Mixed-Criticality Wireless Communication for Robot Swarms

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Introduction

- Real-time wireless networks for swarm robotics applications
- Ad-hoc networks operating over physical layers such as IEEE 802.15.4
- Dual perspectives:
  - Swarm Robotics: Swarm behaviours that work under perfect networking break down when subject to realistic network conditions
  - Real-Time Networking: Timing guarantees are possible for networks with stationary nodes, but (mostly) break down under node mobility

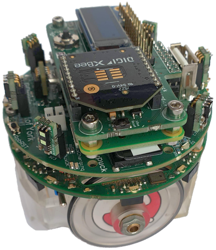
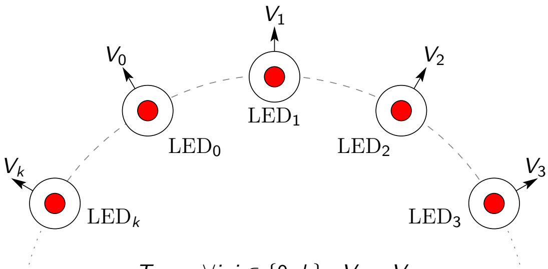


Figure: Pi-Puck Robot [1]

[1] Alan G. Millard et al. "The Pi-puck extension board: A raspberry Pi interface for the e-puck robot platform". In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2017, pp. 741–748. DOI: 10.1109/IROS.2017.8202233

Motivating Example

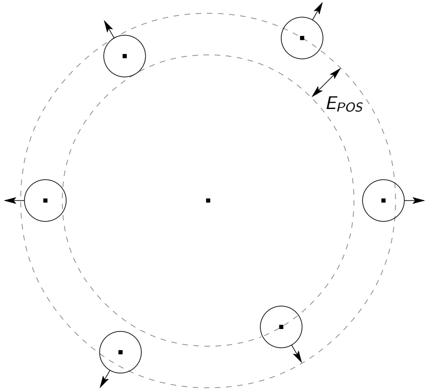
- Set of nodes arranged in circle formation
- Two tasks:
  - T_{POS}: Maintain the circle formation
  - T_{LED}: Maintain equivalent LED colours
- Any node can initiate a change in future formation or LED colour



$$T_{POS} : \forall i, j \in \{0..k\} : V_i = V_j$$
$$T_{LED} : \forall i, j \in \{0..k\} : \mathrm{LED}_i = \mathrm{LED}_j$$

Motivating Example

- Two error metrics:
  - E_{POS}: Maximum distance in effective circle radius of any two nodes
  - E_{LED}: Number of nodes showing an incorrect LED colour
- Define T_{POS} to be of higher importance



Simulation Model

- Extend ARGoS [2] robot simulator with a slot-level wireless network plugin
- Number of simplifying assumptions:
  - Each simulation step is equivalent to one transmission slot
  - Multiple "received" frames per step leads to destructive interference
  - Packet delivery rate inversely proportional to distance squared
  - Successful or unsuccessful delivery is determined independently for each link and transmission

[2] Carlo Pinciroli et al. "ARGoS: a Modular, Parallel, Multi-Engine Simulator for Multi-Robot Systems". In: *Swarm Intelligence* 6.4 (2012), pp. 271–295

AirTight Protocol

- Real-time wireless protocol for mixed-criticality systems [3]
- Slot table assigns transmission slots to nodes
- Node-local scheduling decisions determine which frame is sent in a transmission slot
- Provides timing guarantees but requires extensive prior knowledge of the network
  - Packet flows
  - Communications graph
  - Slot tables
  - Fault-load functions

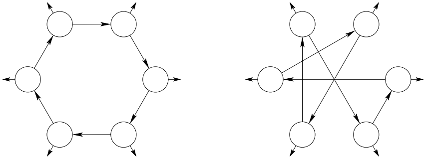


Figure: Node setup showing optimal routing and an example of possible randomised routing.

[3] Alan Burns et al. "AirTight: A Resilient Wireless Communication Protocol for Mixed-Criticality Systems". In: *2018 IEEE 24th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*. Aug. 2018, pp. 65–75. DOI: 10.1109/RTCSA.2018.00017

AirTight Fault Model

- Criticality level determines assumed level of interference
- Fault-model $F(L, t)$ bounds maximum number of failed-transmissions within a busy-period of length t at criticality-level L
- Simplest case: model interference by blackout duration and period
- Crude approach to handling node mobility: $F(L, t) = m$ such that

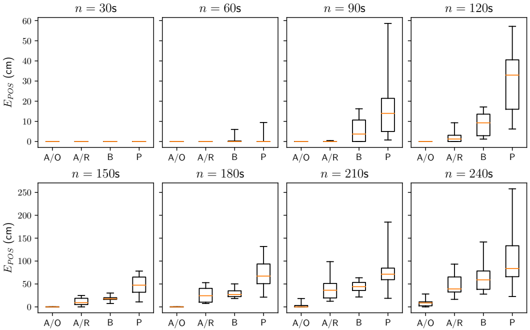
$$\sum_{k=0}^{m} \binom{t}{k} \cdot \left(1 - \mathrm{pdr}(L)^2\right)^k \cdot \left(\mathrm{pdr}(L)^2\right)^{t-k} \geq \mathrm{conf}(L)$$

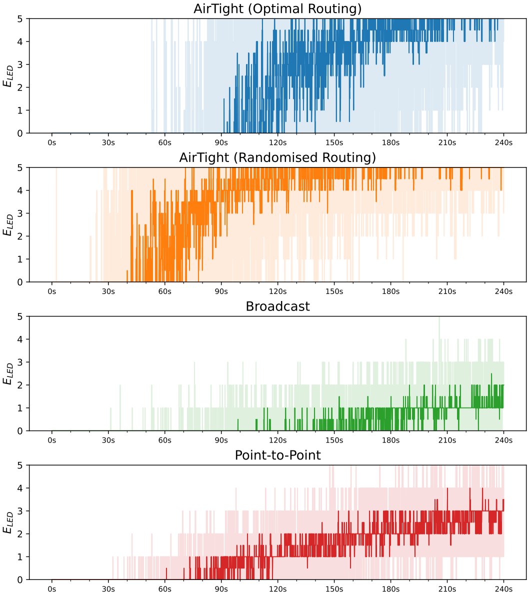
Wireless Protocols

We compare AirTight with two baseline protocols:

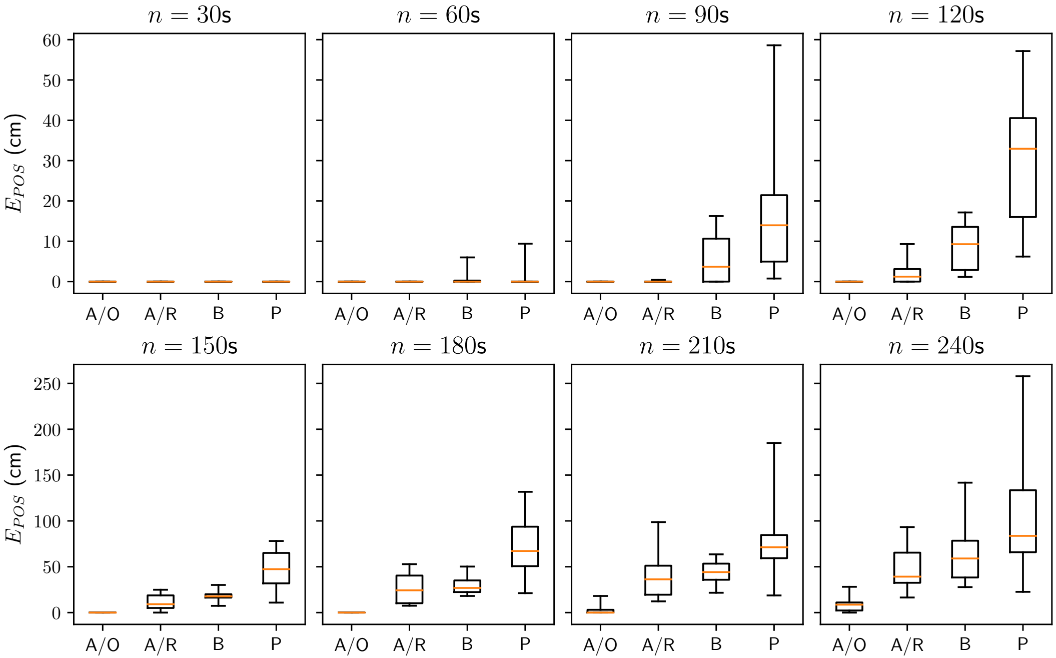
- "Broadcast": Nodes broadcast each message a fixed number of times using carrier sensing to reduce collisions
- "Point-to-Point": Nodes transmit messages to each other node in turn, a CSMA/CA like protocol using carrier sensing and random backoff between retransmissions until an acknowledgement is received or a maximum number of retries has been reached

Simulation Results





Simulation Results



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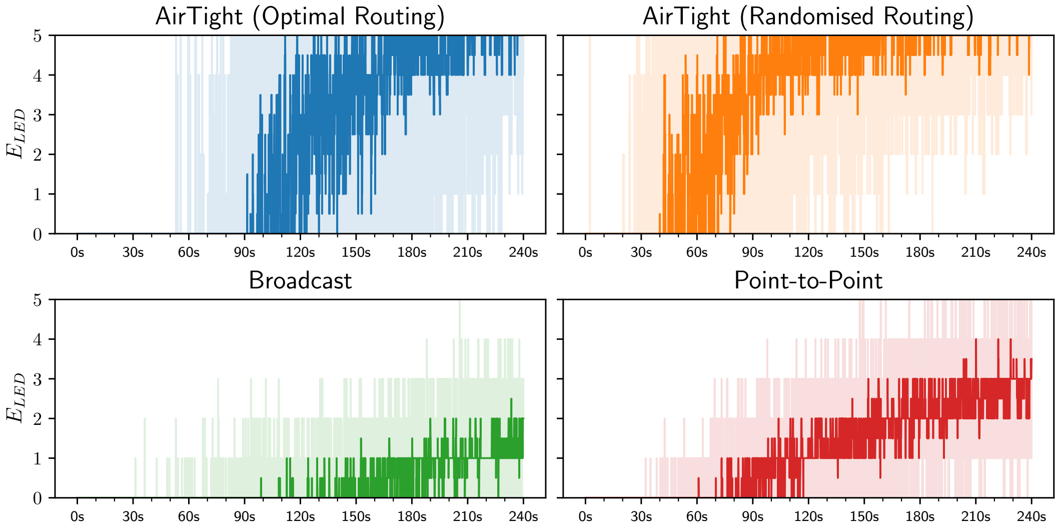
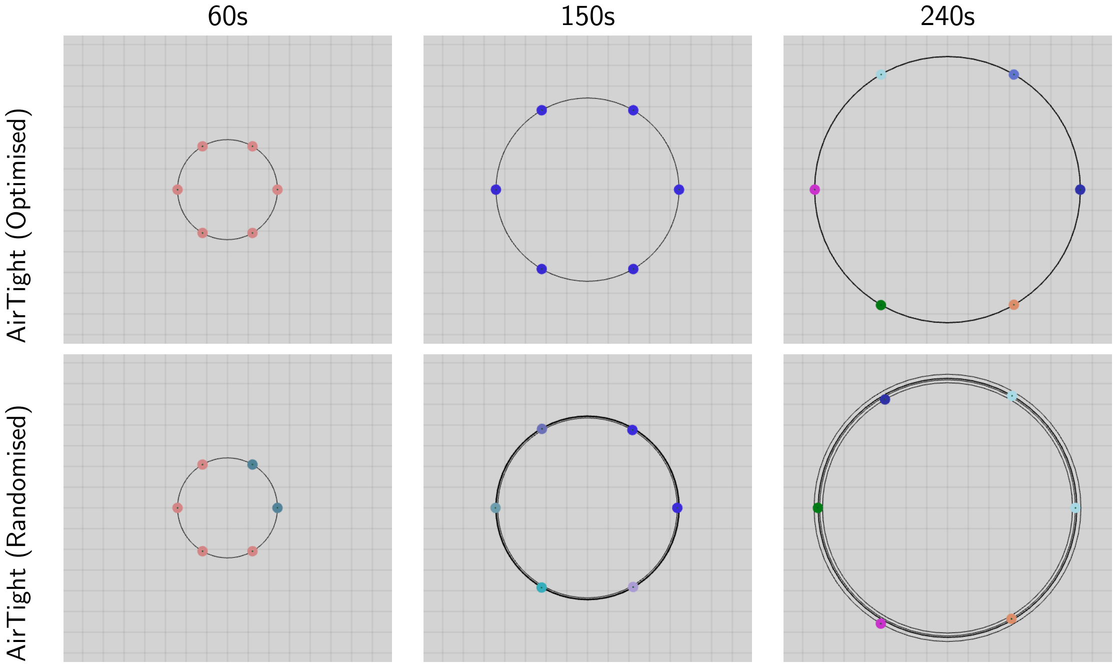
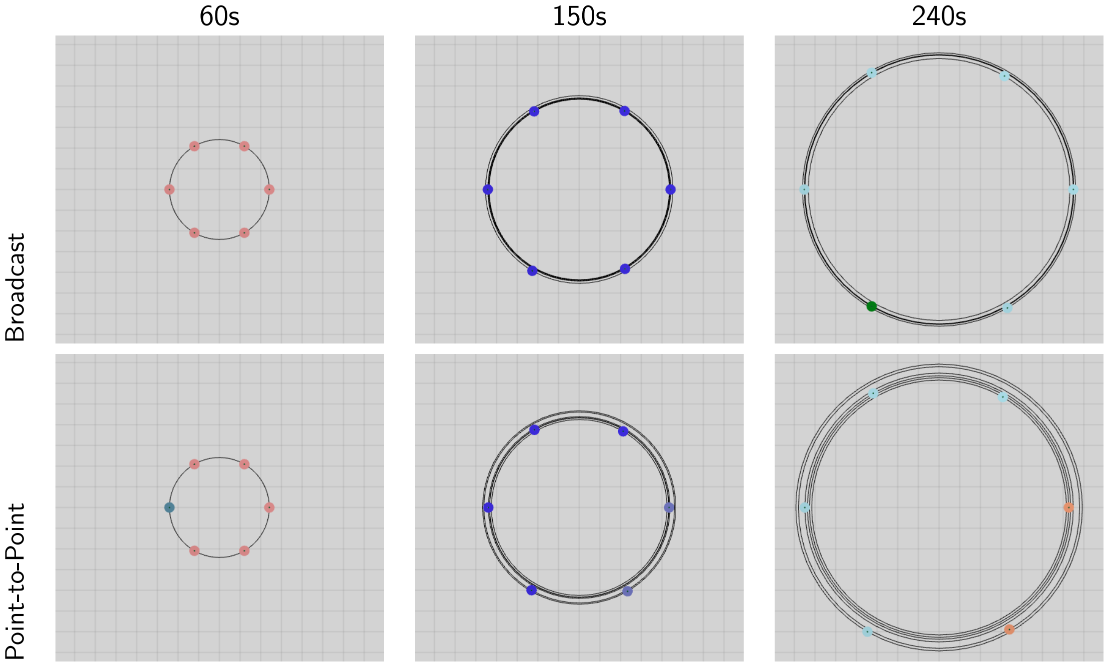


Visualised Behaviour



Visualised Behaviour



Limitations & Future Work

- For swarm robotics applications, AirTight makes unrealistic assumptions of a priori knowledge
  - Extend the protocol to handle dynamic routing and slot tables
- Mixed-criticality is only considered at the network layer
  - Allowing application to adapt according to criticality level might allow for more robust behaviour

Conclusion

- Swarm robotics is a promising area for future mixed-criticality applications
- Mixed-criticality networking allows for more robust and more predictable application-level performance in robot swarms
- Existing wireless protocols are not well suited for swarm robotics

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Links to resources:

- Pi-pucks: `https://www.york.ac.uk/robot-lab/pi-puck/`
- AirTight Paper: doi:10.1109/RTCSA.2018.00017
- ARGoS Simulator: `https://www.argos-sim.info/`