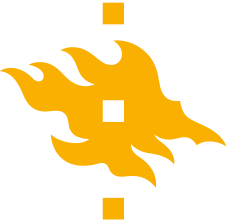


White spaces for sustainable mobile data offloading

Suzan Bayhan (University of Helsinki),

University of Helsinki (UH), Dept. of Computer Science

Collaborative Networking Research Group (CoNe)

http://www.hiit.fi/u/bayhan

Joint work with
Liang Zheng & Mung Chiang (Princeton Univ.)
Jiasi Chen (UC Riverside)
Mario Di Francesco, Gopika Premsankar (Aalto Univ.)
Jussi Kangasharju, Aleksandr Zavodovski (Helsinki Univ.)

April 18, 2016 Nokia Bell Labs, Dublin

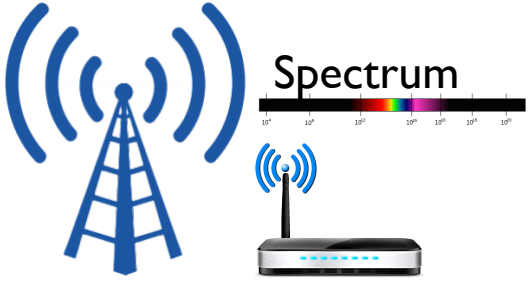
Wireless traffic jam

- Exponential growth in wireless traffic
  - Wireless-capable mobile devices
  - Video traffic
- How to handle/narrow the gap between *network capacity* growth and *the data traffic* growth?

Content

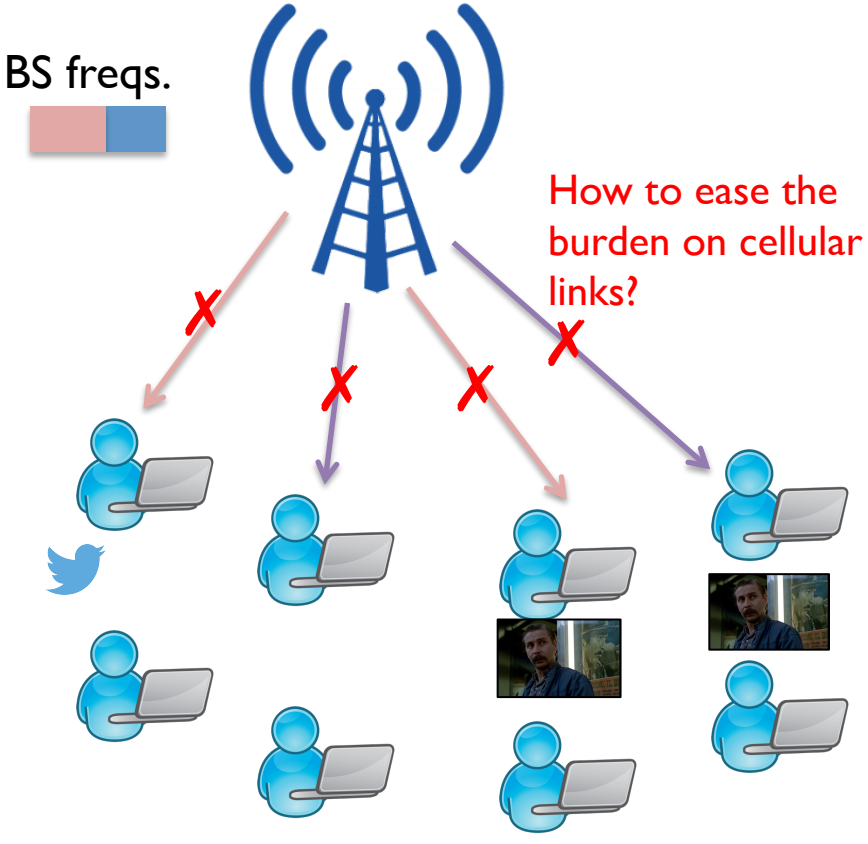
Network resources

Users

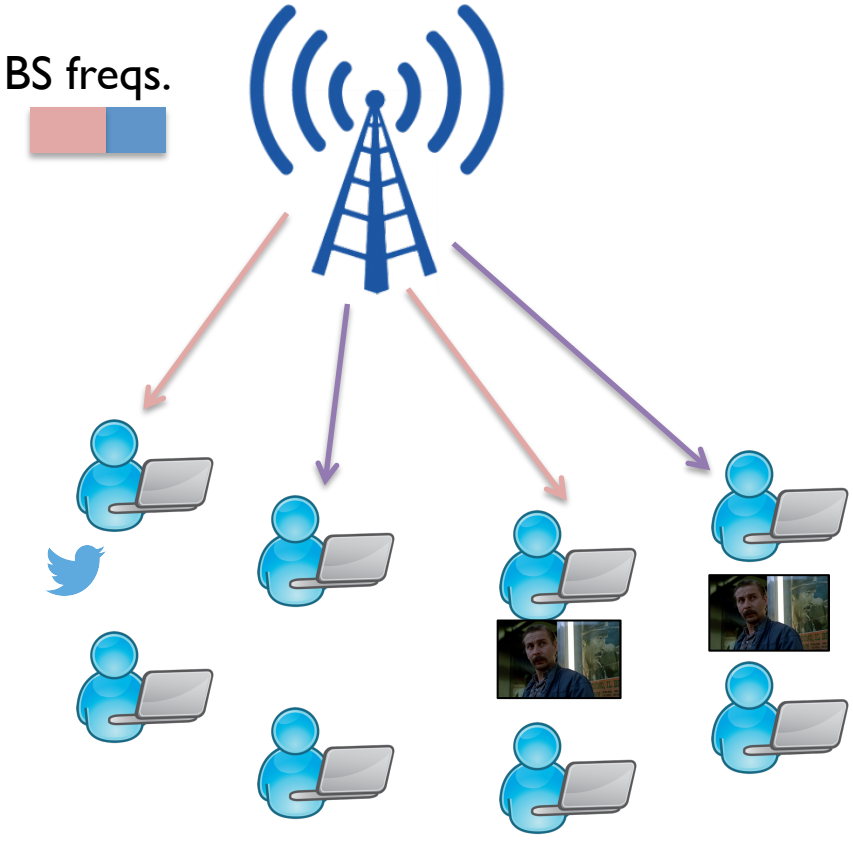


How to allocate *network resources* for a satisfying user experience?

Handling the data tsunami



Handling the data tsunami



Install additional infrastructure

Not cost-effective, not green

Offload to small cells, WiFi ✔

Implemented efficiently (51%), backhaul?

Exploit the Zipf property

Edge caches, less load on the backhaul

Exploit short-range tx (D2D) ✔

A key component of 5G

Exploit mobility ✔

Mobile users as data carriers

Radio spectrum: sharing the wireless roads

Image from http://nybc.net/

Radio spectrum: sharing the wireless roads

- Inefficient: very strictly regulated via auctions, almost a century old
- Opportunistic sharing: sense and transmit till a license holder re-appears

Image from http://nybc.net/

Radio spectrum: sharing the wireless roads

- Inefficient: very strictly regulated via auctions, almost a century old
- Opportunistic sharing: sense and transmit till a license holder re-appears

Our proposal: white space offloading

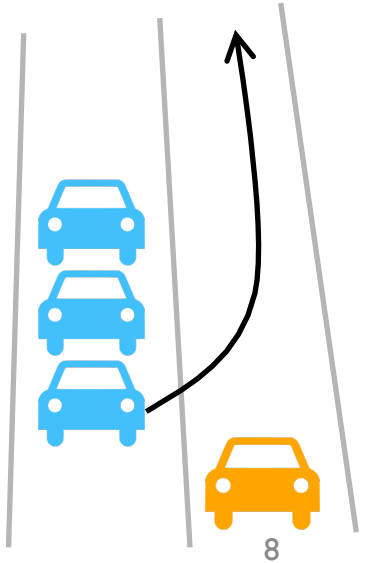


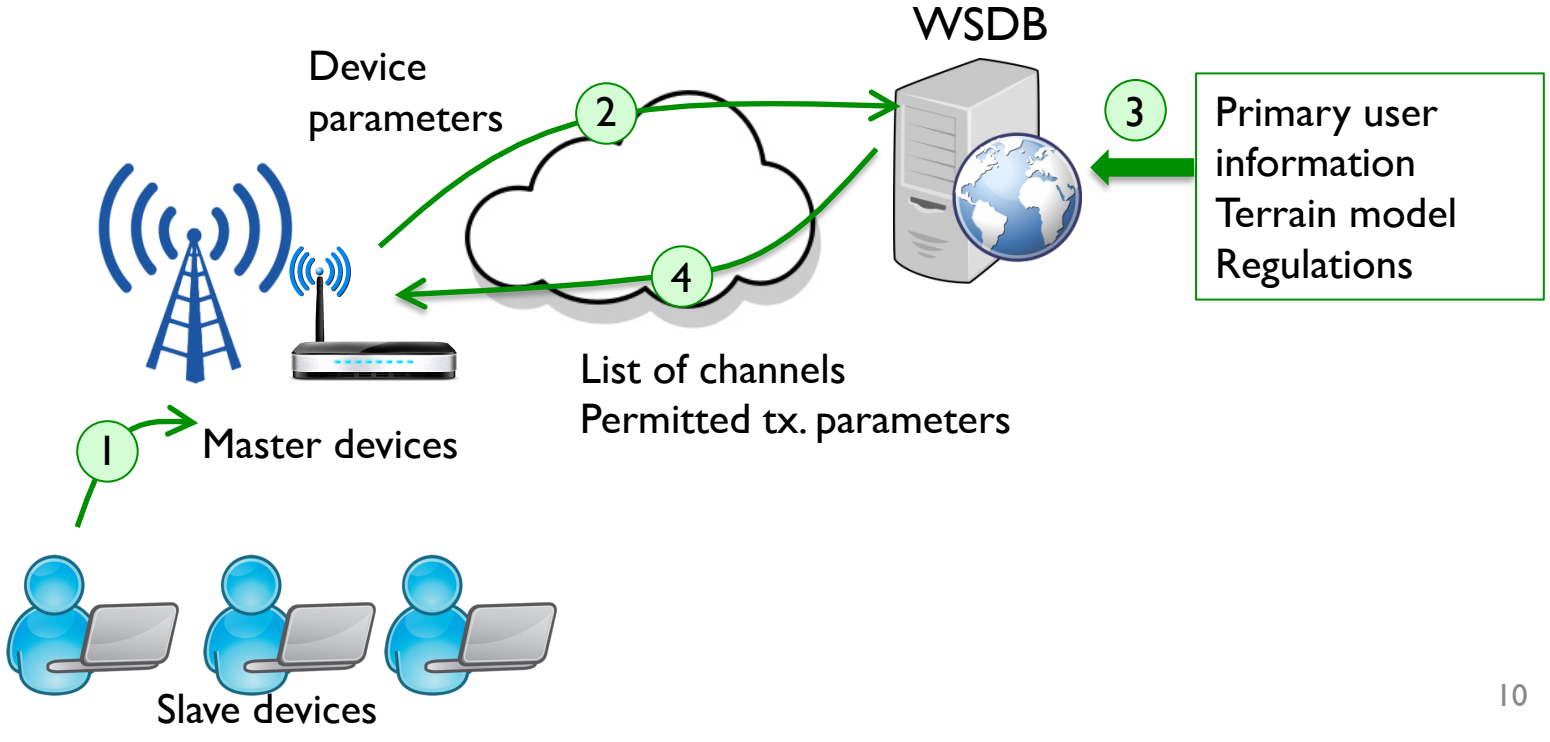
Image from http://nybc.net/

White spaces

- White space: Spatiotemporally unused spectrum open to unlicensed users
- TV white spaces (TVWS): 54-698 MHz in US, 470-790 MHz in Europe

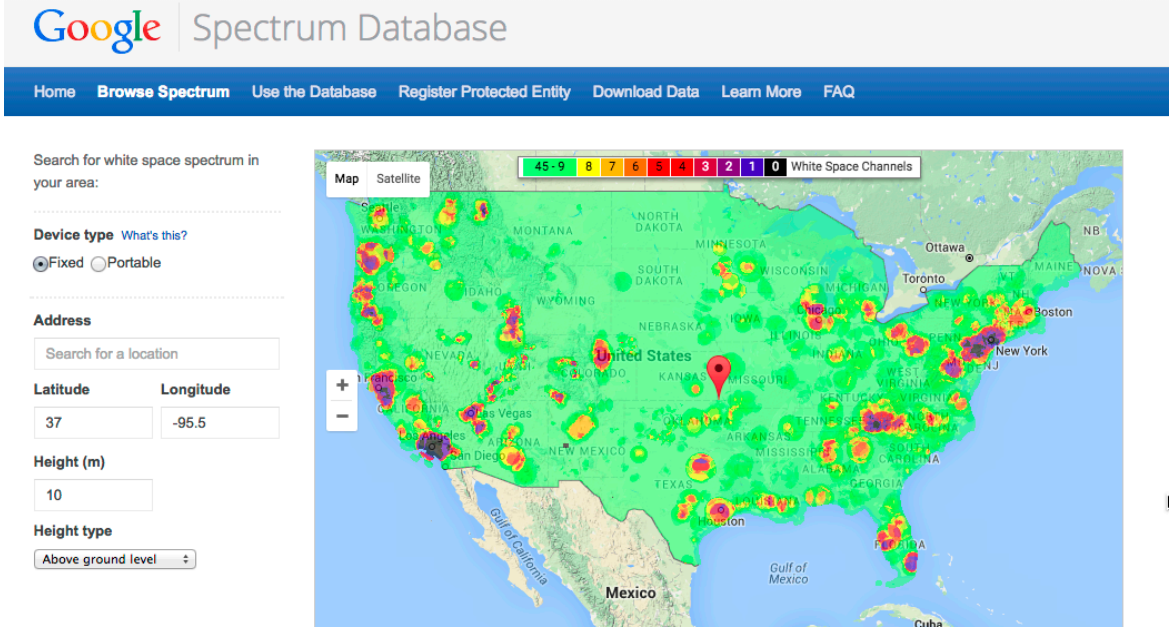
White spaces

- White space: Spatiotemporally unused spectrum open to unlicensed users
- TV white spaces (TVWS): prime range: 54-698 MHz in US, 470-790 MHz in Europe
- White space databases (WSDB): wireless microphones, PMSE devices



White spaces

- White space: Spatiotemporally unused spectrum open to unlicensed users
- TV white spaces (TVWS): 54-698 MHz in US, 470-790 MHz in Europe
- White space databases (WSDB)

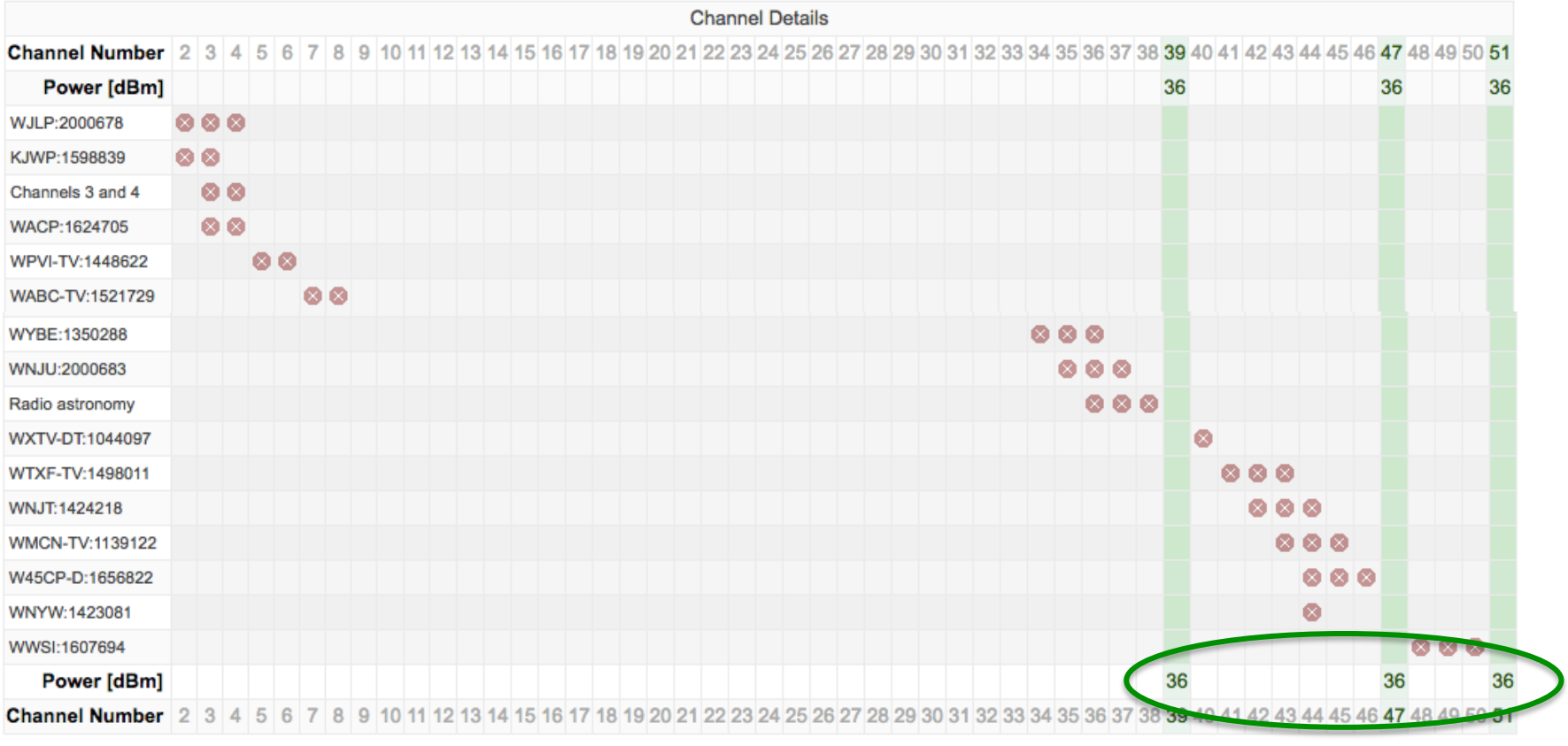


US: 2012
Google, Spectrum Bridge, Microsoft …

UK: 2015
Fairspectrum Oy, Nominet UK, Sony Europe Limited
Spectrum Bridge Incorporated

White spaces for *fixed devices* in New Jersey

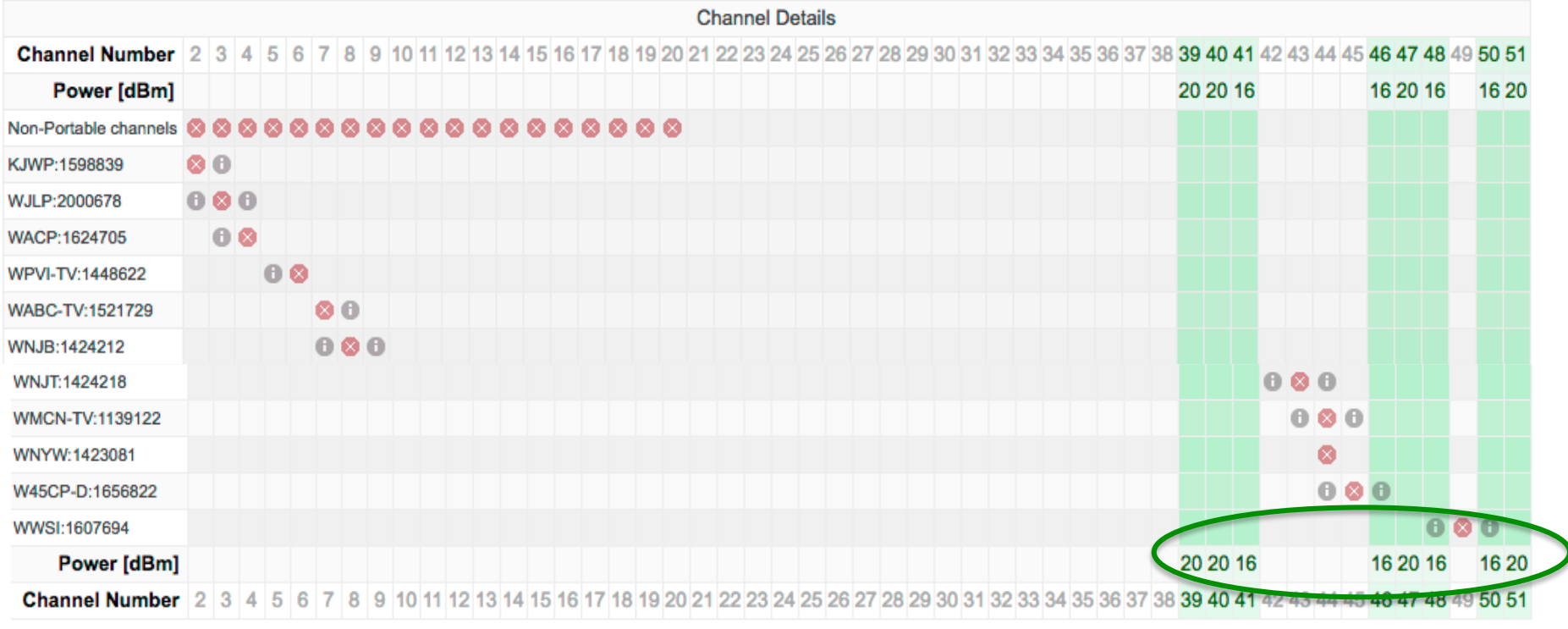
Available Spectrum: 3 Channels (18 MHz)



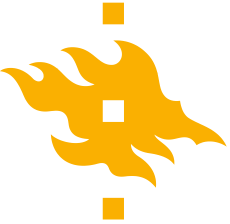
Power level: 4 W

White spaces for *portable devices* in New Jersey

Available Spectrum: 8 Channels (48 MHz)



Power levels 40 mW and 100 mW

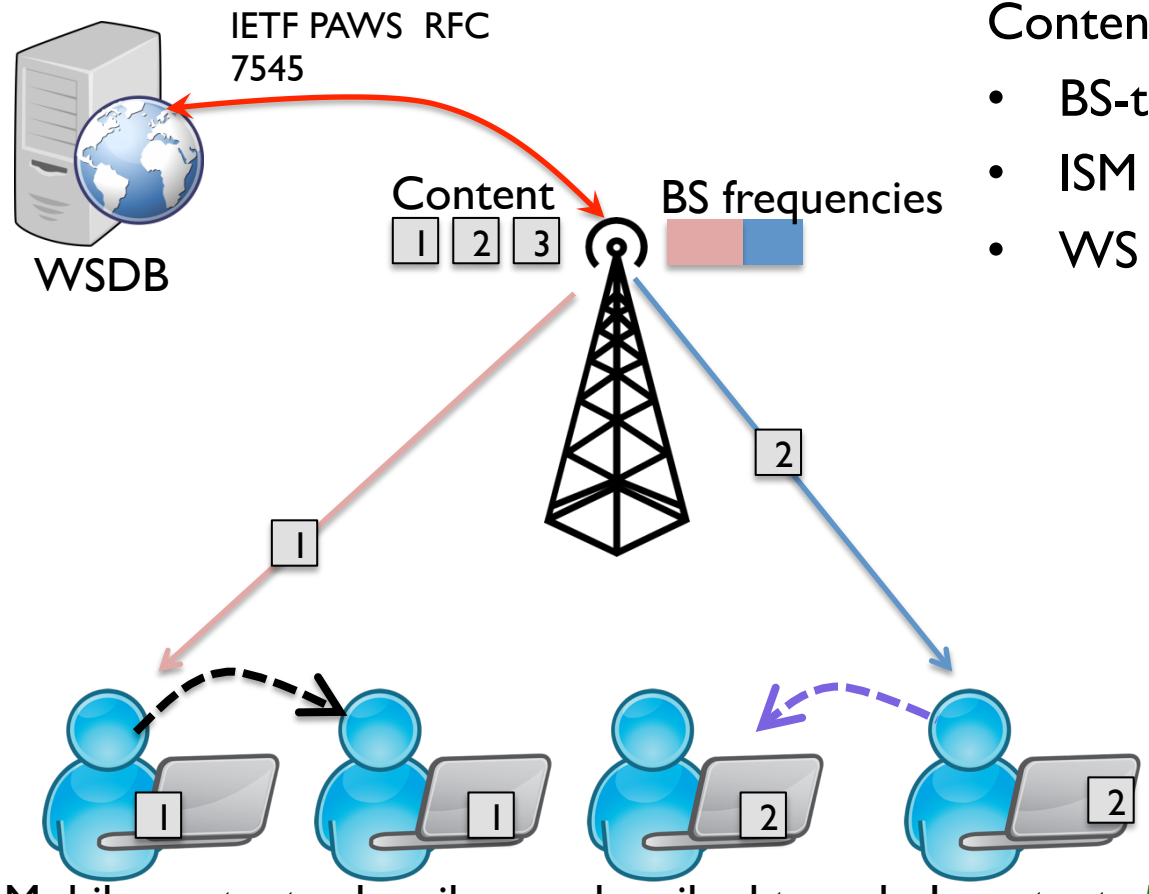


More white space capacity for lower power transmission:

white space (opportunistic) offloading

Mobile Content Offloading in Database-Assisted White Space Networks
Suzan Bayhan, Gopika Premsankar, Mario Di Francesco, and Jussi Kangasharju, CrownCom 2016

Mobile opportunistic data offloading

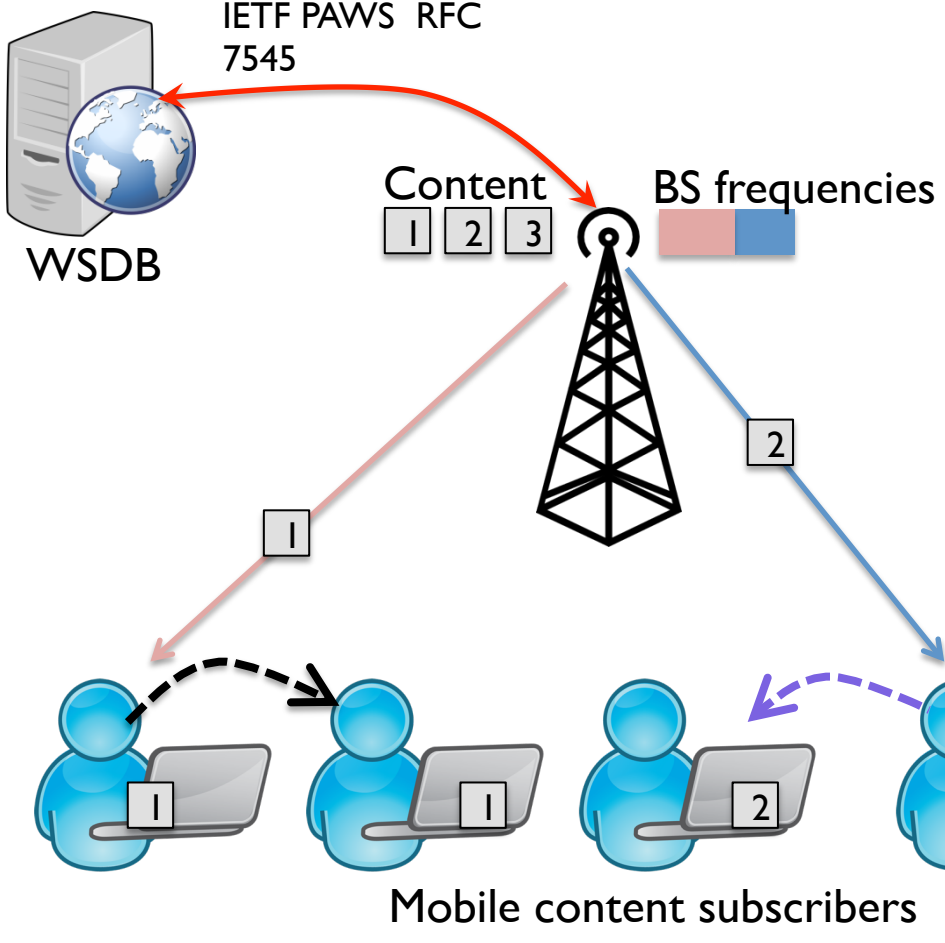


Content delivery (delay-tolerant)

- BS-to-user tx: Unicast transmission
- ISM offloading
- WS offloading

Mobile content subscribers: subscribed to only 1 content, *deadline*

Mobile opportunistic data offloading



Content delivery (delay-tolerant)

- BS-to-user tx: Unicast transmission
- ISM offloading
- WS offloading

Our aim: maximize the offloaded traffic
= minimize the cellular traffic

Exploiting

- the user mobility,
- short-range communications,
- white spaces

Distributor selection problem

BS selects users *(distributors)* which will receive the content *directly* from the BS and deliver to other subscribers via *opportunistic offloading*

Users that cannot receive the content before the deadline, eventually receive it from the BS *directly*

BS:
- F frequencies
- knows the contact rates among nodes

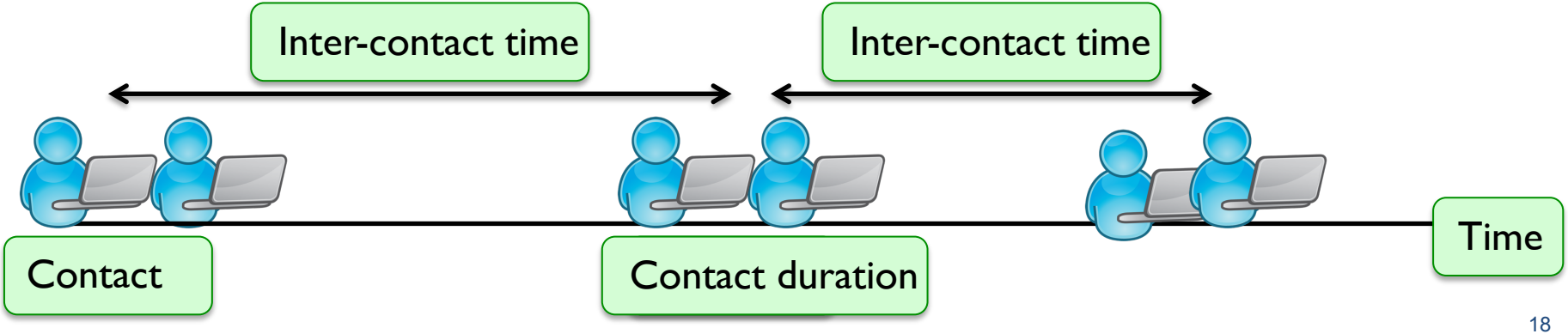
Users:
- contact rates for WS and ISM modes
- subscription info (driven by content popularity distribution)
- contact duration is long enough to offload content completely

Content:
- size, popularity, deadline for delivery

WSDB:
- White spaces
- Regulations

Key insight for the design of a smart scheme

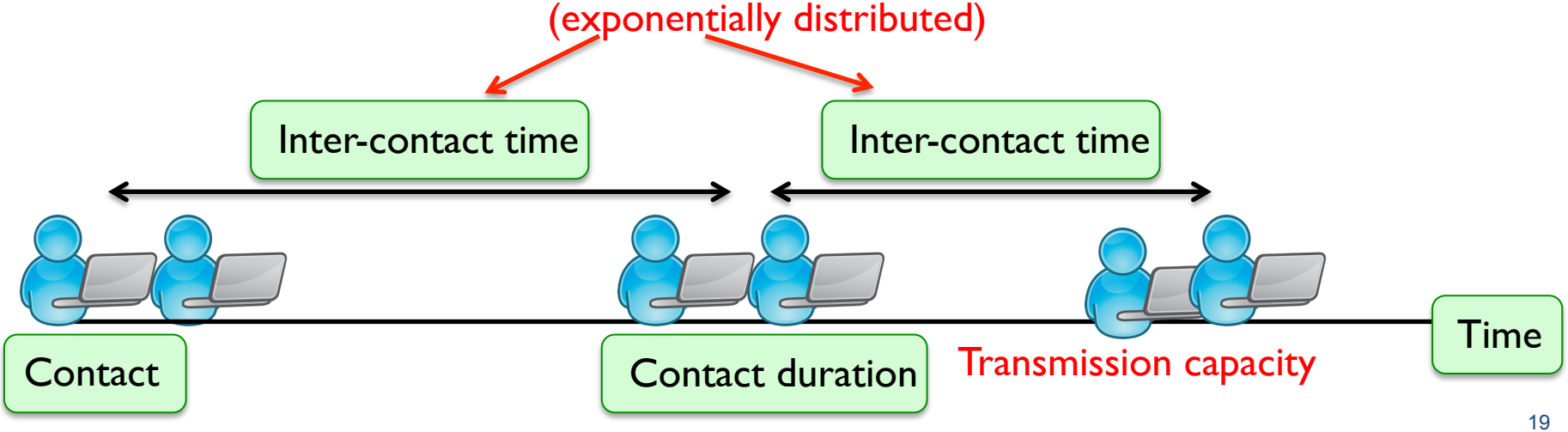
- Select users as distributors which have *high chance* of meeting other users subscribed to the same content before the content deadline
- Avoid users who have *high chance* of receiving content from distributors before the content deadline



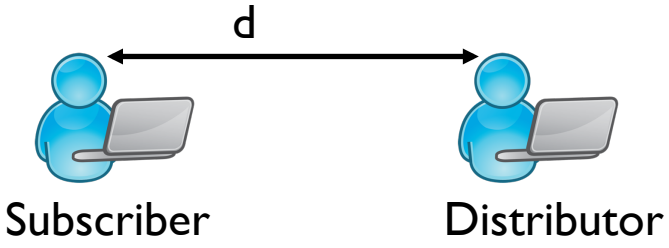
Key insight for the design of a smart scheme

- Select users as distributors which have *high chance* of meeting other users subscribed to the same content before the content deadline
- Avoid users who have *high chance* of receiving content from distributors before the content deadline

Hard problem due to the stochastic contact events



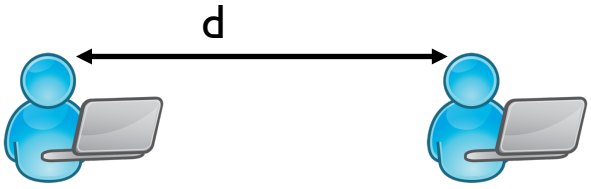
Opportunistic offloading



ISM offloading is possible only if:
- d < offloading range

WS offloading is possible only if
- d < offloading range and
- user receives an available ws from the WSDB

Opportunistic offloading



	TVWS	ISM
Channel bandwidth	8 MHz (US), 6 MHz (Europe)	22 MHz ☺
Range	Longer range (km) ☺	Shorter range (10-100s m)
Availability	received from WSDB	Available ☺

ISM offloading is possible only if:
- d < offloading range

WS offloading is possible only if
- d < offloading range and
- user receives an available ws from the WSDB

Inter-contact time: exponentially distributed with parameter

λ^{ws}_{ij}

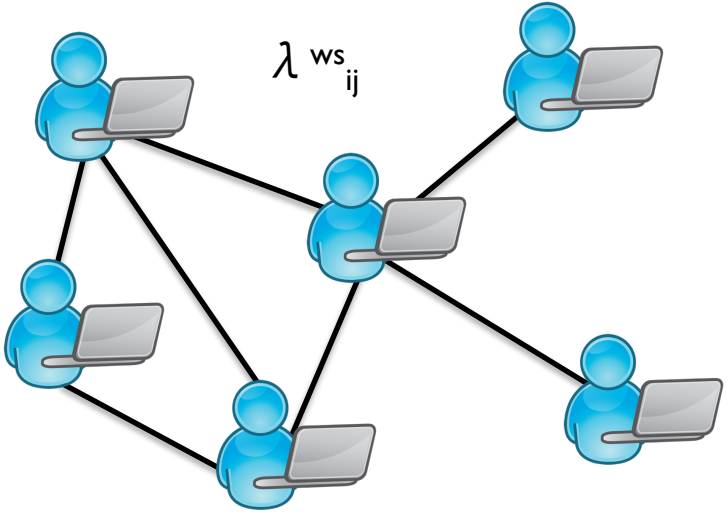
λ^{opp}_{ij}

WSDB abstraction

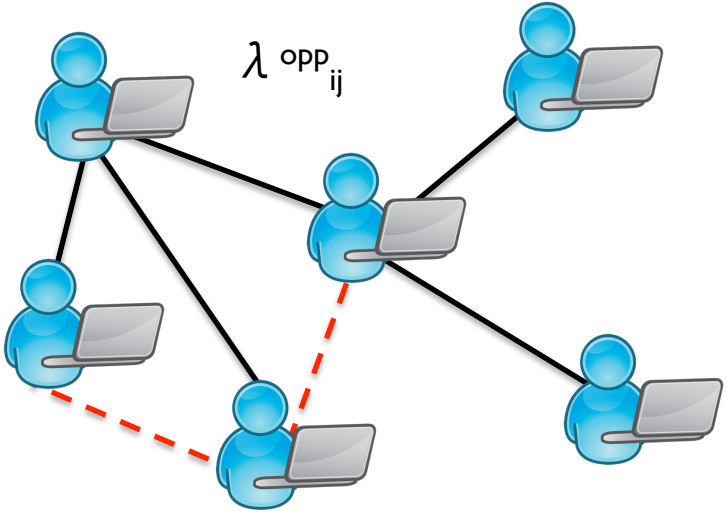
- Requirements according to IETF PAWS, ETSI EN 301 598, IEEE 802.11af
  - Re-query if location changes more than 50 m from the last query location
  - Cease transmission if no connection to the database
  - *Probability of outage (p_{out}):* node cannot use white spaces
- Reported inaccuracy in WSDB in US, e.g. bogus entries, incorrect location, etc.
  - May lead to collision between white space and licensed users
  - *Unregistered primary user (PU) probability (p_{un})*: results in collision and packet loss

For content k: connectivity graph of its subscribers

Connectivity graph in *white spaces*

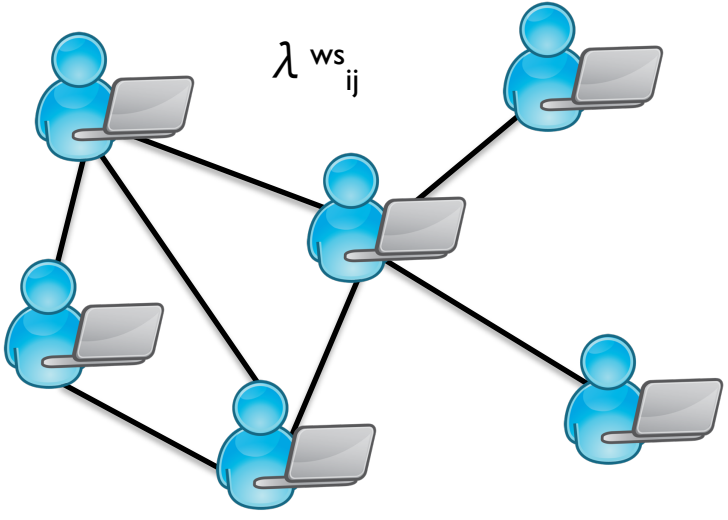


Connectivity graph in *ISM*



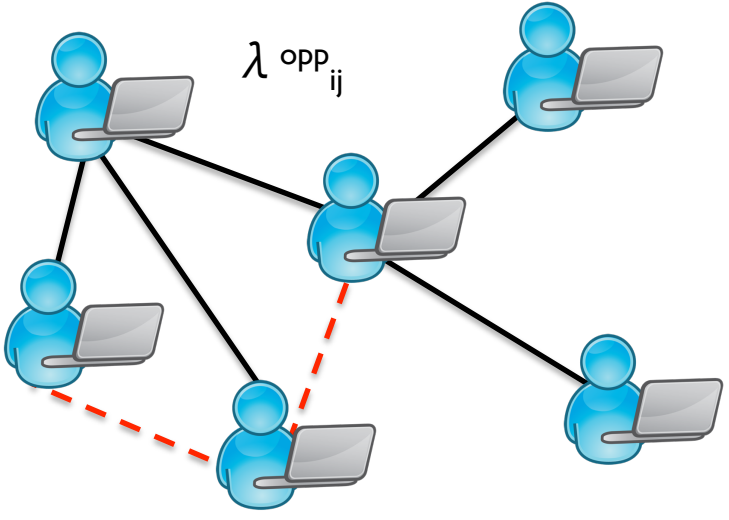
For content k: connectivity graph of its subscribers

Connectivity graph in *white spaces*



Prob(user in ws range but out of ISM range)
(1-Pr.outage)(1-P.collision)

Connectivity graph in *ISM*

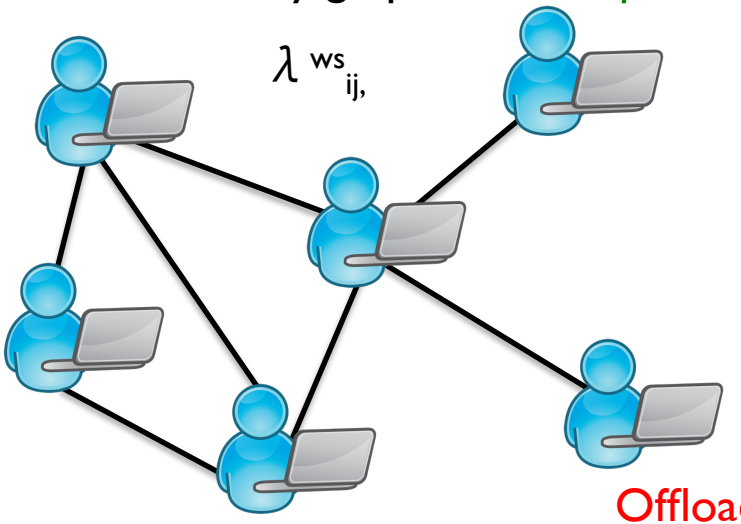


Content deadline T_k
Prob(inter-contact time < T_k)

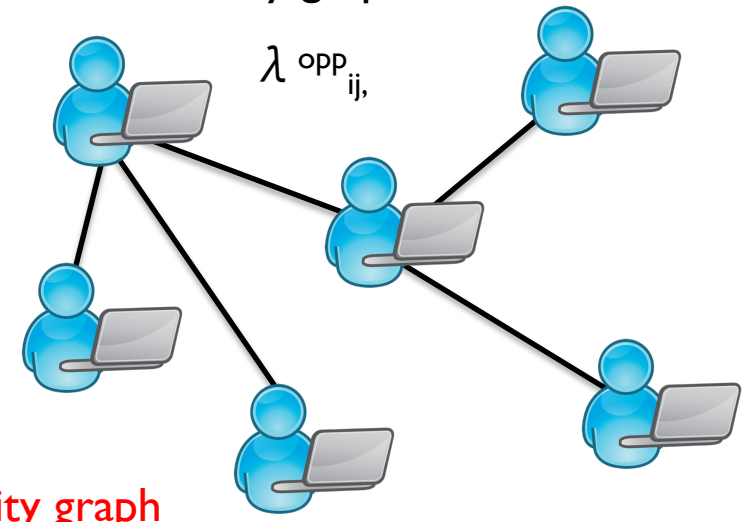
$$p_{i,j,k}^{opp} = 1 - \mathrm{e}^{-\lambda_{i,j}^{opp} T_k}$$

Probability of getting content via offloading

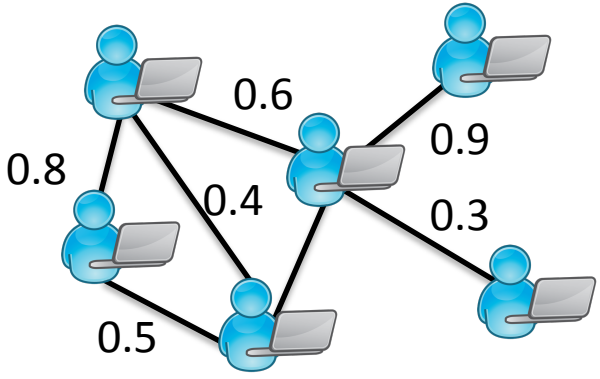
Connectivity graph in *white spaces*



Connectivity graph in *ISM*



Offloading probability graph



Which *F* users to select as distributors given offloading probability graph of all contents?

Formal definition of distributor selection problem

- Size of content k: l_k
- Subscribers of content k: S_k
- Distributors of content k: D_k
- Those who cannot get the content from any of the distributors before the deadline

- *Target-set selection is an NP-hard problem*

D. Kempe, J. Kleinberg, and Eva Tardos, "Maximizing the Spreadof Influence through a Social Network," Proc. Ninth ACM SIGKDD Int'l Conf. Knowledge Discovery and Data Mining (SIGKDD '03), pp. 137-146, Aug. 2003

$$\max_{\mathbf{X}} \sum_{k=1}^{K} l_k \left(S_k - D_k - \sum_{i \in \mathcal{S}_k \setminus \mathcal{D}_k} (1 - p_{i,k}) \right)$$

$$S_k = \sum_{i=1}^{N} y_{i,k} \qquad \forall k \in \mathcal{C}$$

$$D_k = \sum_{i=1}^{N} x_{i,k} \qquad \forall k \in \mathcal{C}$$

$$p_{i,k} = 1 - \prod_{j \in \mathcal{D}_k} (1 - p^{opp}_{i,j,k} - p^{ws}_{i,j,k}) \quad \forall i \in \mathcal{S}_k, k \in \mathcal{C}$$

$$p^{opp}_{i,j,k} = 1 - \mathrm{e}^{-x_{j,k} \lambda^{opp}_{i,j} T_k} \quad \forall i, j \in \mathcal{N}, k \in \mathcal{C}$$

$$p^{ws}_{i,j,k} = (\mathrm{e}^{-x_{j,k} \lambda^{opp}_{i,j} T_k} - \mathrm{e}^{-x_{j,k} \lambda^{ws}_{i,j} T_k})(1 - p^{sh})(1 - p^{un}) \quad \forall i, j \in \mathcal{N}, k \in \mathcal{C}$$

$$p_{i,k} = 0 \qquad \forall i \in \mathcal{N} \setminus \mathcal{S}_k, k \in \mathcal{C}$$

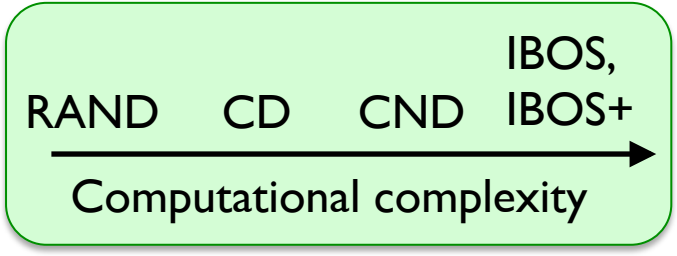
$$x_{i,k} \leqslant y_{i,k} \qquad \forall i \in \mathcal{N}, k \in \mathcal{C}$$

$$\sum_{k \in \mathcal{C}} D_k \leqslant F$$

$$x_{i,k} \in \{0, 1\} \qquad \forall i \in \mathcal{N}, k \in \mathcal{C}.$$

Naïve schemes exploiting content and node diversity

- Randomly select distributors (RAND)
  - Every node equally likely to be selected as a distributor
- Content diversity (CD)
  - More popular content gets more distributors
- Content and node diversity (CND)
  - More popular gets more distributors, distributors are selected based on their mobility profiles



Offloading capacity-based selection

Offloading capacity of node n_i: content size multiplied by sum of probabilities this user will offload content to other users, $U(n_i) = l_k \Sigma\ p_{jik}$

- Iterative best offloader selection (IBOS)
  - Select the node with maximum offloading capacity $U(n_i)$
  - Set the probability of delivery to this user from any other user to zero
  - Update offloading capacity after each assignment

Offloading capacity

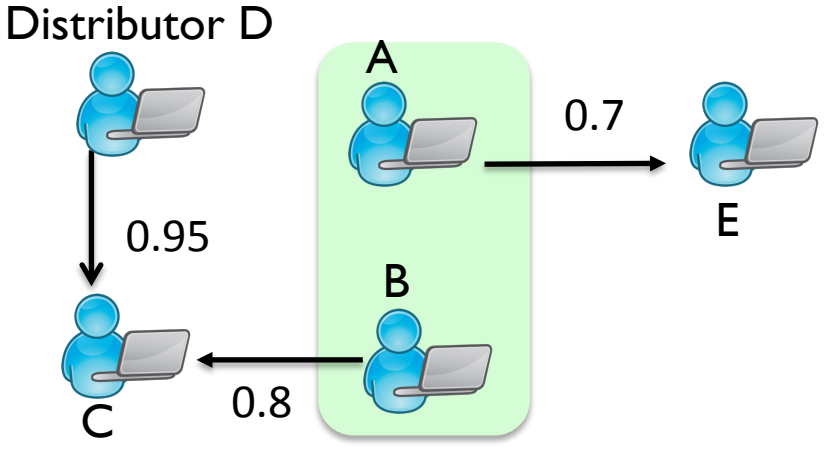
Algorithm 1 IBOS

1: $\mathbb{D} = \emptyset$ and set $p_{j,i,k} = 0$ for all i, j, k
2: **for** $n_i \in \mathcal{N}$ **do**
3: Get the content id k where $n_i \in \mathcal{S}_k$
4: **for** $n_j \in \mathcal{S}_k$ **do**
5: Calculate $p_{j,i,k}$ as in Eq. (3)
6: **for** $f = 1$ to F **do**
7: $U(n_i) = l_k \sum_j p_{j,i,k}$ for all $n_i, n_j \in \mathcal{N} \setminus \mathbb{D}$
8: Select $n_o = \arg\max U(n_i)$ where $n_i \in \mathcal{N} \setminus \mathbb{D}$
9: **if** $U(n_o) > 0$ **then**
10: $\mathbb{D} = n_o \cup \mathbb{D}$ and assign f to n_o for content delivery
11: Set $p_{o,i,k} = 0$ for all $n_i \in \mathcal{N} \setminus \mathbb{D}$
12: **else**
13: return $\mathbb{D}$
14: return $\mathbb{D}$

Offloading capacity-based selection

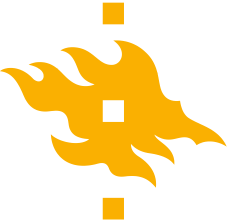
Improved IBOS (IBOS+)

- Store the probability of getting the content from distributors for each node
- Add the nodes with prob. higher than some safety threshold to safe nodes list
- Ignore safe node set while calculating utility



Comparing A and B for their offloading capacity:

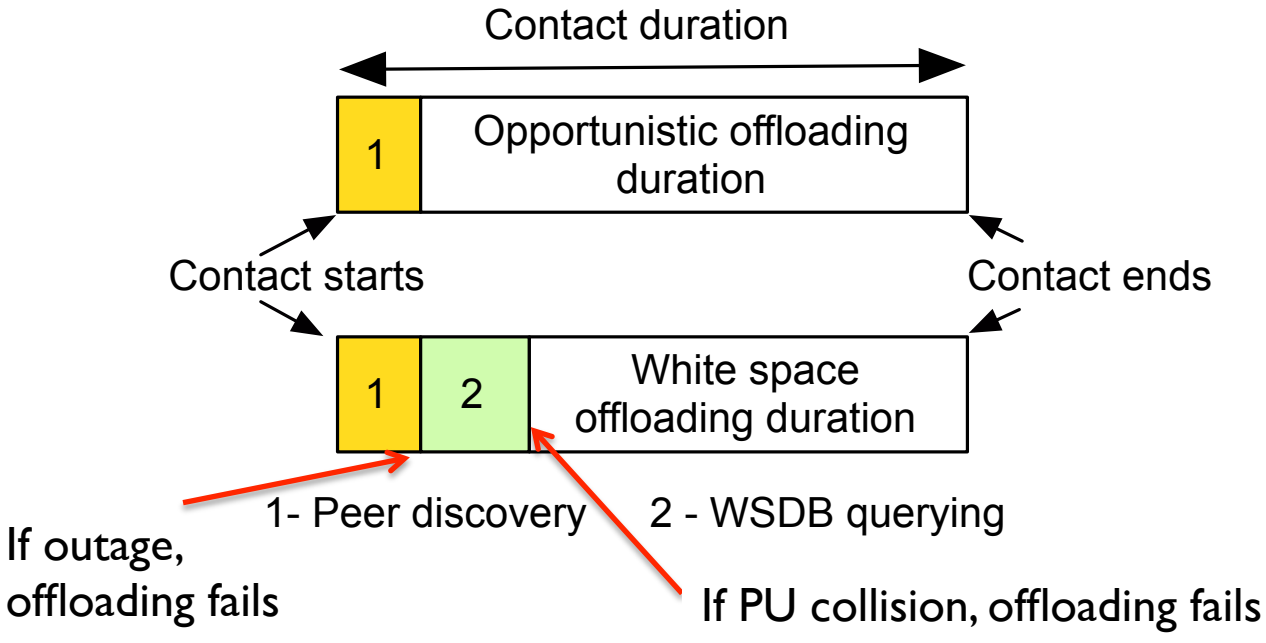
- IBOS selects B
- IBOS+ selects A, because it can reach some other node which is otherwise difficult to reach



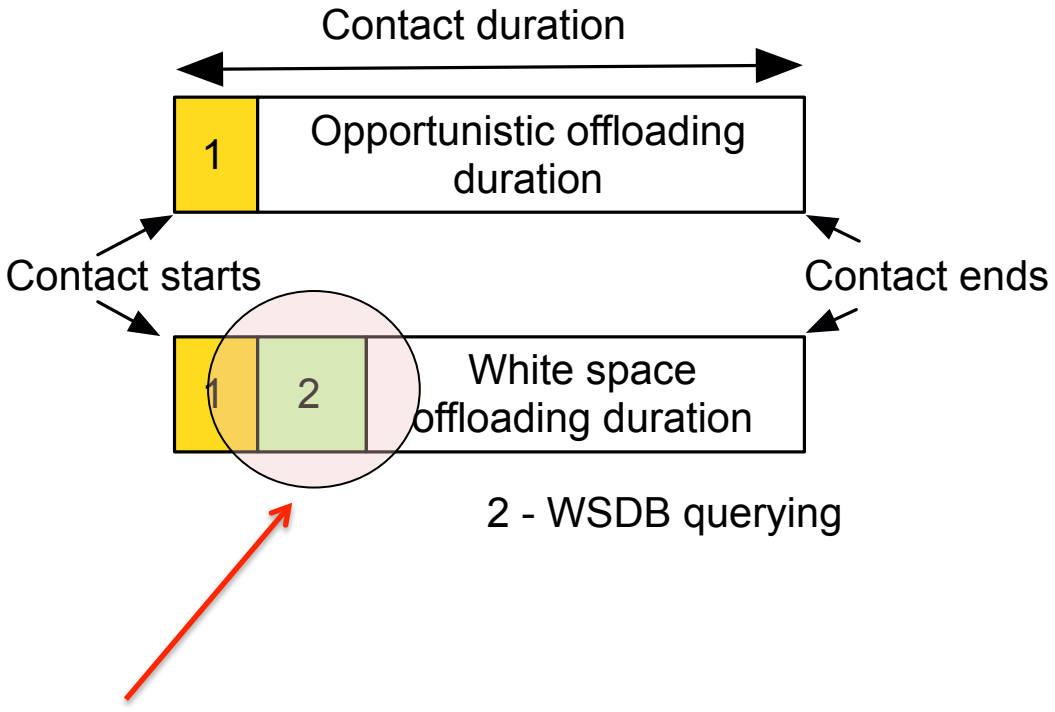
How much *effective offloading capacity* do we have?

Effective offloading capacity = effective contact duration x channel bandwidth

Effective offloading capacity (MHz sec)



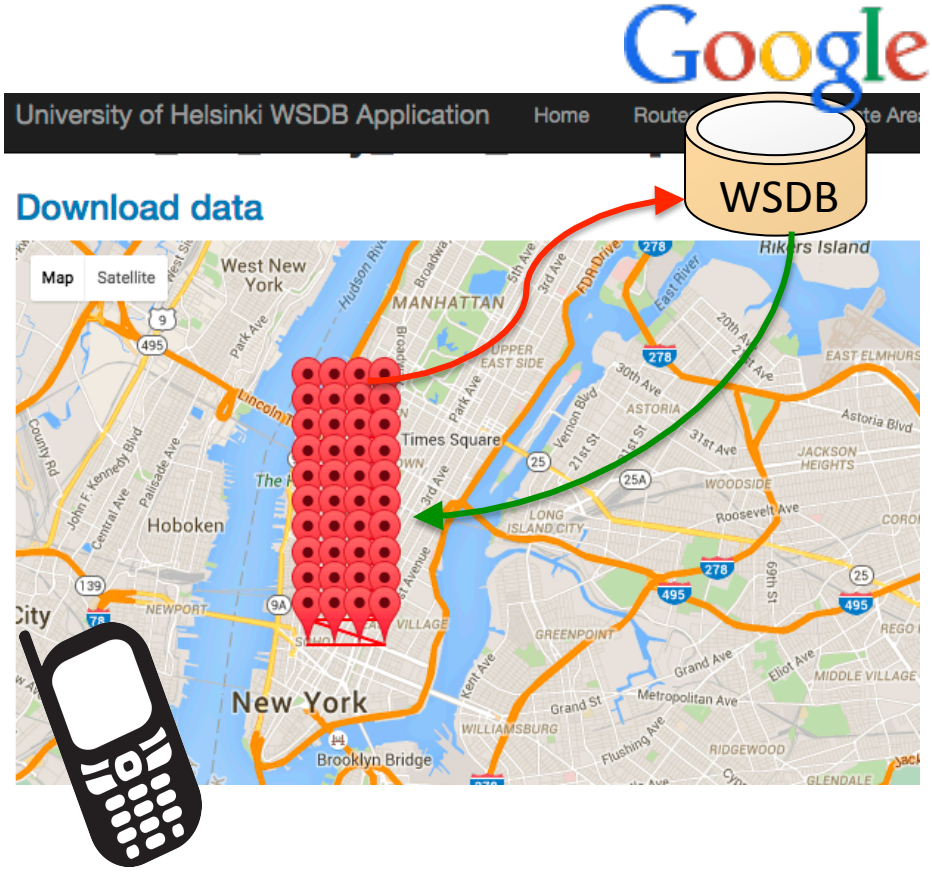
Effective offloading capacity (MHz sec)



How long is WSDB querying time?
compared to contact duration?

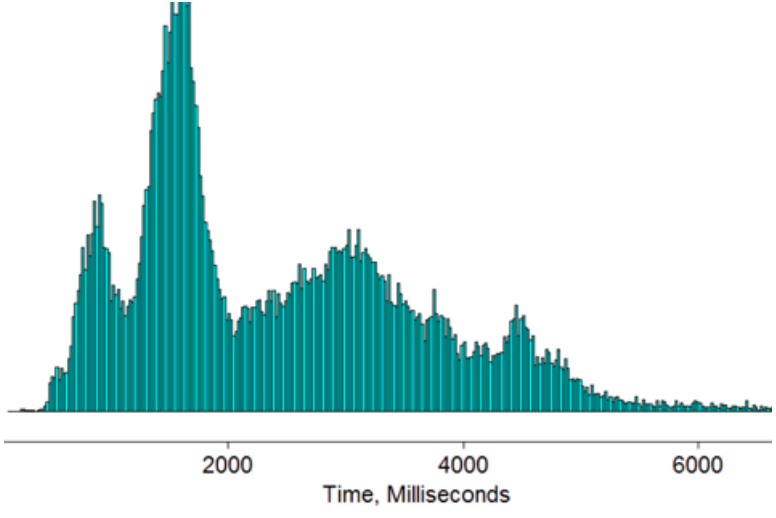
Google Spectrum Database query application

- Android application connects to Google's Spectrum Database (server possibly in US)
- Generates queries on different parts of US cities (6 months of data)
- Measurement of delay (includes app-overhead and network-delay)

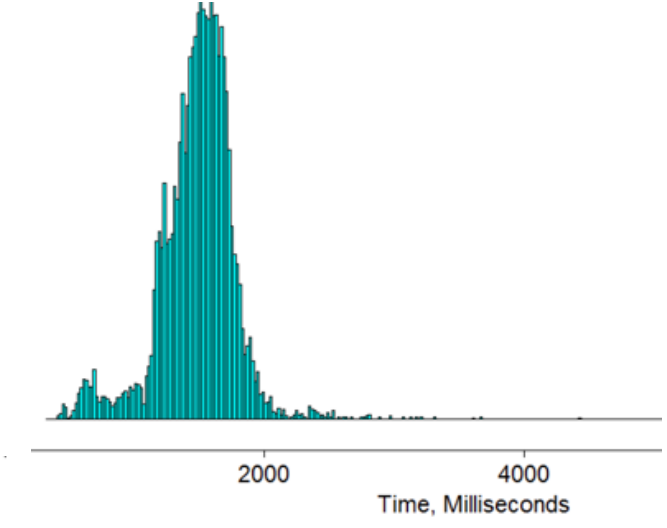


Google Spectrum Database query application

An every-day phone



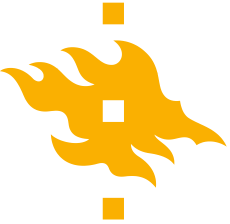
A tablet used only this purpose



90% delays are lower than 4 sec for the phone
Almost 100% delays are lower than 4 sec
Delay smaller than contact-duration

Effective offloading capacity distribution

- 200 nodes, ws range: 100 m, ISM-range: 20 m
- Mobility model based on Helsinki working-day mobility model
- Contacts of nodes: ONE simulator, record contacts and retrieve durations of contacts

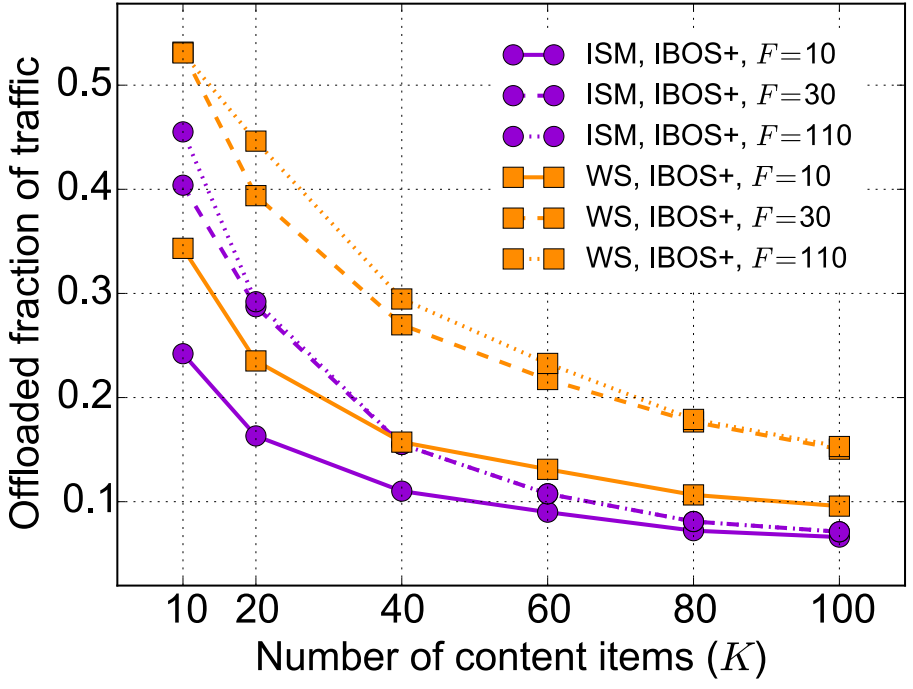


How much of this increased capacity used for content delivery?

How much white space offloading help?

- Content size: (2, 5) MB
- Content deadline: U(1, 3) hours
- Weibull content popularity dist.

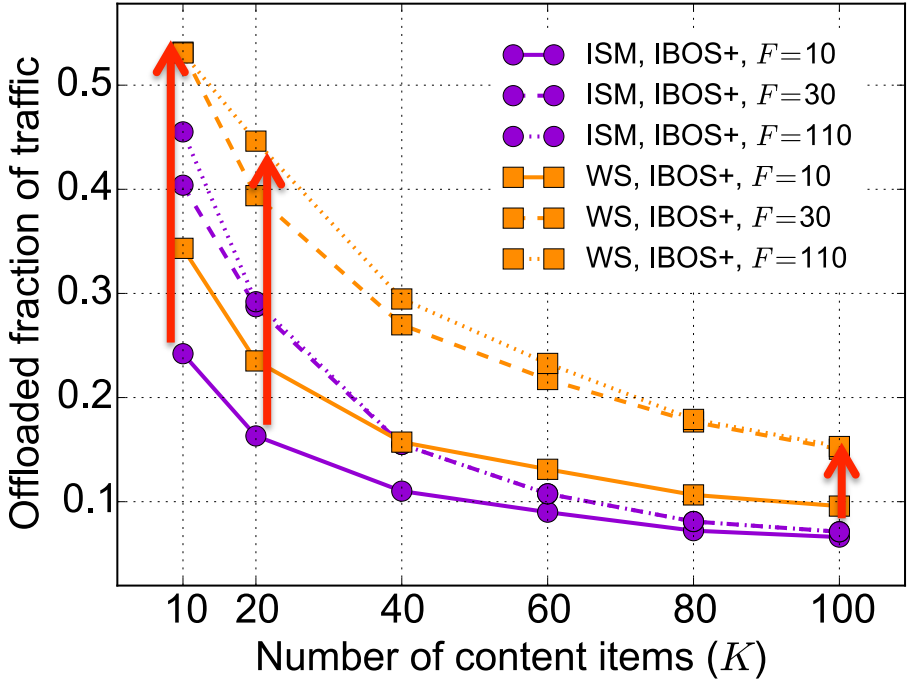
- ISM-only offloading
  - the current approach
- ISM+WS offloading



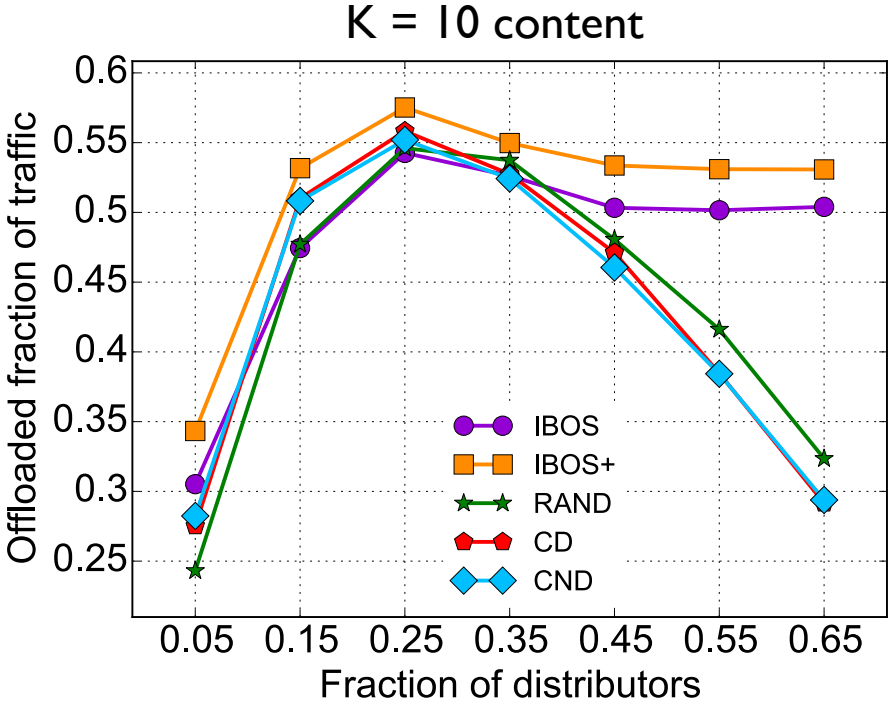
How much white space offloading help?

WS offloading increases offloaded traffic ratio about 20-40%

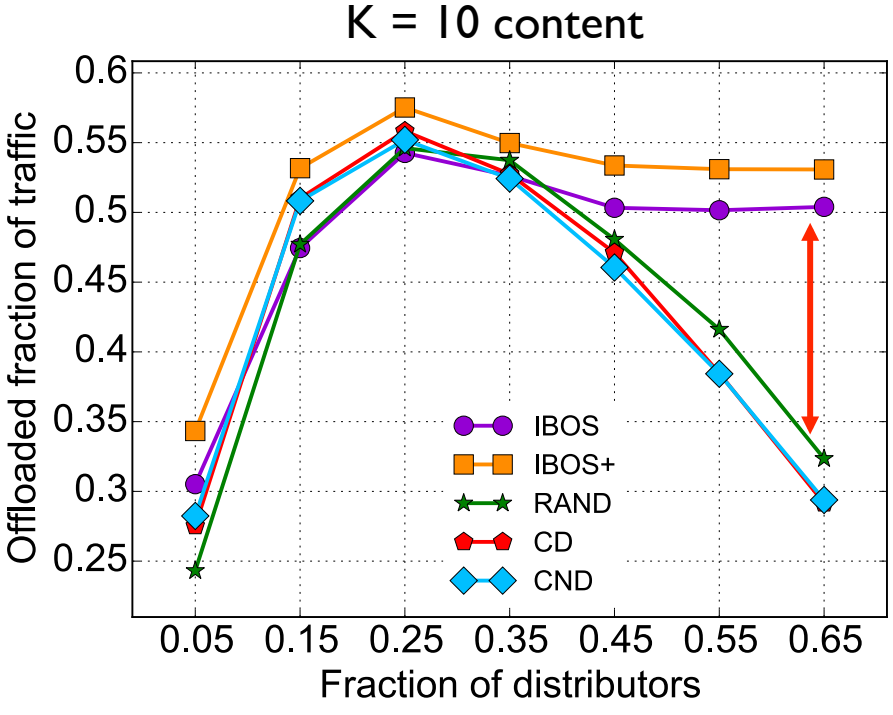
Offloaded traffic ratio depends on content diversity (high K, low offloading ratio)



Heuristics


K = 10 content
Offloaded fraction of traffic
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.05
0.15
0.25
0.35
0.45
0.55
0.65
Fraction of distributors
IBOS
IBOS+
RAND
CD
CND

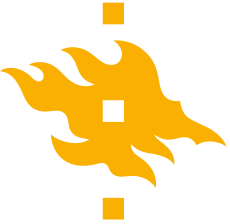
Heuristics



IBOS and IBOS+ avoid redundant selection of distributors

Summary

- *We need to exploit the free resources* for sustainably handling the gap bw. network capacity growth and wireless traffic growth
  - Mobility of increasing number of mobile devices
  - Short-range communications
  - White spaces
- There is white space capacity, especially for low power short-range communications
- White spaces are promising and many open questions
  - Interference ignored (short-range communications)
  - Contents may be large and one contact may not suffice to transmit all
  - White space access requires infrastructure (i.e., WSDB-access)



Thank you

References

- Dynamic Spectrum Alliance, Worldwide Commercial Deployments, Pilots, and Trials, Jan.2016
- Harold Feld Dr. Gregory Rose, Breaking the Logjam: Creating Sustainable Spectrum Access Through Federal Secondary Markets
- Images from http://www.iconsdb.com/