MAC Layer Aspects of Satellite-IoT

When theory meets real-time data !

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Flow of the presentation

Introduction

- Quick look at previous presentation
- Why MAC layer aspects?

Transmission reduction schemes

- Transmission reduction using Shewhart
- Machine learning-based prediction models

Performance analysis

- NB-IoT via LEO satellites
- Reduction percentage, Effective data vs Visibility, Battery lifetime

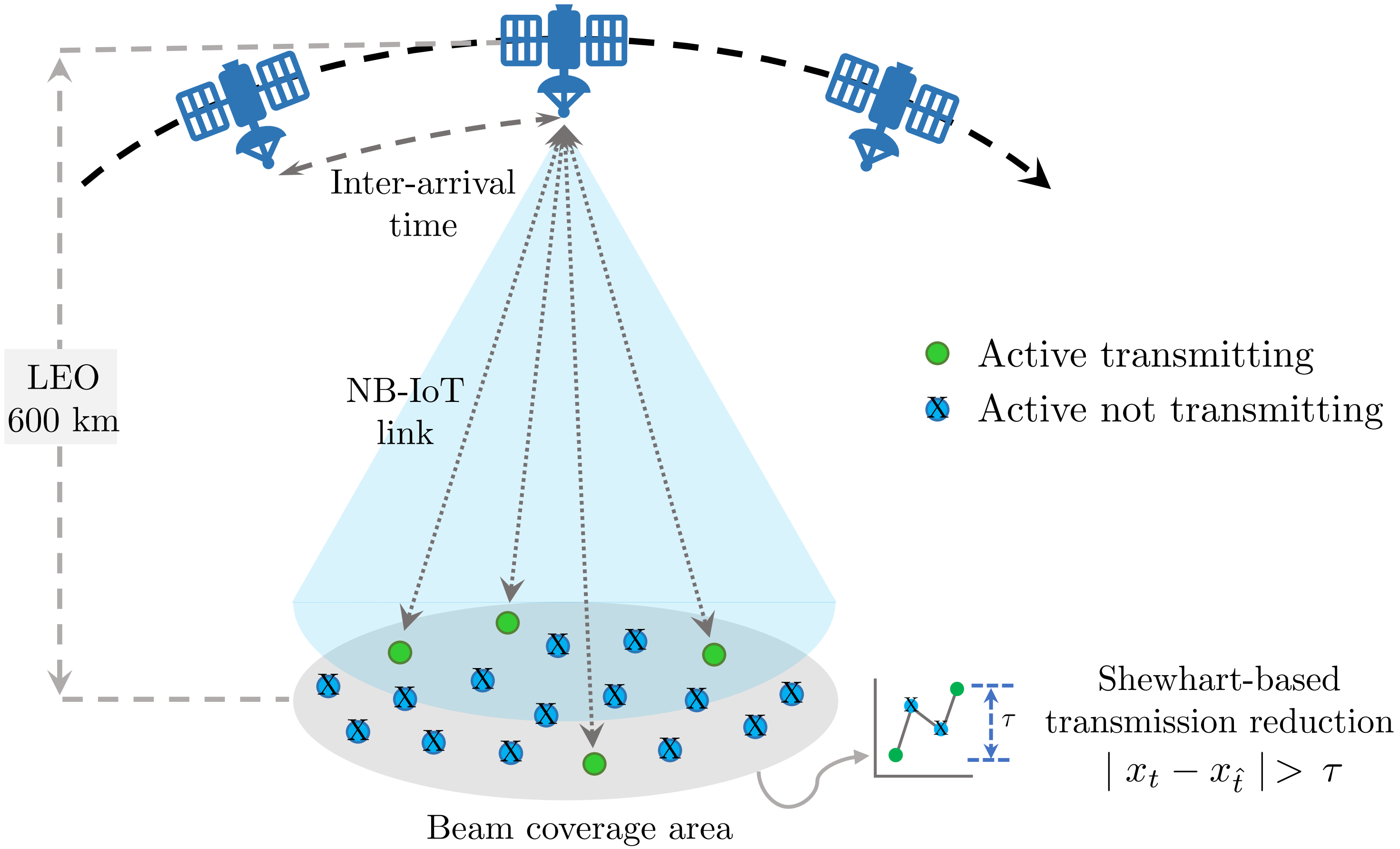
References

- Ayush Kumar Dwivedi, Houcine Chougrani, Sachin Chaudhari, Neeraj Varshney, Symeon Chatzinotas, "**Efficient Transmission Scheme for LEO Satellite-Based NB-IoT: A Data-Driven Perspective**", under review at *IEEE IoT Journal*, 2023.
- 3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network, "**Study on NB-IoT/eMTC support for Non-Terrestrial Networks (NTN) (Rel 17)**," *TR 36.763V17.0.0*, 2021.

I. Introduction

Previous presentation, Why MAC layer aspects?

System Model



Although discontinuous coverage is considered, the observations remain relevant for scenarios where IoT devices connect and follow one satellite at a time to reduce the complexity of antenna and signal processing aspects.

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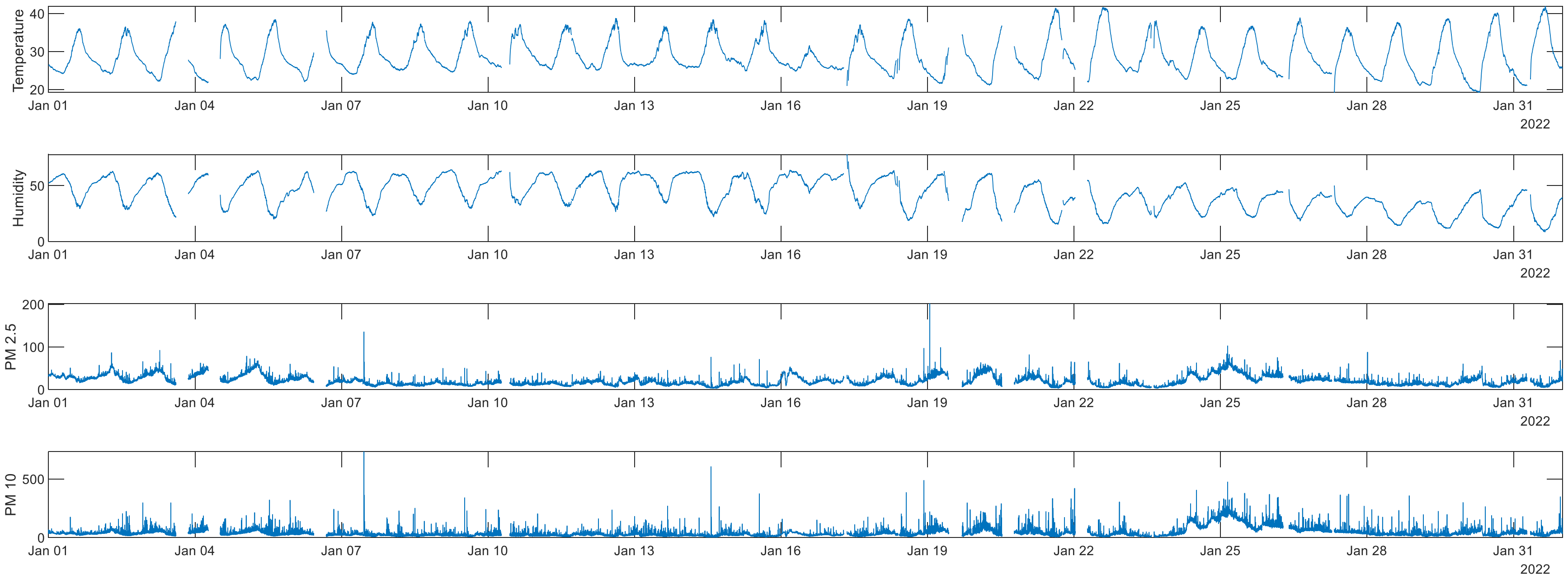
Why MAC layer aspects?

- One of the important function of MAC layer is channel access control and scheduling/queuing
- Traffic generated by IoT networks is unique in many ways.



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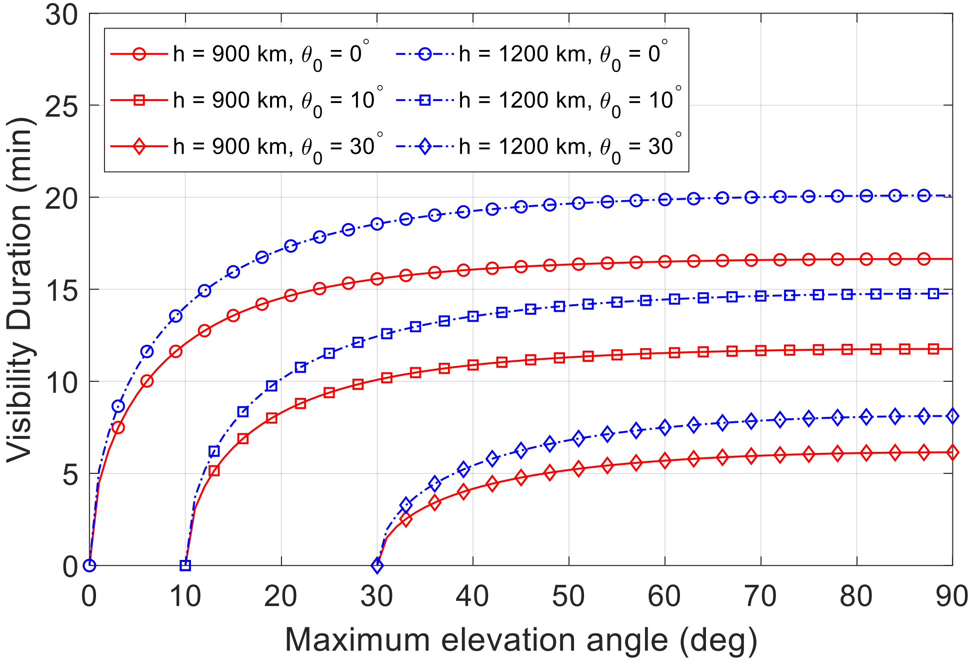
Why MAC layer aspects?

- While using LEO satellites for IoT, time is critical since an individual satellite is only visible for a limited duration.
- Can we better schedule the uplink transmissions to accommodate more devices?



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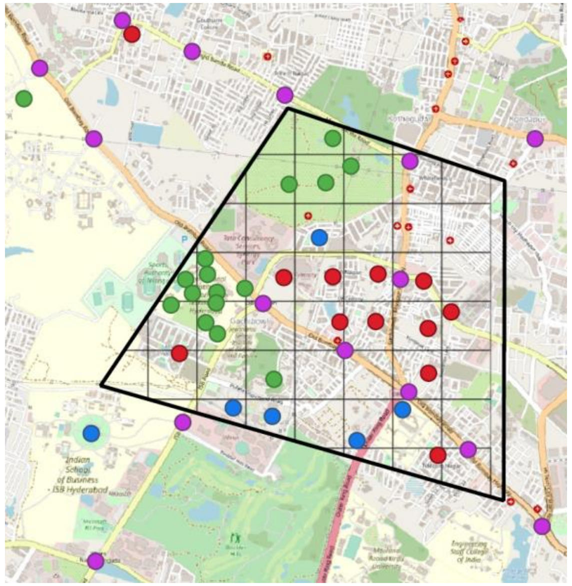
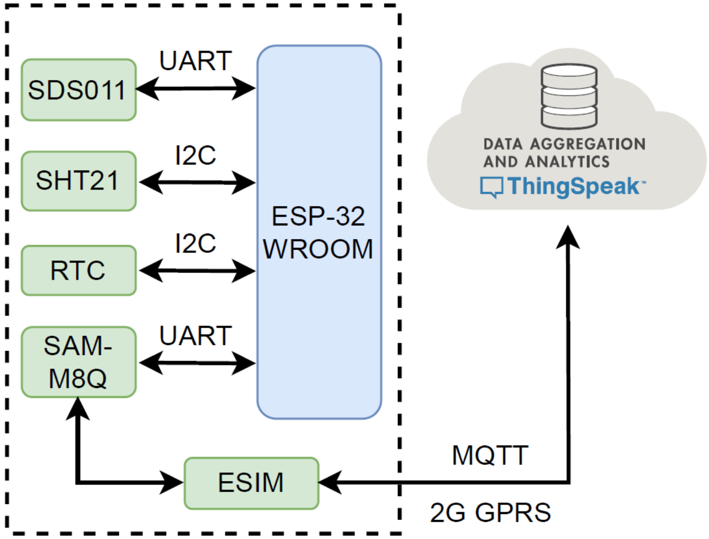
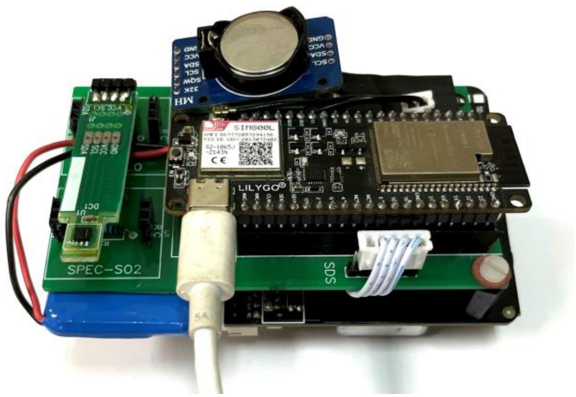
IoT-Testbed: Air Pollution Monitoring

SMARTCITY RESEARCH CENTER





created_at	temperature	humidity	pm25	pm10
01-Jan-2022 00:00:00	26.43	52.93	30.7	39.1
01-Jan-2022 00:00:30	26.42	52.93	30.9	34.8
01-Jan-2022 00:01:00	26.43	52.9	34.8	67.1
01-Jan-2022 00:01:30	26.43	52.9	30.9	34.5
01-Jan-2022 00:02:00	26.43	52.85	31.4	37.7



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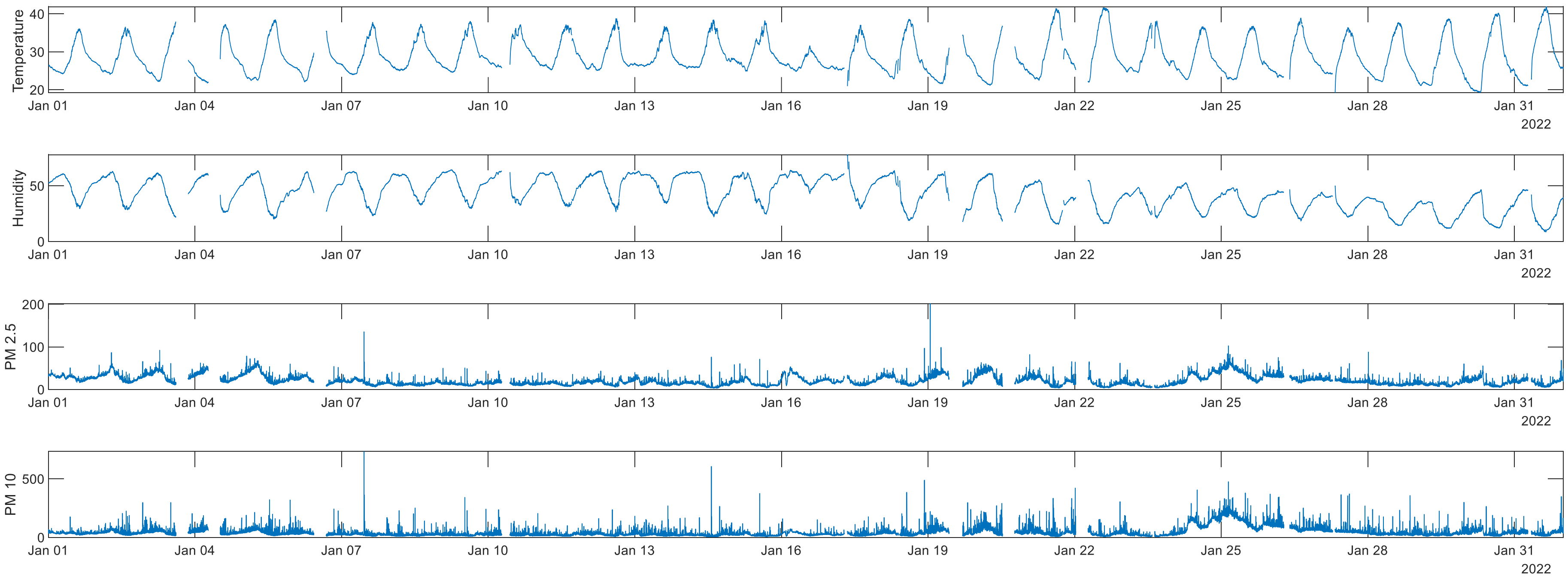
IoT-Testbed: How much data?

- Sensing every 30 sec (2880 datapoints per day, ~1 million per year, per device)
- Around 50 devices deployed (few for 3 years, few for 2 years)
- Sensor data with anomalies of known kinds



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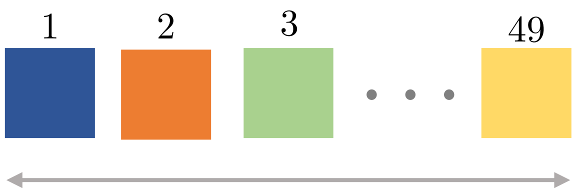
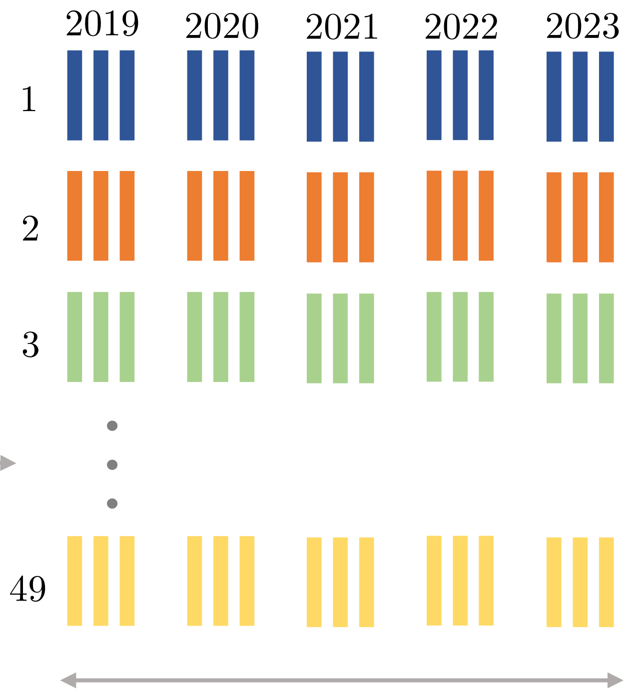
IoT-Testbed: How much data?

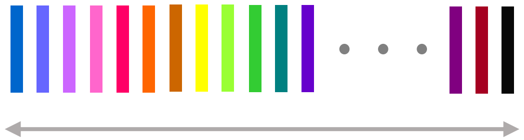


Data of 50 devices deployed in stages from Nov 2019 till Jan 2023

- Segregate into monthly data
- Pick Winter months
- Remove months with >70% missing data



Take Winter season data only
Nov, Dec, Jan months of 2019-2023



Monthly data for 230 devices representing Winter season

- Considering timeseries for individual month from different devices as independent
- Resample into 30 sec frequency

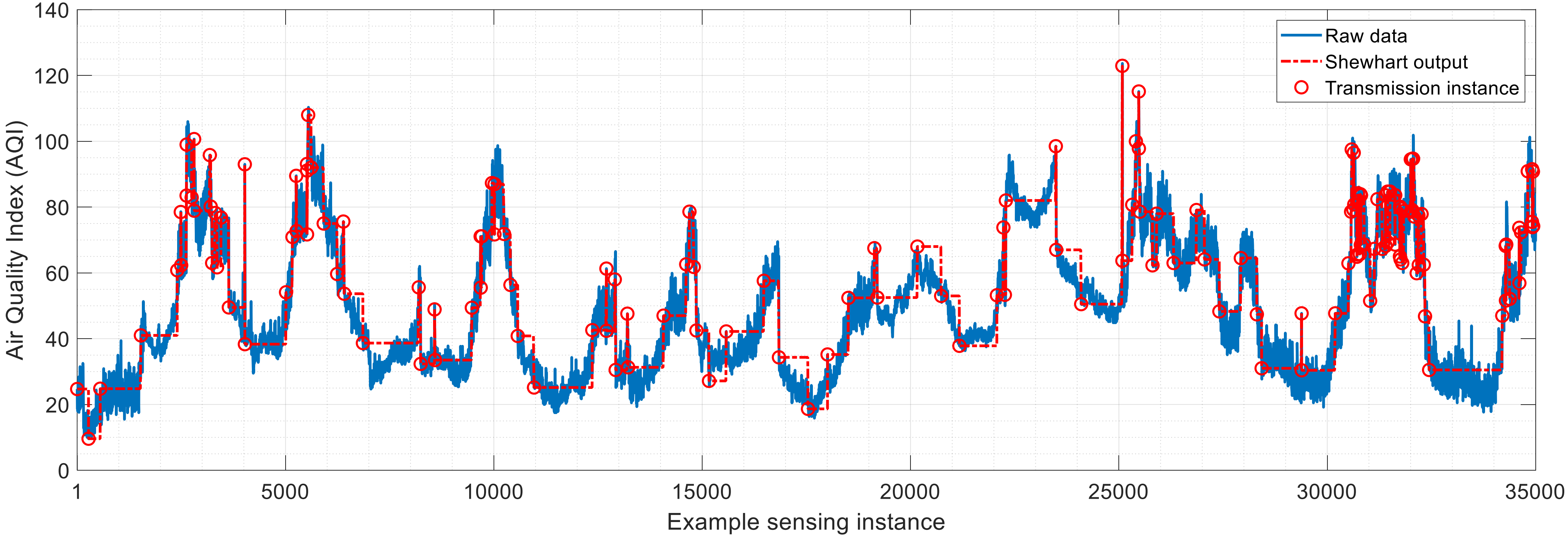
II. Transmission reduction schemes

Transmission reduction using Shewhart, ML-based prediction models

Shewhart-based transmission reduction

Transmit only when new value changes significantly

$$|\, x_t - x_{\hat{t}} \,| > \tau$$



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Shewhart-based transmission reduction

Transmit only when new value changes significantly

$$|\, x_t - x_{\hat{t}} \,| > \tau$$

Transmission Mode		Simultaneously Tx. Nodes	% Reduction	RMSE	
M0	Baseline: Transmit all the parameters	230	0	0	
M1	Shewhart on all parameters	30	87.16	T: 0.16	RH: 0.62
				PM2.5: 1.29	PM10: 2.10
M2	Shewhart on PM10 only (transmit PM10 and predict PM2.5)	26	88.33	PM2.5: 2.34	PM10: 2.22
M3	Shewhart on AQI only (transmit PM10 and predict PM2.5, calculate AQI at the server)	8	96.54	PM2.5: 4.23	PM10: 7.56

ML-based prediction model

- Transmit only few independent parameters, predict others at gateway
- Transmit PM10 only and use PM10 to predict PM2.5

Model	**Configuration**	**RMSE (ppm)**	**R-Squared Validation**
Linear Regression	Ordinary least squares	2.1297	0.9808
Decision Tree Regressor	Max. depth = 10 Min samples split = 5	2.3587	0.9806
Random Forest Regressor	No. of estimators = 100 Max. depth = 10 Min. samples split = 5	2.0563	0.9835

III. Performance Analysis

NB-IoT via LEO satellites, Reduction %, Effective data vs Visibility, Battery lifetime

NB-IoT via LEO satellite scenario

In NB-IoT, communication unfolds in two distinct phases:

- **Access or contention:** Nodes vying for connection through NPRACH, transmitting a preamble during random access opportunities (RAO).
- **Data phase:** Exchanging messages on allocated resources.

$$\mathbb{P}[X_i = k] = \binom{N}{k} \left(\frac{1}{m_{\text{RAO}}} \right)^k \left(\frac{m_{\text{RAO}} - 1}{m_{\text{RAO}}} \right)^{N-k}$$

$$\begin{aligned} N_{\text{coll}} &= N - (m_{\text{RAO}} \times \mathbb{P}[X_i = 1]) \\ &= N \left(1 - e^{-N/m_{\text{RAO}}} \right) \end{aligned}$$

$$\mathcal{P}_{\text{coll}} = 1 - \exp \left(- \frac{N_{\text{coll}} \, P_{\text{BO}}}{m_{\text{RAO}}} \right)$$

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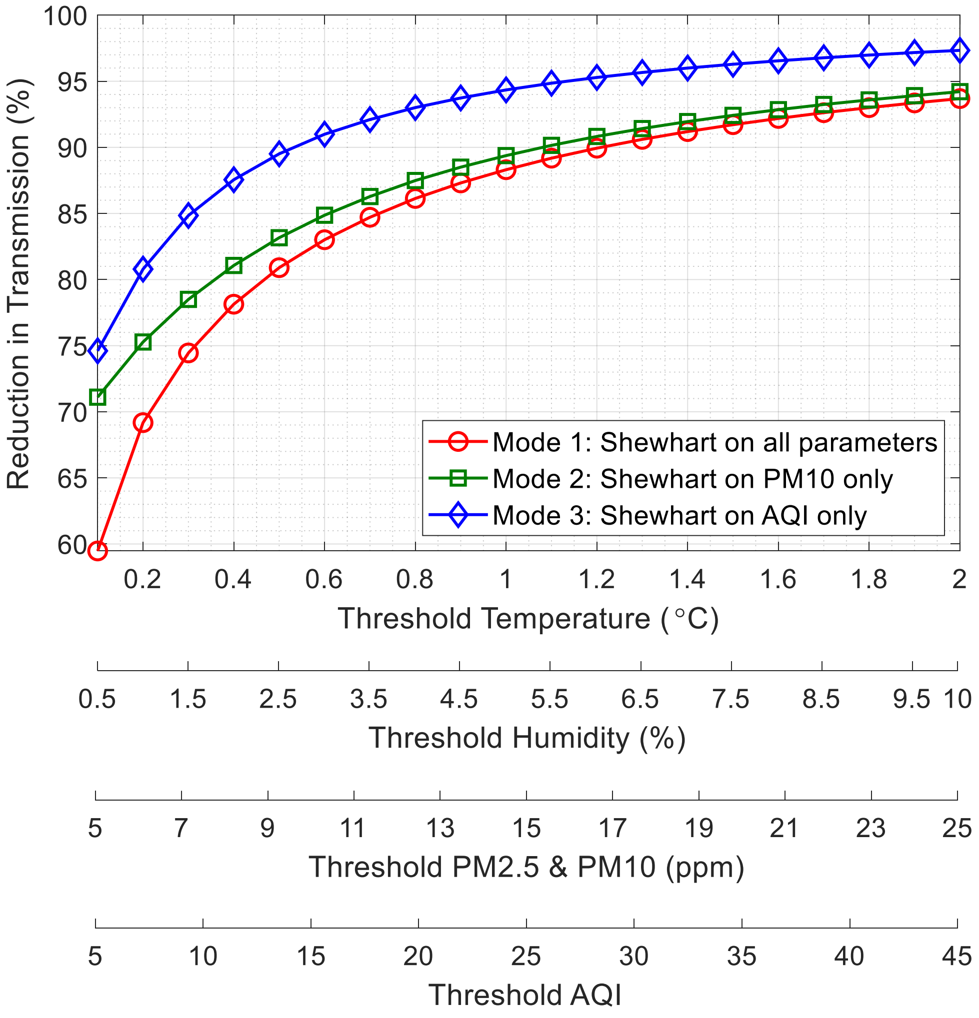
Percentage reduction



- Reduction percentage sharply increases with higher thresholds.
- 96% reduction in transmission would mean sending only 4 out of every 100 newly sensed samples instead of sending all of them otherwise.

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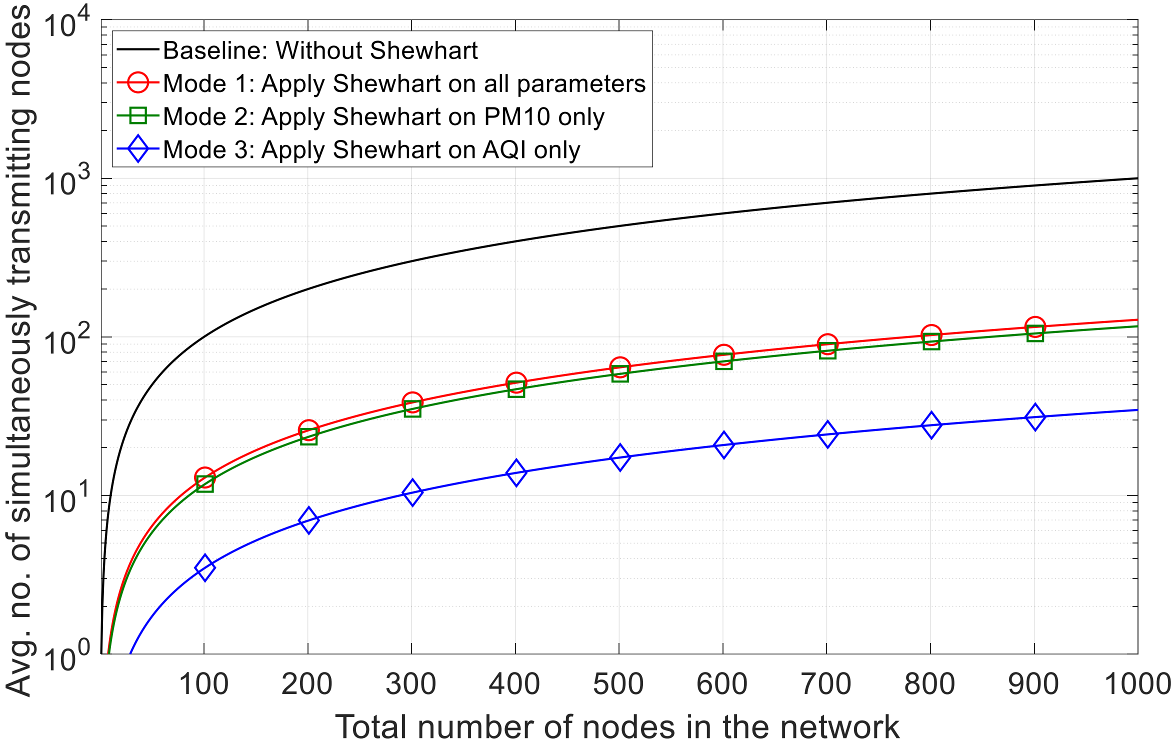
Percentage reduction



- Simultaneously transmitting devices increase linearly with network size but are significantly fewer in number with Shewhart compared to the baseline scheme.
- The result from this plot is crucial for examining other KPIs in larger networks - serves as a tool to simulate the effects of the proposed transmission modes.

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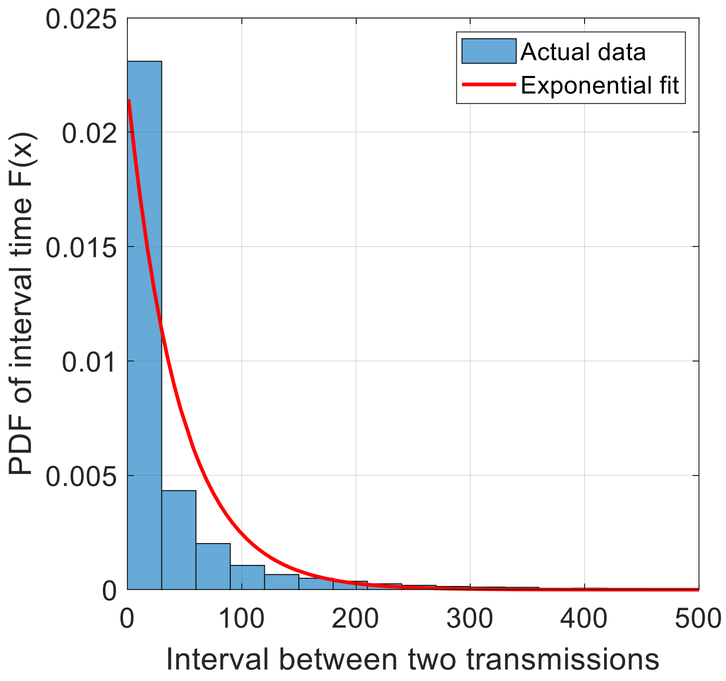
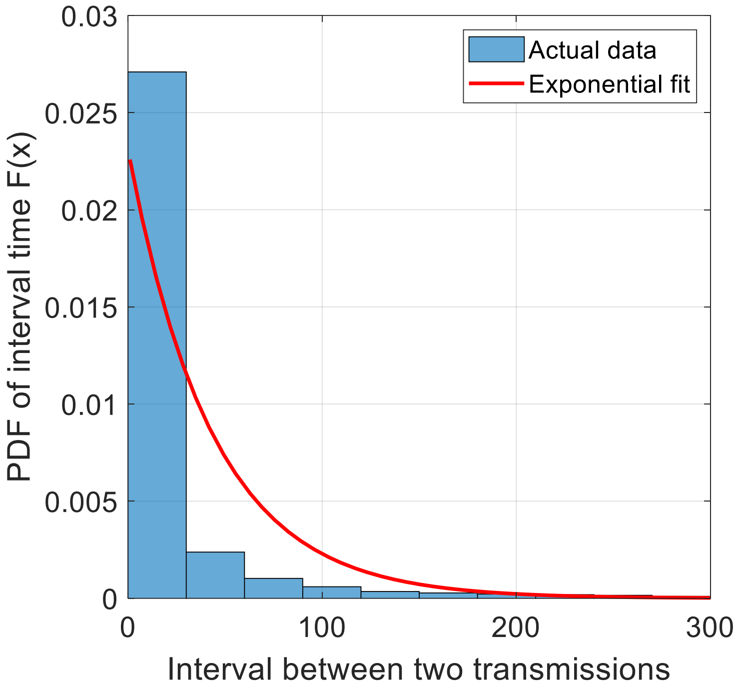
Traffic pattern

- The traffic pattern generated by Shewhart is not Poisson!



Temperature data with 0.5°C threshold



Particulate matter data with 25ppm threshold

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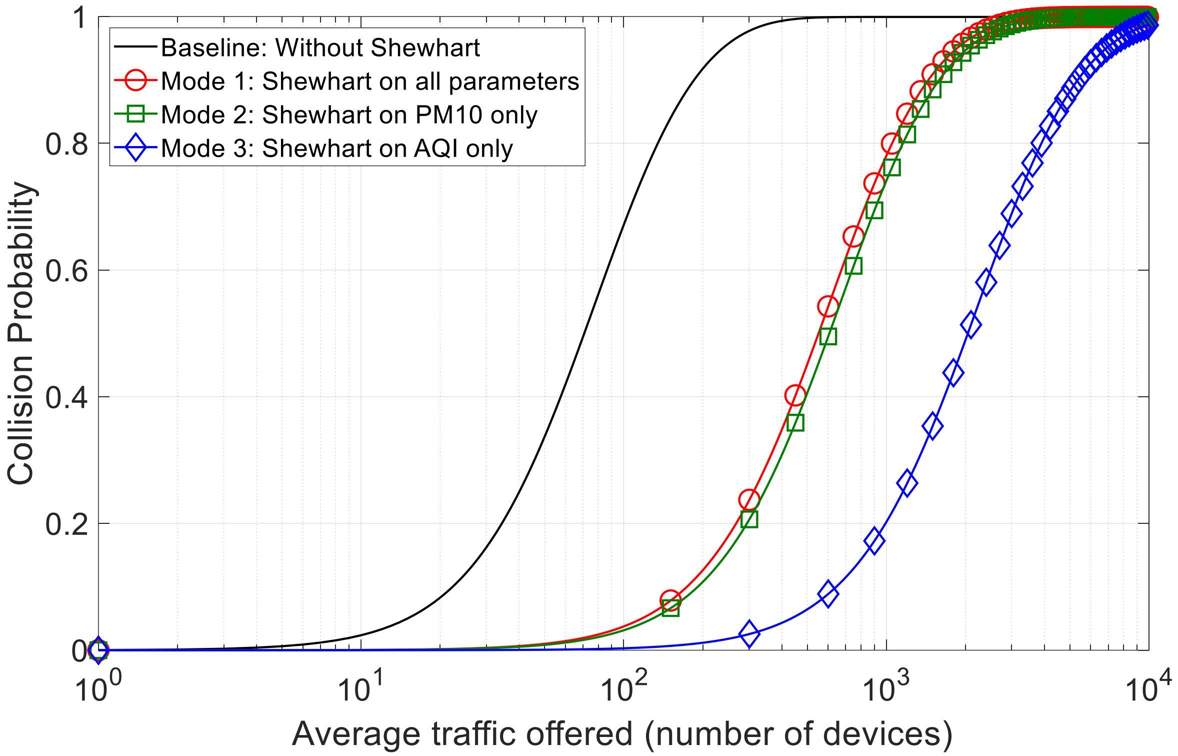
Collison Probability



- The figure underscores the potential for increased load capacity by implementing the proposed transmission scheme.
- Ex: for a target collision probability of 0.4, while the baseline method supports only 57 devices, Mode 1 and 2 can accommodate nearly 450 devices, and Mode 3 can support close to 1650 devices.

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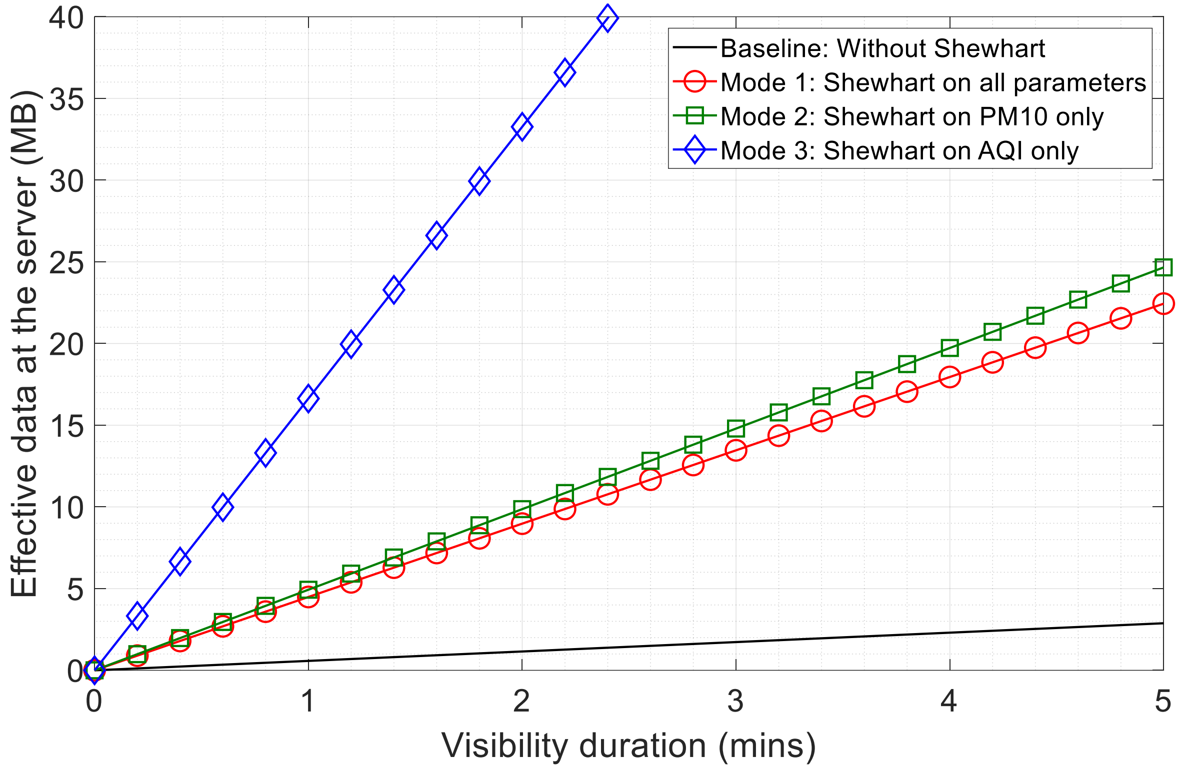
Effective Data



- Effective data is defined to encompass the data not transmitted by the nodes due to Shewhart but predicted at the server.
- For example, what Shewhart-based access modes can transmit in less than a minute would otherwise take 5 minutes in the baseline transmission method.
- Valuable, particularly in LEO scenarios with discontinuous coverage, where visibility duration is a crucial and limited resource.
- Even with continuous coverage, it is advantageous by reducing the required bandwidth to transmit target effective data.

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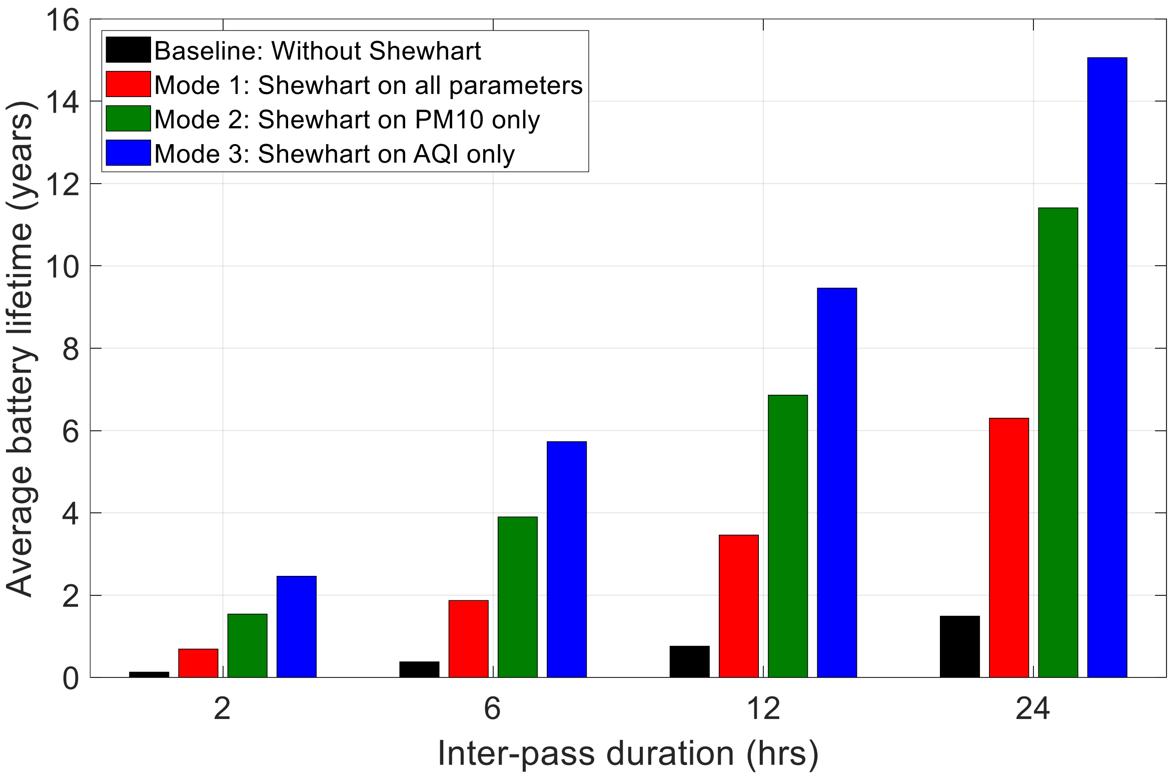
Battery Lifetime

State	Operation	Duration (ms)	Power (mW)
Reception (DL)	Sync, MIB, RAR Msg2, Msg4, UL grant, HARQ ACK, IP ACK, PDCCH monitoring,	371	90
Transmission (UL)	PRACH, RA Msg3 RAR, IP Report, HARQ ACK	50B UL: 335 200B UL: 1006	543
Idle (not in sleep)	MIB acquisition, waiting IP ACK, PRACH, ready timer, scheduling	22423	2.4
Power save (sleep)	Sleeping state when the satellite is not visible	based-on visibility	0.015
GNSS	GNSS reception	2000	37

Inter-pass duration (hrs)	Baseline	Mode 1	Mode 2		Mode 3	
			200B UL	50B UL	200B UL	50B UL
2	0.13	0.69	0.87	1.54	1.60	2.46
6	0.38	1.87	2.23	3.90	3.67	5.73
12	0.76	3.46	4.04	6.86	6.23	9.46
24	1.49	6.30	7.18	11.41	10.62	15.06

Battery Lifetime



- Expected average battery lifetime of a 5000 mWh battery under specific conditions, such as a maximum coupling loss (MCL) of 164 dB (worst-case scenario).
- Estimated enhancement in battery lifetime, coupled with the capacity to accommodate more devices, underscores the viability of the proposed transmission scheme.

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Conclusion

- Shewhart traffic significantly reduces the number of simultaneously transmitting nodes and associated collision probability compared to the baseline without transmission reduction.
- Integrating ML algorithms for payload reduction substantially extends the battery lifetimes of IoT devices.
- A compelling solution for addressing the challenges of limited visibility, low data rates, and energy constraints in satellite-based IoT networks.

Thank you !

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