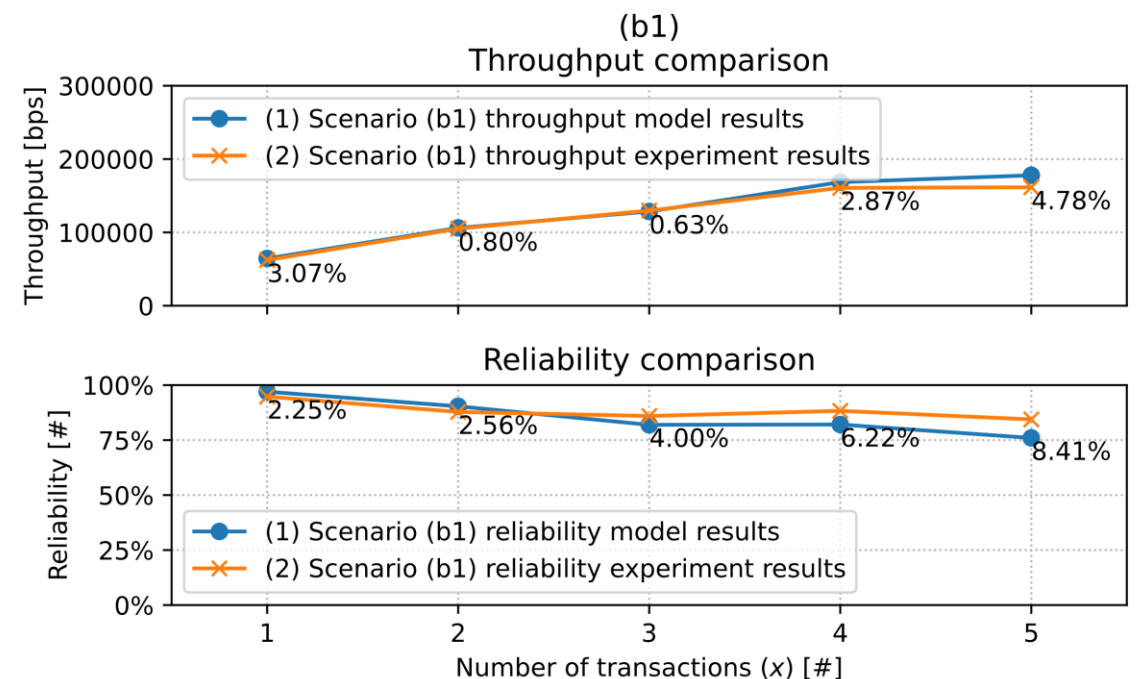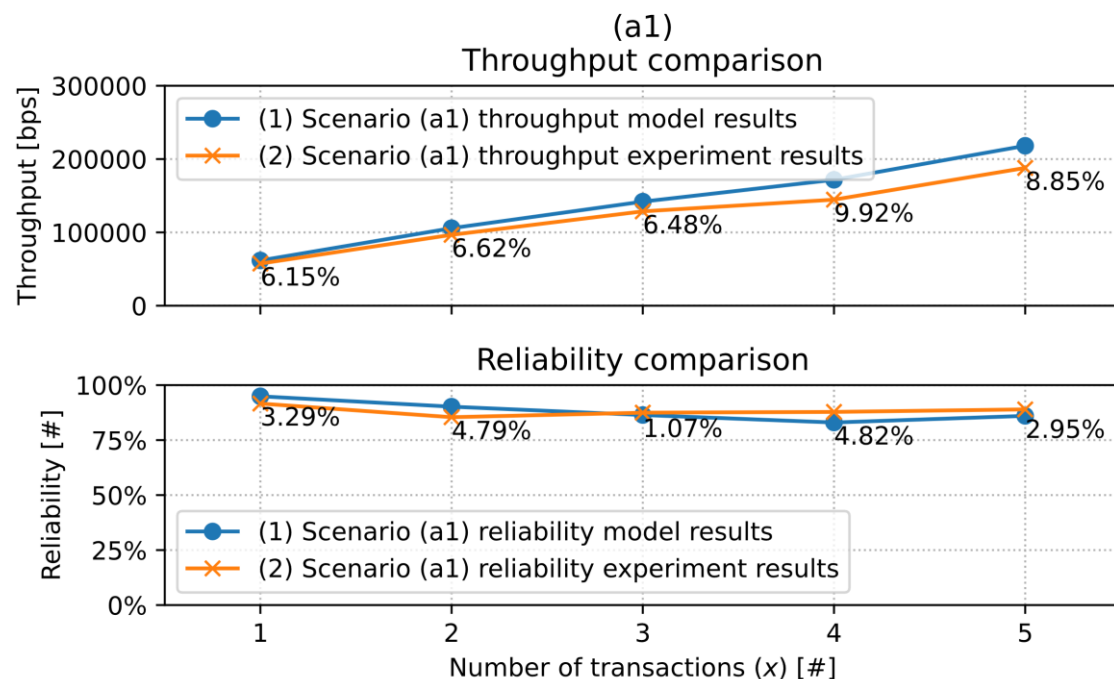# RO2.3: Quantification

- A mathematical model for BLE throughput

- An equation to quantify throughput of a BLE connection
  - Markov chain
  - Inputs
    - Various parameters
  - Output
    - Throughput

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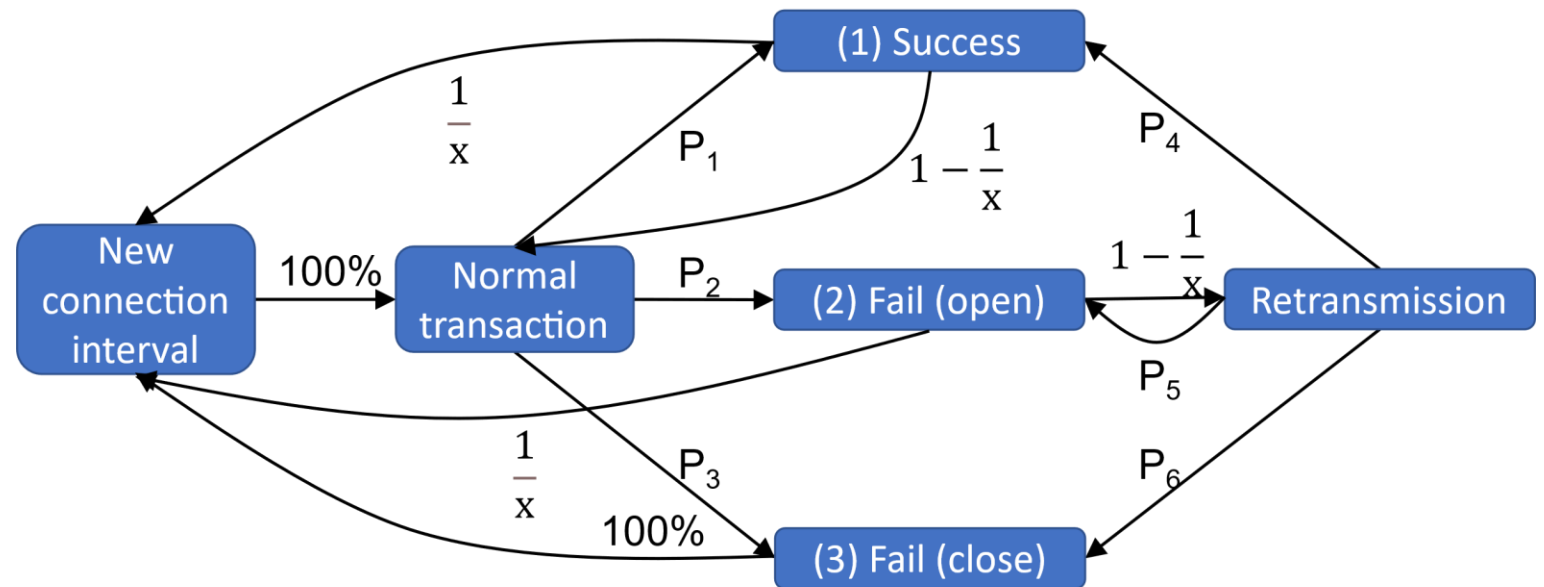
RQ2: BLE vs BLE
RO2.3: Quantification

- Validation of the models

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RQ2:   BLE vs BLE
RO2.3: Quantification

Reliability model ☑	Throughput model ☑
Inputs	
• Packet length • Number of packets • …	
Output	
Reliability	Throughput

The trade-off / relationship in between

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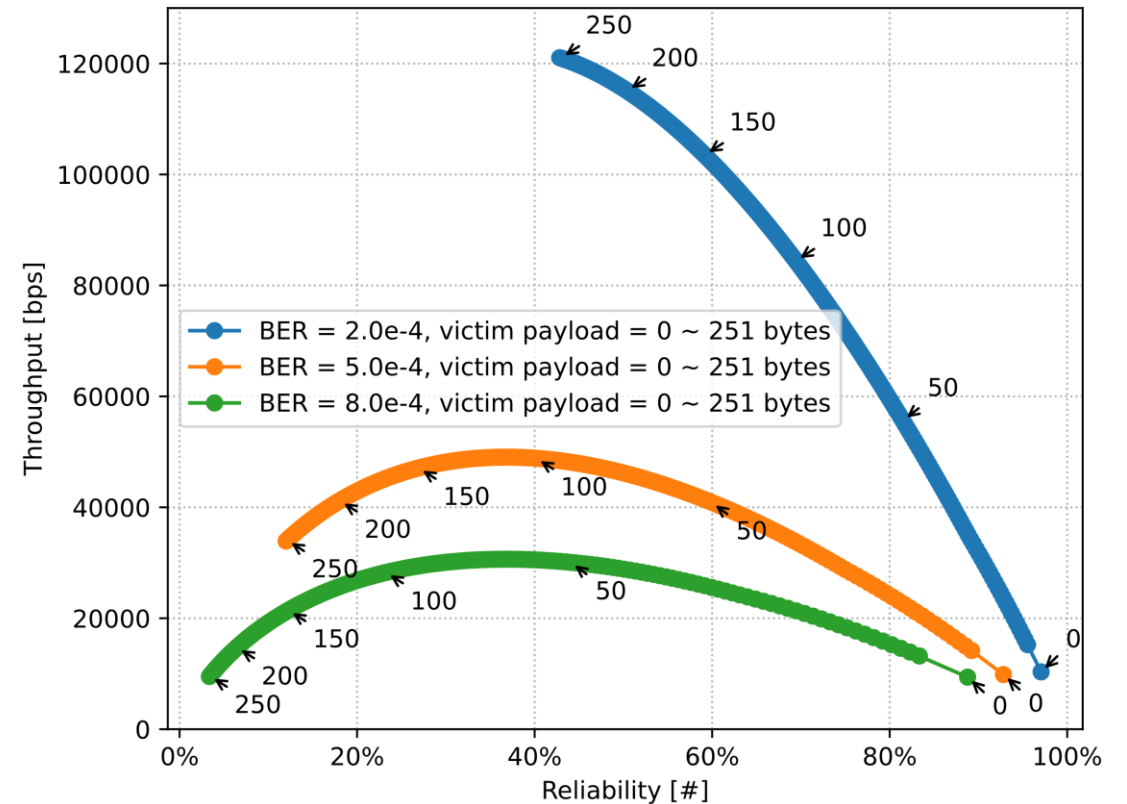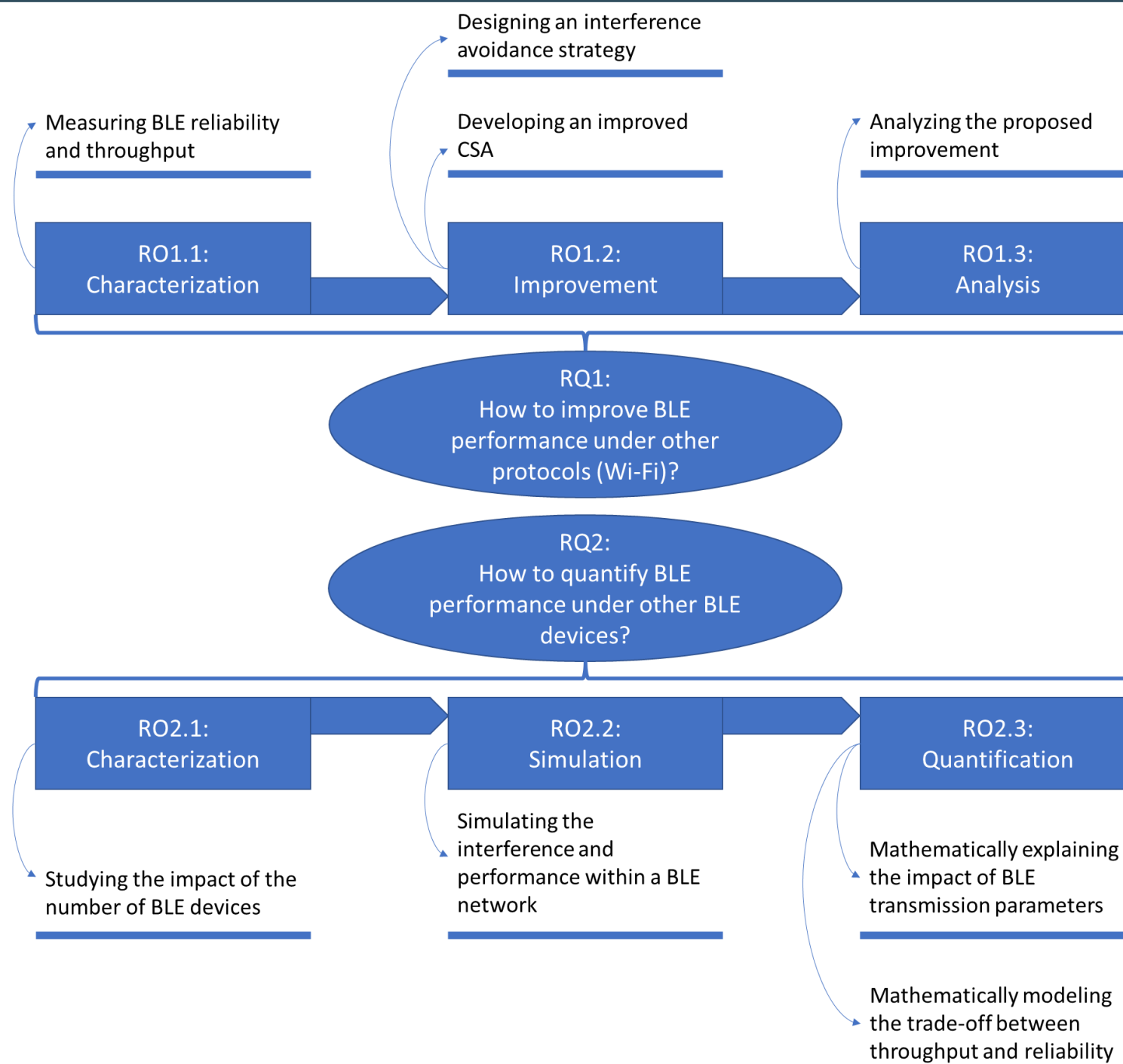# RQ2:   BLE vs BLE
RO2.3: Quantification

- Validated models

⬇

- The relation between
  - Reliability (X)
  - Throughput (Y)

Surprisingly, …

- A peak 👉 trade-off
- Payload ↘
  - reliability ↗
  - throughput ⬆

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Measuring BLE reliability and throughput

Designing an interference avoidance strategy

Developing an improved CSA

Analyzing the proposed improvement

RO1.1: Characterization

RO1.2: Improvement

RO1.3: Analysis

RQ1: How to improve BLE performance under other protocols (Wi-Fi)?

RQ2: How to quantify BLE performance under other BLE devices?

RO2.1: Characterization

RO2.2: Simulation

RO2.3: Quantification

Studying the impact of the number of BLE devices

Simulating the interference and performance within a BLE network

Mathematically explaining the impact of BLE transmission parameters

Mathematically modeling the trade-off between throughput and reliability

Future work

- Near future

- BLE
  - Other performance metrics (latency, energy efficiency, ...)
  - More complicated interference environments
  - An Intelligent Management Framework for BLE
  - BLE audio
  - BLE mesh
  - …

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Future work

- Near future

- RIOT?
    - NimBLE?
    - What can I do with it?
    - Can I develop something?
    - Further discussions are needed
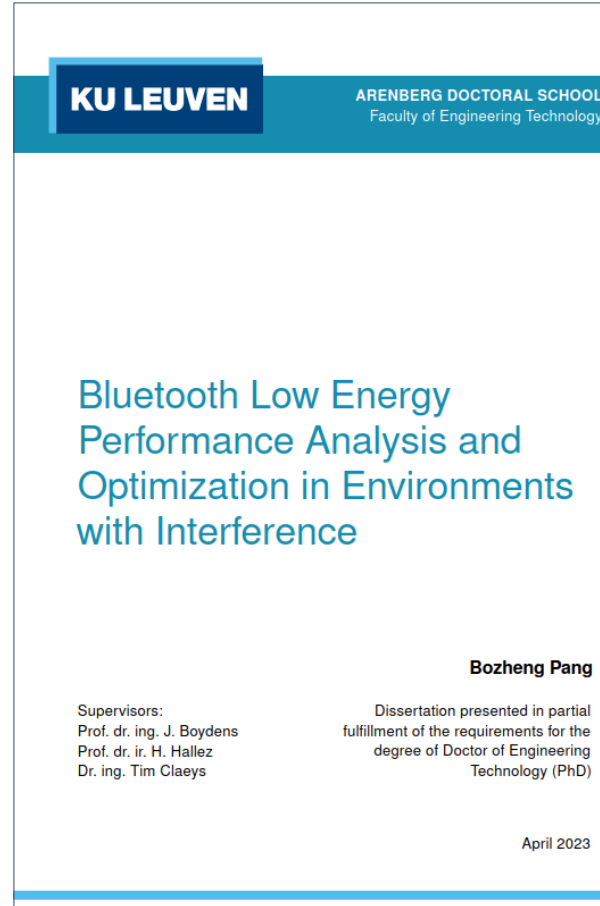
- Integration into Germany

Future work

- Far future

- Full duplex wireless communication
- Energy harvesting
- Deprotocolization
- …

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Gifts from Belgium to Germany delivered by a Chinese

Happy Easter holiday!

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Gifts from Belgium to Germany made by a Chinese

KU LEUVEN — ARENBERG DOCTORAL SCHOOL
Faculty of Engineering Technology

Bluetooth Low Energy Performance Analysis and Optimization in Environments with Interference

Bozheng Pang

Supervisors:
Prof. dr. ing. J. Boydens
Prof. dr. ir. H. Hallez
Dr. ing. Tim Claeys

Dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Engineering Technology (PhD)

April 2023

Pang Bozheng

Postdoc

Chair of Distributed and Networked Systems, TU Dresden, Germany

Q & A
Thanks for your time!

bozheng.pang@tu-dresden.de
03 April, 2024

Computer Graphics
and Visualization