Towards Automatic Phone-to-Phone Communication for Vehicular Networking Applications

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Motivation

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richer
traffic info

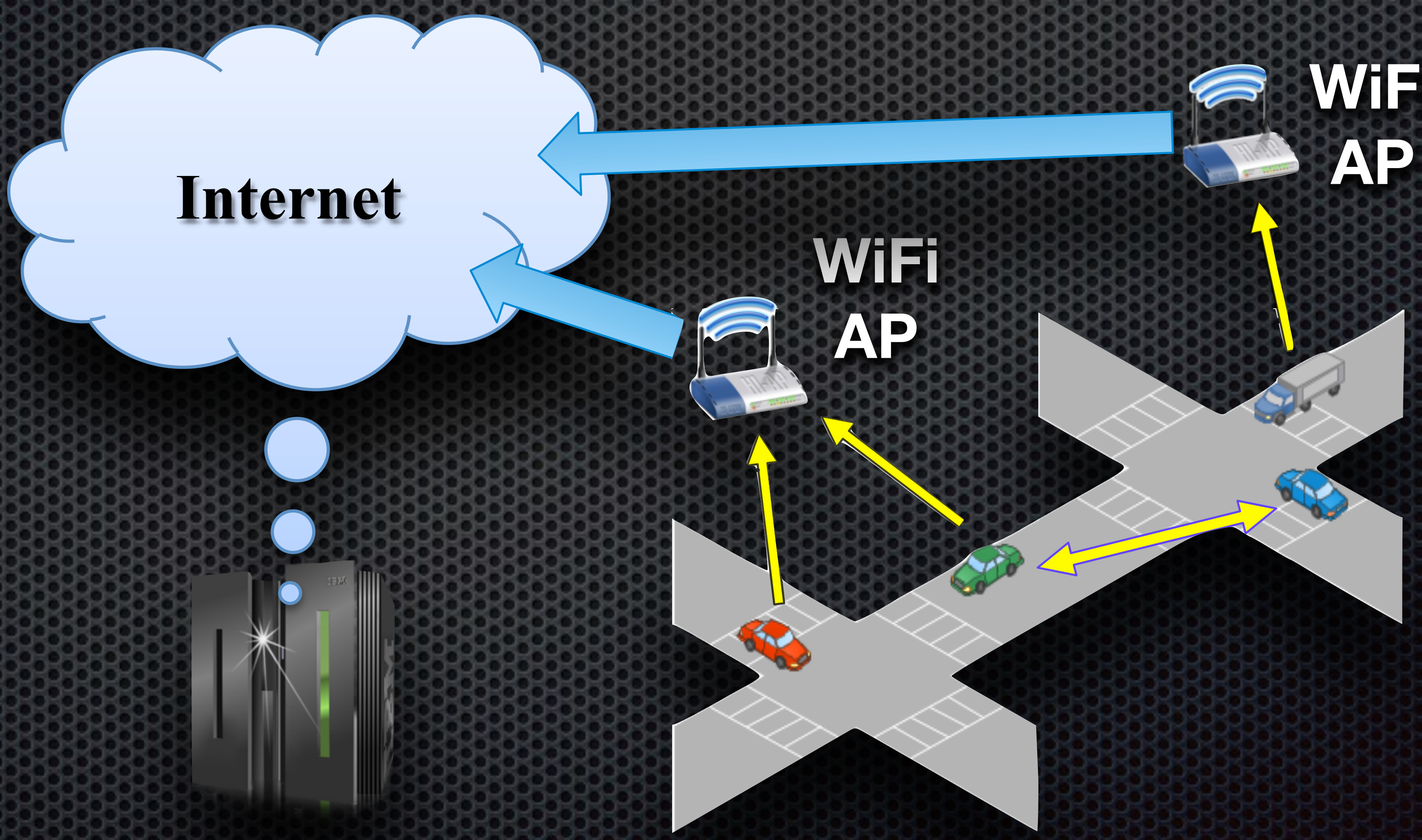
infotainment
opportunities

higher road
awareness

... and more!

Goal

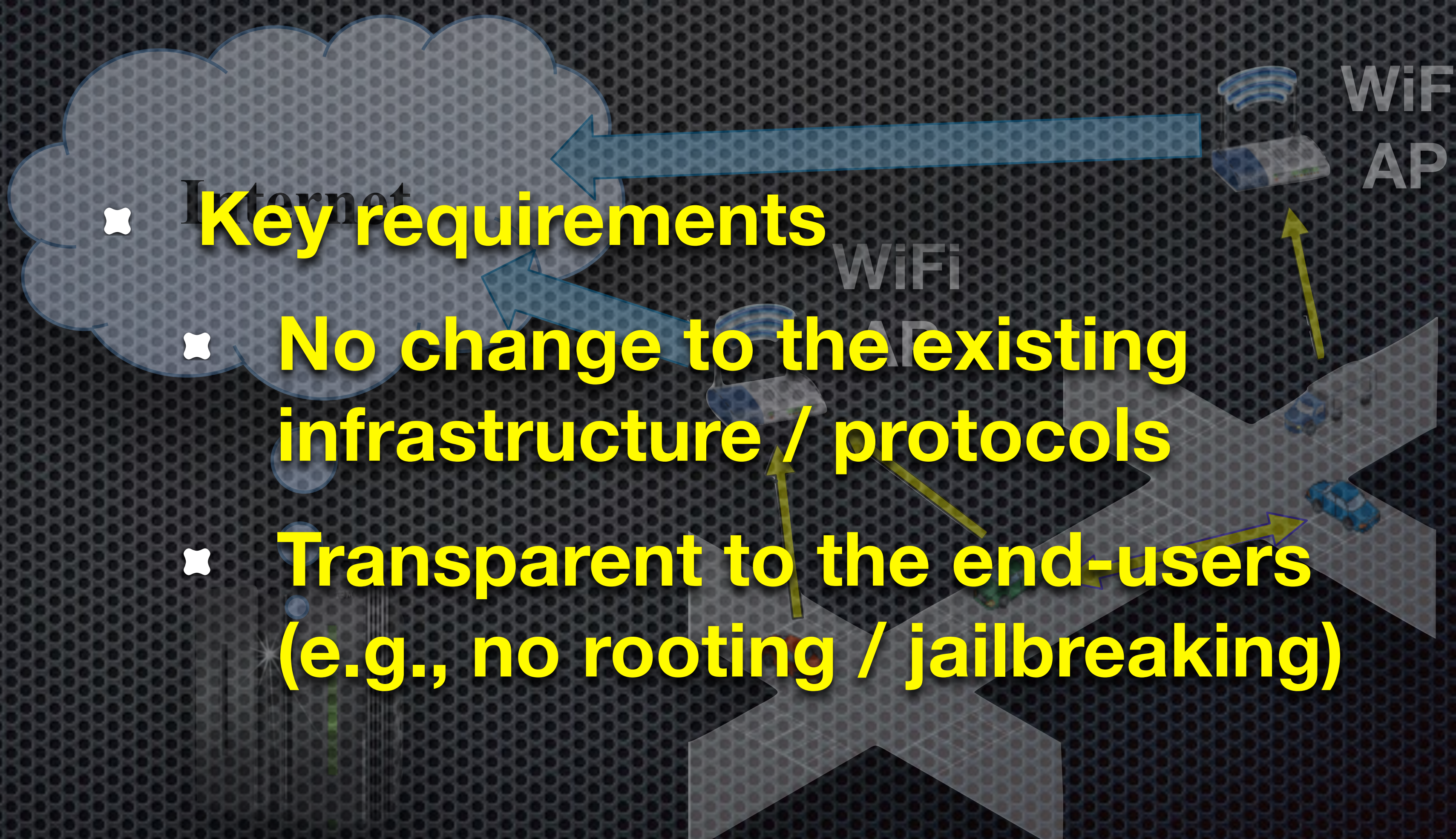
Build a Phone-to-Phone communication system for the tens of millions of vehicles on the roads today



Goal

Build a Phone-to-Phone communication system for the tens of millions of vehicles on the roads today

- Key requirements
  - No change to the existing infrastructure / protocols
  - Transparent to the end-users (e.g., no rooting / jailbreaking)



System Model

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- Vehicle-resident phones toggle between **hotspot** and **client** modes

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- Only considering pairwise communication: T-Drive dataset => ~80% encounters are pairwise (T-Drive: ~10k taxicabs' 1-week traces in Beijing, collected by MSRA)

Problem Statement

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Analytical Formulation

t_0 Hotspot: r t_0 Client: s

Time Frame: $f = 2t_0 + r + s$

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- M_1 (or M_2) : Phone-Phone (or Phone-AP) meeting duration
- T_1 (or T_2) : Phone-Phone (or Phone-AP) expected transmission duration
- β (or γ) : Phone-Phone (or Phone-AP) meeting rate

Solution Sketch

- M_1, M_2, β, γ (**meeting times and rates**): estimated from empirical data ✓
- T_1, T_2 (**expected transmission times**): derived analytically ?
- $\langle r^*, s^* \rangle$ (**optimal mode-toggling policy**): solved using off-the-shelf non-linear optimization solver ✓

Expected Transmission Time

Phone-to-Phone

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Phone-to-Phone

Define a periodic function

$$f(t) = \begin{cases} 0, & 0 \leq t \leq t_0 \\ 1, & t_0 < t \leq t_0 + r \\ 0, & t_0 + r < t \leq 2t_0 + r \\ -1, & 2t_0 + r < t \leq 2t_0 + r + s \end{cases}$$

=> during mode switching
=> in **hotspot** mode
=> during mode switching
=> in **client** mode

with period $f = 2t_0 + r + s$.

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Then, the time since meeting when two phones establish connection is

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with period $f = 2t_0 + r + s$.

Then, the time since meeting when two phones establish connection is

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Therefore, the expected phone-to-phone transmission time is

$$T_1 = E_{t_1,t_2}[M_1 - t^*] = \frac{1}{f^2} \int_{t_1} \int_{t_2} (M_1 - t^*) dt_2 dt_1$$

Expected Transmission Time

Phone-to-Phone

t_1	t_2	t^*	M_1	$E(M_1 - t^*)$
$[0, t_0)$	$[0, t_0)$	∞	$\sim$	0
$[0, t_0)$	$[t_0, t_0 + r)$		$M_1 \geq t_0 + r$	$\frac{1}{2f^2}\left[(M_1 - t_0)^2 - \frac{1}{3}(M_1 - r)^3 + \frac{1}{3}(M_1 - t_0 - r)^3\right]$
	or	$2t_0 + r - t_2$	$r \leq M_1 < t_0 + r$	$\frac{1}{2f^2}\left[(M_1 - t_0)^2 t_0 - \frac{1}{3}(M_1 - r)^3\right]$
$[t_0, t_0 + r)$	$[0, t_0)$		$t_0 \leq M_1 < r$	$\frac{t_0}{2f^2}(M_1 - t_0)^2$
$[0, t_0)$	$[t_0 + r, 2t_0 + r)$	$\max(t_0 - t_1, 2t_0 + r - t_2)$	$M_1 \geq t_0$	$\frac{2}{f^2}\left(\frac{M_1}{2}t_0^2 - \frac{1}{3}t_0^3\right)$
			$M_1 < t_0$	$\frac{1}{3f^2}M_1^3$
$[0, t_0)$	$[2t_0 + r, f)$	$t_0 - t_1$	$M_1 \geq t_0$	$\frac{1}{f^2}\left[\frac{1}{3}t_0^3 - \frac{1}{2}(M_1 + s)t_0^2 + M_1 s t_0\right]$
			$M_1 < t_0$	$\frac{1}{f^2}\left(\frac{1}{2}sM_1^2 - \frac{1}{6}M_1^3\right)$
$[t_0, t_0 + r)$	$[t_0, t_0 + r)$	$2t_0 + r - \max(t_1, t_2)$	$M_1 \geq r$	$\frac{2}{f^2}\left[\frac{r - t_0}{2}(M_1 - t_0)^2 - \frac{1}{6}(M_1 - t_0)^3 + \frac{1}{6}(M_1 - r)^3\right]$
			$t_0 \leq M_1 < r$	$\frac{1}{f^2}\left[(r - t_0)(M_1 - t_0)^2 - \frac{1}{3}(M_1 - t_0)^3\right]$
$[t_0, t_0 + r)$	$[t_0 + r, 2t_0 + r)$	$2t_0 + r - t_2$	$M_1 \geq t_0$	$\frac{1}{f^2}\left[\frac{r}{2}M_1^2 - \frac{r - t_0}{2}(M_1 - t_0)^2 - \frac{1}{6}M_1^3 + \frac{1}{6}(M_1 - t_0)^3\right]$
			$M_1 < t_0$	$\frac{1}{f^2}\left(\frac{r}{2}M_1^2 - \frac{1}{6}M_1^3\right)$
$[t_0, t_0 + r)$	$[2t_0 + r, f)$	0	$\sim$	$\frac{M_1 r s}{f^2}$

Case analysis for expected transmission time

Expected Transmission Time

Phone-to-Phone

Collecting the cases:

$$\begin{aligned} T_1 &= \frac{2rs}{f^2}M_1 + I_{(M_1<t_0)}f_1(r,s,M_1) + I_{(M_1\geq t_0)}f_2(r,s,M_1) + I_{(t_0\leq M_1<r+t_0)}f_3(r,s,M_1) \\ &\quad + I_{(M_1\geq r+t_0)}f_4(r,s,M_1) + I_{(t_0\leq M_1<s+t_0)}f_5(r,s,M_1) + I_{(M_1\geq s+t_0)}f_6(r,s,M_1), \end{aligned}$$

where the I's are indicator functions, and f's are

$$\begin{aligned} f_1(r,s,M_1) &= \frac{s+r}{f^2}M_1^2 \\ f_2(r,s,M_1) &= \frac{1}{f^2}\left[\frac{2}{3}M_1^3 - \frac{2}{3}(M_1-t_0)^3 - 2t_0(M_1-t_0)^2 + 2M_1t_0(r+s) + \frac{4}{3}t_0^3 - (2M_1+r+s)t_0^2\right] \\ f_3(r,s,M_1) &= \frac{1}{f^2}\left[r(M_1-t_0)^2 - \frac{1}{3}(M_1-t_0)^3\right] \\ f_4(r,s,M_1) &= \frac{1}{f^2}\left[r(M_1-t_0)^2 + \frac{1}{3}(M_1-t_0-r)^3 - \frac{1}{3}(M_1-t_0)^3\right] \\ f_5(r,s,M_1) &= \frac{1}{f^2}\left[s(M_1-t_0)^2 - \frac{1}{3}(M_1-t_0)^3\right] \\ f_6(r,s,M_1) &= \frac{1}{f^2}\left[s(M_1-t_0)^2 + \frac{1}{3}(M_1-t_0-s)^3 - \frac{1}{3}(M_1-t_0)^3\right]. \end{aligned}$$

Expected Transmission Time

Phone-to-AP

Taking a similar approach (see AP's as nodes stuck in hotspot mode)

$$\begin{aligned} T_2 &= \frac{M_2 r}{f} + I_{(M_2 \geq 0)} \frac{1}{2f} \left[M_2^2 - (M_2 - t_0)^2 \right] + I_{(t_0 \leq M_2 < f-r)} \frac{1}{2f} (M_2 - t_0)^2 \\ &\quad + I_{(M-2 \geq f-r)} \frac{1}{2f} \left[(M_2 - t_0)^2 - (M_2 - f + r)^2 \right] + I_{(M_2 < t_0)} \frac{M_2^2}{2f} \end{aligned}$$

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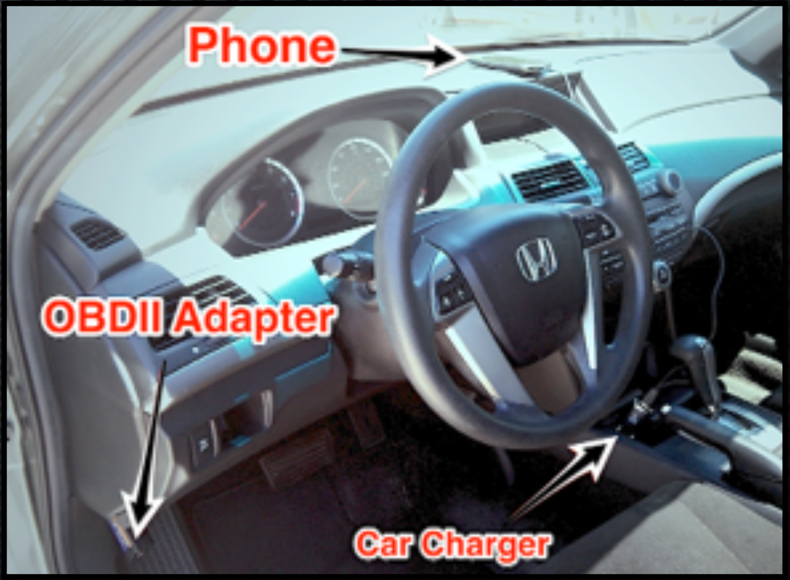
\end{aligned}
$$

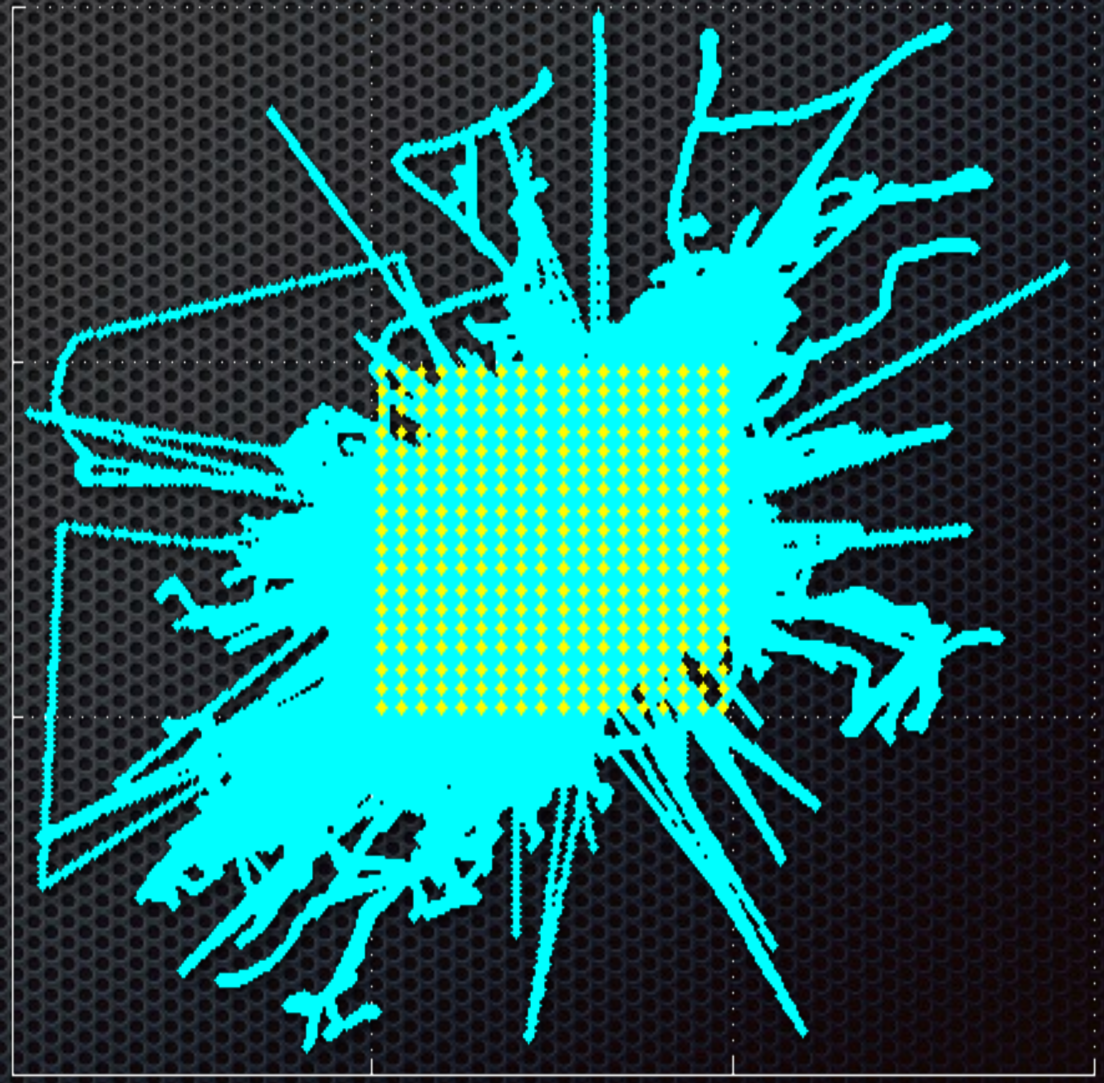
Finally, given $T_1, T_2, \beta, \gamma,$ the optimal mode toggling schedule $\langle r^*, s^* \rangle$ is solved for using off-the-shelf solver.

Implementation

- On Android Galaxy Nexus and Nexus S phones
- Using Java Reflection, no rooting is required
- Driving data: GPS trajectories & car OBD-II readings
- Measured mode switching overhead and communication range, and tested functional system in practice

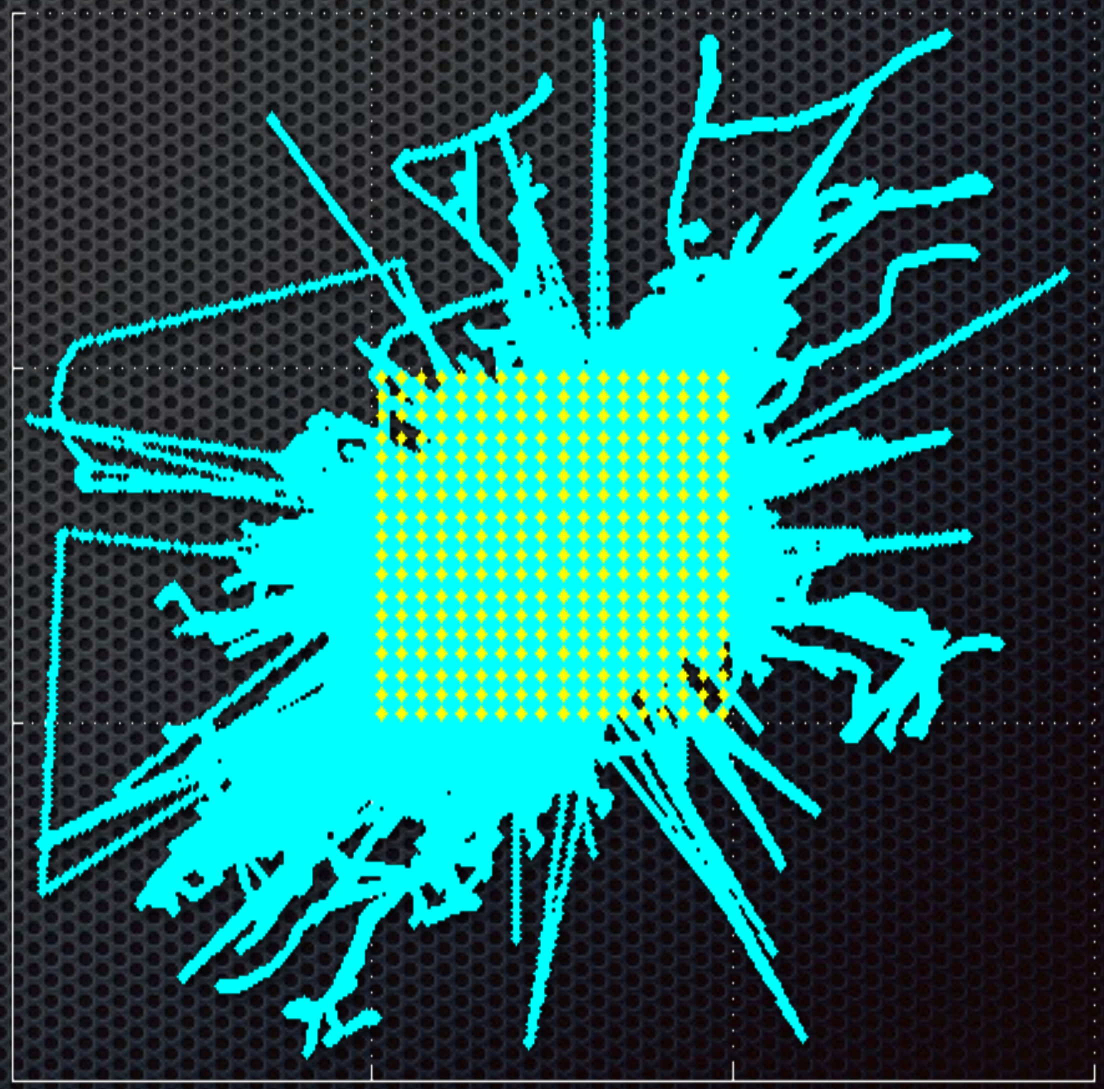


Large-Scale Simulation



Large-Scale Simulation

- MSRA T-Drive taxicab dataset
  - Central Beijing (50 km x 50 km)
  - Feb 2~8, 2008
  - 9211 taxicabs
  - Assumed 10% WiFi coverage



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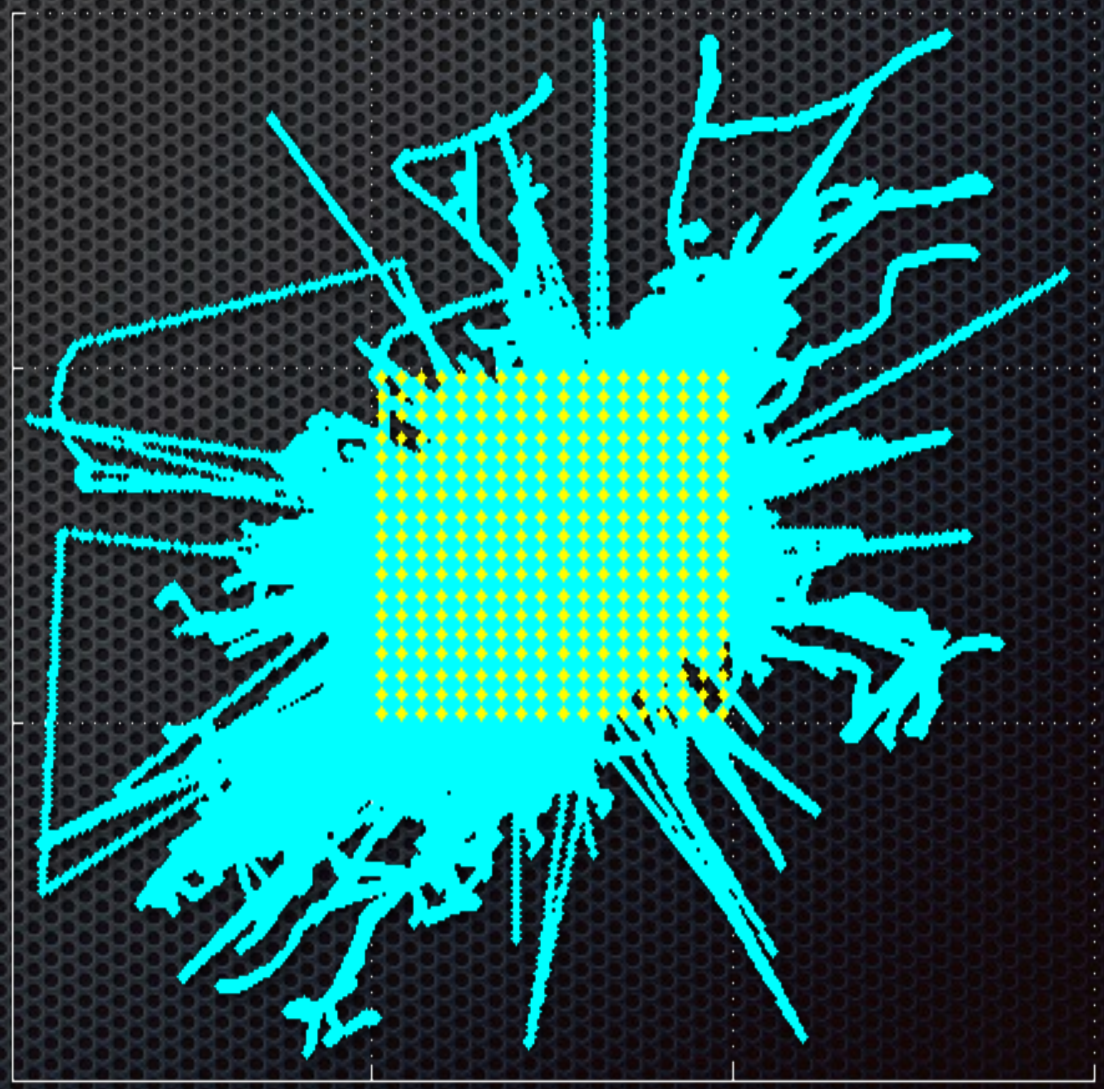
  - Cars collect driving data, share with each other
  - Cars offload data to backend server when encountering APs



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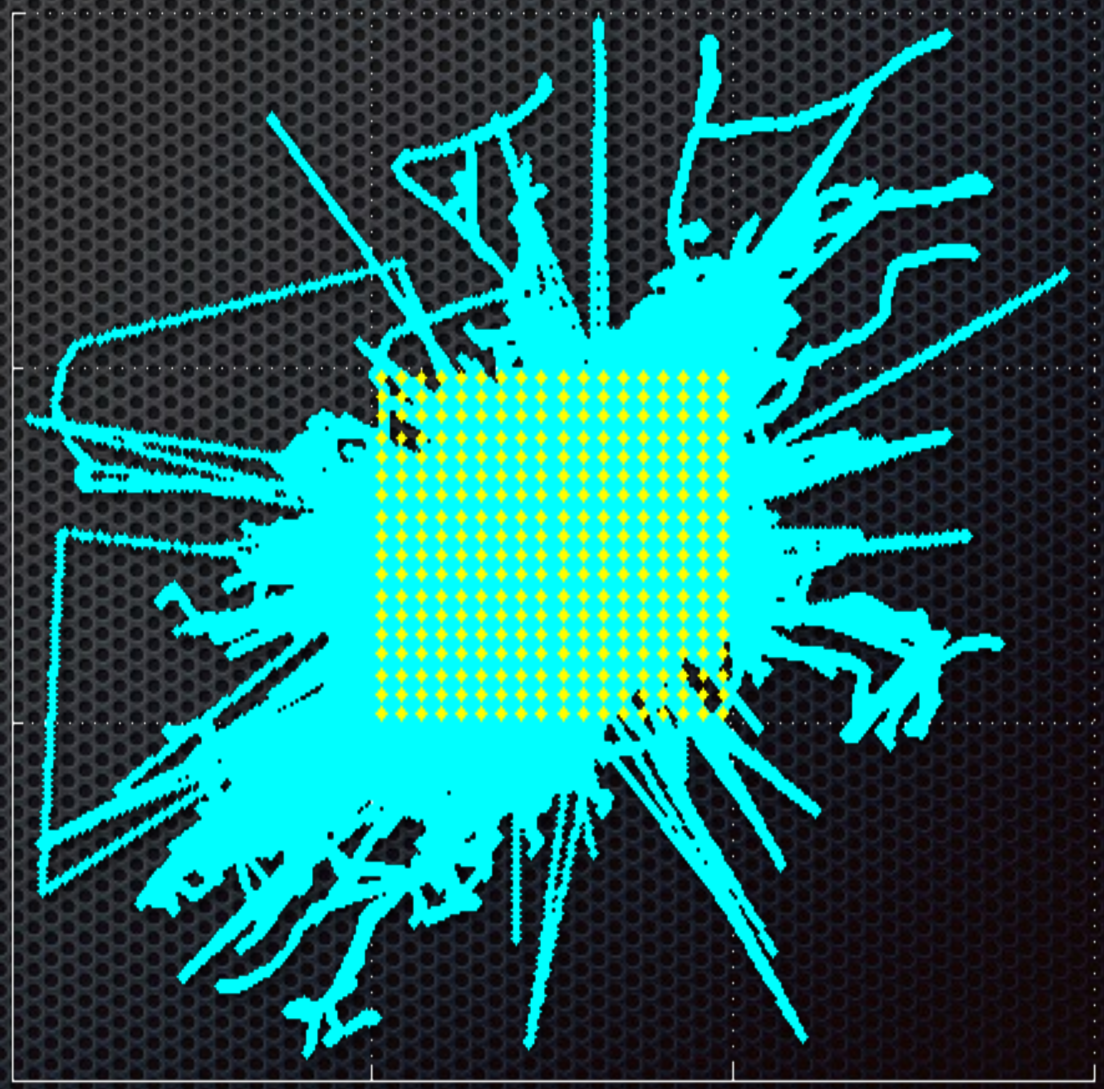
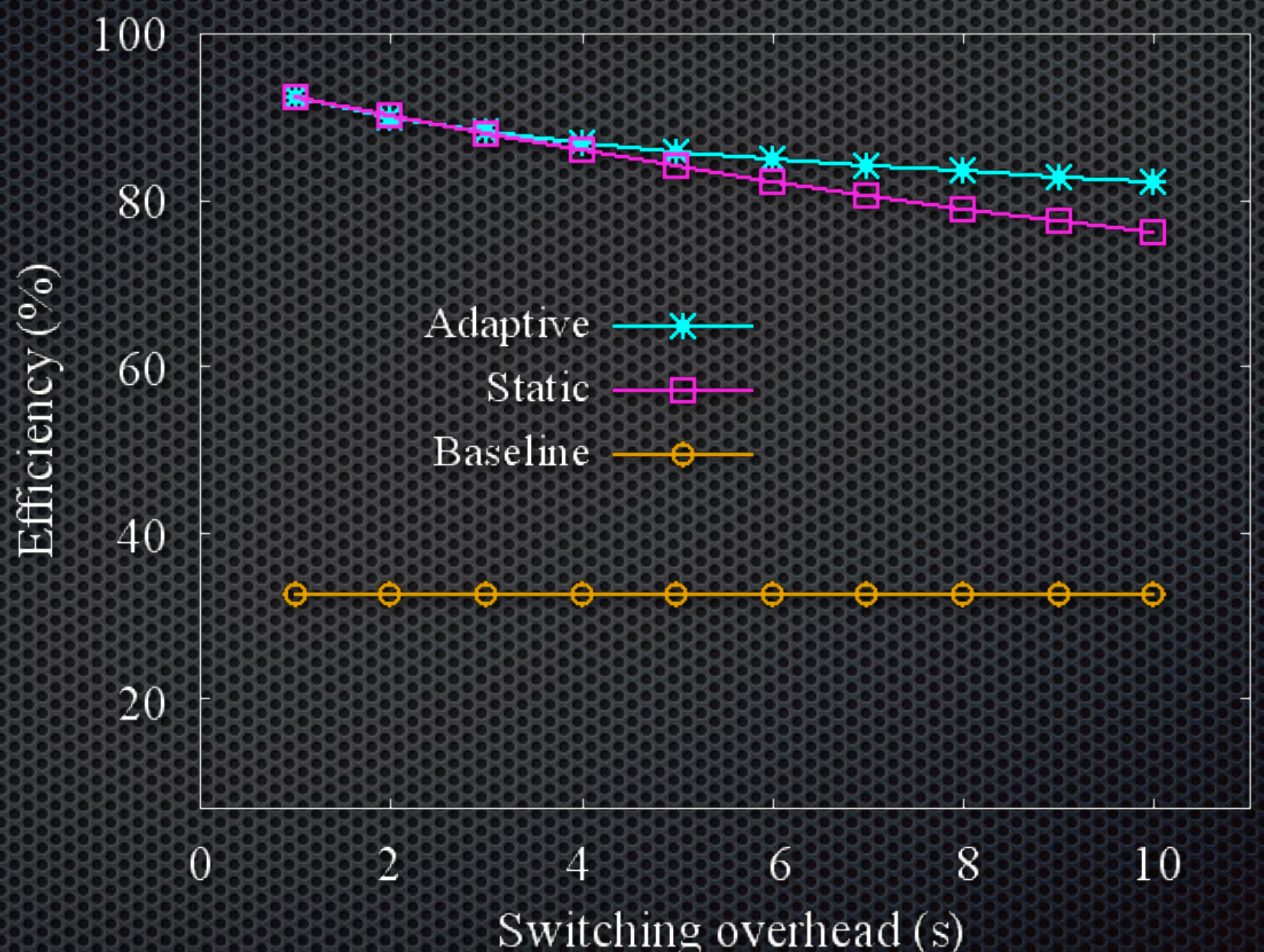
- Schemes
  - Baseline: no phone-to-phone communication
  - Adaptive: system parameters are updated every hour using historical data
  - Static: system parameters are computed using the first hour of data only

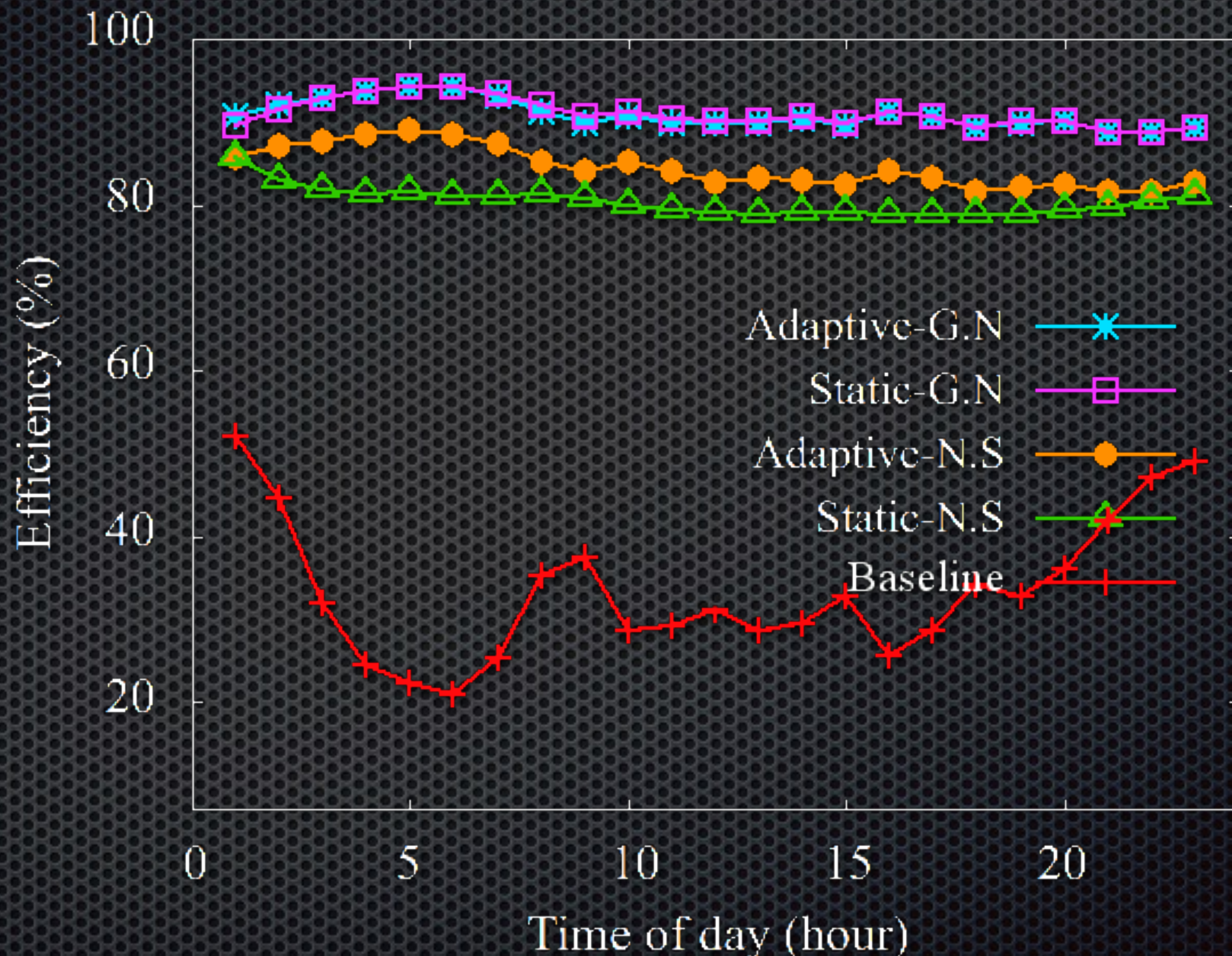


Simulation Results



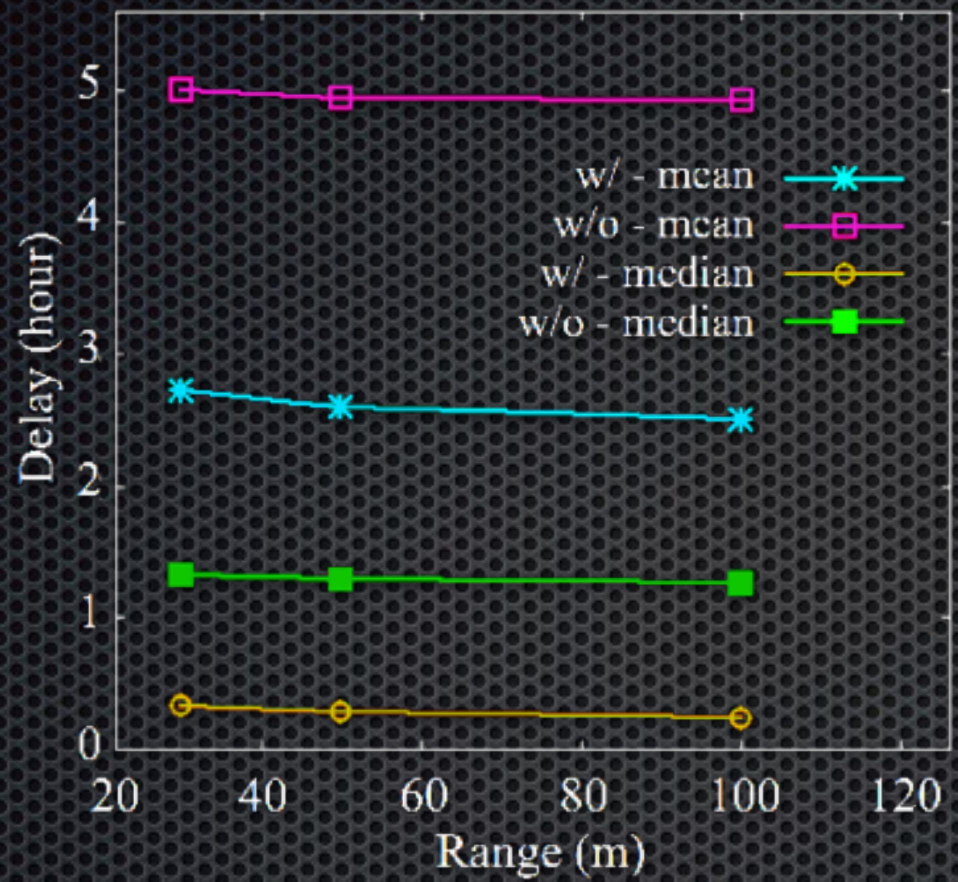
How does the mode switching overhead affect optimal system efficiency?

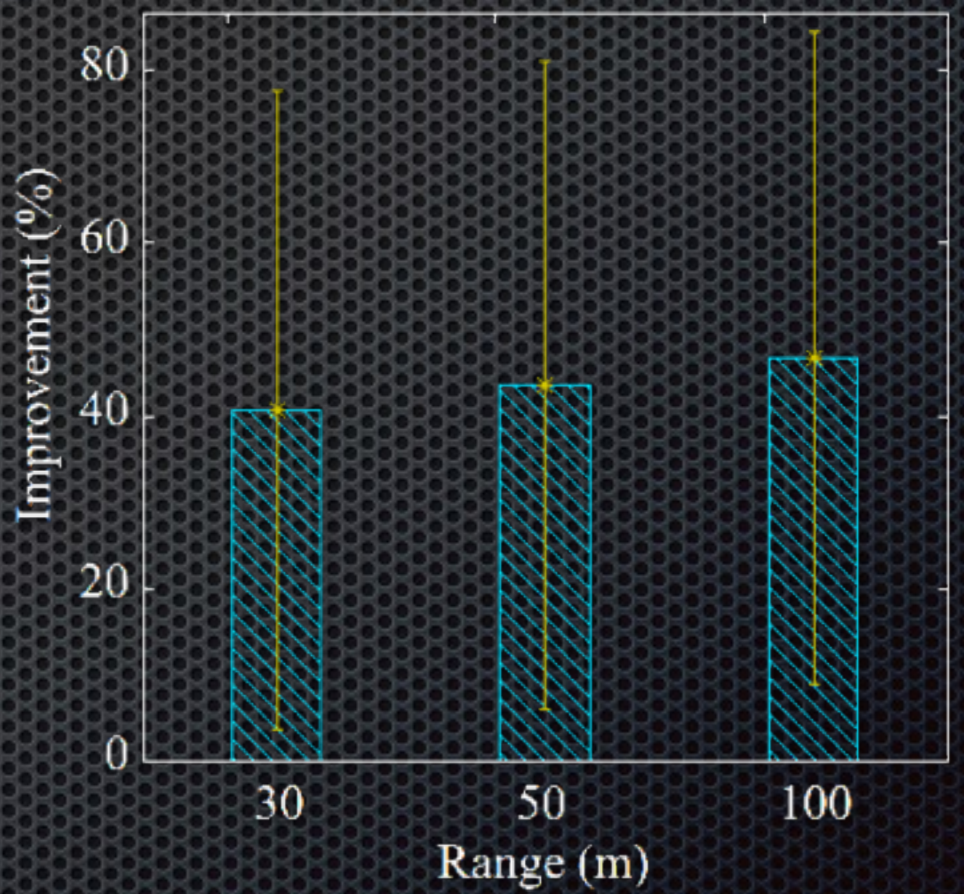
Simulation Results



How does time-of-day affect the optimal system efficiency?

Simulation Results





Improvement on transmission delay (mean and median) w/ phone-to-phone communication enabled v.s. w/o

Conclusion

- Our system enables vehicle-vehicle communications using off-the-shelf smartphones
  - No change to existing infrastructure
  - Transparent to end users
- Analytical formulation and results for optimal system efficiency
- Experiments show
  - Over 80% system efficiency
  - Significantly reduces data transfer delay time

Thanks