Delay Tolerant Networking to Extend Internet Coverage Using Informal Public Transport Systems: Design and Analysis*

Workshop on Empowering Connectivity: Bridging Space and Earth with DTN
ICTP, Trieste, 2025

Presented by: Salah Abdeljabar
Collaborators: Marco Zennaro (ICTP)
Mohamed-Slim Alouini (KAUST)

[*] S. Abdeljabar, M. Zennaro, and M-S. Alouini: "Delay tolerant networking to extend Internet coverage using public transport systems: Design and Analysis". ***IEEE Internet of Things Journal**, under review*.

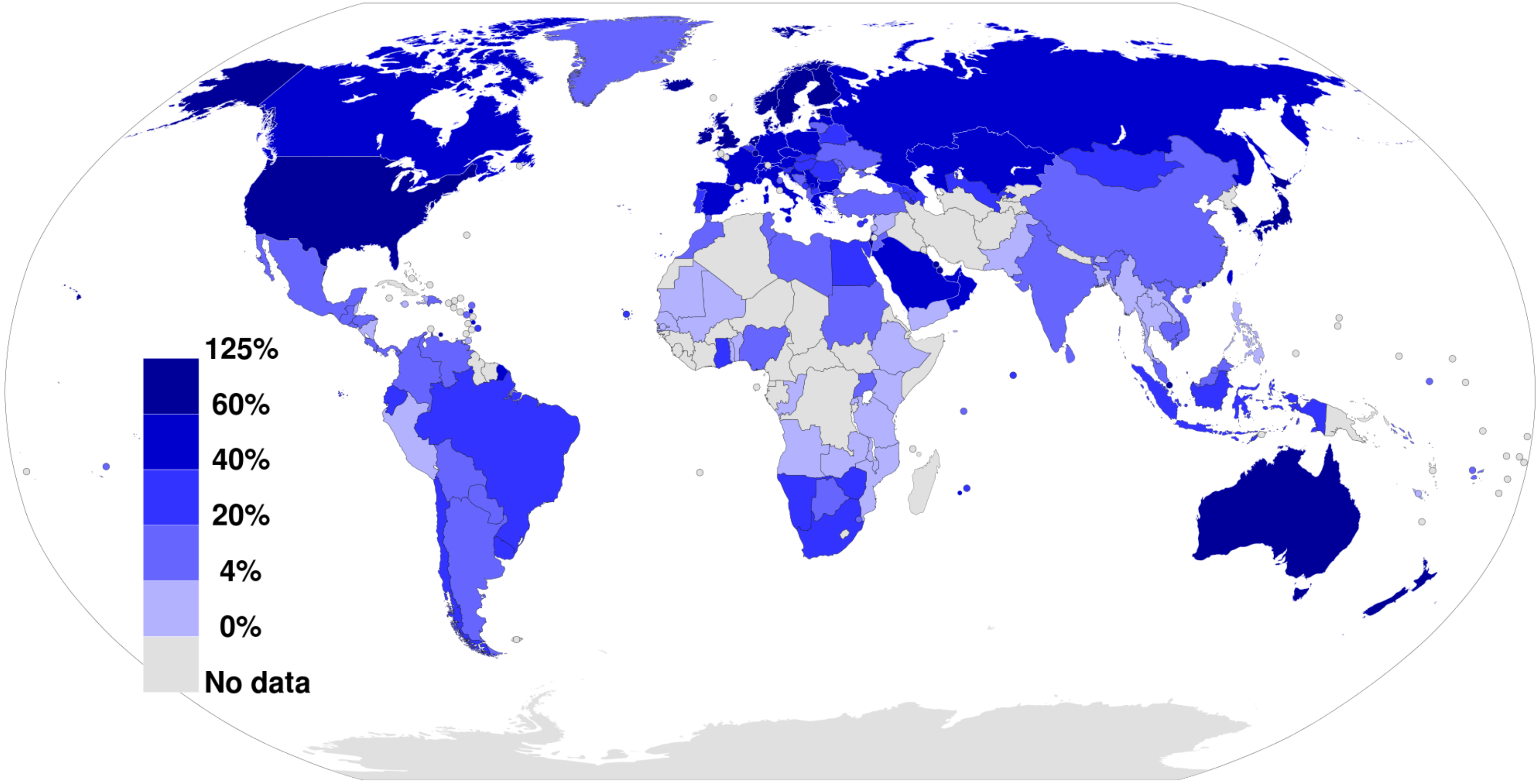
Motivation

unesco
United Nations
Educational, Scientific
and Cultural Organization

90%
Schools
without Internet
In developing countries

unicef

60%
Primary Schools
without Internet
In the world



2.9B

People

without Internet

In the world

United Nations

Common Agenda

"universal access to the Internet as a human right"

Report of the Secretary-General

The Economist INTELLIGENCE UNIT

+6.6% Brazil

+7.2% Krysgyzstan

+9.1% El Salvador

+14.2% Sierra Leone

+19.4% Niger

GDP Gain

– https://connectinglearners.economist.com/connecting-learners/?utm_source=Paid-EIU-Social&utm_medium=Twitter&utm_campaign=Ericsson&utm_content=Report

UNESCO

KAUST
King Abdullah University of Science and Technology

unesco
Chair on Education
Connect the Unconnected

ICTP
The Abdus Salam
International Centre for Theoretical Physics

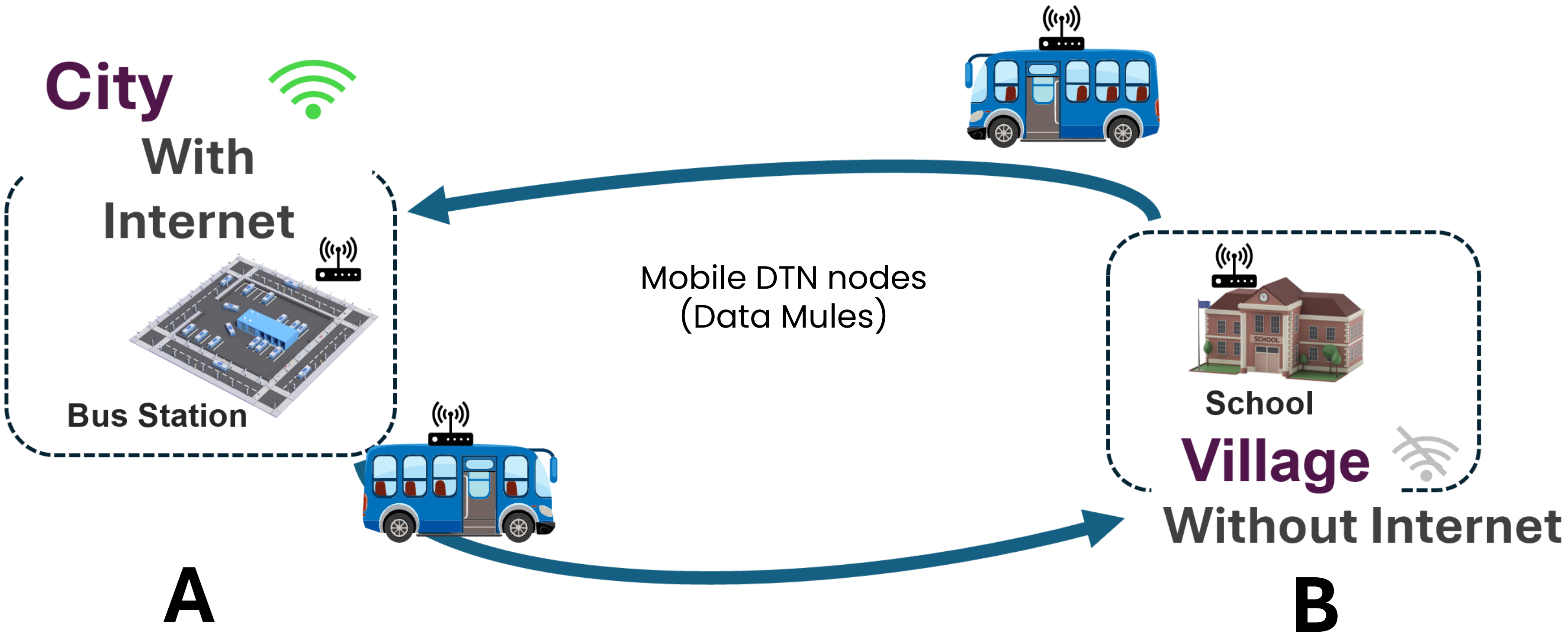
Harnessing Existing Mobility

[3]

[3]

- ***80%*** of the African population relies on informal transport [1].
- In South Africa, minibus taxis serve over ***60%*** of the population, transporting around **14** million people daily [2].

[1] 2021. SLOCAT Transport and Climate Change Global Status Report – 2nd edition. Focus Feature on Paratransit. https://bit.ly/3wW3IRI
[2] I. Ndibatya and M. J. Booysen, "Modelling of inter-stop minibus taxi movements: Using machine learning and network theory," in UMICTA, 2014.
[3] Galati, Adriano, et al. "Mobile-enabled delay tolerant networking in rural developing regions." IEEE Global Humanitarian Technology Conference (GHTC 2014). IEEE, 2014.



Research question:

How to incorporate informal transportation systems in the DTN design?

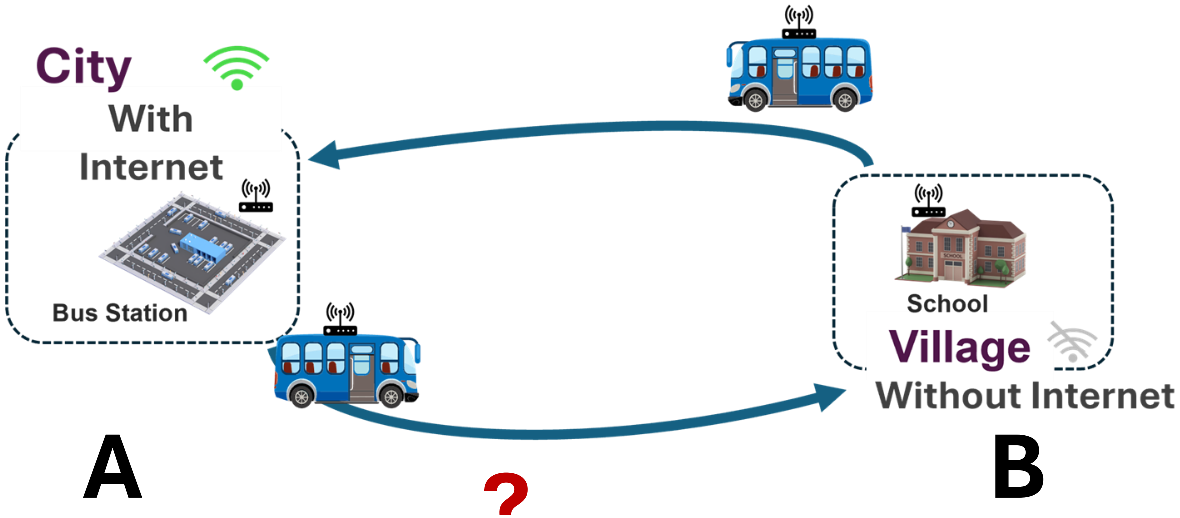
Methodology

01 **Develop probabilistic models** that captures travel time, wating time at bus stops, and data rates of data mules.

02 **Incorporate communication metrics** into the probabilistic model (freshness of information, transmission rate, etc.).

03 Find the **minimum number of vehicles** needed to fulfill the applications requirements.

System Model – DTN Data Mule



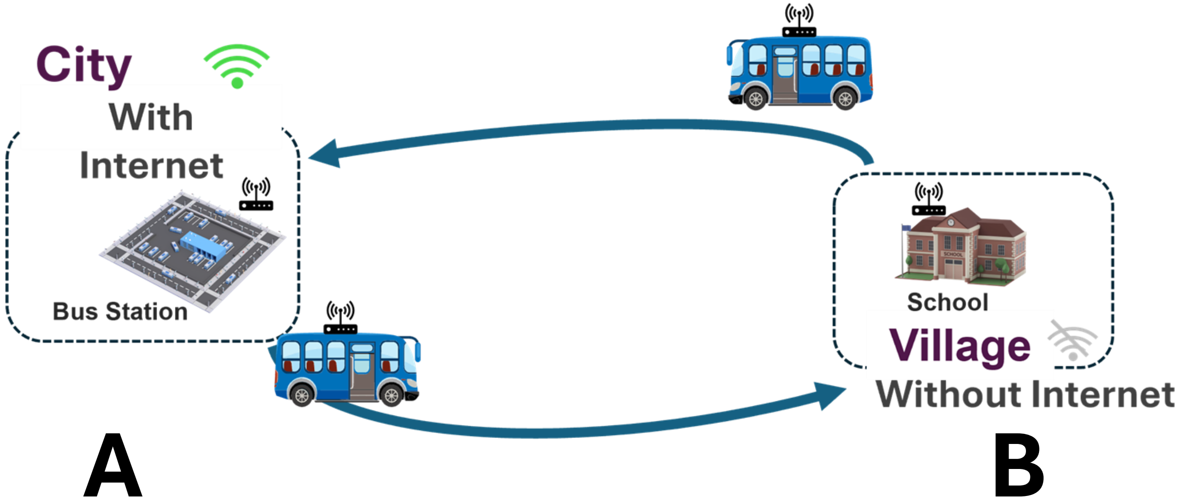
?

$$n \leq \mathcal{N}$$

Contact Time

Travel Time

Interarrival of vehicles



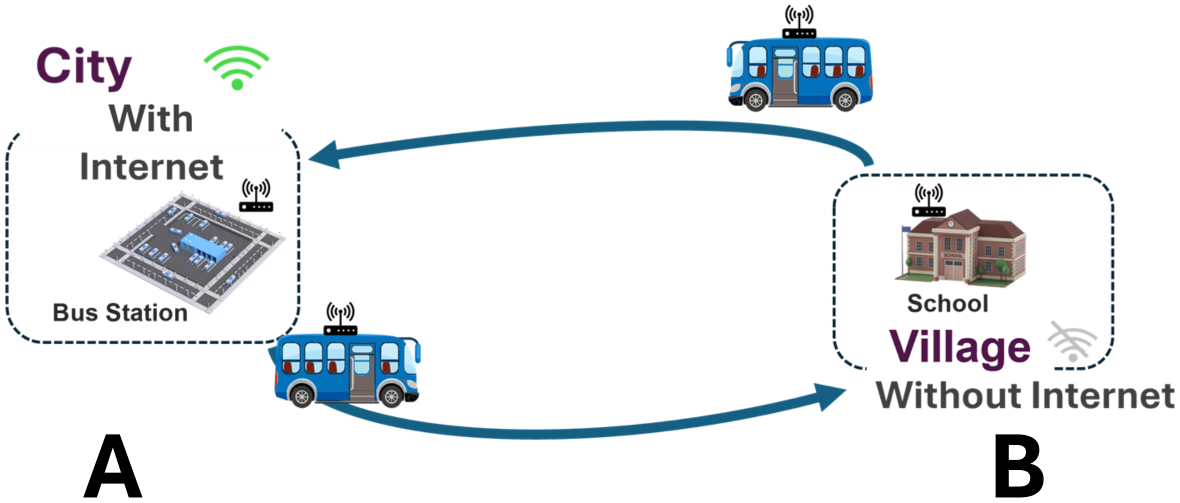
Contact Time

- Follows a uniform distribution, $\boldsymbol{T_{c,\{A,B\}} \sim Unif(T_{c,min}, T_{c,max})}$.
- Data size depends on $\boldsymbol{T_{c,\{A,B\}}}$ and data rate $\boldsymbol{R}$.

Travel Time

- $T_{\{AB,BA\}} = T_{min} + T_d$
- T_{min}: Minimum travel time based on distance and optimal route.
- T_d: Delay time, Follows an exponential distribution $\boldsymbol{T_d \sim Exp(\lambda_{\{AB,BA\}})}$.

System Model – DTN Data Mule



Interarrival time of vehicles

- Total of $\mathcal{N}$ vehicles, with n vehicles $(n \leq \mathcal{N})$ equipped with DTN for data delivery.
- Each vehicle modeled as a renewal process, $N_v(t)$, with i.i.d. renewal times $T_{v,i}$.
- $T_{v,i} = T_{c,A} + T_{AB} + T_{c,B} + T_{BA}$, representing vehicles round-trip time.
- Arrival process is a superposition of n independent renewal processes:

$$N(t) = N_1(t) + N_2(t) + \cdots + N_n(t)$$

- T_s represents arrival time of the superimposed process.
- At equilibrium, the mean inter-arrival time $E[T_s]$ for the superimposed process is given by:

$$E[T_s] = \frac{E[T_v]}{n} = \frac{\mu}{n} \qquad \lambda_s = \frac{1}{E[T_s]} = \frac{n}{\mu}$$

Downlink/Uplink Transmission Rate

Lemma 1 (Mean Transmitted Data Size). *The data size for uplink/downlink is proportional to the time needed to pick up the package from node A/B and deliver it to node B/A. Thus, the transmitted data size for the v^{th} vehicle is given by:*

$$m_v = \mathbf{R} \cdot \min\{T_{c,A}, T_{c,B}\} \tag{5}$$

where the complementary cumulative distribution function (CCDF) of the data size is:

$$F_m(m) = \left(\frac{\mathbf{R}c_2 - m}{\mathbf{R}\left(c_2 - c_1\right)} \right)^2, \quad m \in \mathbf{R} \cdot [c_1, c_2] \tag{6}$$

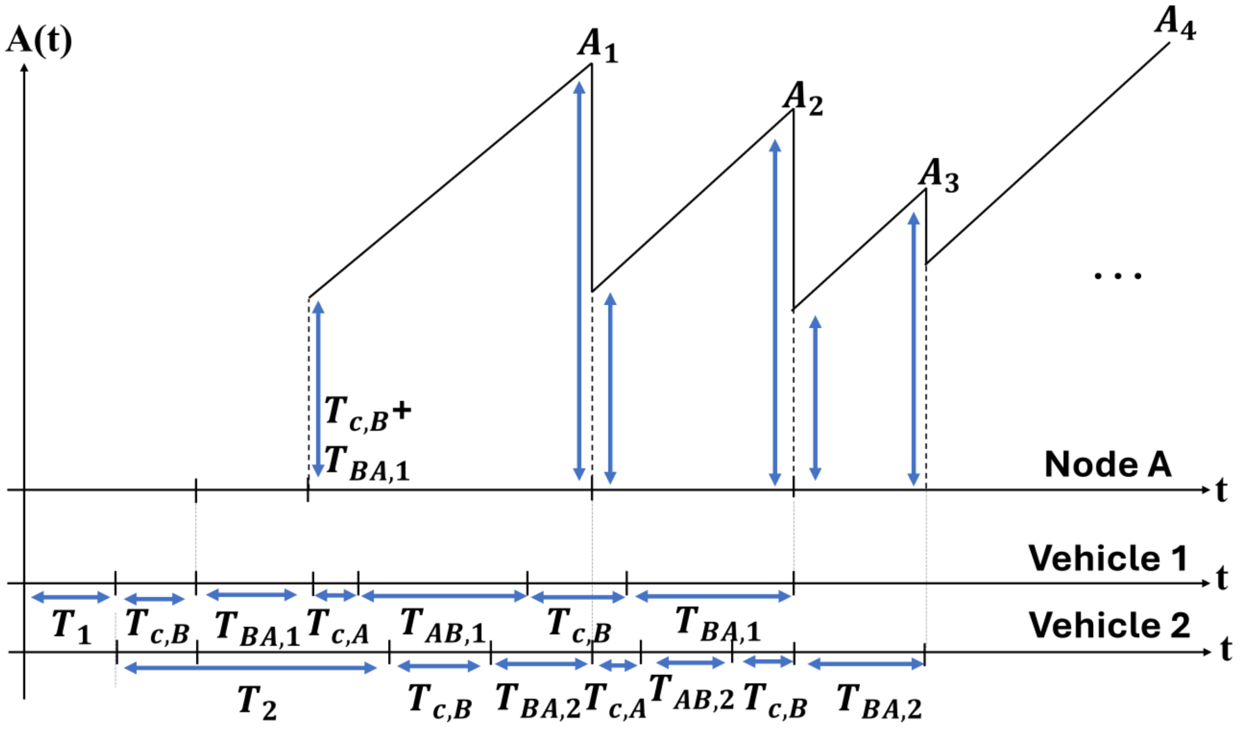
The mean transmitted data size for uplink/downlink is:

$$\mathbb{E}[m_v] = \mathbf{R} \cdot \left[\frac{c_2^2 + c_1 c_2 - c_1^2}{3\left(c_2 - c_1\right)} \right] \tag{7}$$

Lemma 2 (Mean Transmission Rate). *For the mean data size per vehicle arrival, $\mathbb{E}[m_v]$, and vehicle arrival rate, λ_s, the mean transmission rate is:*

$$\mathbb{E}[\mathcal{R}] = \mathbb{E}[m_v]\lambda_s = \mathbb{E}[m_v] \cdot \frac{n}{\mu}, \tag{8}$$

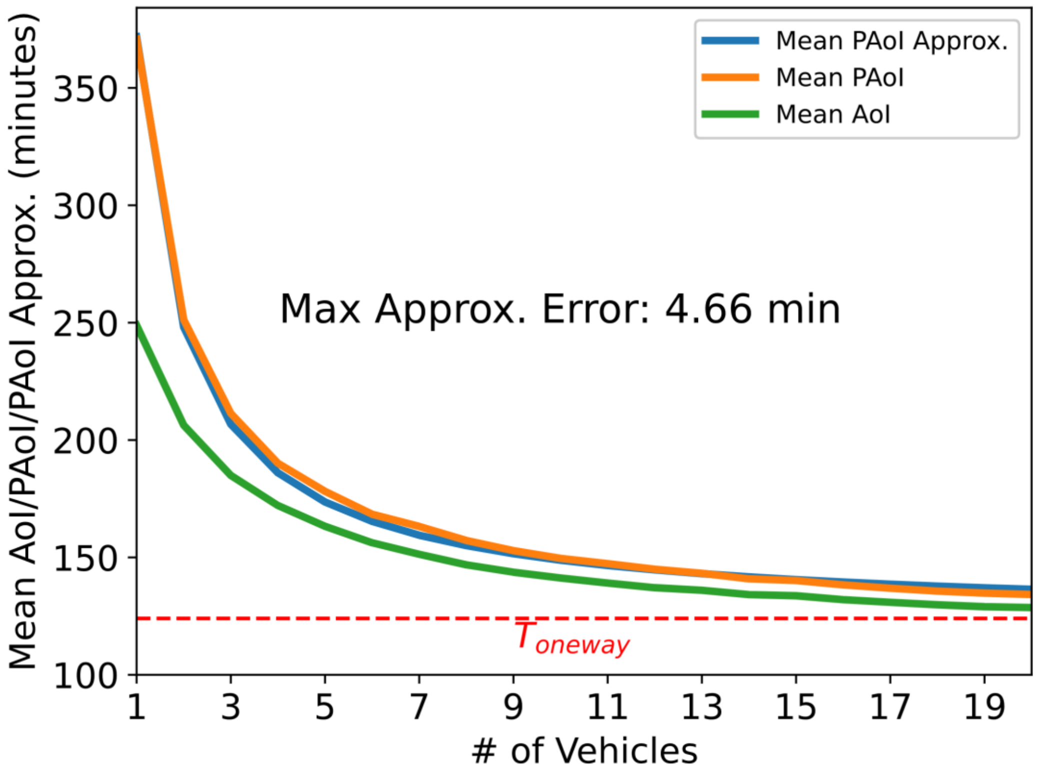
Mean Peak Age of Information (PAoI)

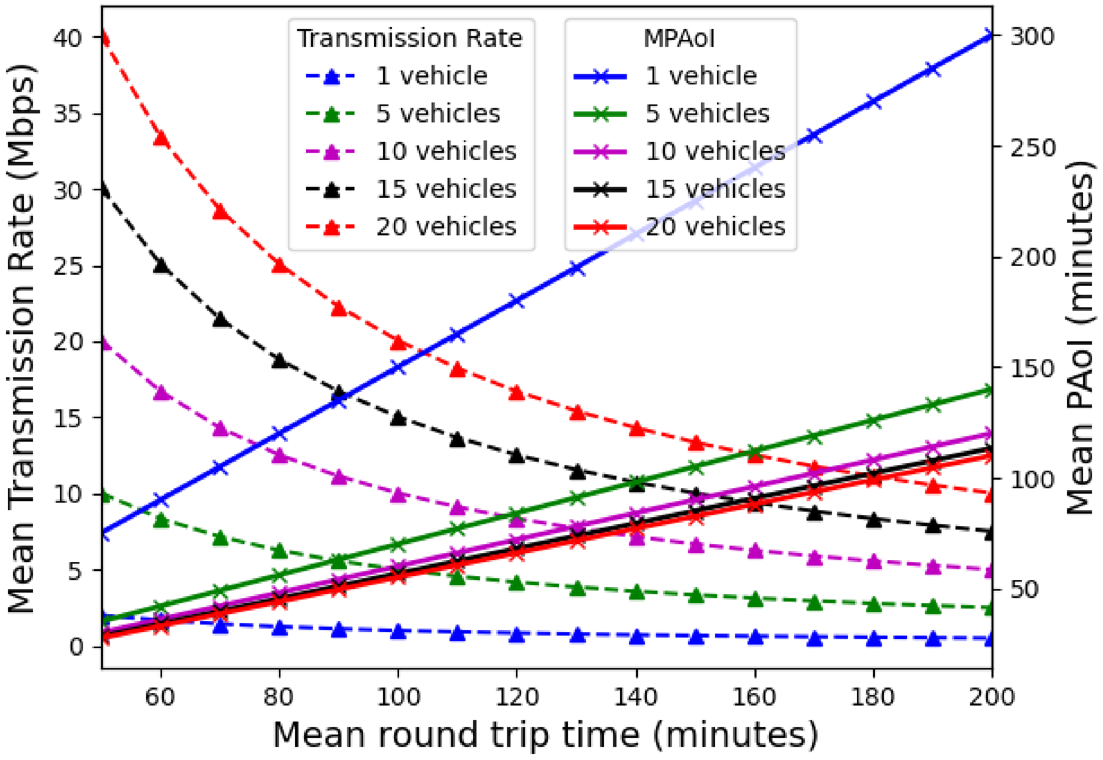


$$MPAoI \approx \mathbb{E}[T_{c,B} + T_{BA}] + \frac{\mu}{n}$$

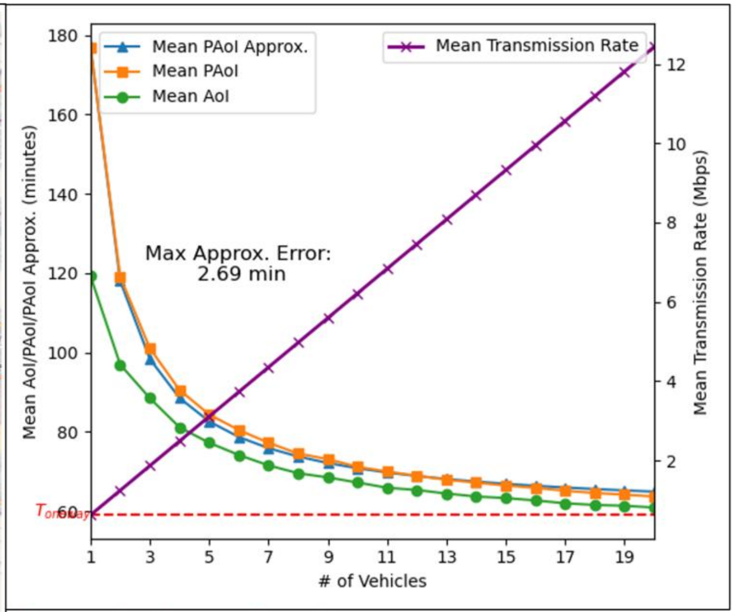
Performance Metrics – Simulation Results

Parameter	Value
$c_{1\{A,B\}}$	3
$c_{2\{A,B\}}$	5
$T_{min\{AB,BA\}}$	100
$1/\lambda_d$	20



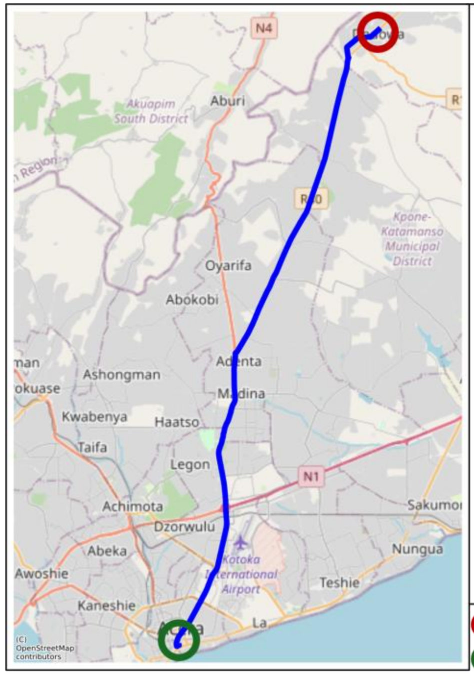


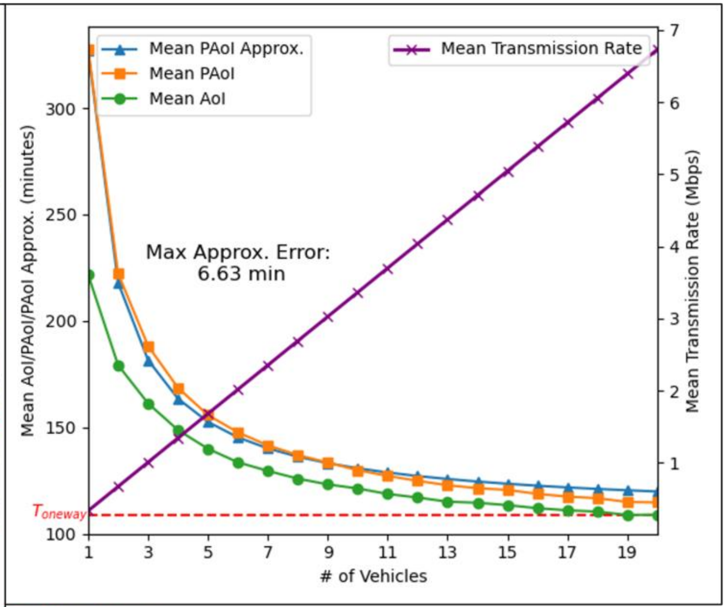
Performance Metrics – Case Study



Nouakchott University
Bamako crossroads

- Distance: ~ 25km.
- Travel time: ~ 55 min.



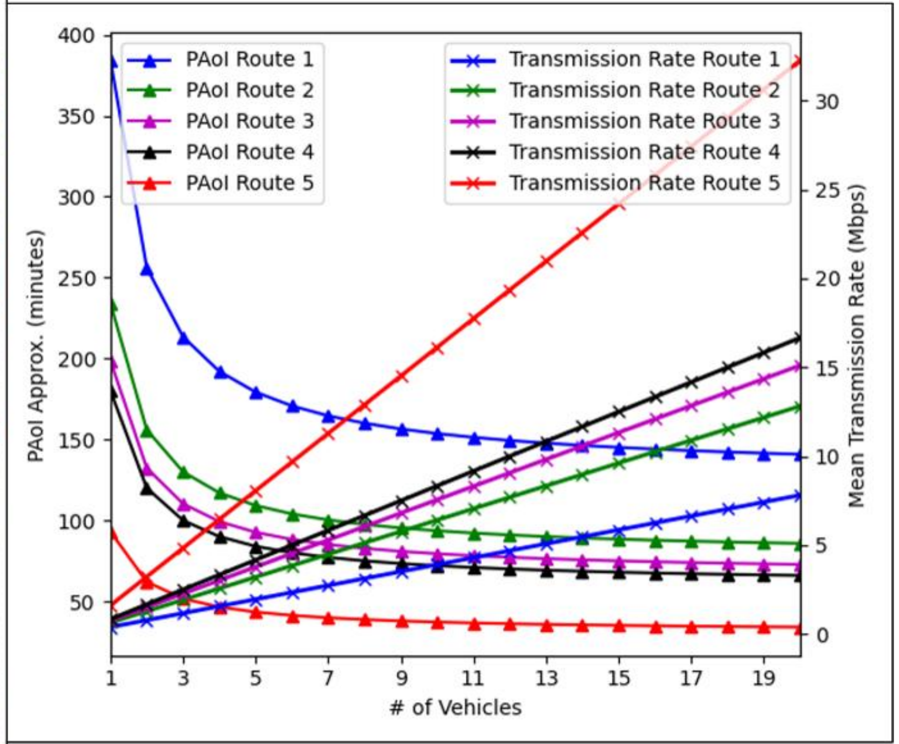


Dodowa
Accra Central

- Distance: ~ 56km.
- Travel time: ~ 104 min.

K. M. Mittal, M. Timme, and M. Schr¨oder, "Efficient self-organization of informal public transport networks," Nature Communications, vol. 15, no. 1, p. 4910, 2024.

Performance Metrics – Case Study



Tulu Dimtu

K. M. Mittal, M. Timme, and M. Schr¨oder, "Efficient self-organization of informal public transport networks," Nature Communications, vol. 15, no. 1, p. 4910, 2024.

Conclusion

- This study explores using **informal public transport** as DTN data mules to provide Internet-like connectivity to remote regions.
- We developed probabilistic models for vehicles traversing between regions, contact time, and data transmission rates.
- The framework incorporates communication metrics such as freshness of information and data transmission rate.
- We introduced an approximation for the Peak Age of Information (PAoI) based on vehicle inter-arrival times.
- Increasing the number of DTN-equipped vehicles significantly reduces PAoI, enhances transmission rates, and improves scalability.
- We validated our framework using public transport systems in Ethiopia, Mauritania, and Ghana.

Thank you!
Questions?