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Scheduling software updates for connected cars with limited availability

Carlos E. Andrade

Simon D. Byers

Vijay Gopalakrishnan

Emir Halepovic

Milap Majmundar

David J. Poole

Lien K. Tran

Christopher T. Volinsky

AT&T Labs Research

Bedminster and Middletown, NJ, USA

AT&T Labs

Austin, TX, USA

Agenda

- 1 Introduction
- 2 Current/Common connected car constraints
- 3 Model
- 4 Solving the problem
- 5 Results

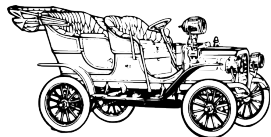
Disclaimer

All presented information does neither reflect nor imply an actual business case for AT&T and/or associated companies. They are generalized data used to assess performance of the algorithms only.

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Ford Model T is long gone...



- Today - cars, trucks, tractors rely heavily on software^[1]:
 - ▶ Estimated 100 million lines of code residing in various systems
 - ▶ Updates are tens of Megabyte to Gigabytes in size
- Forecast - 90% of cars will be connected by the year 2020^[2]:
 - ▶ Millions of connected cars are already on the roads today
- Software usually requires updates^[3]:
 - ▶ In 2015, more than 5 million software-only recalls in USA
 - ▶ At the dealerships, **per-service cost is roughly \$100**

[1] J. Zurschmeide, 2016. *Your next car will update itself while you sleep, and maybe watch you too.* <https://goo.gl/1Wtvv8>

[2] Telefonica, 2014. *Connected Car Industry Report 2014.* <https://goo.gl/CJgRrv>

[3] Redbend, 2015. *Updating Connected Car Software Over-The-Air — Why Wait?* <http://www.redbend.com/en/resources/white-papers#resource=231>

Tesla (connected) cars during Hurricane Irma

☰ 🇺🇸 🔍 The New York Times [SUBSCRIBE NOW](#) [LOG IN](#)

BUSINESS DAY

Tesla Boosts Car Battery Power During Irma, Raising Questions of Control

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NOT TOPICS: 2017's Best Stocks - 25 Investing Rules - Daily Booyah - Trading Strategies - Apple Releases Its New Products - Inside Bitcoin M

Tesla Dropping a Software Upgrade to Help Hurricane Irma Evacuees Pays Off

Tesla performed an automatic update on Model S/X60/60D vehicles that unlocked the full capacity of the 75kWh battery

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Tesla triggers upgrade for cars in Irma's path



Connected cars

≠



Smartphones

- *Availability*: connected cars appear rarely on the network, compared to smartphones (average of 1 hour)
- *Update priority*: critical could mean **life-critical!**
- *Hardware*: very limited capabilities
- *Lifetime*: average lifetime of modern cars is over 11 years^[1]

[1] D. DeMuro, 2015. *Buying a Car: How long can you expect a car to last?*
<http://www.autotrader.com/car-shopping/buying-a-car-how-long-can-you-expect-a-car-to-last-240725>

Alternatives to visiting the dealership



USB sticks or using smartphones as intermediaries:

- ▶ Require human intervention to ensure the update is completed



WiFi:

- ▶ Cars must have a client WiFi module
- ▶ A human must set up and maintain WiFi connectivity to the car



Satellite:

- ▶ Requires additional hardware and may not offer adequate control

So, let's do it over the cellular network



Firmware over-the-air (FOTA)



Widespread availability of the network



Estimated \$35 billion in annual savings by 2022 using FOTA^[1]

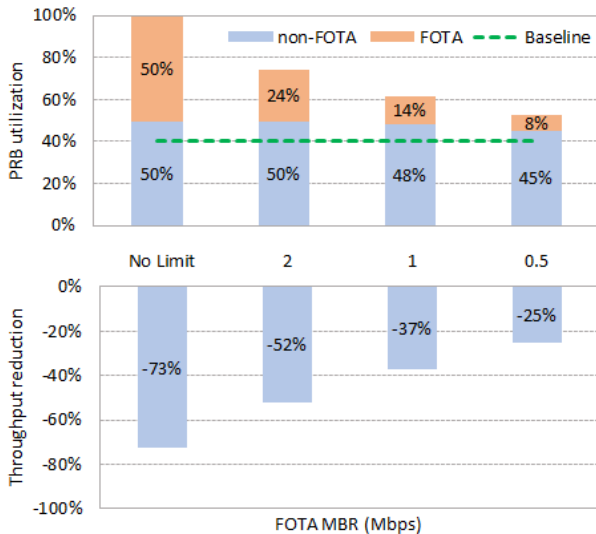


But there are some issues:

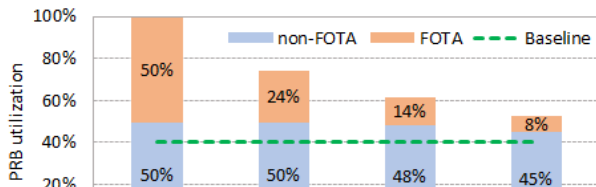
- ▶ Network impact during FOTA updates
- ▶ Hard constraints in the cars

[1] Automotive News, 2016. *Over-the-air updates on varied paths*.
<http://www.autonews.com/article/20160125/OEM06/301259980/over-the-air-updates-on-varied-paths>

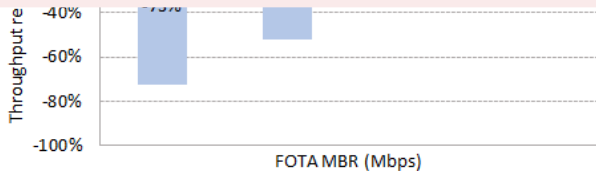
Simulated Physical Resource Block (PRB) impact with different Maximum Bit Rate (MBR) limits



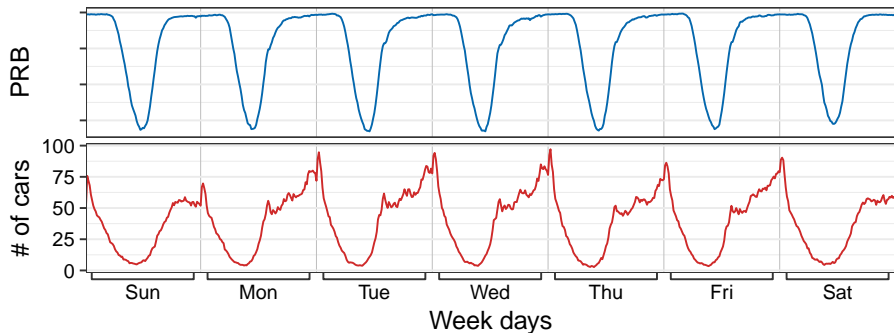
Simulated Physical Resource Block (PRB) impact with different Maximum Bit Rate (MBR) limits



Even with throttling,
the impact can be significant!



Car count and PRB utilization over one week for a busy radio (15-minute bins)



Car behaviour follows a shifted network behaviour with peaks in the evenings

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Car constraints

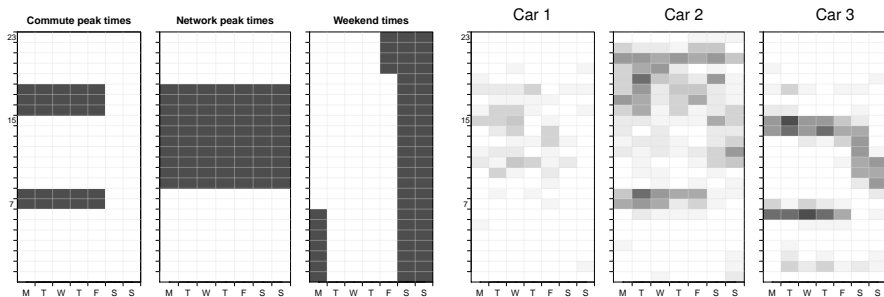
#1: Download (and update) **only happen while the engine is on!**

- Significantly limits opportunities for download
- Car rush hours overlap with network busy hours

Car constraints

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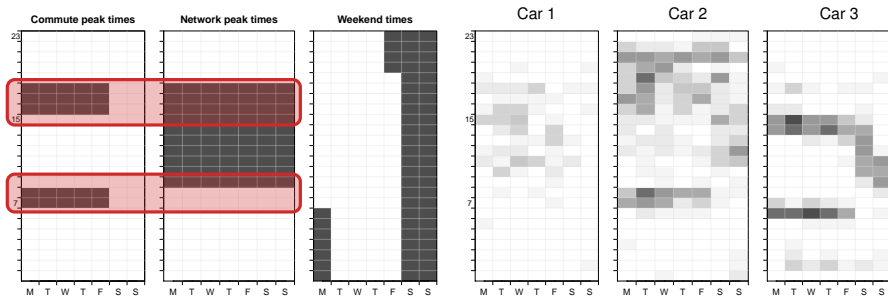
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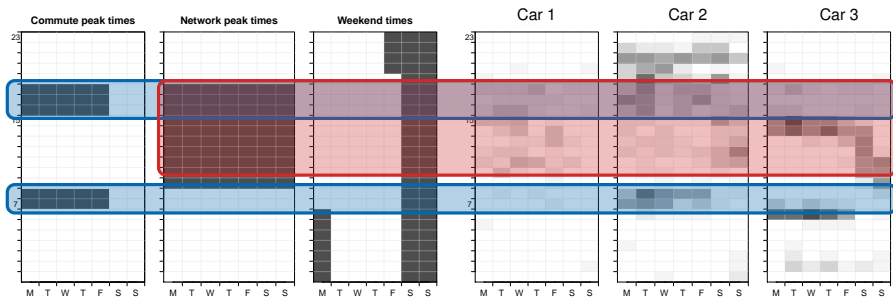
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Car constraints

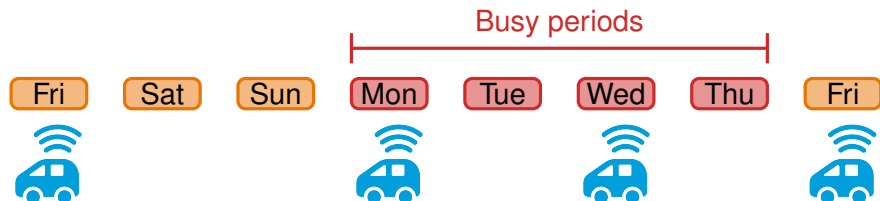
#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

- Network does not have total control over the download

Car constraints

#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

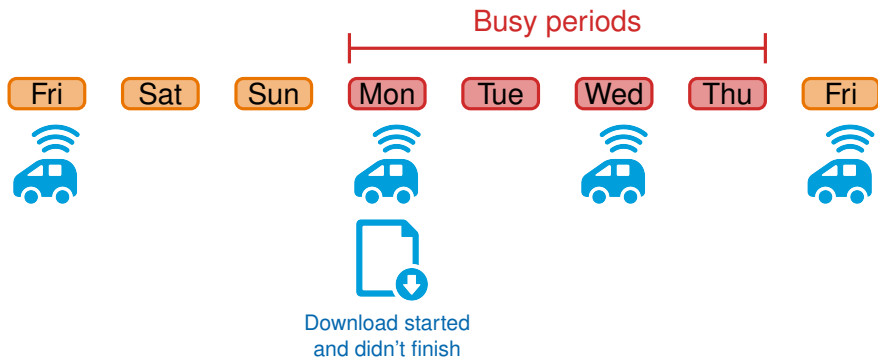
- This car typically appears 3 days/week; [Mon-Thu] are busy days



Car constraints

#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

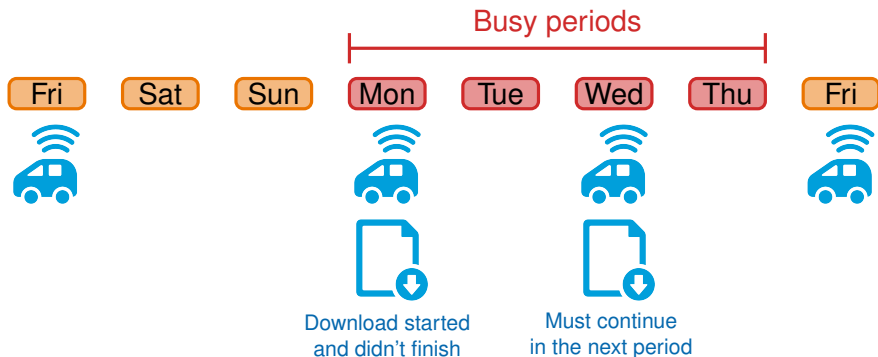
- Let's consider a case where FOTA download starts on Monday



Car constraints

#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

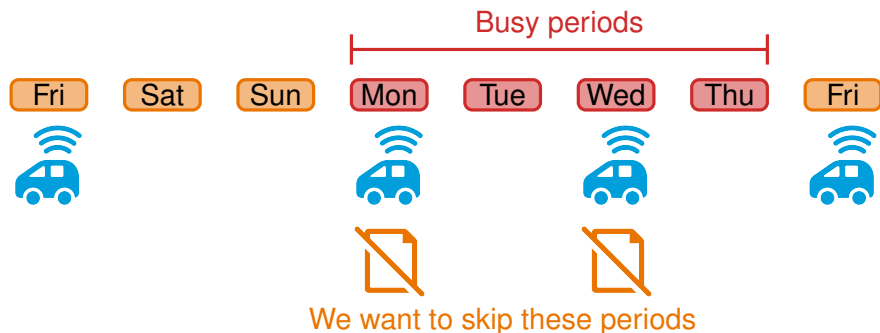
- ... and has to continue and finish on Wednesday



Car constraints

#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

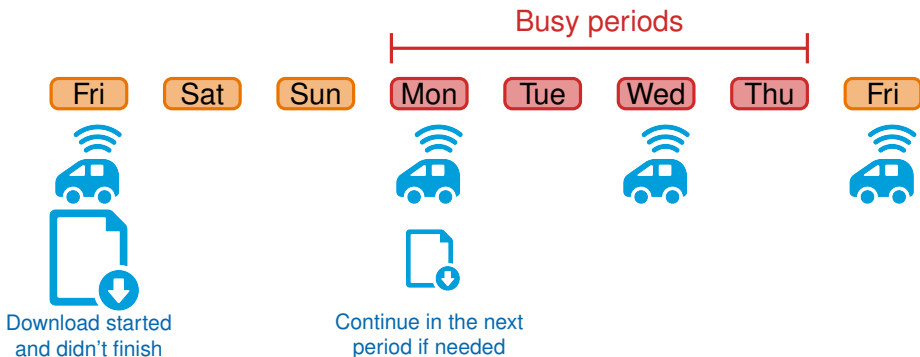
- It is not desirable to download during busy periods



Car constraints

#2: Once the car starts downloading, it stops only when the download finishes, possibly taking several days.

- Much better scenario we wish to achieve - push data off peak



Network constraints

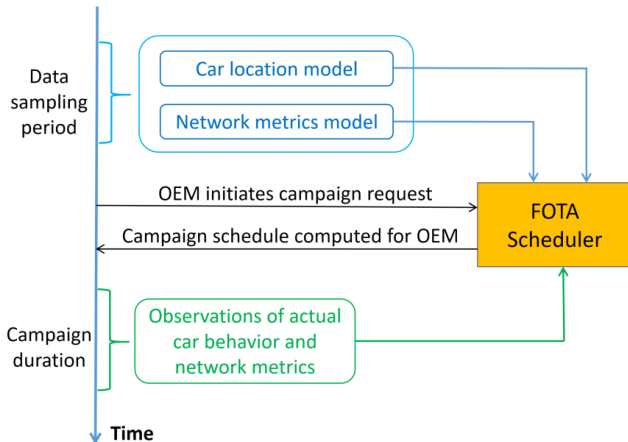
- Radio communication capacity in a given period of time – for LTE expressed in Physical Resource Blocks (PRBs)
- Capacity of other network elements
- Number of users and overall network traffic load

Objectives

- Control the admission of the cars in the network
 - ▶ Schedule the best time, for each car, to start the download
- We expect to:
 - ▶ Shift the traffic to quieter radios and non-busy periods
 - ▶ Reduce the total download time and completion rate
 - ▶ Better utilize network resources

FOTA campaign simulation model

- PRB and car usage models are built over the sampling period
- FOTA schedule is simulated over the campaign period using actual car's network behavior



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Sets and constants

- Set of cars C
- Set of sectors S (region covered by a radio)
- Set of periods $P = \{0, \dots, p^{final}\}$ where p^{final} is a valid makespan upper bound (time that the last car completes its download)
- Demand / download size d_c , for $c \in C$
- Maximum number of cars per period C^{max}

Network model

- Based on *Physical Resource Block (PRB)* utilization
- PRBs are given in percentages (0 to 100%)
- For each period of time $p \in P$ and each sector $s \in S$:
 - ▶ PRB_{sp} : average PRB utilization
 - ▶ $Volume_{sp}$: volume of data in Megabits (Mb)
- PRB utilization rate: $\gamma_{sp} = \frac{Volume_{sp}}{PRB_{sp}}$

Car model

- We only have radio connection information
- For each car $c \in C$:
 - ▶ $time_{csp}$: time spent under sector $s \in S$ in period $p \in P$ (in seconds)

- ▶ Car PRB consumption: $k_{csp} = \frac{r \times time_{sp}}{\gamma_{sp}}$

where r is the download rate (in Megabits per second, Mbps)

Variables – Mixed Integer Program (MIP)

- $x_{csp} \in \{0, 1\}$: $x_{csp} = 1$ indicates that car c is scheduled to download from sector s in period p
- $y_{csp} \in \mathbb{R}^+$: amount of PRB capacity from sector s consumed by car c in period p
- $s_{cp} \in \{0, 1\}$: $s_{cp} = 1$ if car c starts its download in period p
- $a_{cp} \in \{0, 1\}$: $a_{cp} = 1$ if car c is scheduled/active in period p
- $f_{cp} \in \{0, 1\}$: $f_{cp} = 1$ if car c “(pseudo-) finishes” its download in period p

Constraints – MIP

Constraint (1) restricts the car to not connect to two or more sectors simultaneously:

$$\sum_{s \in S} x_{csp} \leq 1, \quad \forall c \in C, p \in P \quad (1)$$

Constraint (2) ensures that the car is active when scheduled for a sector:

$$a_{cp} \geq \sum_{s \in S} x_{csp} / |S|, \quad \forall c \in C, p \in P \quad (2)$$

Constraints – MIP

Constraint (3) ensures that each car has one start period:

$$\sum_{p \in P} s_{cp} = 1, \quad \forall c \in C \quad (3)$$

Constraints (4) and (5) establish that when a car starts its download, it will be active (downloading) over following periods it hits the network:

$$a_{c0} = s_{c0}, \quad \forall c \in C \quad (4)$$

$$a_{cp} \leq s_{cp} + a_{c,p+1}, \quad \forall c \in C, p \in \{0, \dots, p^{final} - 1\} \quad (5)$$

Constraints – MIP

Constraint (6) allows PRB utilization only when the car is scheduled in the sector.

$$y_{csp} \leq k_{csp}x_{csp}, \quad \forall c \in C, s \in S, p \in P \quad (6)$$

Constraint (7) ensures that there is enough PRBs for the download using its maximum PRB consumption for a given sector and period, except the last period:

$$y_{csp} \geq k_{csp}(x_{csp} - f_{cp}), \quad \forall c \in C, s \in S, p \in P \quad (7)$$

Both Constraints (6) and (7) **reflect Car Constraint #3.**

Constraints – MIP

Only one (pseudo-) finish time

$$f_{cp^{final}} = a_{cp^{final}}, \quad \forall c \in C \quad (8)$$

$$f_{cp} \leq 1 - \sum_{p' > p} a_{cp'} / |P|, \quad \forall c \in C, p \in P \setminus p^{final} \quad (9)$$

Constraints – MIP

Constraint (10) ensures that the total PRB utilization during the downloads does not exceed the PRB capacity in the sector for a given period:

$$\sum_{c \in C} y_{csp} \leq 100 - PRB_{sp}, \quad \forall s \in S, p \in P \quad (10)$$

Constraint (11) limits the number of simultaneous downloads:

$$\sum_{c \in C} a_{cp} \leq C^{max}, \quad \forall p \in P \quad (11)$$

Constraint (12) guarantees that the download is completed for all cars:

$$\sum_{s \in S} \sum_{p \in P} \gamma_{sp} y_{csp} = d_c, \quad \forall c \in C \quad (12)$$

Objective function – MIP

Minimize the average completion time (to improve schedule balance)

$$\min \sum_{c \in C} z_c / |C|, \quad (13)$$

$$\text{subject to } z_c \geq pa_{cp}, \quad c \in C, p \in P \quad (14)$$

where $z \in \mathbb{Z}^+$ is a variable that defines the makespan of each car.

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Input considerations

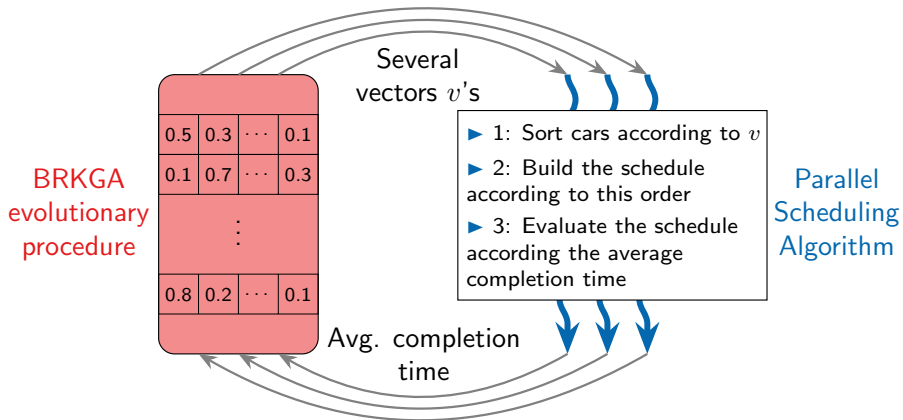
- A campaign is usually **very large**. It may have:
 - ▶ Millions of cars
 - ▶ Hundreds of thousands of sectors
 - ▶ Weekly to monthly schedules with hundreds to thousands of periods:
 - Coarse to fine granularity of the network/car behavior (we selected 15-minute time bins)

Dimensionality reduction

- Pre-processing:
 - ▶ Reduce the size of the problem by segmenting cars by geographical region
 - ▶ Pre-schedule rarely seen cars
 - ▶ Pre-schedule predictable cars that appear during non-busy hours
- The remaining segments to schedule are still large:

Subset	Cars			Radios			Car/Radio Ratio
	Min.	Max.	Median	Min.	Max.	Median	
Category 1	505	45,771	5,710	1,463	21,913	5,287	1.53±1.18
Category 2	107	16,844	1,514	1,262	65,456	5,071	0.42±0.40

Solution: Biased Random-Key Genetic Algorithm



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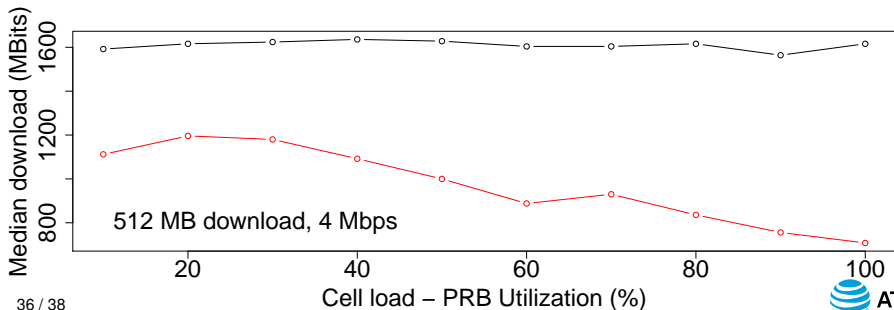
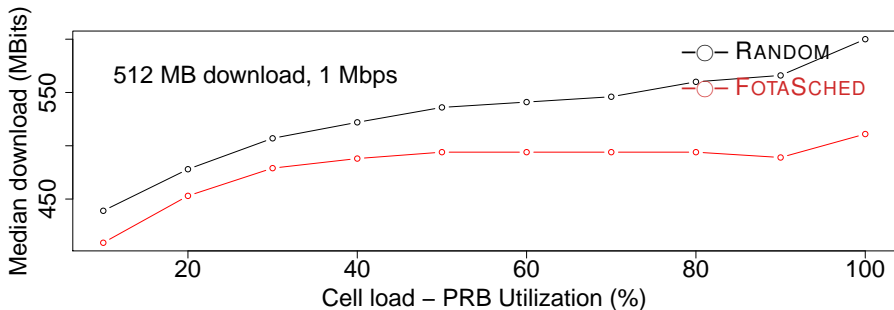
FOTA campaign simulation parameters

- 1,000,000 cars
- 200,000 sectors
- PRB model for each day of the week and 15-minute timebins makes 672 data points per cell
- Download sizes: 128 MB and 512 MB
- Download rate: 1 Mbps, 2 Mbps, 50 Mbps (proxy for “unlimited” in LTE)

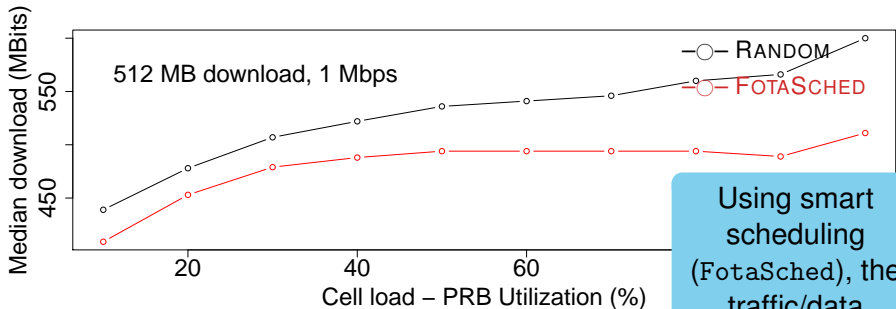
Scheduling results for the simulation scenarios

MBR (Mbps)	Size (MB)	Scheduling Strategy	Startup delay (minutes)	Incomplete downloads	Data on busy radios
1	128	RANDOM FOTASCHED	397 189 (52%)	53K 41K (22%)	6.5% 4.1%
	512	RANDOM FOTASCHED	397 266 (33%)	108K 97K (10%)	7.5% 7.1%
4	128	RANDOM FOTASCHED	397 194 (51%)	36K 27K (25%)	6.2% 6.1%
	512	RANDOM FOTASCHED	397 182 (54%)	108K 44K (59%)	6.5% 4.4%
50	128	RANDOM FOTASCHED	397 199 (49%)	24K 19K (20%)	— —
	512	RANDOM FOTASCHED	397 193 (51%)	30K 24K (20%)	— —

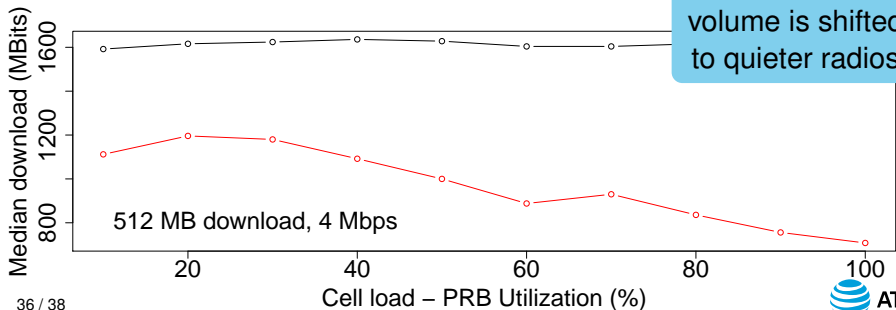
Data allocation to radio by PRB decile



Data allocation to radio by PRB decile

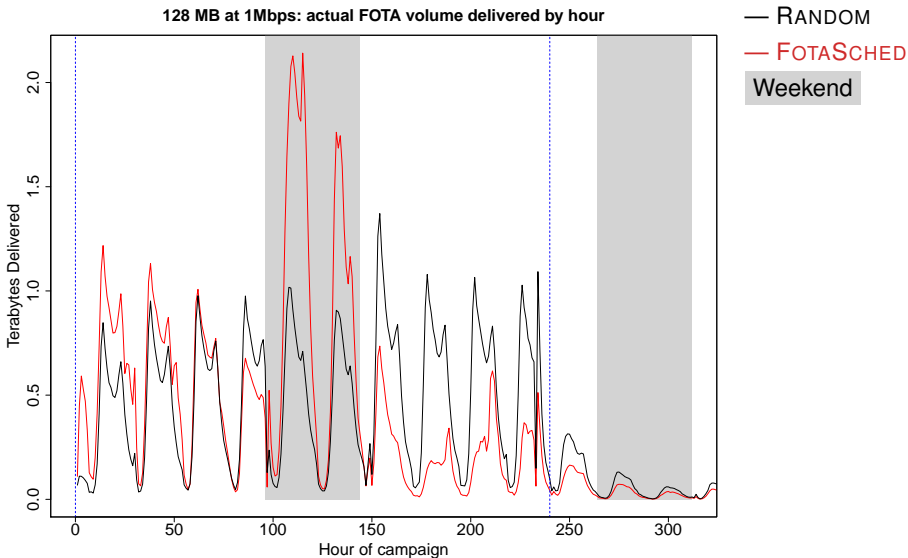


Using smart scheduling (FotaSched), the traffic/data volume is shifted to quieter radios



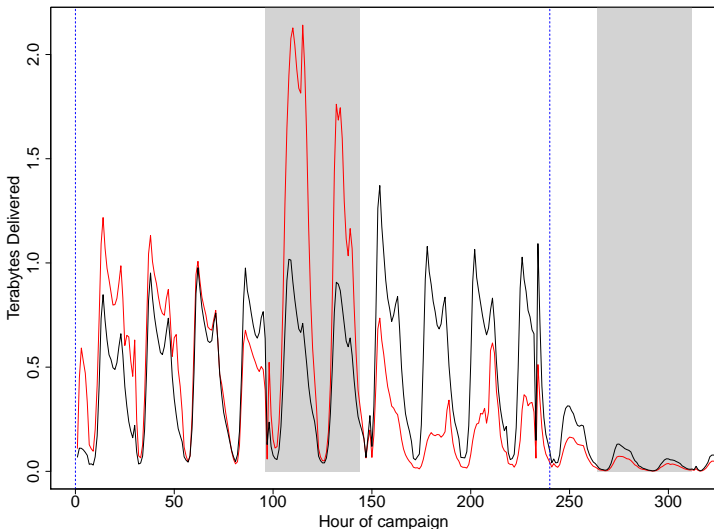
FOTA volume (TB) delivery over the campaign time

128 MB at 1Mbps: actual FOTA volume delivered by hour



FOTA volume (TB) delivery over the campaign time

128 MB at 1Mbps: actual FOTA volume delivered by hour



— RANDOM
— FOTASCHED
Weekend

Using smart scheduling (FotaSched), the traffic/data volume is shifted to quieter radios (weekends) and front part of the campaign

Thank you!



C.E. Andrade, S.D. Byers, V. Gopalakrishnan, E. Halepovic, D.J. Poole, L.K. Tran, C.T. Volinsky. *Connected cars in a cellular network: A measurement study*. Proceedings of the 17th ACM Internet Measurement Conference (IMC 2017), London, 2017.



C.E. Andrade, S.D. Byers, V. Gopalakrishnan, E. Halepovic, D.J. Poole, L.K. Tran, C.T. Volinsky. *Managing massive firmware-over-the-air updates for connected cars in cellular networks*. Proceedings of the 2nd ACM International Workshop on Connected and Automated Vehicle Mobility (CarSys 2017, a workshop of MobiCom 2017). Snowbird, USA, 2017.