Delay Bounds in IEEE 802.11 Networks Under Non-Saturated Conditions: Do Practical Models Improve Accuracy?

Instituições Associadas

Orangel Azuaje Contreras [1,2]
Ana Aguiar [1,2]

1. Faculdade de Engenharia da Universidade do Porto (FEUP)
2. Instituto de Telecomunicações (IT-Porto)

Trondheim, June 2025

Outline

Introduction

Delay Guarantees for Delay-sensitive Applications – 802.11 Network

- Applications that require low delay and minimal variation to function properly
- Service provided in an 802.11 network is determined by the Distribution Coordination Function (DCF)
- Computing delay guarantees is essential to meet strict quality and regulatory requirements
- DCF has not been widely studied within Stochastic Network Calculus (SNC)

DCF as GPS	DCF as time-domain server model	DCF as periodic process
Saturated conditions[1]	Saturated conditions[2]	Non-saturated conditions[3]

---

1. Bredel, M., & Fidler, M. (2009, April). Understanding fairness and its impact on quality of service in IEEE 802.11. In *IEEE INFOCOM 2009* (pp. 1098-1106)
2. Xie, J., & Jiang, Y. (2010, October). A network calculus approach to delay evaluation of IEEE 802.11 DCF. In IEEE Local Computer Network Conference (pp. 560-567)
3. Azuaje, O., & Aguiar, A. (2024). Delay Guarantees for a Swarm of Mobile Sensors in Safety-Critical Applications. IEEE Open Journal of the Communications Society

Introduction

Limitations/Challenges

- Most delay-sensitive applications operate under non-saturated conditions.
- Analytical analysis of the service provided in these non-saturated conditions is very challenging
- Modeling the service offered by the DCF relies on simplifying assumptions to make the computations tractable

Research Question

- Can a practical model of an IEEE 802.11 networks under non-saturated conditions be included into SNC?
  - Would the delay bounds actually improve, or would they get worse?

Methodology

Delay bound and distribution

- To compute delay bounds, we model the DCF by:
  - A periodic process – where the period corresponds to the average per-packet service time obtained from network simulations.
  - Estimating its own service process directly from network simulation data
- Additionally, we compute the actual delay distribution of a tagged node using network simulations
- We argue that using data from network simulations provide a more real implementation of the DCF

Methodology

How the DCF works?

$$\text{Idle} \rightarrow \underbrace{\text{DIFS} \rightarrow \text{Backoff}}_{\text{Channel must be idle}} \rightarrow \text{Packet} \rightarrow \underbrace{\text{SIFS} \rightarrow \text{ACK}}_{\text{Receiver replies}}$$

- Service time is the time between the start of channel contention and the reception of the acknowledgment (ACK)

How do we define the service process?

- $S(0, t)$ is the cumulative service process, i.e., the maximum amount of data (in packets) that the system could have transmitted in the time interval $(0, t]$, assuming backlogged conditions
- Not dependent of actual arrivals but in the system (e.g., channel capacity, contention, DCF behavior)

Methodology

How do we define the service process?

- $A_1(0,t)$ → fast enough to have backlogged conditions
- $A_2(0,t) \dots A_N(0,t)$→ Poisson process with a defined mean arrival rate λ

$$M_N(\theta,t) = e^{\lambda t(e^{\theta}-1)}.$$

$$M_A(\theta,t) = M_N(\theta/\nu,t).$$

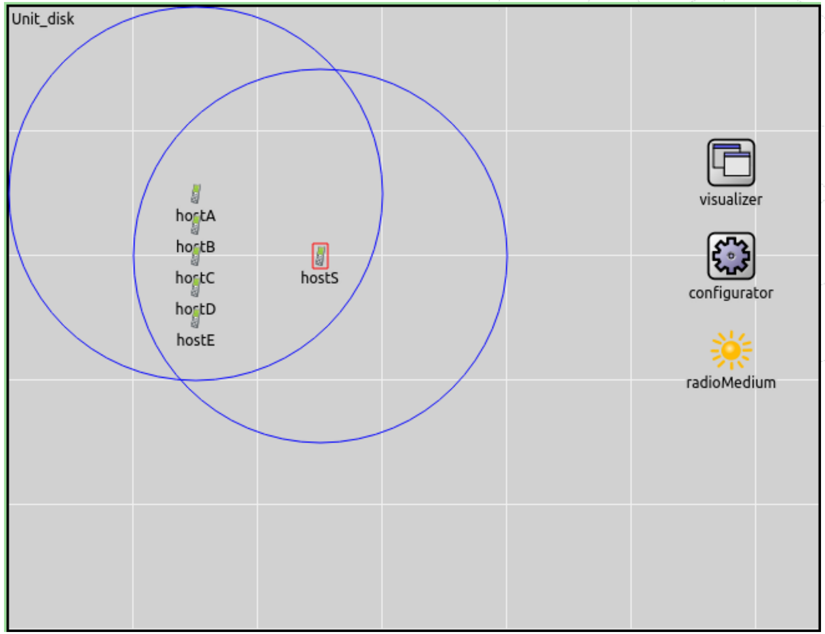
How is the delay bound computed?

$$d = \inf_{\theta>0}\left[\inf\left[\tau : \frac{1}{\theta}\left(\ln\sum_{s=\tau}^{\infty}\mathrm{M}_A(\theta, s-\tau)\overline{\mathrm{M}}_S(\theta, s) - \ln\varepsilon\right) \leq 0\right]\right]$$

Methodology

Simulation Setup

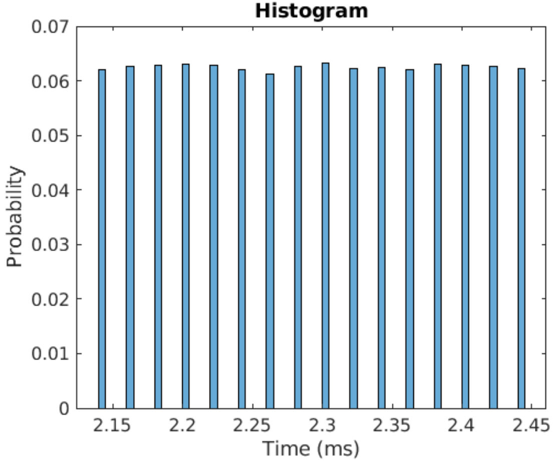
- IEEE 802.11 single-cell created in OMNeT++
- 1-hour of traffic
- 1436 bytes – application layer
- Physical data rate = 6Mbps
- CWmin = 15
- What is the service time?
- What is the service process?



Service Time – Periodic Process

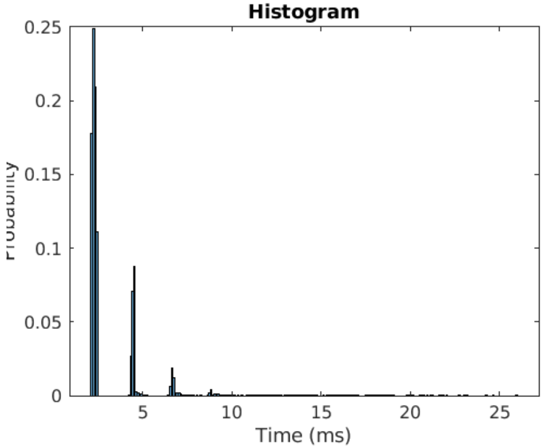
Simulation Results

Service time (1-node)



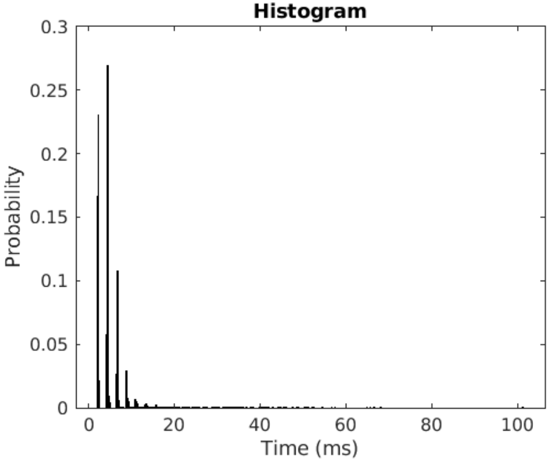
Average service time = 2.29ms

Service time (2-node) – $\exp(10ms)$



Average service time = 3.02ms

Service time (2-node) – $\exp(5ms)$

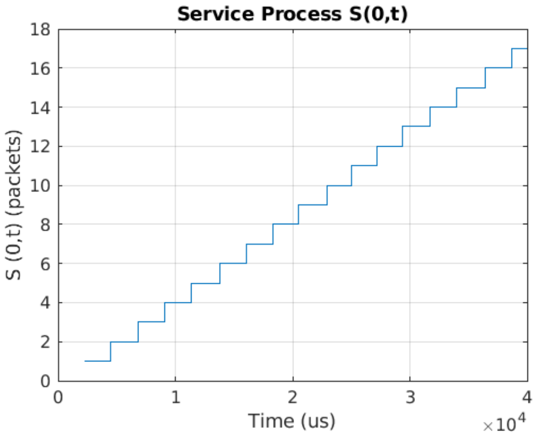


Average service time = 4.47 ms

Service Process - Estimation

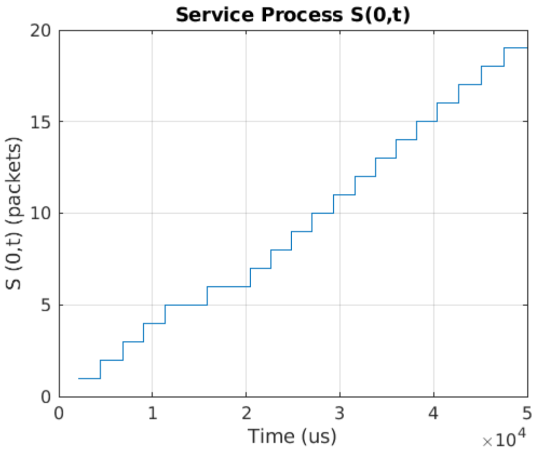
Simulation Results

Service process (1-node)



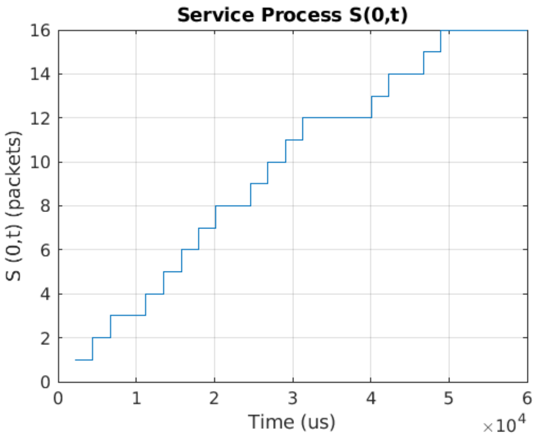
Time between TX opportunities is constant

Service process (2-node)–$exp(10ms)$



Time between TX opportunities start to change

Service process (2-node) – $\exp(5ms)$



Time between TX opportunities spread even more

Service Process - Estimation

How to estimate the MGF?

- Definition of the MGF → $M_S(\theta, t) = E[exp(\theta \cdot S(0,t))]$

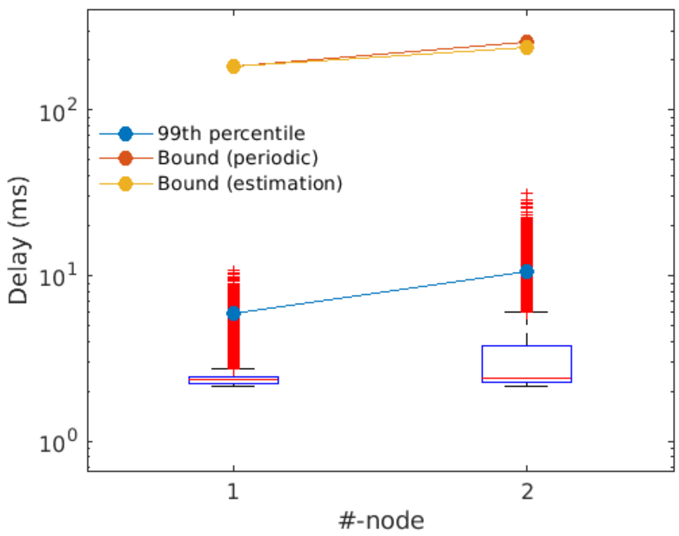
- Estimation of the MGF → Suppose we have N realizations of $S(0,t)$, say $\{s_1(0,t), s_2(0,t), \dots s_N(0,t)\}$ Then we can estimate the MGF as:

$$\widehat{M_S}(\theta, t) = \frac{1}{N}\sum_{i=1}^{N} \exp(\theta s_i(0,t))$$

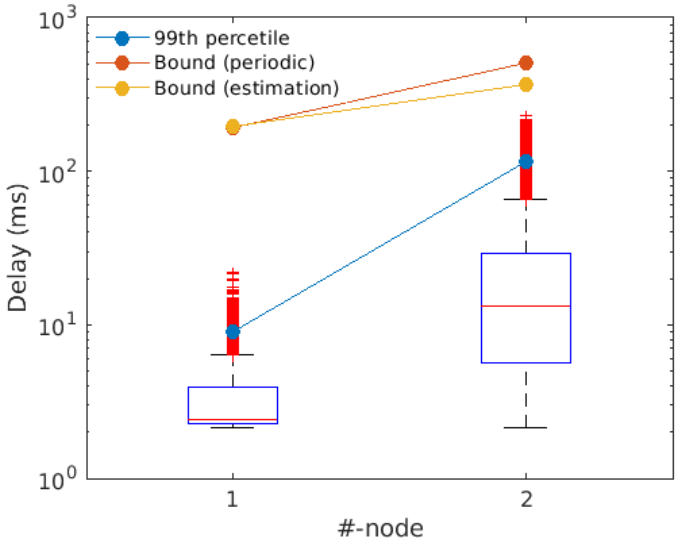
Delay Results

Delay bounds and distribution (99th percentile)

$A_1, A_2 \rightarrow exp(10ms)$



$A_1, A_2 \rightarrow exp(5ms)$



Conclusion and Future Work

- OMNeT network simulation provides us more realistic service time, specially in non-saturated conditions
- Besides modeling the DCF as a periodic process, we estimated it from data in network simulations
- Service process estimation presented better delay bounds for the delay distribution (with medium load)

- Verify the trend (service estimation outperforms periodic process) with more load and more nodes
- Look for alternatives to Boole’s inequality (e.g., Bonferroni) and Chernoff bound (e.g., Hoeffding's inequality)

Thanks. Any question or comment?

Acknowledgments:
This work is a result of the project Route 25 [Nr. C645463824-00000063] funded by European Union/Next Generation EU, through Programa de Recuperação e Resiliência (PRR); Project Sensitive Industry, co-funded by ERDF, through COMPETE 2020, under the PORTUGAL 2020 Partnership Agreement and by FCT/MECI through national funds and when applicable co-funded EU funds under UID/50008: Instituto de Telecomunicações.