KU LEUVEN

Bozheng Pang and His Story of Bluetooth Low Energy

Bozheng Pang

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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 ?)

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
    - (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

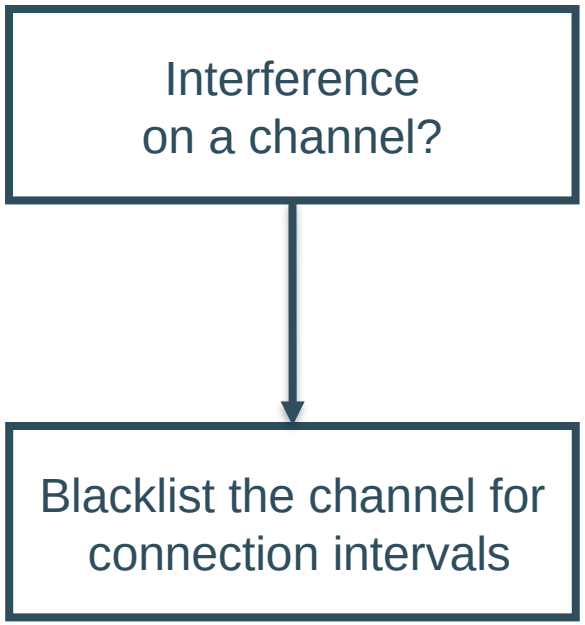
- RQ1: How to **improve** BLE performance under Wi-Fi interference?
  - RO1.1: Characterization
  - **RO1.2: Improvement**
  - RO1.3: Analysis (of improvement)

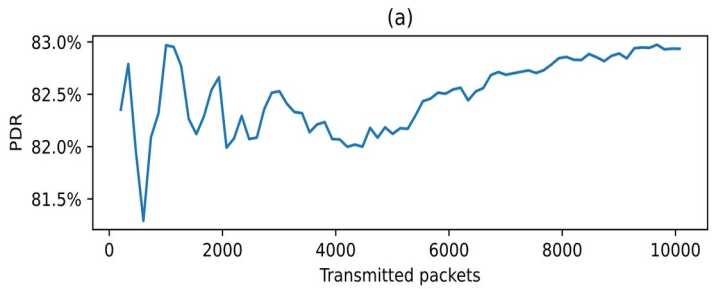
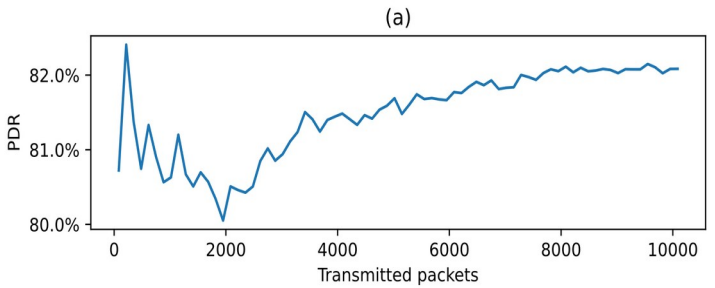
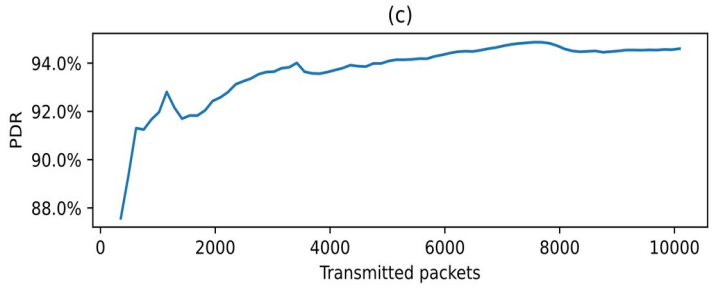
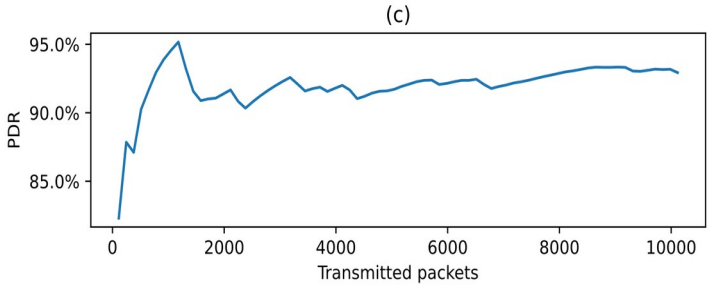
BLE vs BLE

- 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
BLE standard		
BLE standard + Exponential back-off algorithm		

PANG, B., Claeys, T., Hallez, H., Boydens, J. (2022). An Exponential Back-off Algorithm Based Interference Avoidance Strategy for Bluetooth Low Energy against Wideband Interference. In: *2022 International Symposium on Electromagnetic Compatibility – EMC Europe*, (661-666). Presented at the 2022 International Symposium on Electromagnetic Compatibility – EMC Europe, Gothenburg, Sweden. ISBN: 978-1-6654-0788-5. doi: 10.1109/EMCEurope51680.2022.9901045

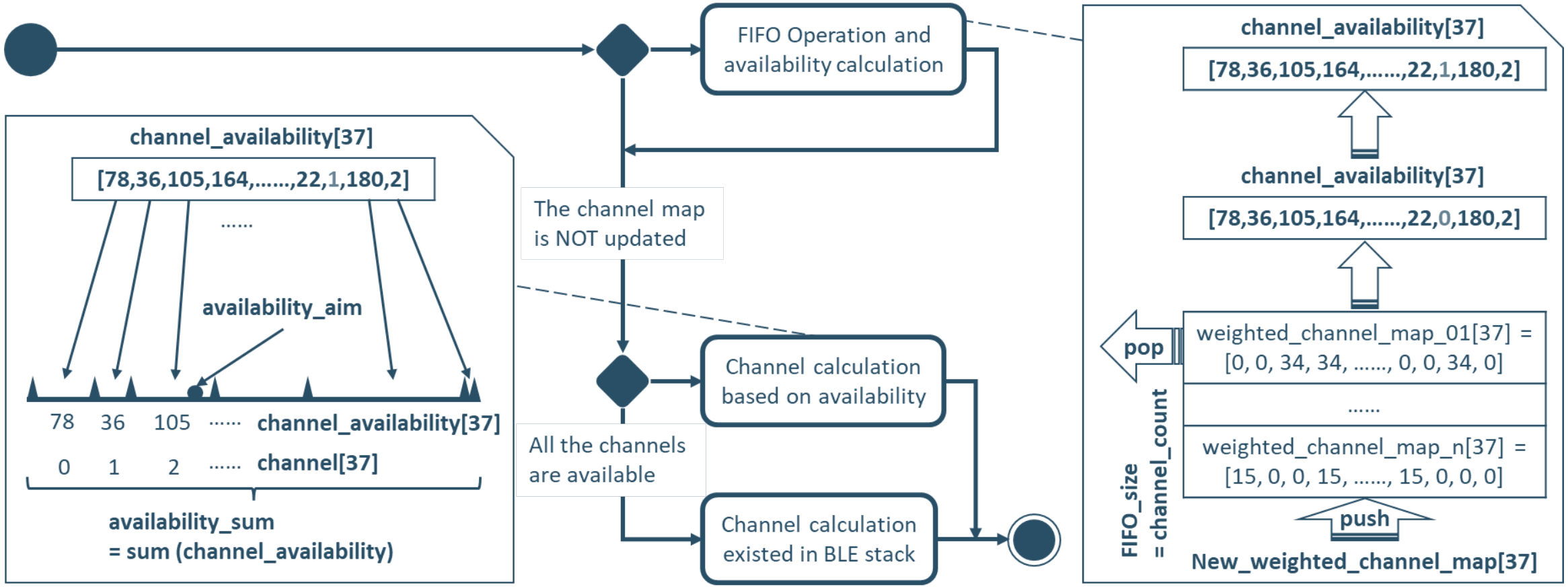
RQ1: BLE vs Wi-Fi
RO1.2: Improvement

- **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%

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

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



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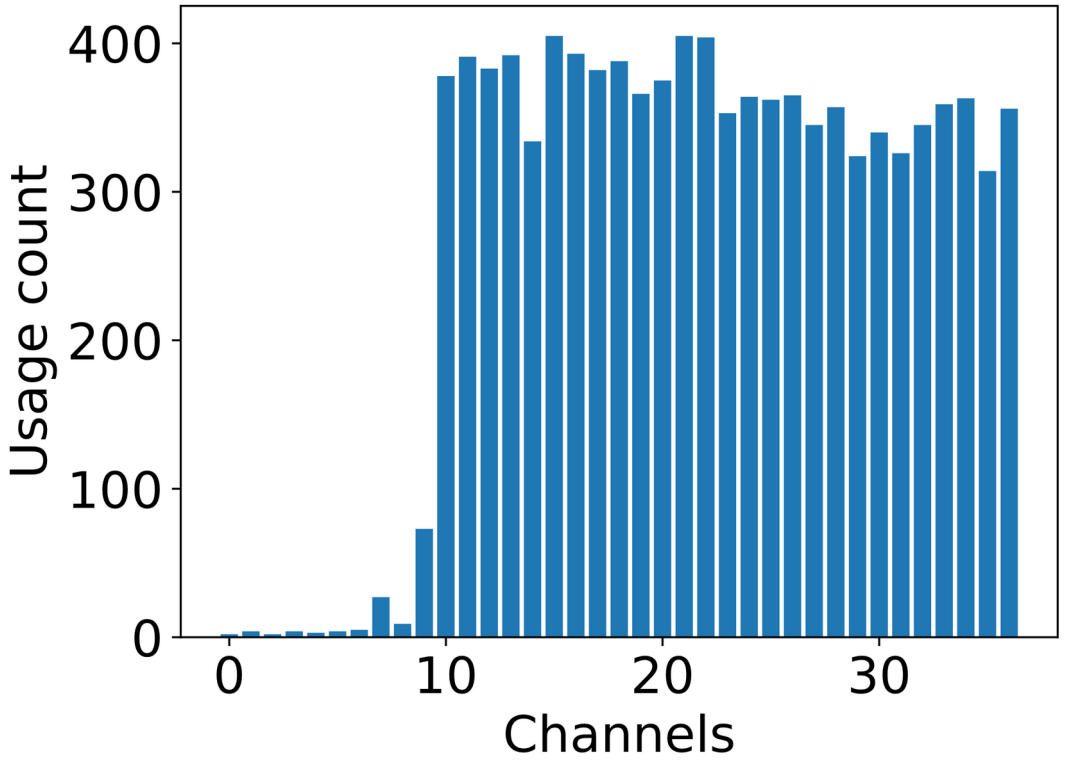

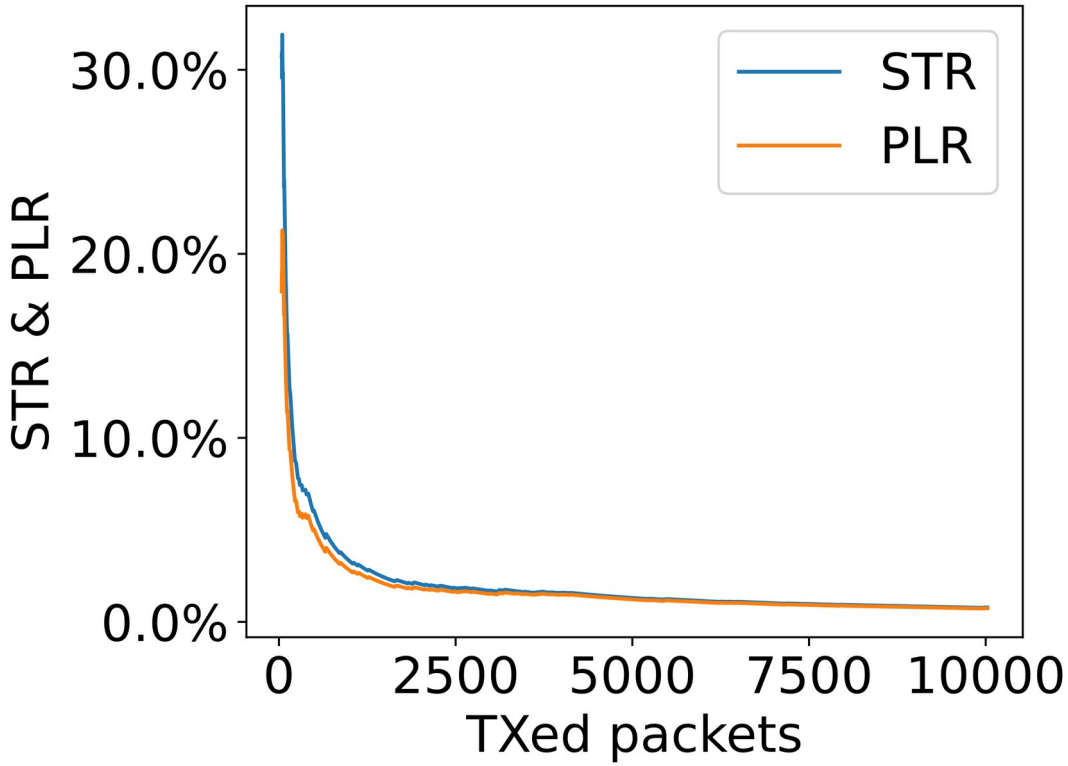

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Research on Bluetooth Low Energy

BLE vs Wi-Fi

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  - **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**

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

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

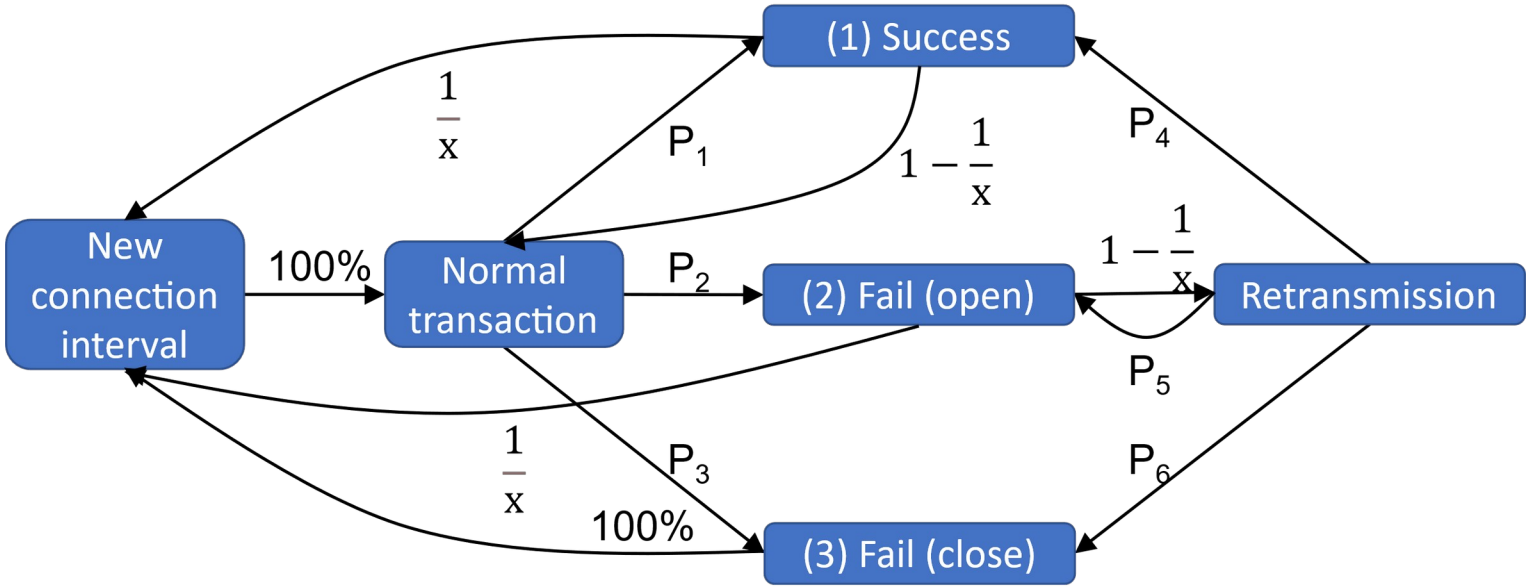
$$P_{TF} = (1 - (1 - BER_V)^{2 \cdot L_V}) \cdot \min(1, \frac{m \cdot (\overline{PT_V} + IFS) + n \cdot (\overline{PT_D} + IFS)}{CI_D}) \cdot (1 - \max(0, n \cdot \frac{IFS - \overline{PT_V}}{n \cdot (\overline{PT_D} + IFS) - IFS})^m)$$

PANG, B., Claeys, T., Vankeirsbilck, J., T'Jonck, K., Hallez, H., Boydens, J. (2022). A Novel Model to Quantify the Impact of Transmission Parameters on the Coexistence between Bluetooth Low Energy Pairs. *Ieee Internet Of Things Journal*. doi: 10.1109/JIOT.2022.3209874

RQ2: BLE vs BLE
RO2.3: Quantification

- A mathematical model for BLE throughput

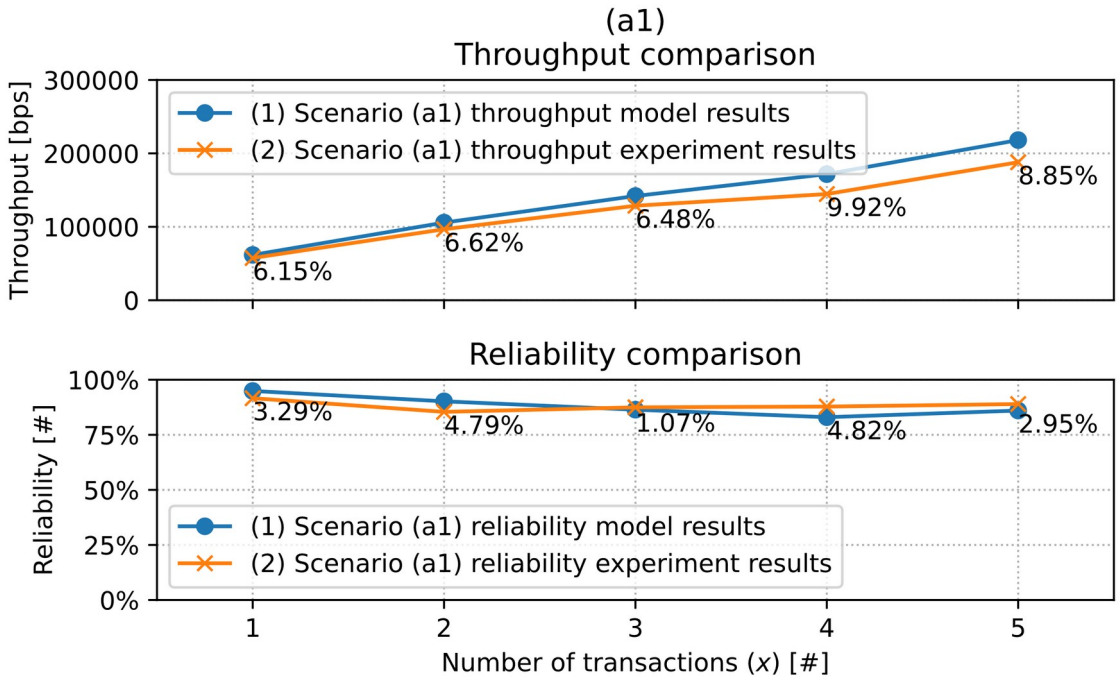
- An equation to quantify throughput of a BLE connection
  - Markov chain
  - Inputs
    - Various parameters
  - Output
    - Throughput

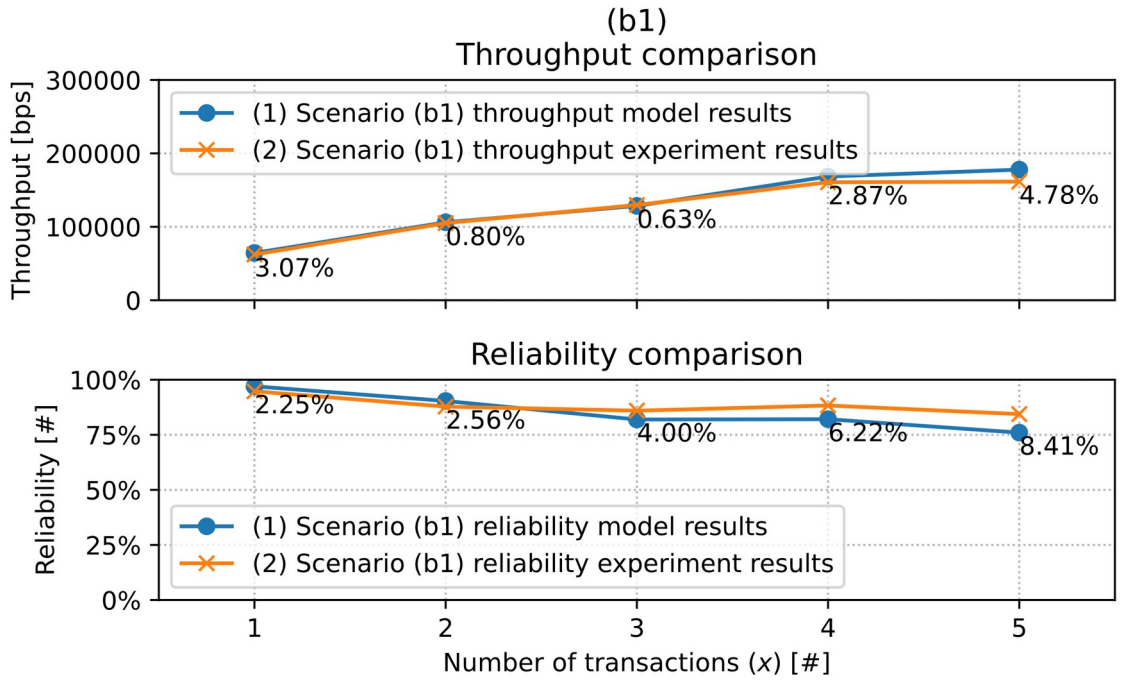


B. Pang, T. Claeys, H. Hallez, and J. Boydens, “Modeling the Trade-off between Throughput and Reliability in a Bluetooth Low Energy Connection”. (Accepted by EWSN 2023)

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

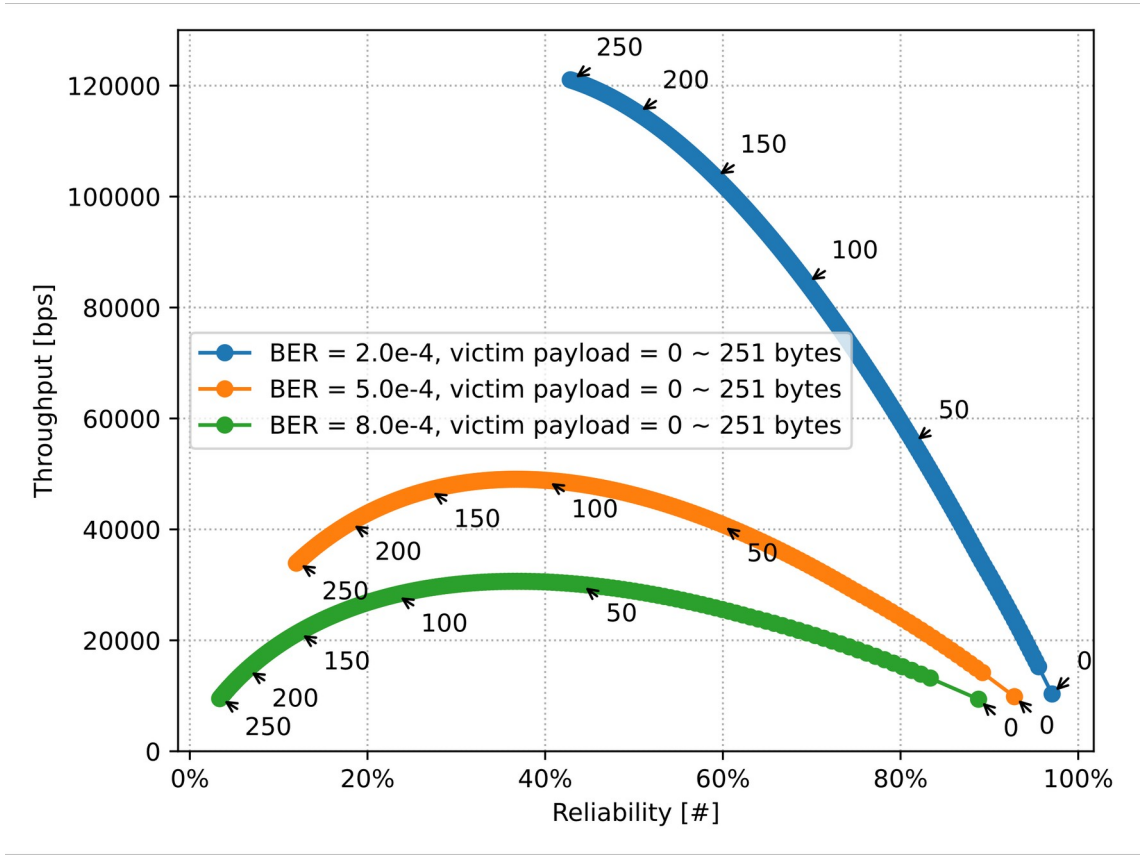
RQ2: BLE vs BLE
RO2.3: Quantification

- Validated models

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

Surprisingly, …

- A peak trade-off
- Payload
  - reliability
  - throughput



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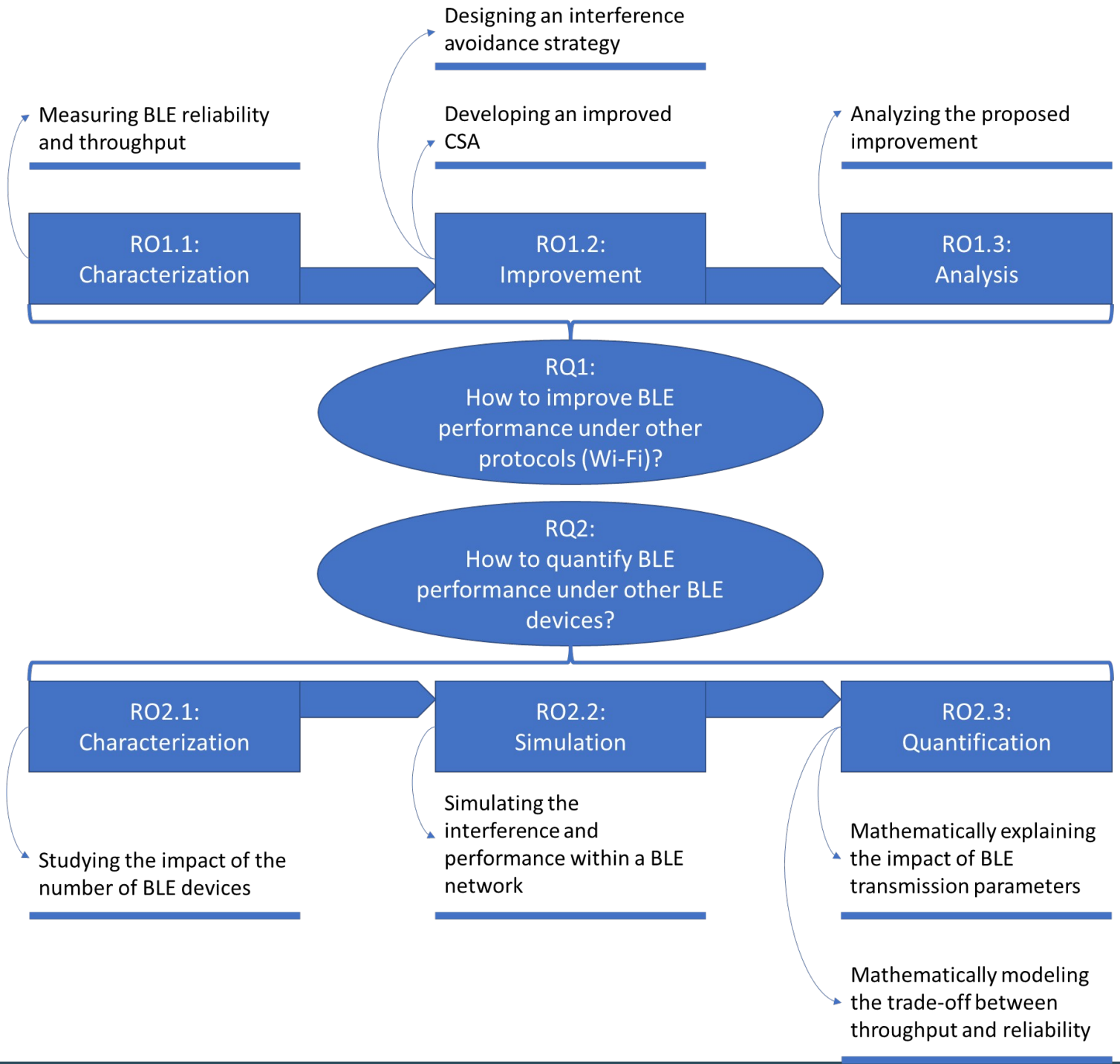

Designing an interference avoidance strategy
Measuring BLE reliability and throughput
Developing an improved CSA
Analyzing the proposed improvement
RO1.1: Characterization
RO1.2: Improvement
RO1.3: Analysis
RQ1: How to improve BLE performance under other protocols (Wi-Fi)?
RQ2: How to quantify BLE performance under other BLE devices?
RO2.1: Characterization
RO2.2: Simulation
RO2.3: Quantification
Simulating the interference and performance within a BLE network
Mathematically explaining the impact of BLE transmission parameters
Studying the impact of the number of BLE devices
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
  - ...

Future work

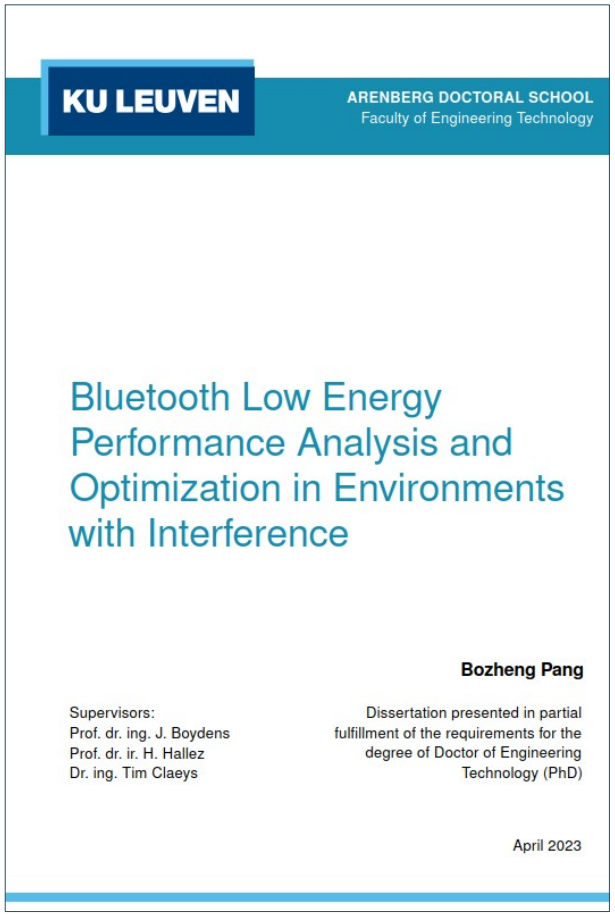
- Near future
- RIOT?
  - NimBLE?
  - What can I do with it?
  - Can I develop something?
  - Further discussions are needed
- Integration into Germany

Future work

- Far future

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

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

TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Pang Bozheng
Postdoc
Chair of Distributed and Networked Systems, TU Dresden, Germany

Q & A

Thanks for your time!

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03 April, 2024

Computer Graphics and Visualization