Autonomous Spectrum Awareness for Smart Spectrum Access and Sharing

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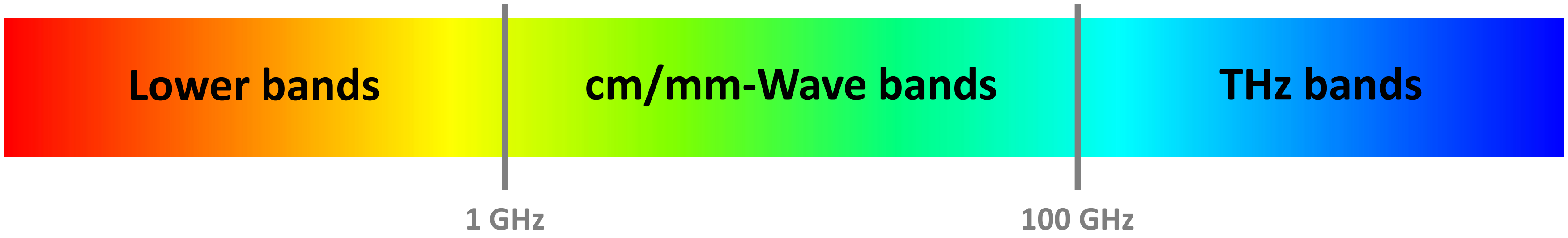
6G: Software Defined Radio and RF Sampling, 16 September 2021

Current spectrum landscape



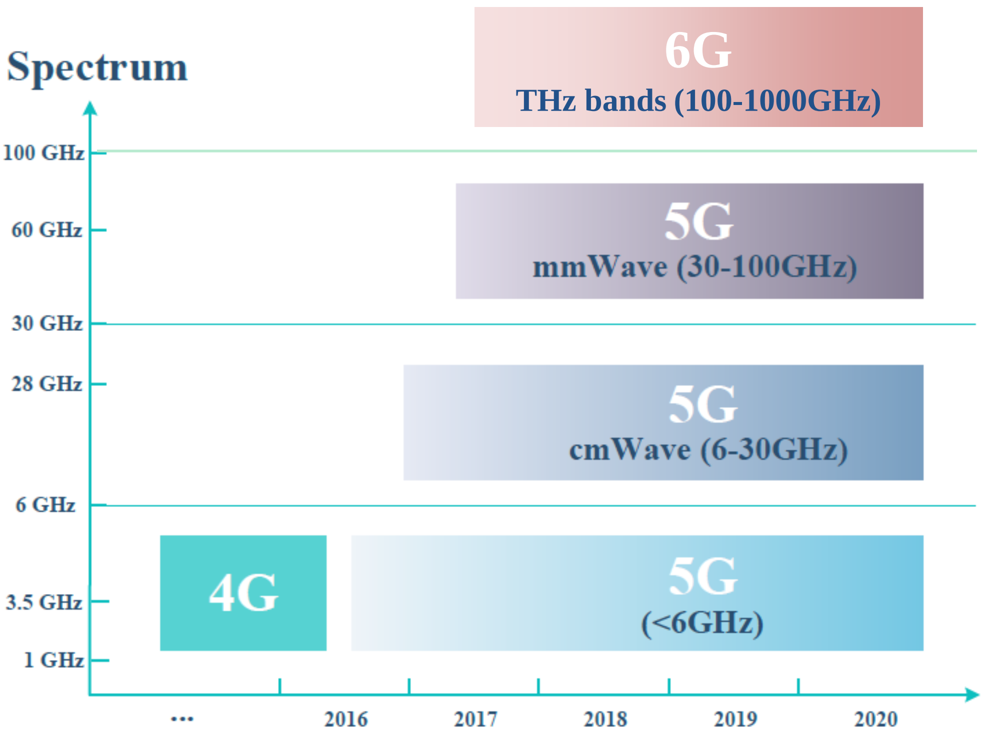
Good propagation
Wide area coverage
Bandwidth ~ 10-100 MHz
Datarate ~ 10-100 Mbps

Limited propagation
Reduced area coverage
Bandwidth ~ 100-1000 MHz
Datarate ~ 100-1000 Mbps

Poor propagation
Small area coverage
Bandwidth ~ GHz
Datarate ~ Gbps

- Spectrum use is worth well over £50bn a year to the UK economy.
- The most important resource of wireless communication systems.
- Desirable spectrum (sub-6 GHz) is crowded with legacy systems.
- Deployment of new systems:
  - Higher frequency bands
  - Sharing of lower spectrum

What spectrum band?



Source: Feng Hu et al., IEEE Access, vol. 6, Feb. 2018 (adapted)

Unprecedented bandwidths → High data rates
Unused spectrum (free capacity & easy exploitation)
Unfavourable propagation → Very short coverage
Unreliable links → Momentary unavailability (URLLC)
Availability/deployment: Medium / long-term

Limited RF bandwidth (and data rates)
Crowded (limited capacity & difficult exploitation)
Favourable propagation → Longer coverage
More reliable links (and communications)
Availability/deployment: Now! / short-term

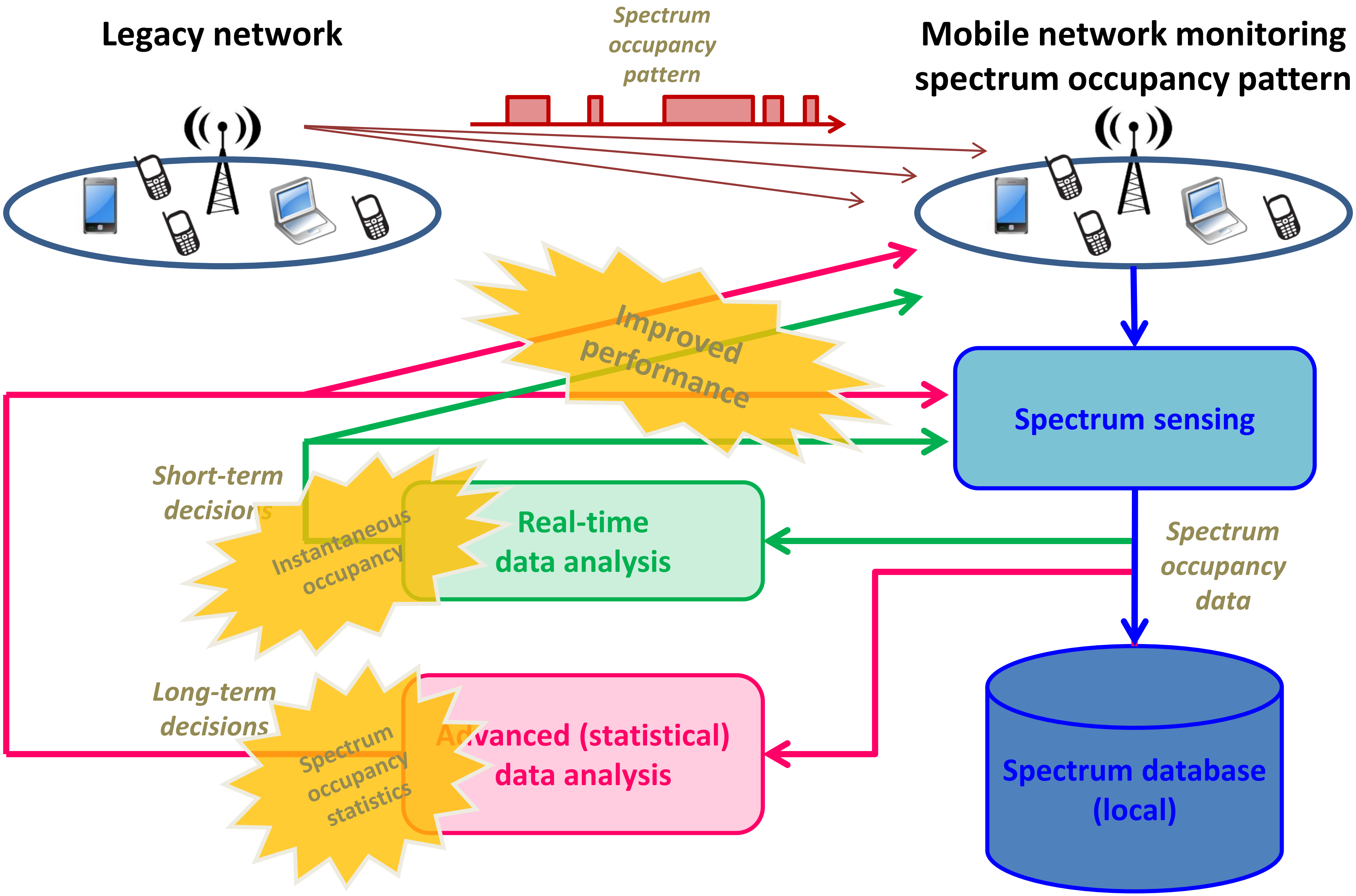
- What spectrum band?
  - Many 6G applications will require higher capacity → mmWave/THz bands
  - Many 6G applications will still require wide coverage → sub-6 GHz
- Sub-6 GHz spectrum remains critically important
  - Spectrum sharing is the way forward to further exploit sub-6 GHz spectrum
- Unique opportunity to also embed spectrum sharing in higher frequency bands
- Long history of spectrum sharing – Regulators' fears overcome (WRAN, LSA/ASA, CBRS, 5G NR-U)

Spectrum awareness approaches

	Spectrum sensing	Geolocation databases
Infrastructure complexity/cost	Low	High
Terminal complexity/cost	High	Medium
Legacy compatibility	High	Medium/Low
Reliability	Low/Medium	High
Spectrum dynamism	High	Low
Need for external system/provider	No	Yes
Need for additional spectrum	No	No
Specific issues	Time and energy consumption	Positioning system

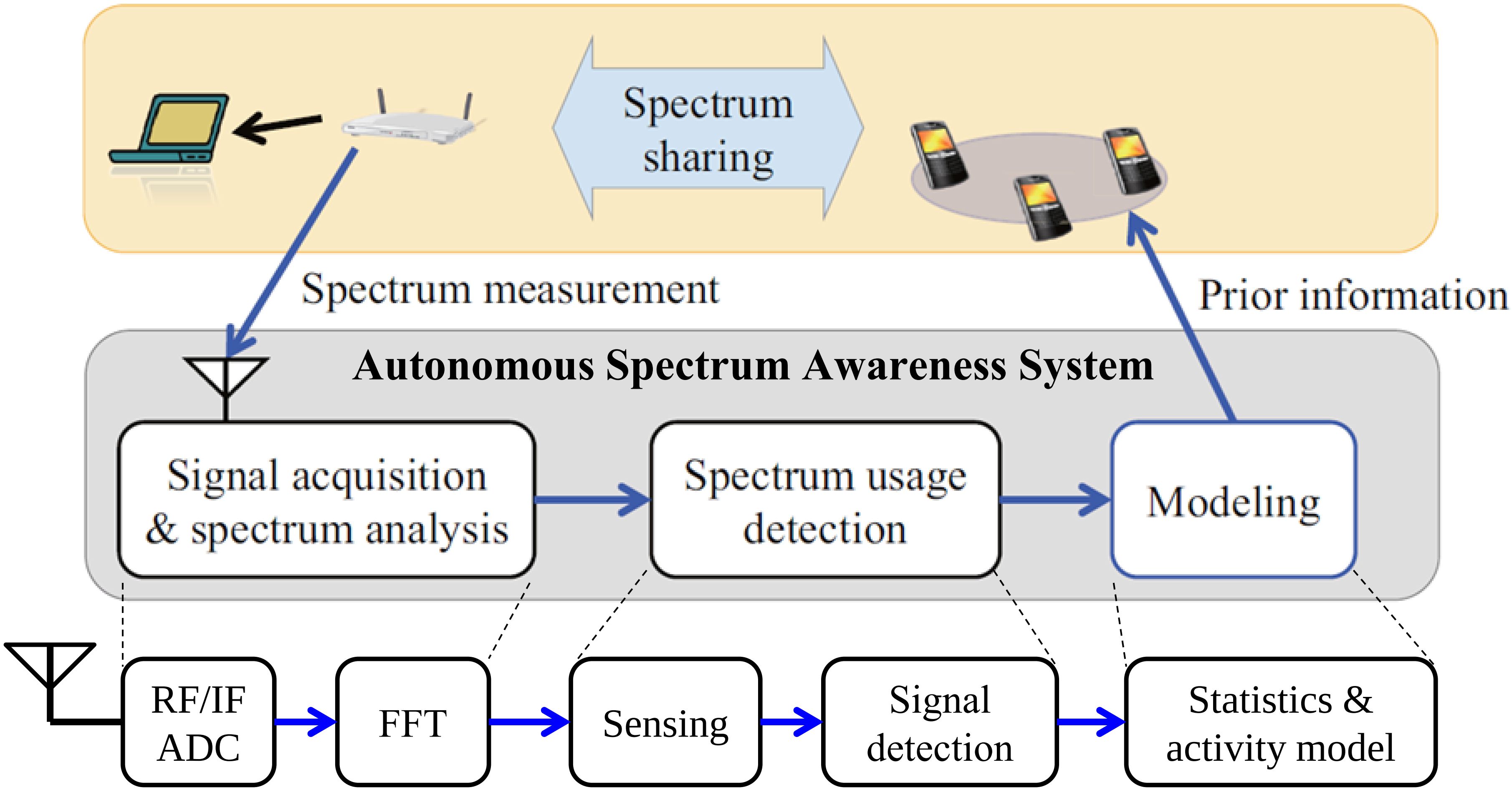
- Databases seem to have been a preferred option (WRAN, LSA, CBRS)
- Local sensing seen as a secondary/complementary requirement
- What about local sensing only? → **Autonomous spectrum awareness**

Autonomous spectrum awareness



Autonomous spectrum awareness

Two-layer smart spectrum access
(based on spectrum sensing)

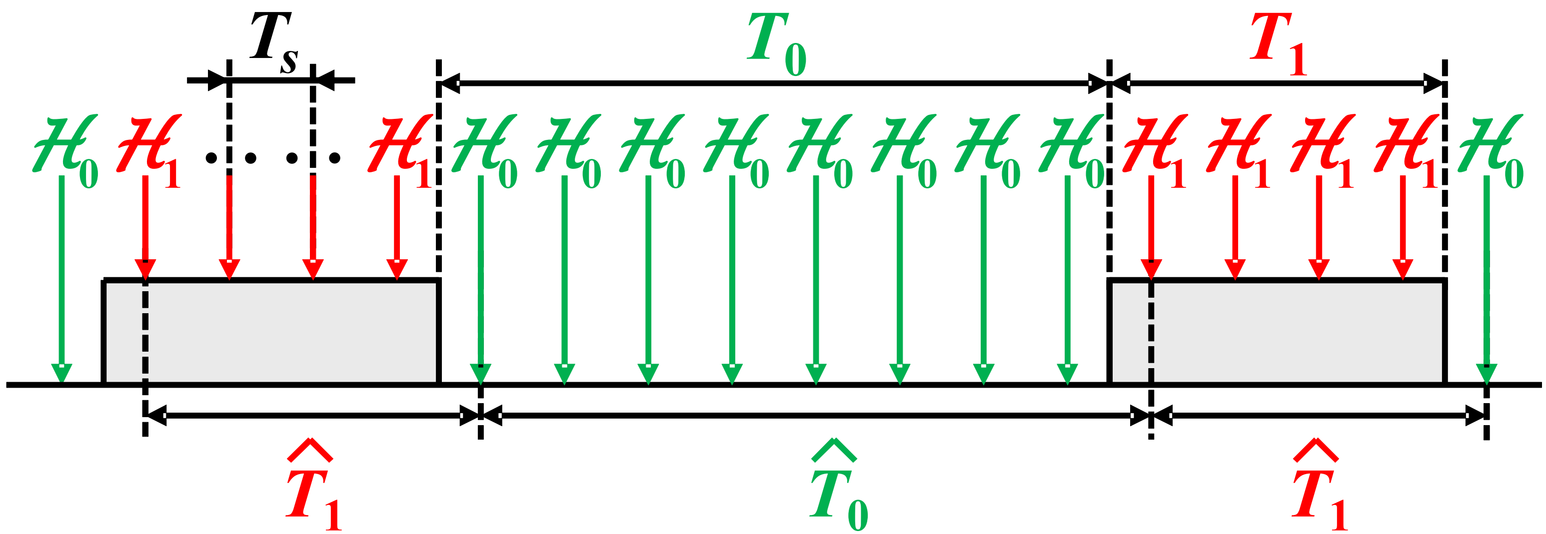


K. Umebayashi, Y. Tamaki, M. López-Benítez, J. J. Lehtomäki, "Design of spectrum usage detection in wideband spectrum measurements", IEEE Access, August 2019

Estimation of statistics based on sensing

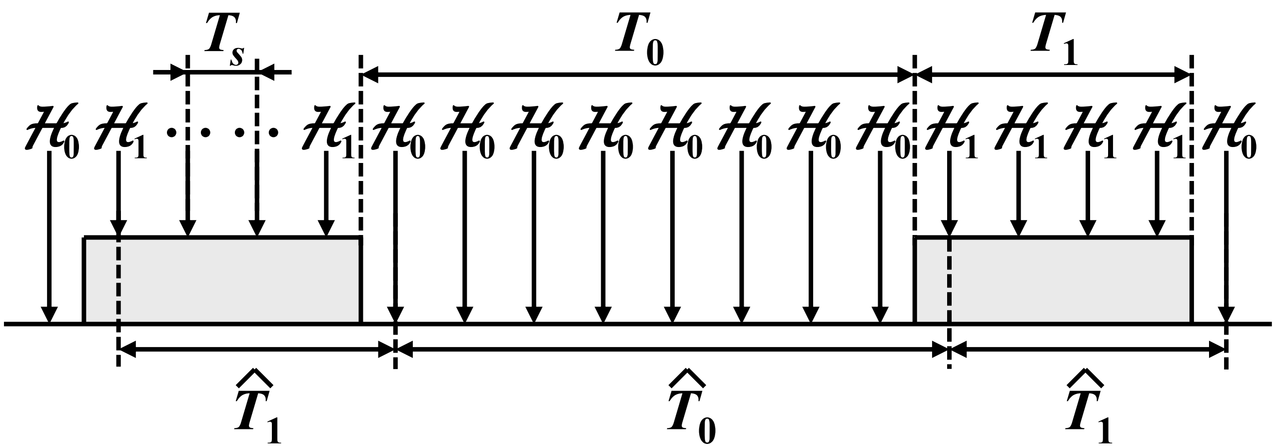
- How do we estimate spectrum activity statistics from sensing?

  1) Sense the channel with a given sensing period (T_s)
  2) Decide channel states → Idle (H_0) or Busy (H_1)
  3) Estimate individual period durations (T_i)
  4) Compute activity statistics from sequence of estimated periods:
     Min/max period, mean & variance (moments), distribution



Sources of inaccurate awareness info

- Finite sensing period:
  - Fundamental limit to the time resolution to which idle/busy periods can be observed
  - Estimated periods are integer multiples of the sensing period
  - True periods have in general a continuous domain



M. López-Benítez, A. Al-Tahmeesschi, D. K. Patel, J. Lehtomäki, K. Umebayashi, "Estimation of primary channel activity statistics in cognitive radio based on periodic spectrum sensing observations," IEEE Trans Wireless Comms, February 2019

- Limited number of observations:
  - Activity statistics need to be computed based on a reduce set of period durations

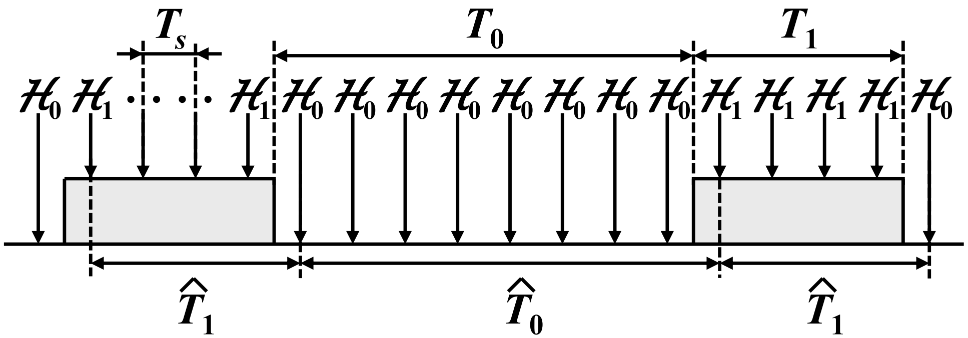
A. Al-Tahmeesschi, M. López-Benítez, D. K. Patel, J. Lehtomäki, K. Umebayashi, "On the sample size for the estimation of primary activity statistics based on spectrum sensing," IEEE Trans Cognitive Comms and Networking, March 2019

Sources of inaccurate awareness info

- Imperfect sensing performance:

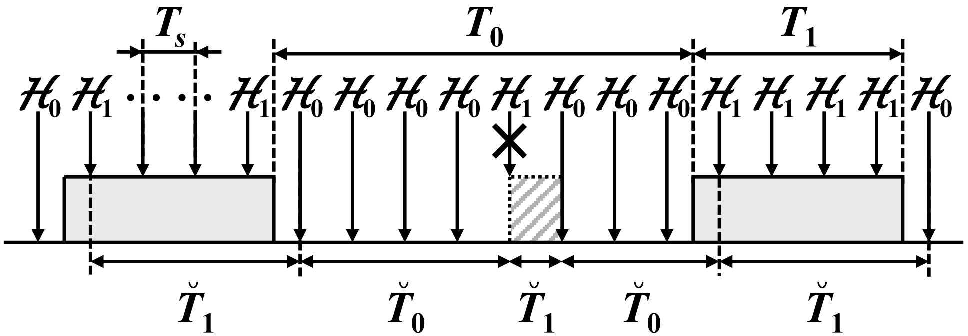
Perfect Spectrum Sensing (PSS)

(e.g., high SNR)



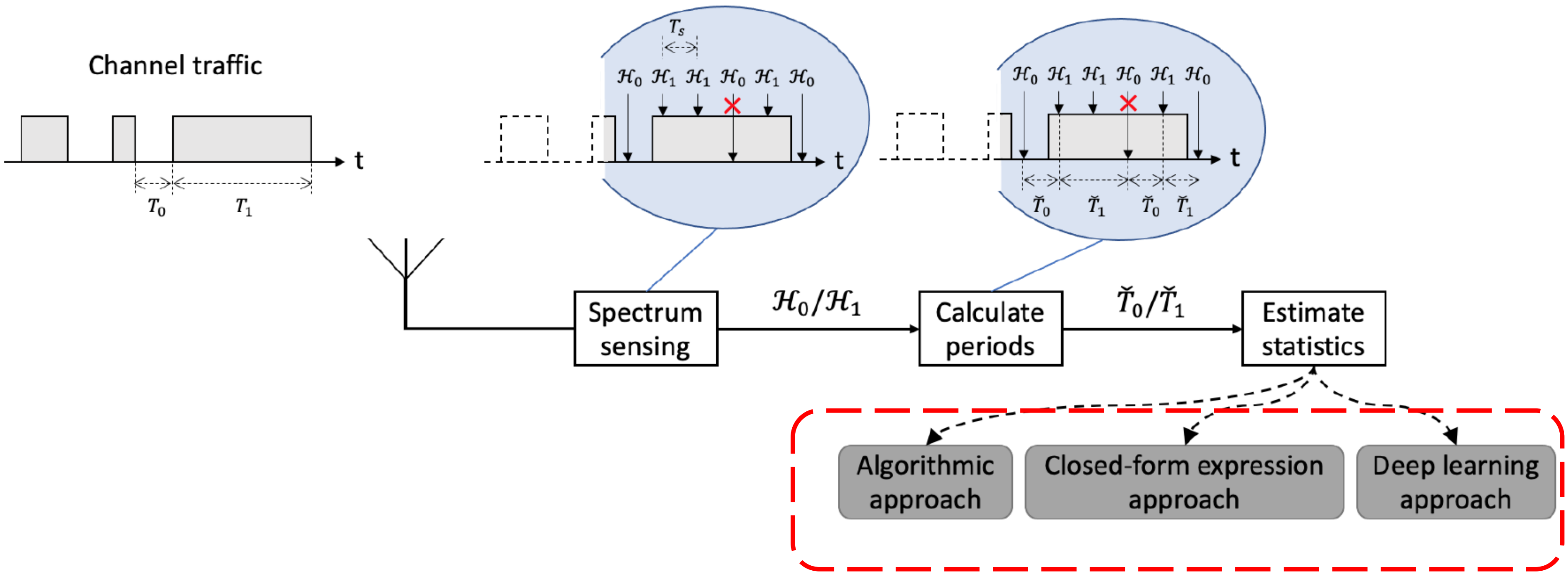
Imperfect Spectrum Sensing (ISS)

(e.g., low SNR)



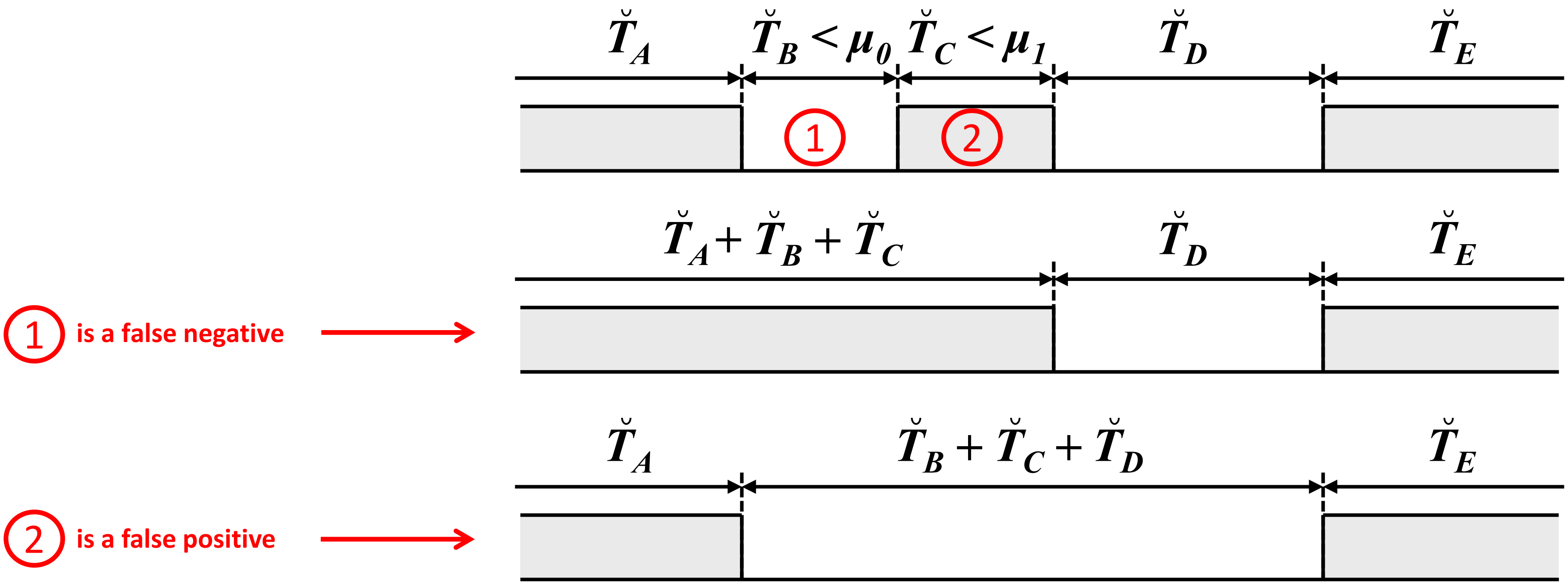
O. H. Toma, M. López-Benítez, D. K. Patel, K. Umebayashi, "Estimation of primary channel activity statistics in cognitive radio based on imperfect spectrum sensing," IEEE Trans Comms, April 2020

Methods for statistics estimation



Approaches for autonomous spectrum awareness

- **Approach 1:** Reconstruction algorithms



O. H. Toma, M. López-Benítez, D. K. Patel, and K. Umebayashi, "Reconstruction algorithm for primary channel statistics estimation under imperfect spectrum sensing", IEEE WCNC 2020

- **Approach 2:** Mathematical analysis

$$X \longrightarrow \boxed{\text{Wireless channel}} \longrightarrow \boxed{\text{Spectrum detection}} \longrightarrow \breve{X}$$

$$\breve{X} = f\left(X, T_s, P_{fa}, P_{md}, N\right)$$

$$\tilde{X} = f^{-1}\left(\breve{X}, T_s, P_{fa}, P_{md}, N\right) \approx X$$

M. López-Benítez, A. Al-Tahmeesschi, D. K. Patel, J. Lehtomäki, K. Umebayashi, "Estimation of primary channel activity statistics in cognitive radio based on periodic spectrum sensing observations," IEEE Trans Wireless Comms, February 2019

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O. H. Toma, M. López-Benítez, D. K. Patel, K. Umebayashi, "Estimation of primary channel activity statistics in cognitive radio based on imperfect spectrum sensing," IEEE Trans Comms, April 2020

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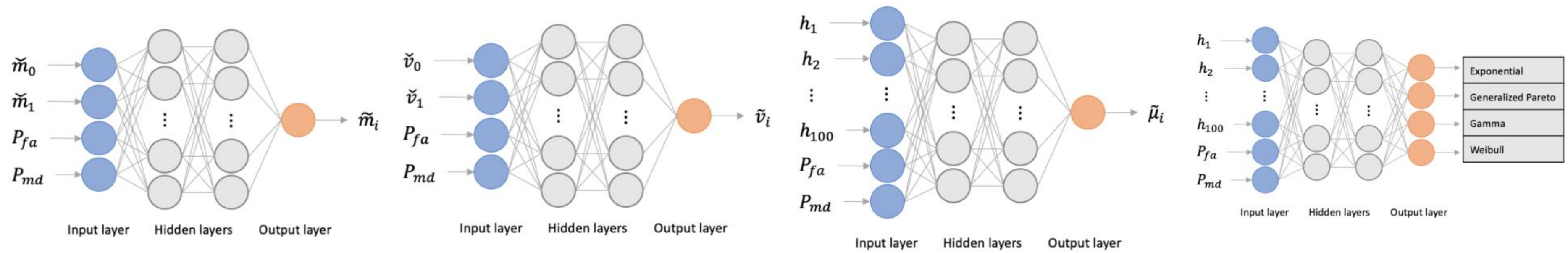
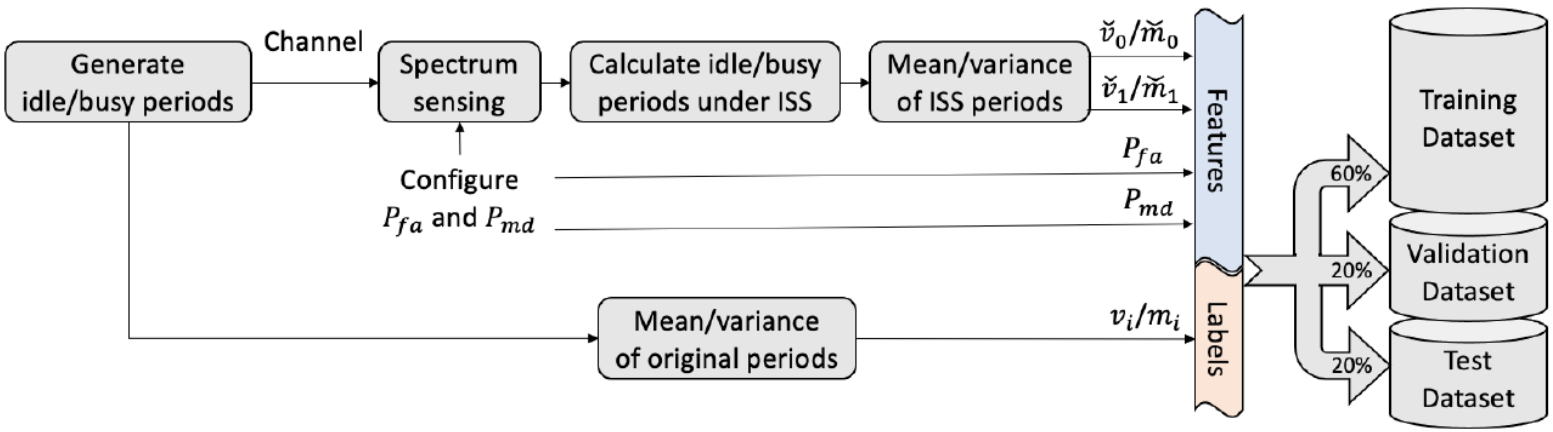
- **Approach 3:** Deep learning

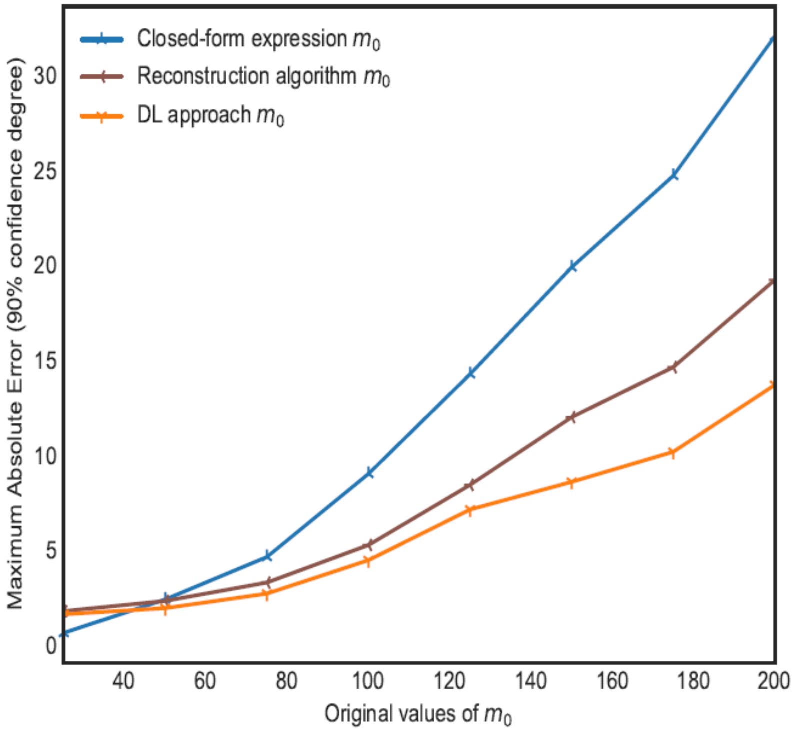


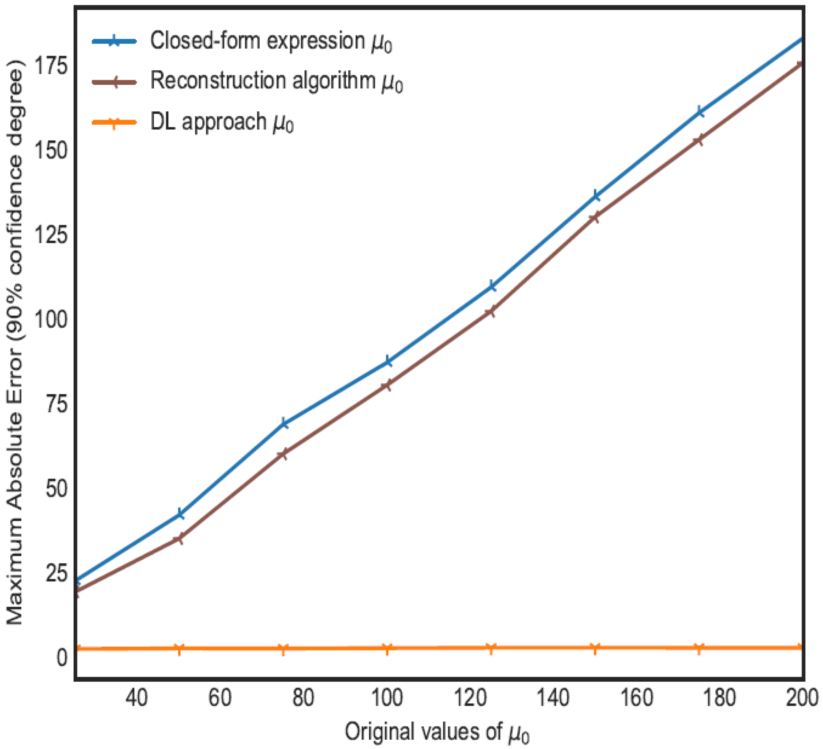


O. H. Toma, M. López-Benítez, "Traffic Learning: a Deep Learning Approach for Obtaining Accurate Statistical Information of the Channel Traffic in Spectrum Sharing Systems", IEEE Access, September 2021

A. Al-Tahmeesschi, K. Umebayashi, H. Iwata, J. Lehtomäki, M. López-Benítez, "Feature-Based Deep Neural Networks for Short-Term Prediction of WiFi Channel Occupancy Rate," IEEE Access, June 2021

Performance comparison





Performance comparison

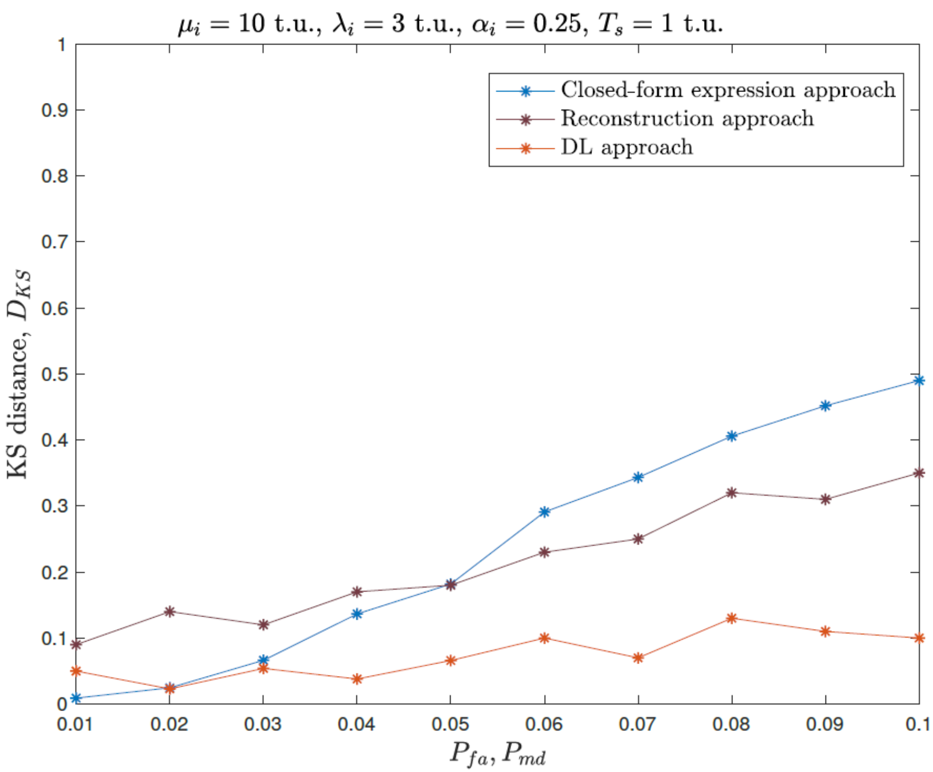
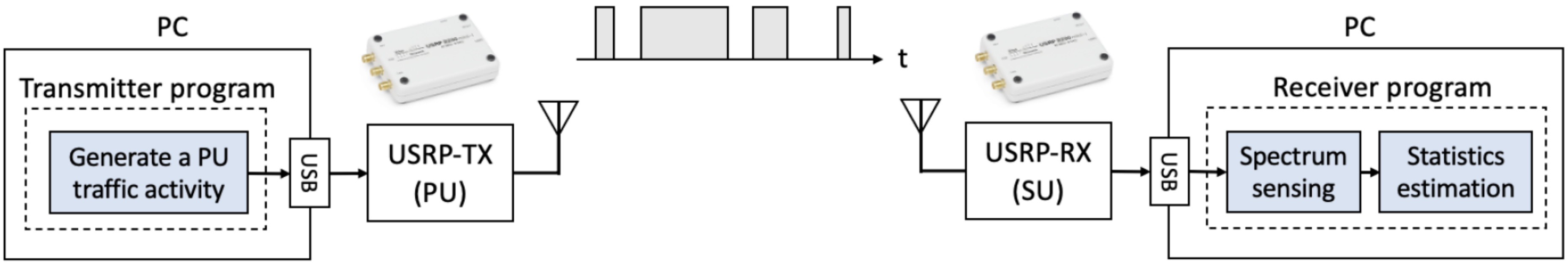
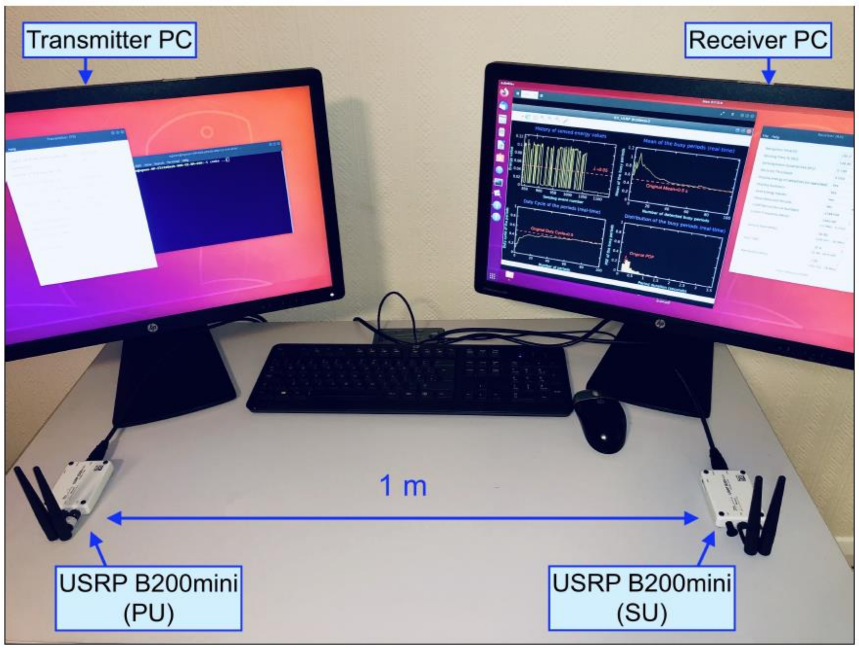


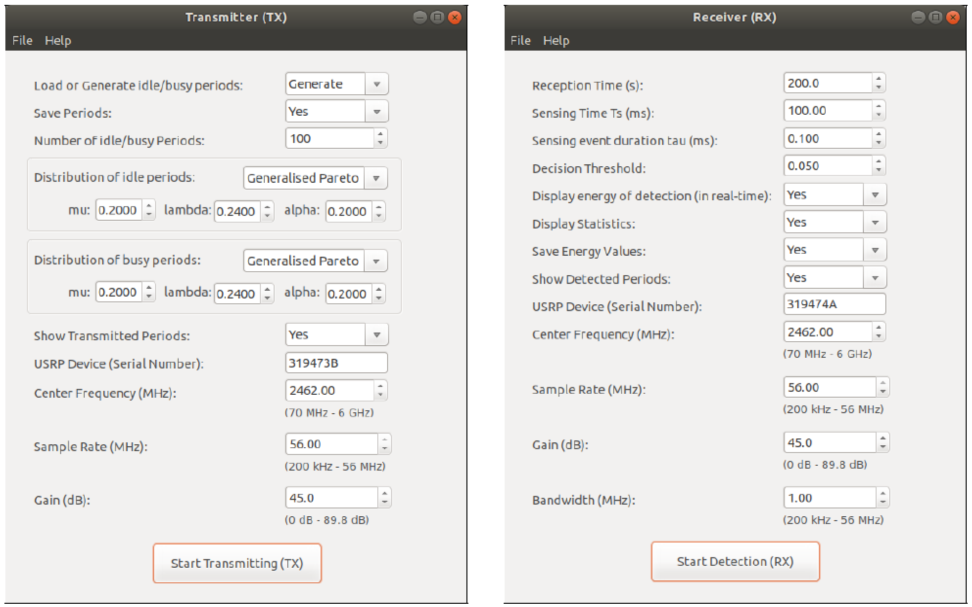
TABLE 6. Computation time (in seconds) required by each approach to provide 100 estimations for different statistical metrics.

Approach	Mean	Variance	Minimum	Distribution
Closed-form expressions	0.037	–	0.001	0.52
Reconstruction algorithms	200.7	243	266.8	280
Deep Learning	0.4	0.42	0.47	1.7
+ training	50.8	51.4	50.74	162.1

Experimental validation





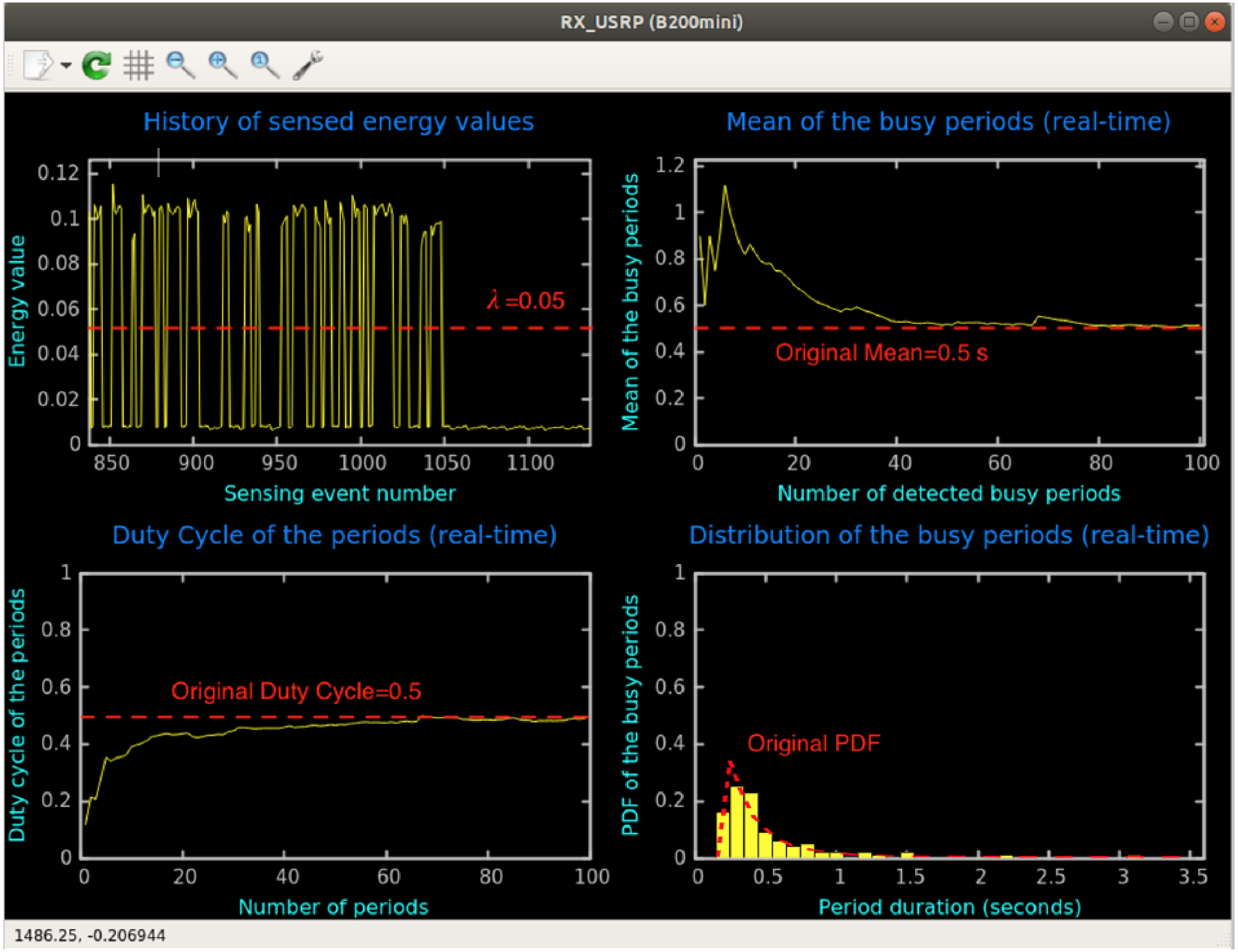


(a) Transmitter GUI

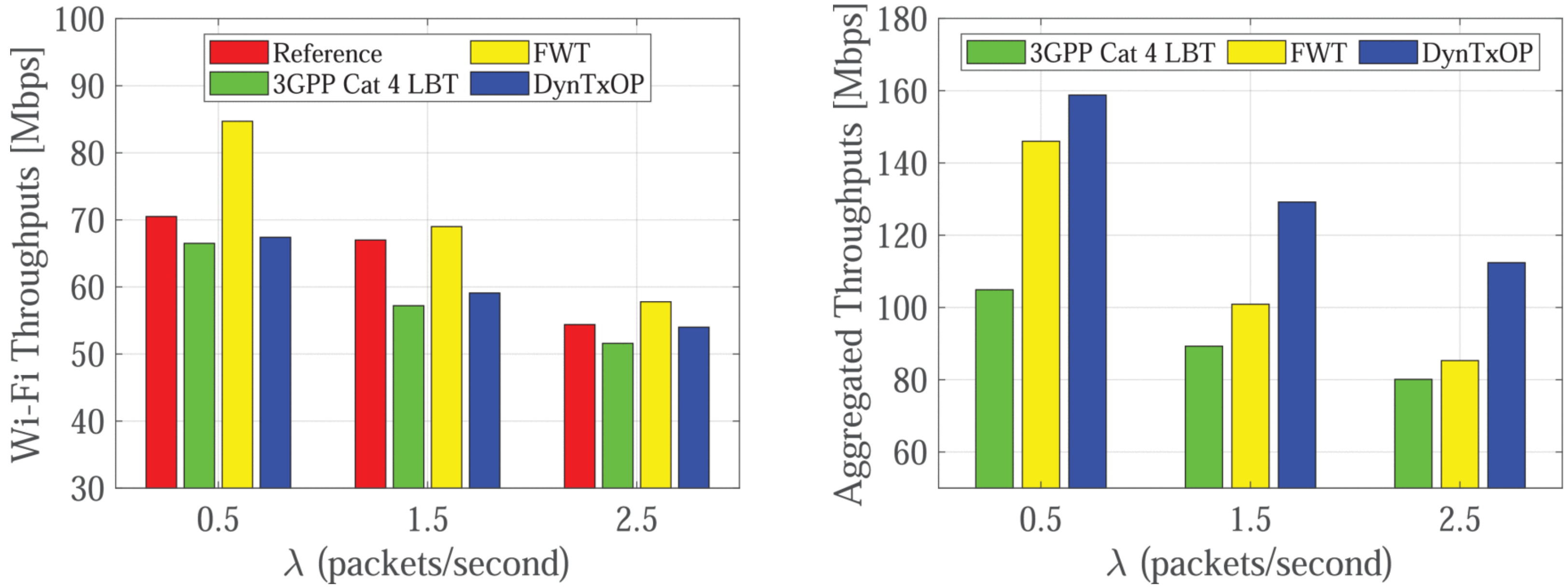
(b) Receiver GUI

O. H. Toma, M. López-Benítez, "USRP-Based Prototype for Real-Time Estimation of Channel Activity Statistics in Spectrum Sharing", IEEE ISWCS 2021
Available: https://github.com/ogeen-toma/USRP-prototype-for-channel-statistics-estimation

Experimental validation



- Mobile networks in WiFi unlicensed spectrum (LAA)



- ➢ 3GPP Cat 4 LBT does not meet “fairness” requirements
- ➢ <u>Fairness can be achieved by adjusting waiting times</u> based on WiFi activity statistics (FWT method)
- ➢ <u>Aggregated capacity can be maximised by adjusting transmission times</u> based on WiFi activity statistics (DynTxOP method)

M. Alhulayil, M. López-Benítez, "Novel LAA waiting and transmission time configuration methods for improved LTE-LAA/Wi-Fi coexistence over unlicensed bands", IEEE Access, September 2020

Thank you

for your attention !

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Final editorial decisions:	February 1, 2022
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