# Mobile Content Offloading in Database-Assisted White Space Networks

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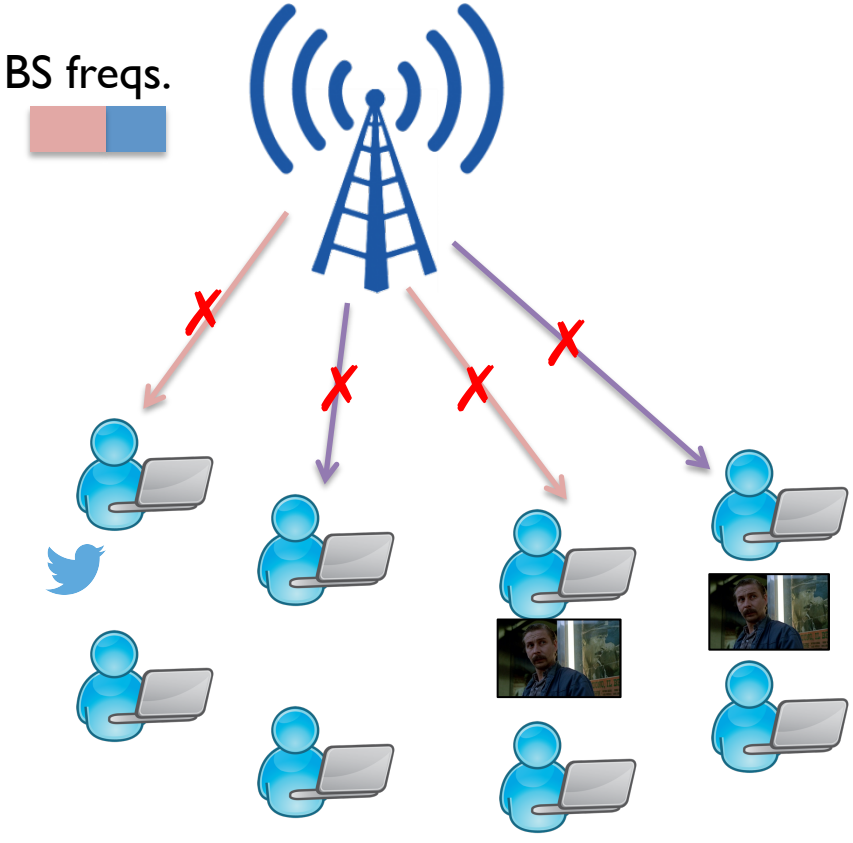
How can we narrow the gap between

*network capacity* and the exponentially increasing

*wireless data traffic*?

# Narrowing the gap



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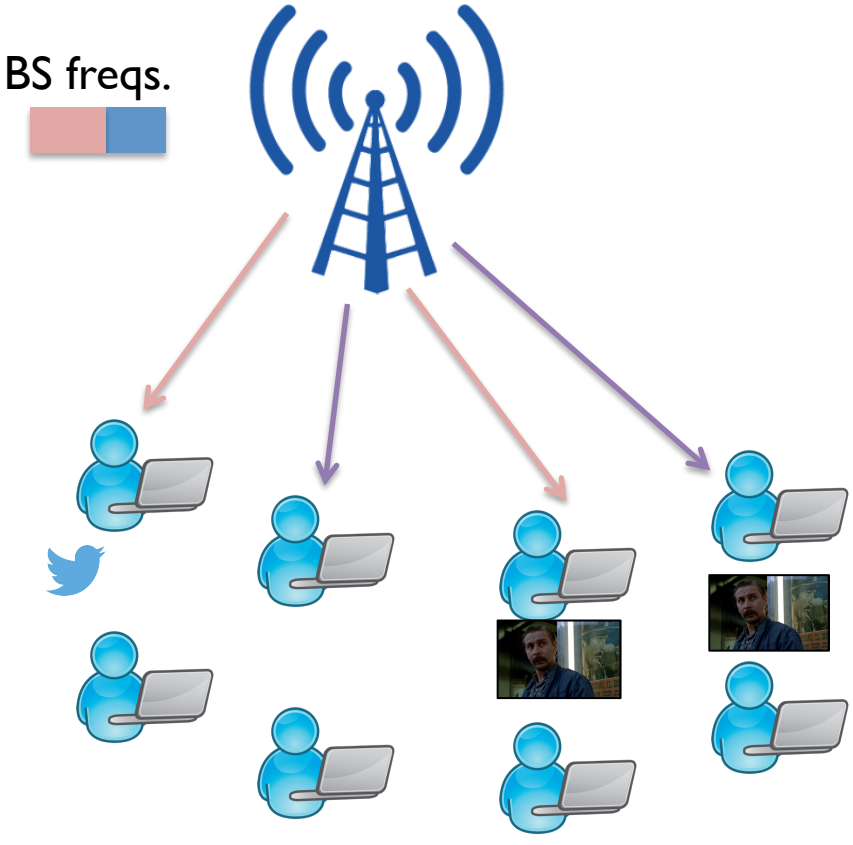



Install additional infrastructure

Not cost-effective, not green

Offload to small cells, WiFi ✔

Implemented efficiently (51%), backhaul?

Exploit the Zipf property

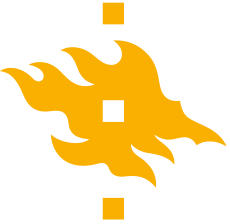
Edge caches, less load on the backhaul

Exploit short-range tx (D2D) ✔

A key component of 5G

Exploit mobility ✔

Mobile users as data carriers



# *Sustainably* narrowing the gap

exploiting the *free* resources

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exploiting the *free* resources

1. Radio spectrum: sharing the wireless roads (dynamic spectrum access)
2. Exploit the mobility of users (mobile data carriers)
3. Exploit the short-range communications (also a key component of 5G)

Our proposal: white space opportunistic offloading

# 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

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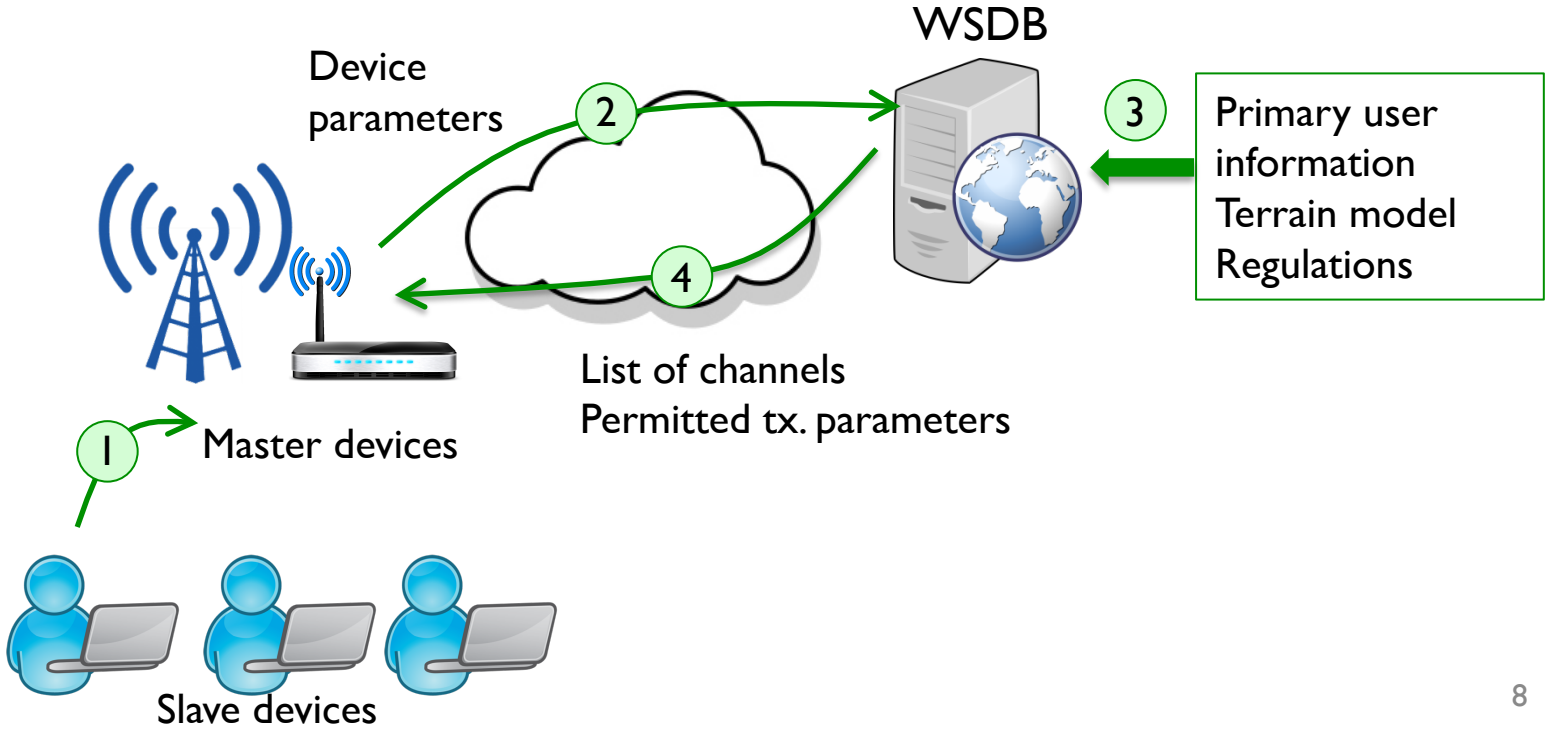
- TV white spaces (TVWS): 54-698 MHz  in US, 470-790 MHz in Europe
- White space databases (WSDB) : wireless microphones, PMSE devices



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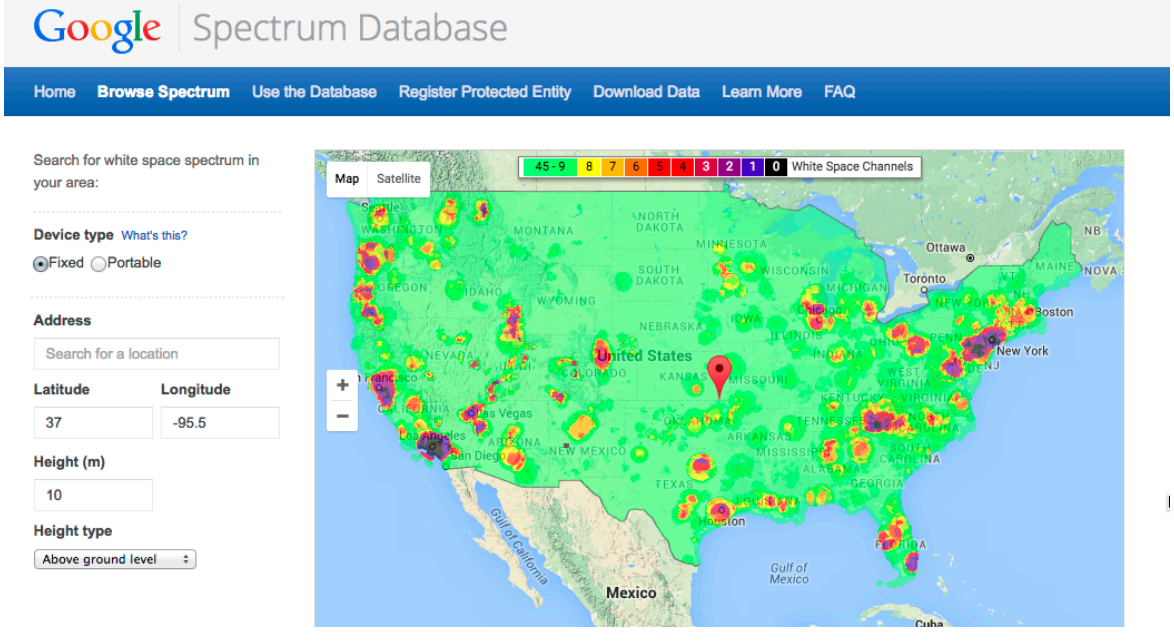


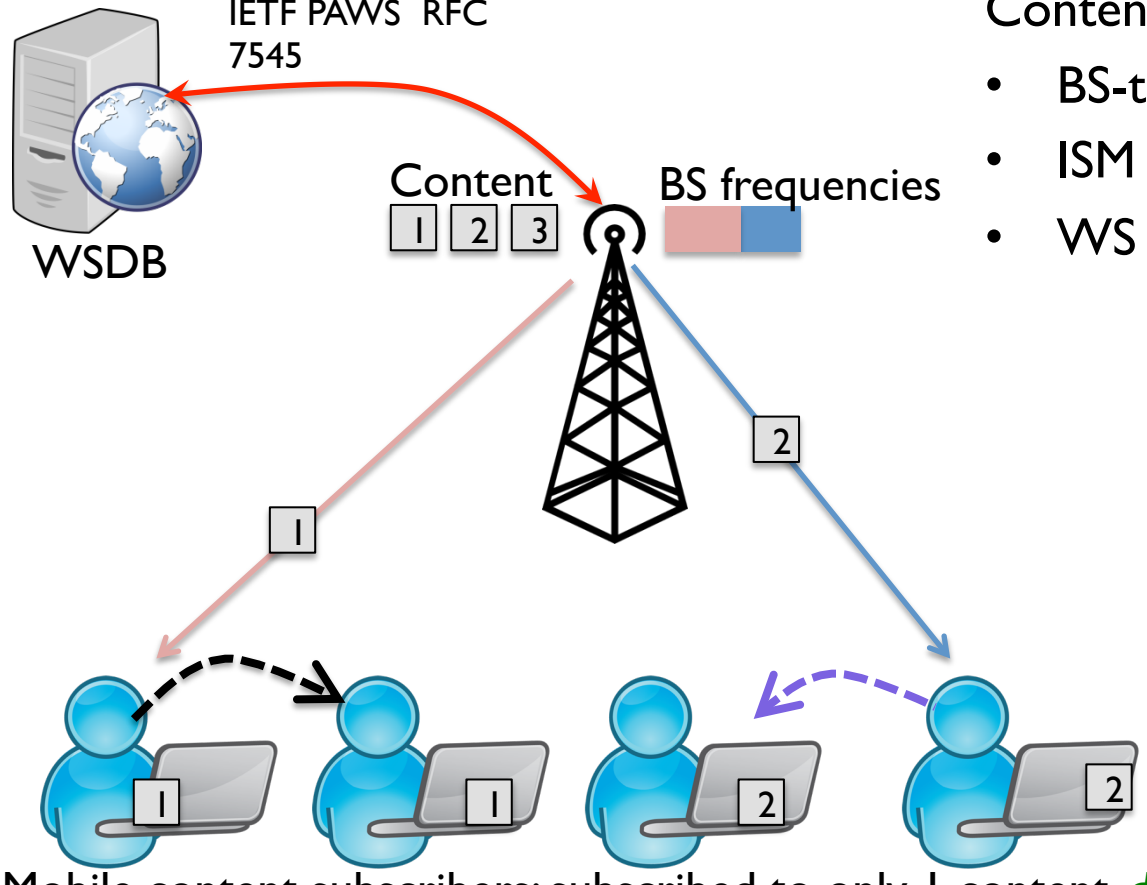

US: 2012
Google, Spectrum Bridge, Microsoft …

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

More white space capacity for lower power transmission:

*white space (opportunistic) offloading*

# Cellular content delivery: system model




Content delivery (delay-tolerant)

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

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

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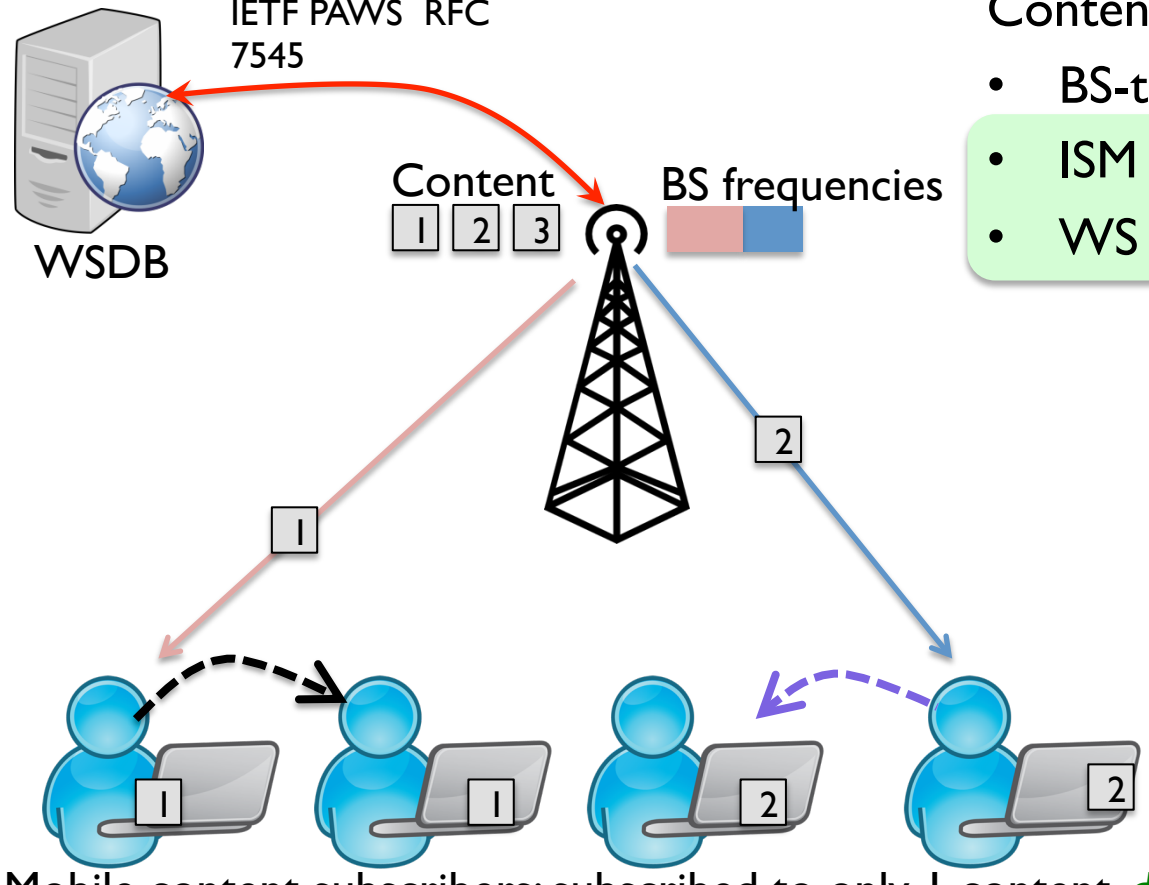



Content delivery (delay-tolerant)

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

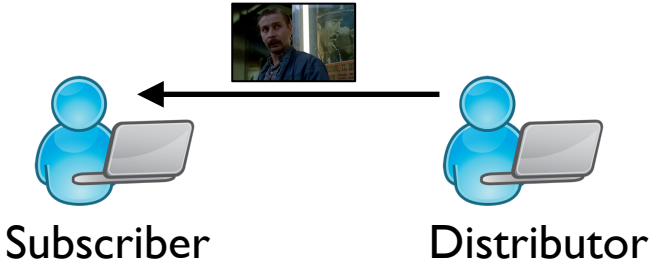
Maximize

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

# Distributor selection problem

- BS selects users *(distributors)* which will receive the content *directly* from the BS and deliver to other subscribers via *offloading* either using *ISM* or using *white spaces*
- Users that cannot receive the content before the deadline, eventually receive it from the BS *directly*

# ISM vs. TVWS




| | TVWS (400-800 MHz) | ISM (WiFi 2.4 GHz, 5 GHz) |
|---|---|---|
| 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 vs. TVWS

Subscriber Distributor

| | TVWS (400-800 MHz) | ISM (WiFi 2.4 GHz, 5 GHz) |
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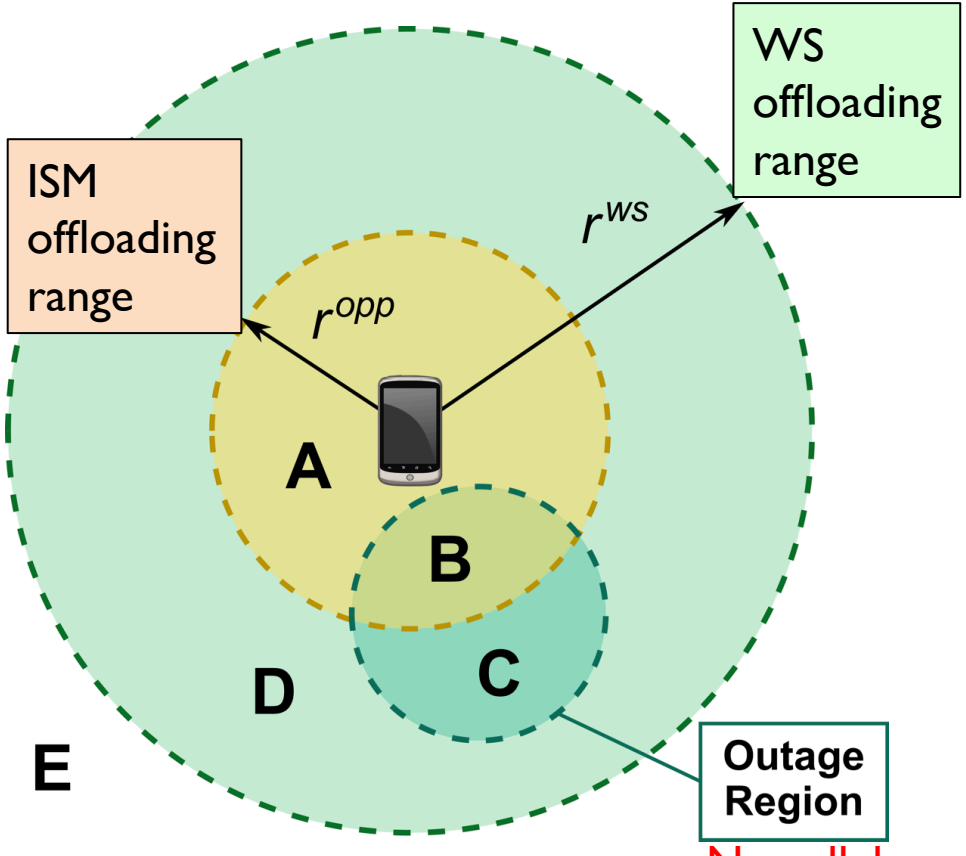
| Range | Longer range (km) ☺ | Shorter range (10-100s m) |
| Availability | received from WSDB | Available ☺ |

Must consult WSDB
Must have an uplink to the BS
*Probability of outage ($p_{out}$)*

Inaccuracy in the WSDB
*Probability of unregistered PU ($p_{un}$)*

# Offloading regions

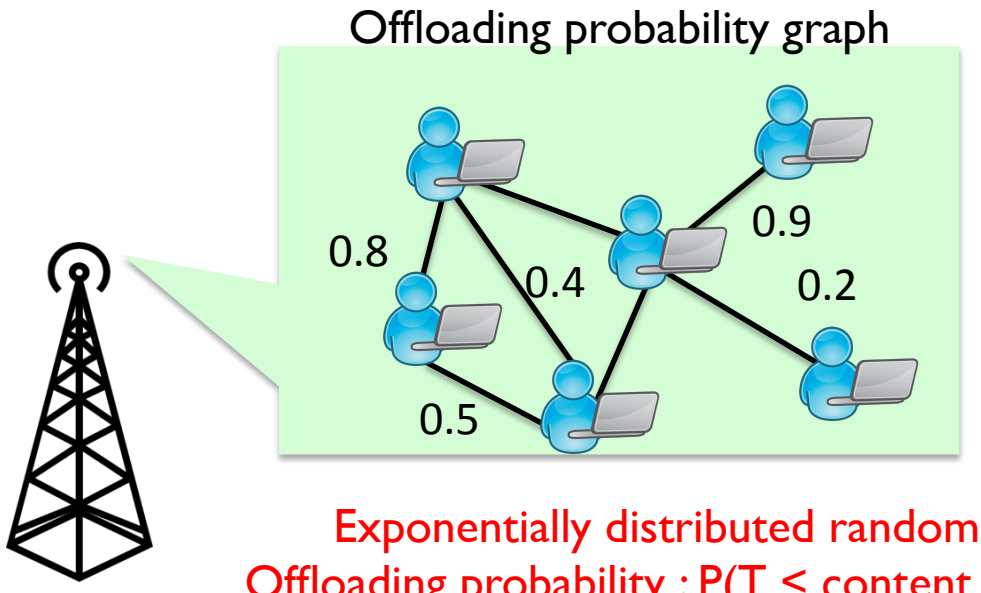



This mobile node gets the content from a distributor if the distributor is in:

- ISM offloading is possible in
  - A and B
- WS offloading is possible in
  - Only D
    - ISM prioritized in A and B
    - Outage in C and B
    - Out of range in E

No cellular service in this region

# Distributor selection at the BS




Exponentially distributed random vars
Offloading probability : P(T < content deadline)

Given *content deadline*, BS calculates from node i to node j:

- ISM offloading probability: inter-contact time for ISM $\lambda^{opp}_{ij}$
- WS offloading probability based on inter-contact time for WS $\lambda^{ws}_{ij}$
- Offloading probability in either mode from node *i* to node *j*
- Probability node *i* gets content *k* from one of the other nodes $p_{ik}$

# Maximizing the offloaded traffic

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

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

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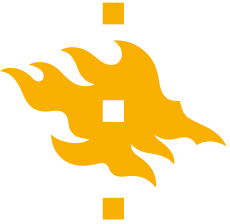

# of subscribers of content k

# of distributors of content k

Size of content k

Prob. that node i cannot get content k via offloading

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

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Calculation of offloading probabilities

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Only subscriber of content k can be a distributor of content k

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BS can select at most F distributors

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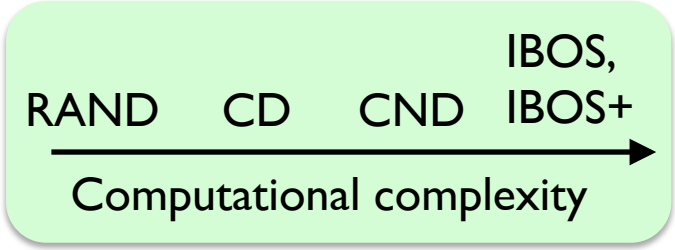
# Computationally hard problem

B.Han et al, Mobile Data Offloading through opportunistic communications and social participation, IEEE TMC, 2012.

# 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

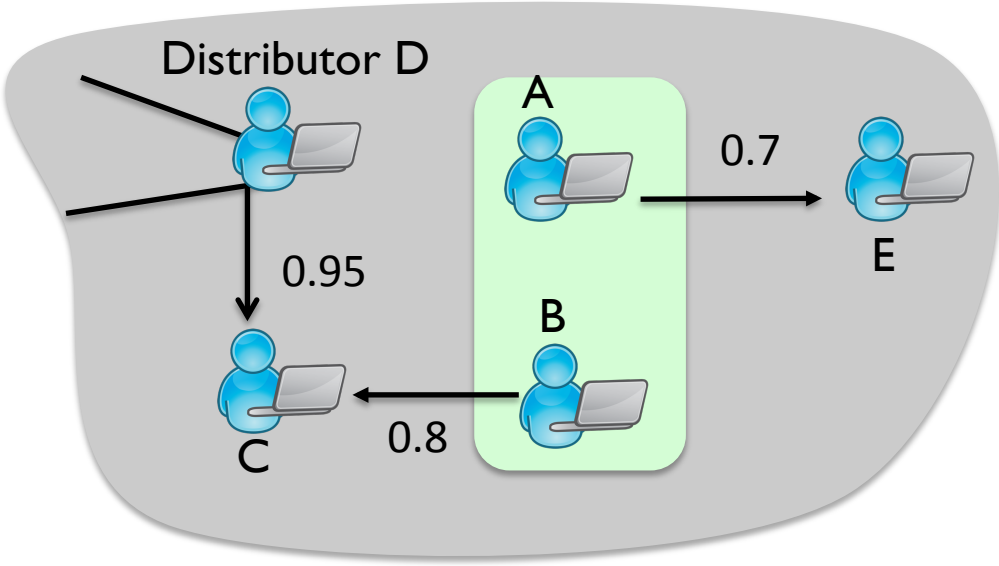
- Offloading capacity of node $n_i$:
  - content size multiplied by sum of probabilities this user will offload content to other users, $U(n_i) = l_k \Sigma p_{jik}$

- Iterative best offloader selection (IBOS)
  - Select the node with maximum offloading capacity $U(n_i) > 0$ (if none, exit)
  - Set the probability of delivery to this user from any other user to zero
  - Update offloading capacity after each assignment

# IBOS+: ignore “safe nodes”

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



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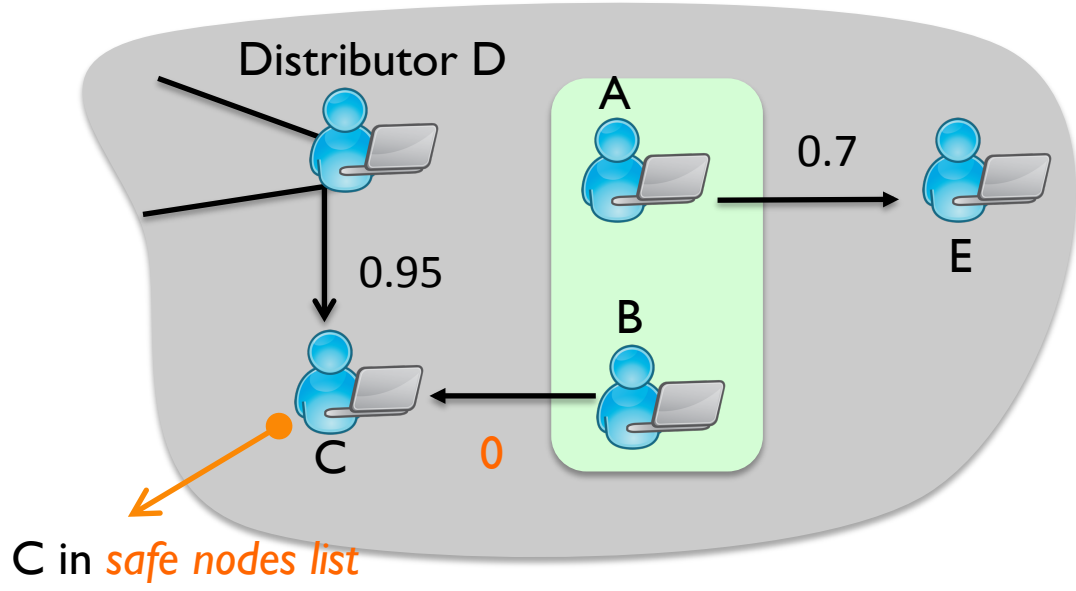
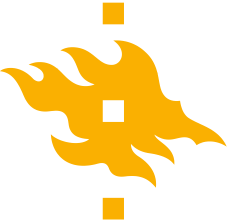



Improved IBOS (IBOS+)

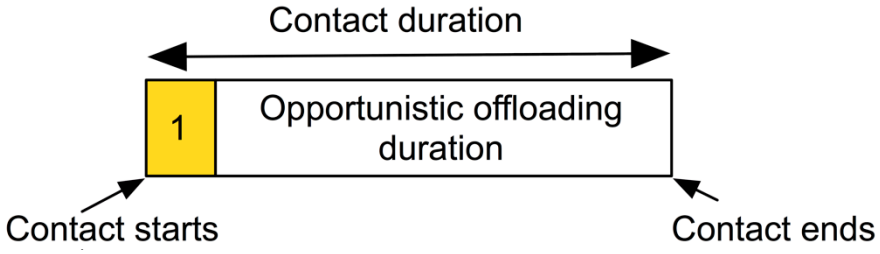
- Store the probability of getting the content from distributors for each node
- Add the nodes with prob. higher than some safety threshold to safe nodes list
- Ignore safe node set while calculating utility



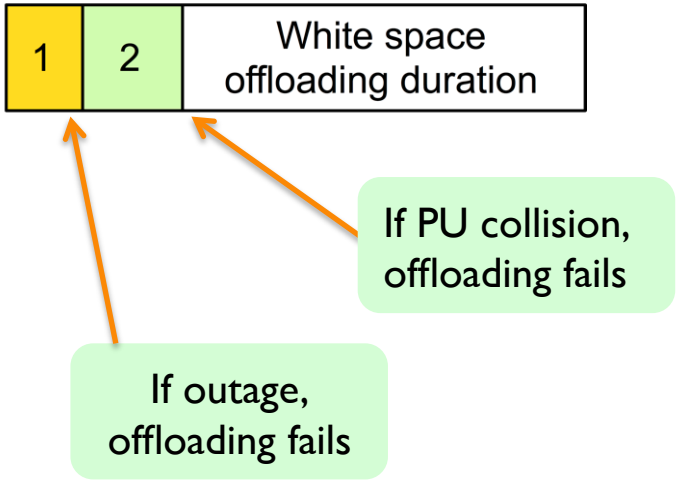
# How much *effective offloading capacity* do we have?

Effective offloading capacity = effective contact duration x channel bandwidth

# Effective offloading capacity (MHz sec)




1. Peer discovery
2. WSDB querying



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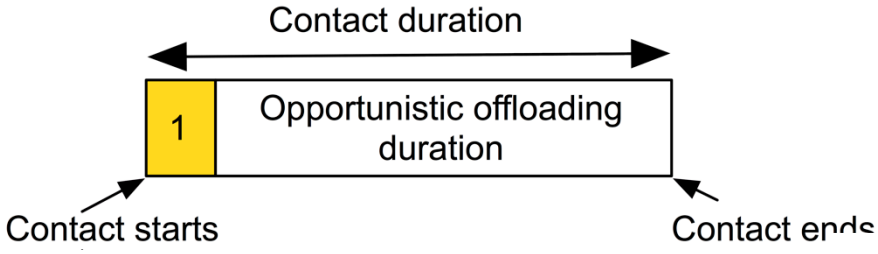
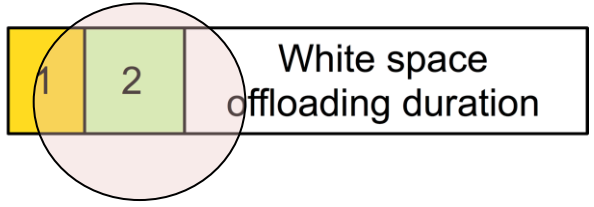


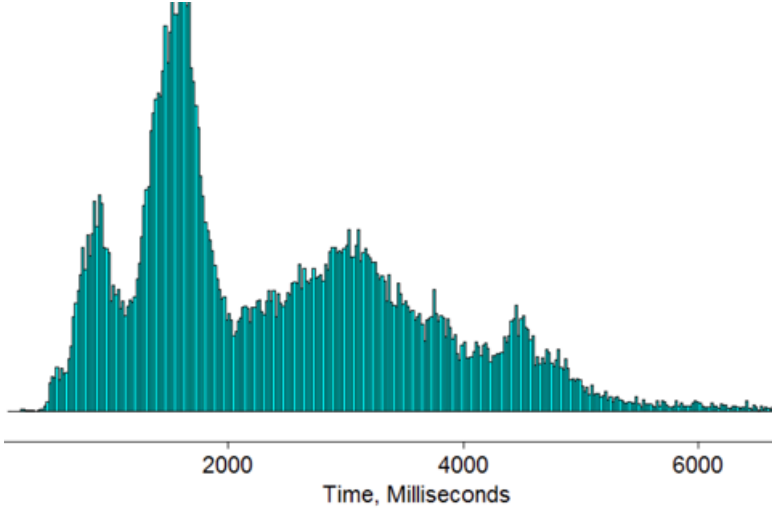




1. Peer discovery
2. WSDB querying

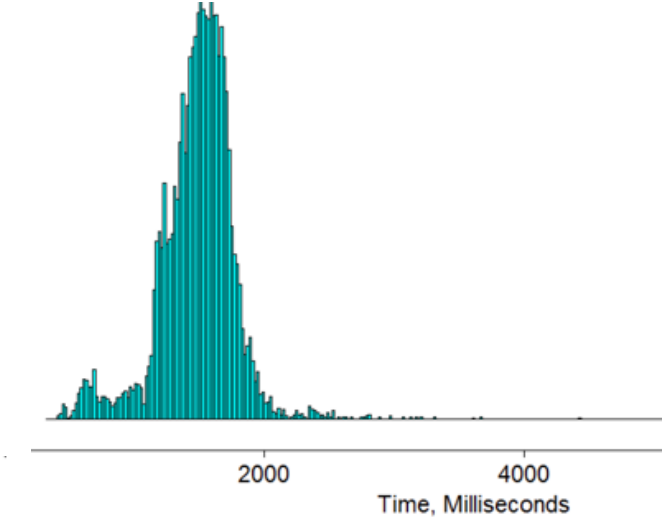
How long is WSDB querying time?
compared to contact duration?

# Google Spectrum Database query application

An every-day phone




A tablet used only for this purpose




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

# 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

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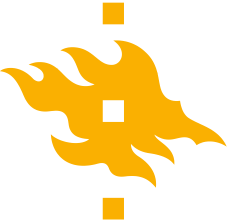
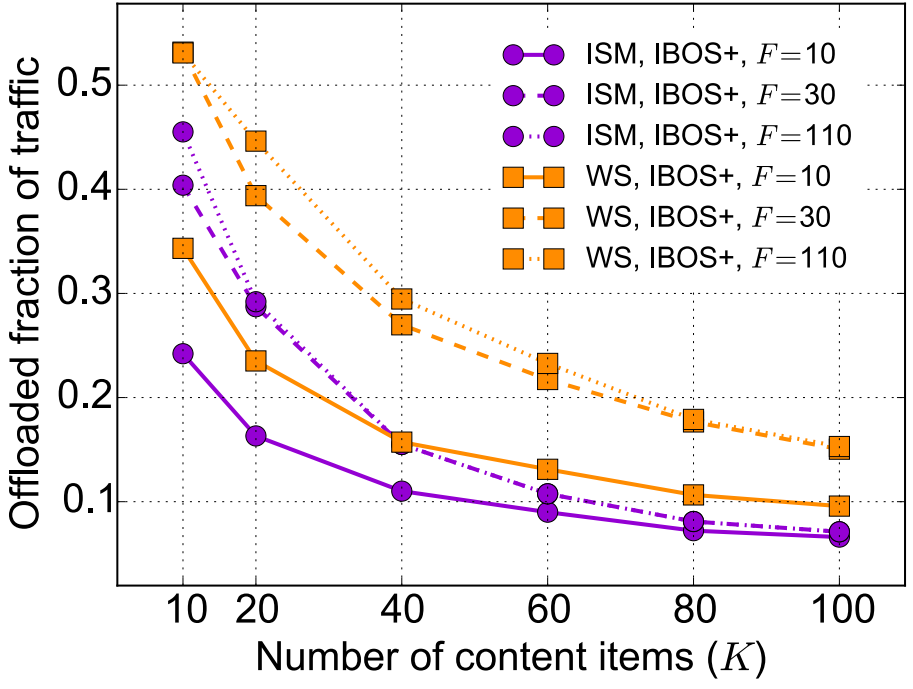


How much of this extra capacity used for offloading?

# How much does white space offloading help?

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

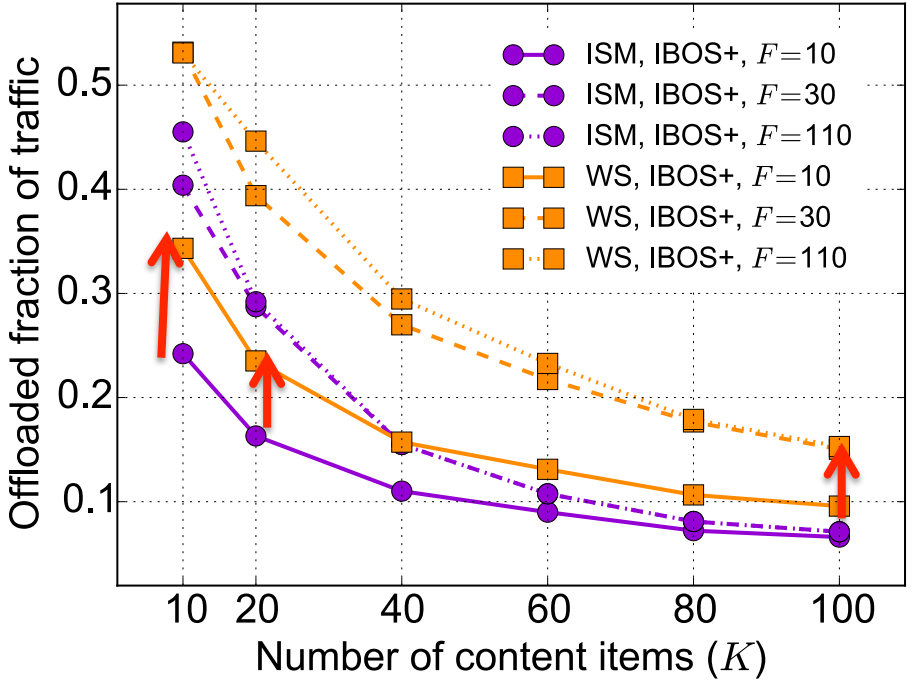
- ISM-only offloading
  - the current approach
- ISM+WS offloading



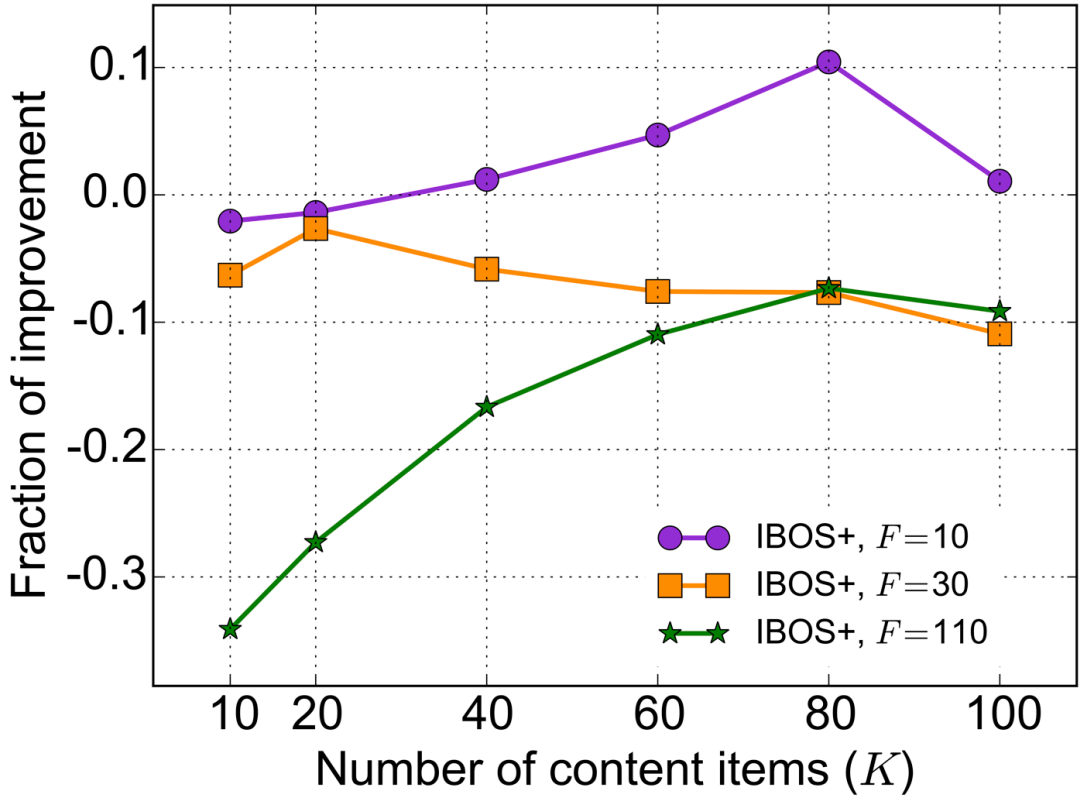
# How much does white space offloading help?

WS offloading increases offloaded traffic ratio about 20-40%

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



# Change in the delivery delay

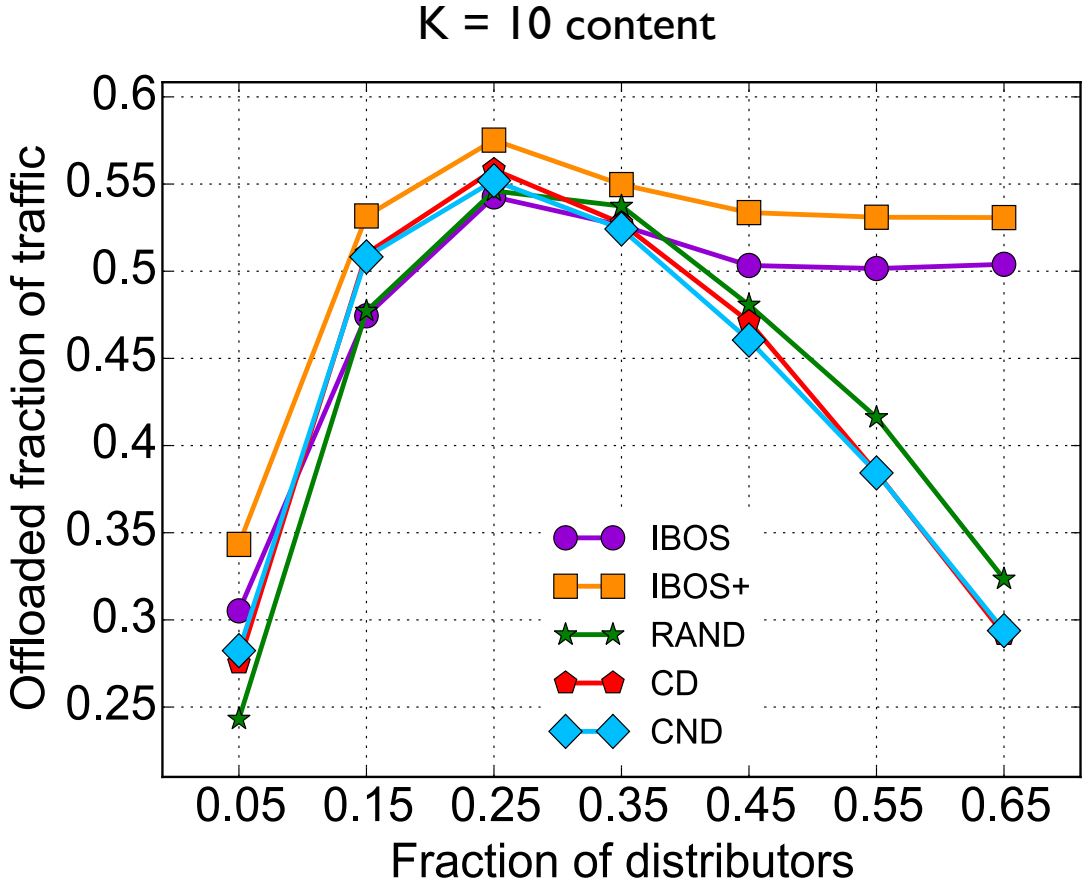



Delay of only offloaded content

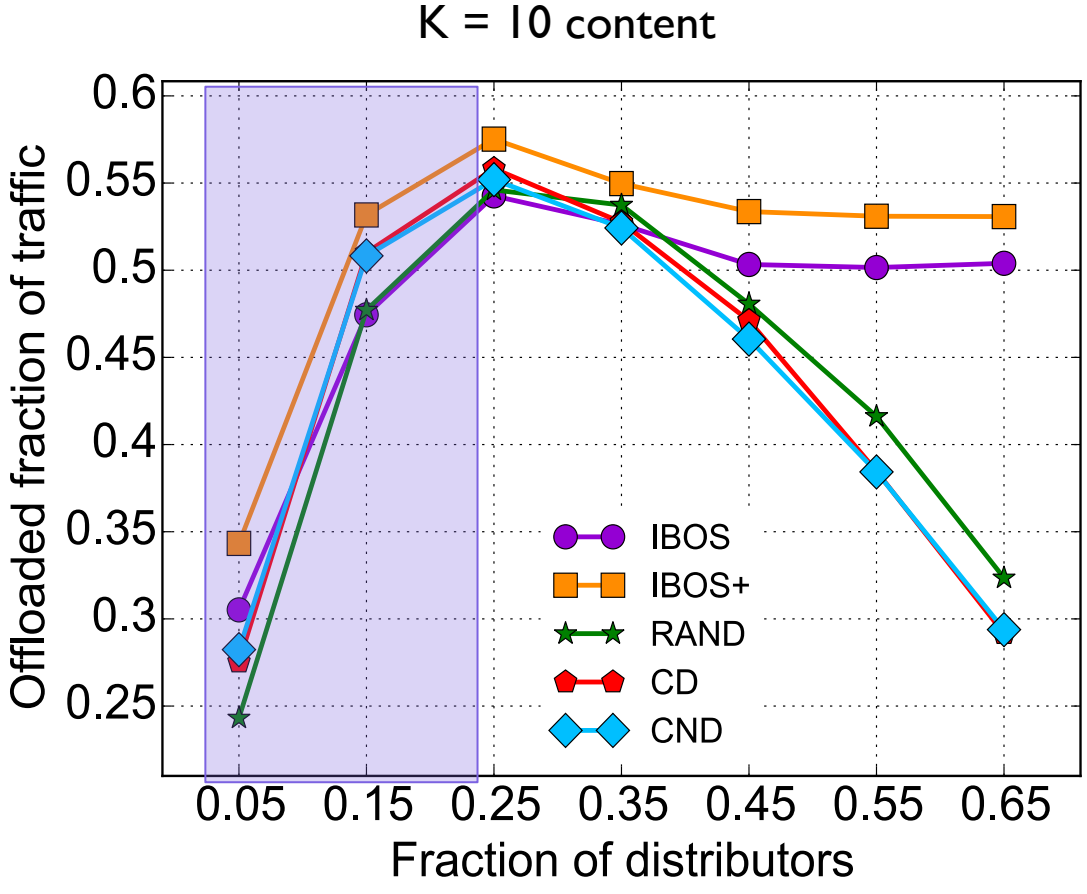
For high number of distributors, white spaces provide faster delivery

For low number of distributors, the increase in delay is due to increase in offloaded traffic

# Effect of fraction of distributors

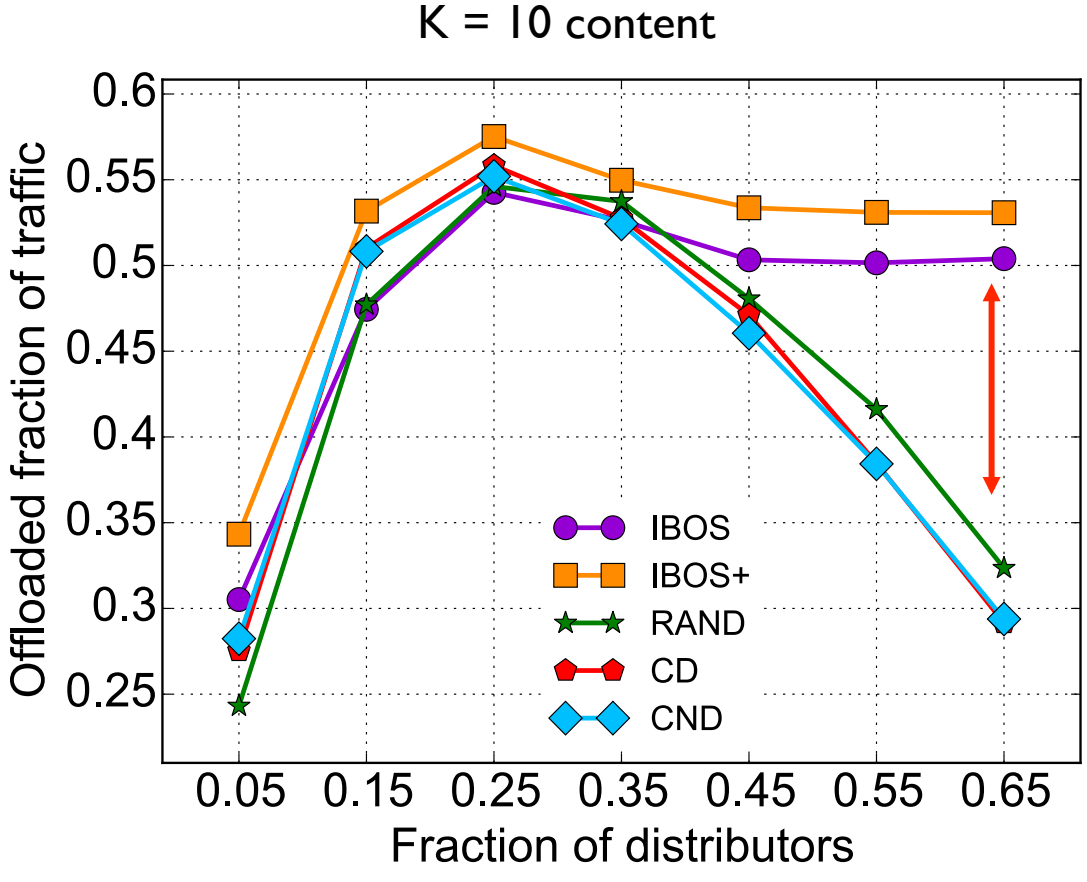


# Effect of fraction of distributors



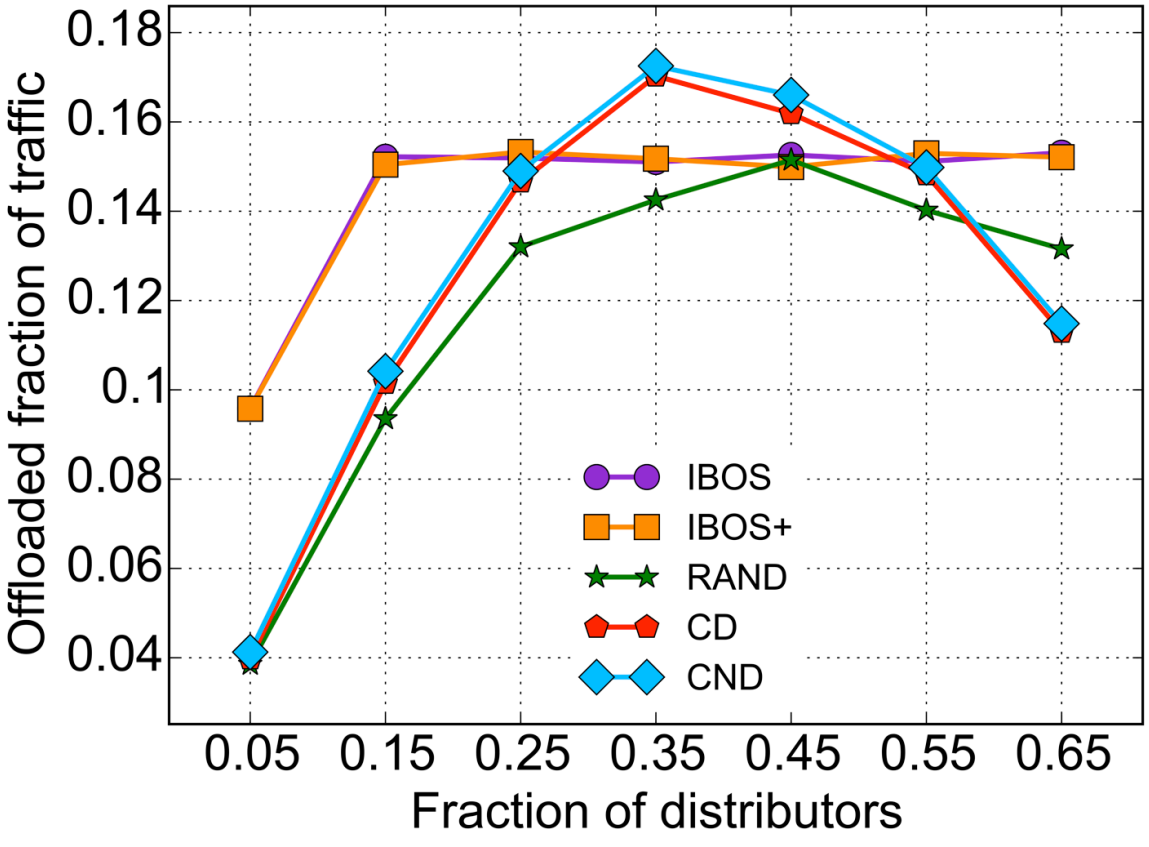

Low number of distributors
IBOS+

# Effect of fraction of distributors

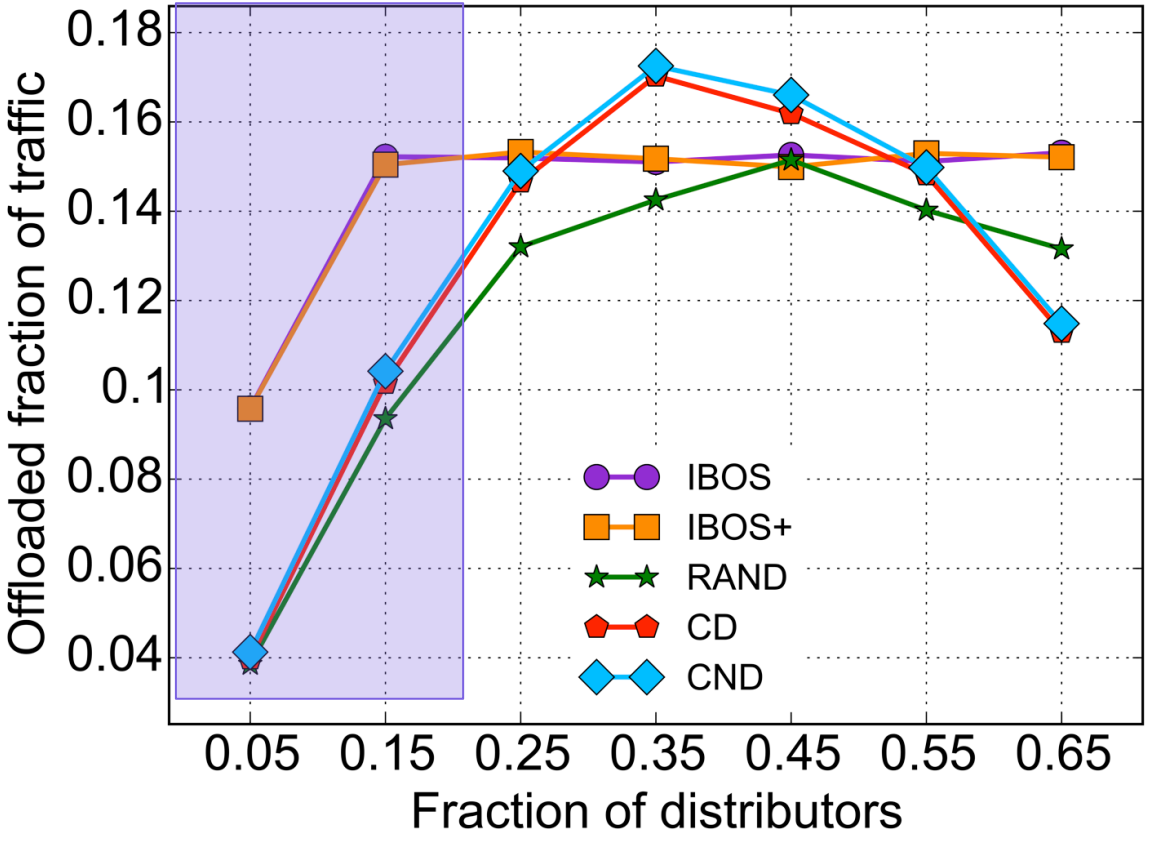



IBOS and IBOS+
avoid redundant selection of distributors

# High content diversity: K=100

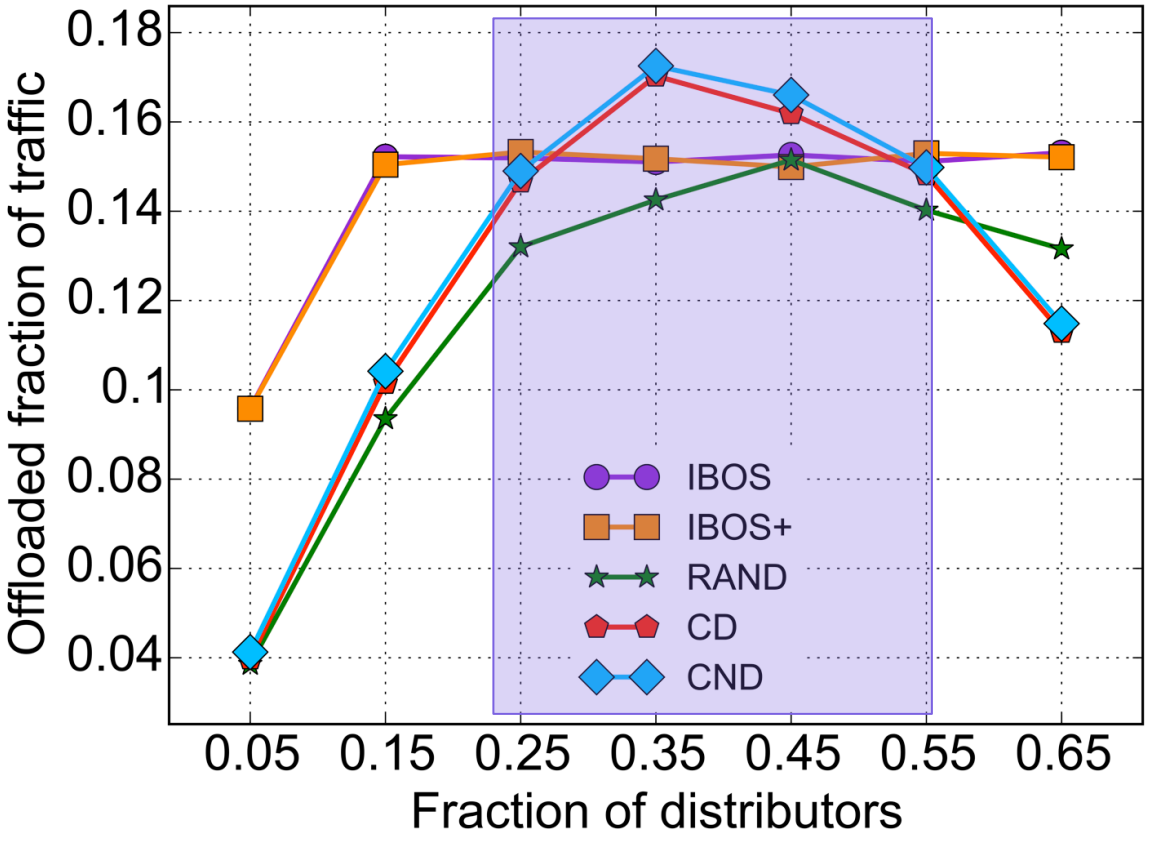


# High content diversity: K=100




For low fraction of distributors:
IBOS and IBOS+ same performance due to the safety threshold setting in IBOS+

# High content diversity: K=100



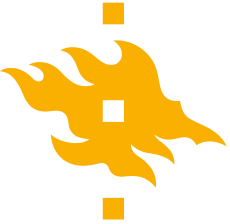

For high fraction of distributors:

IBOS/IBOS+ underperforms
Divergence bw. the real mobility and exponential assumption

# Summary

- *Exploit the free resources* for sustainably handling the gap
  - White spaces
  - Mobility of increasing number of mobile devices
  - Short-range communications

- White spaces are promising especially for short-range offloading and many open questions
  - Interference ignored (short-range communications)
  - Analytical modeling to understand the effect of mobility, content diversity, size



# Thank you

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# References

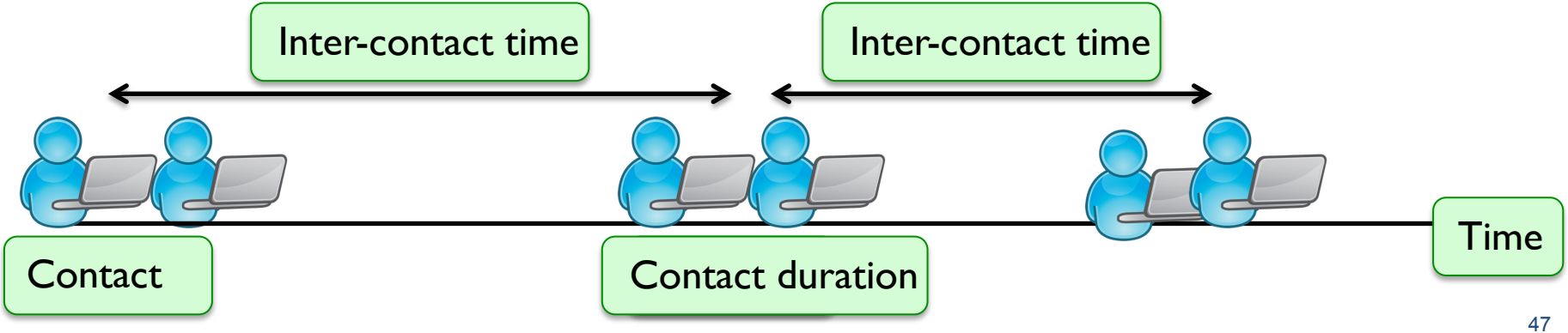

- Dynamic Spectrum Alliance, Worldwide Commercial Deployments, Pilots, and Trials, Jan.2016
- Harold Feld Dr. Gregory Rose, Breaking the Logjam: Creating Sustainable Spectrum Access Through Federal Secondary Markets
- Images from http://www.iconsdb.com/

# 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)

# Key insight for the design of a smart scheme

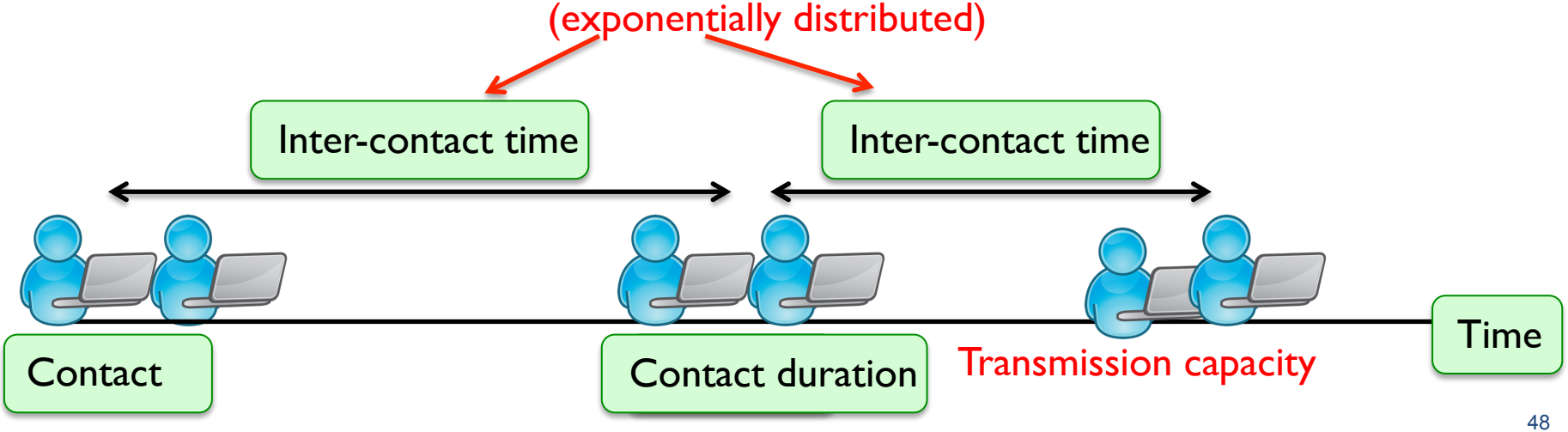
- Select users as distributors which have high chance of meeting other users subscribed to the same content before the content deadline
- Avoid users who have high chance of receiving content from distributors before the content deadline



# 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**



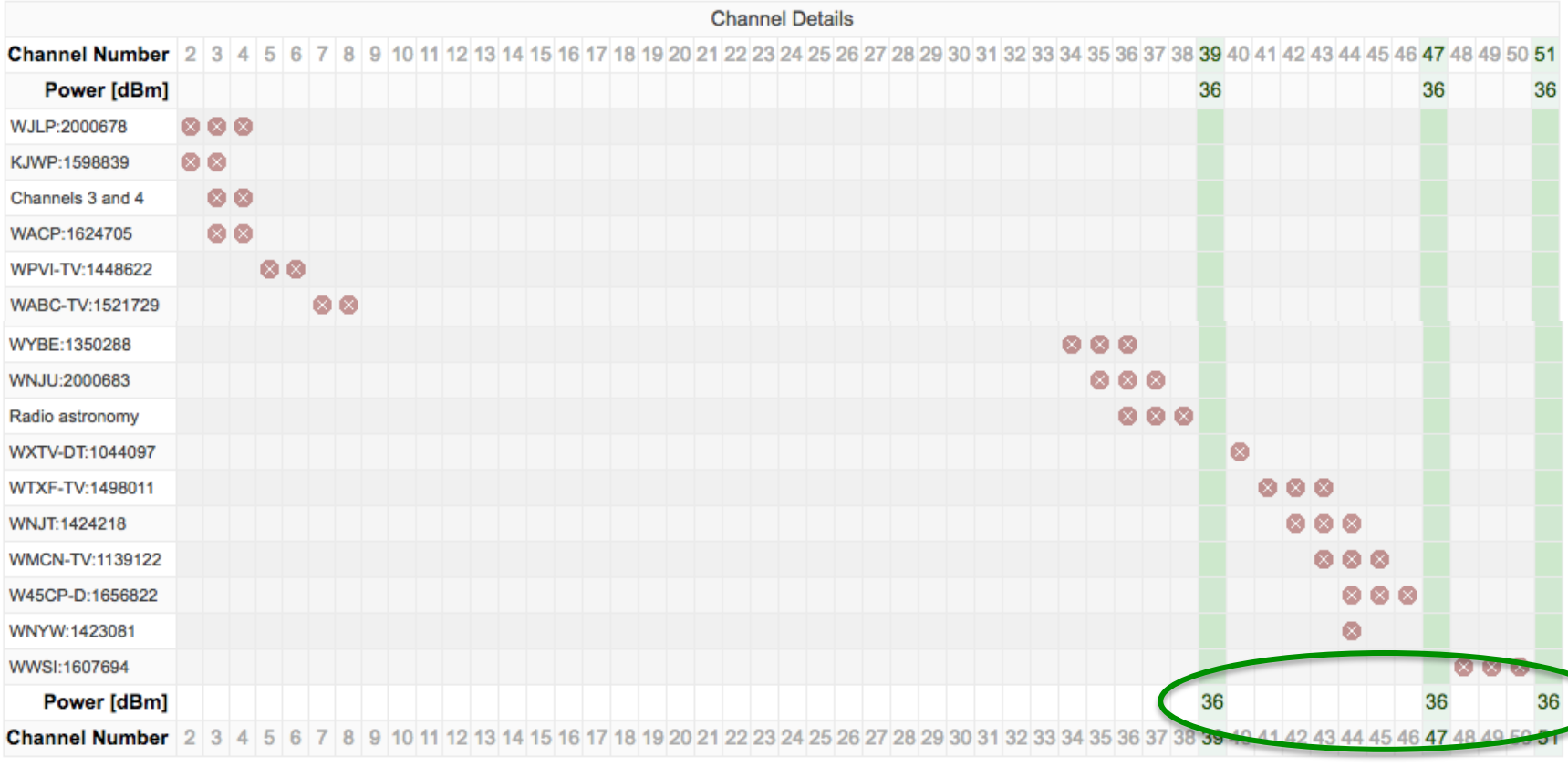
# WSDB abstraction

- 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

# White spaces for *fixed devices* in New Jersey

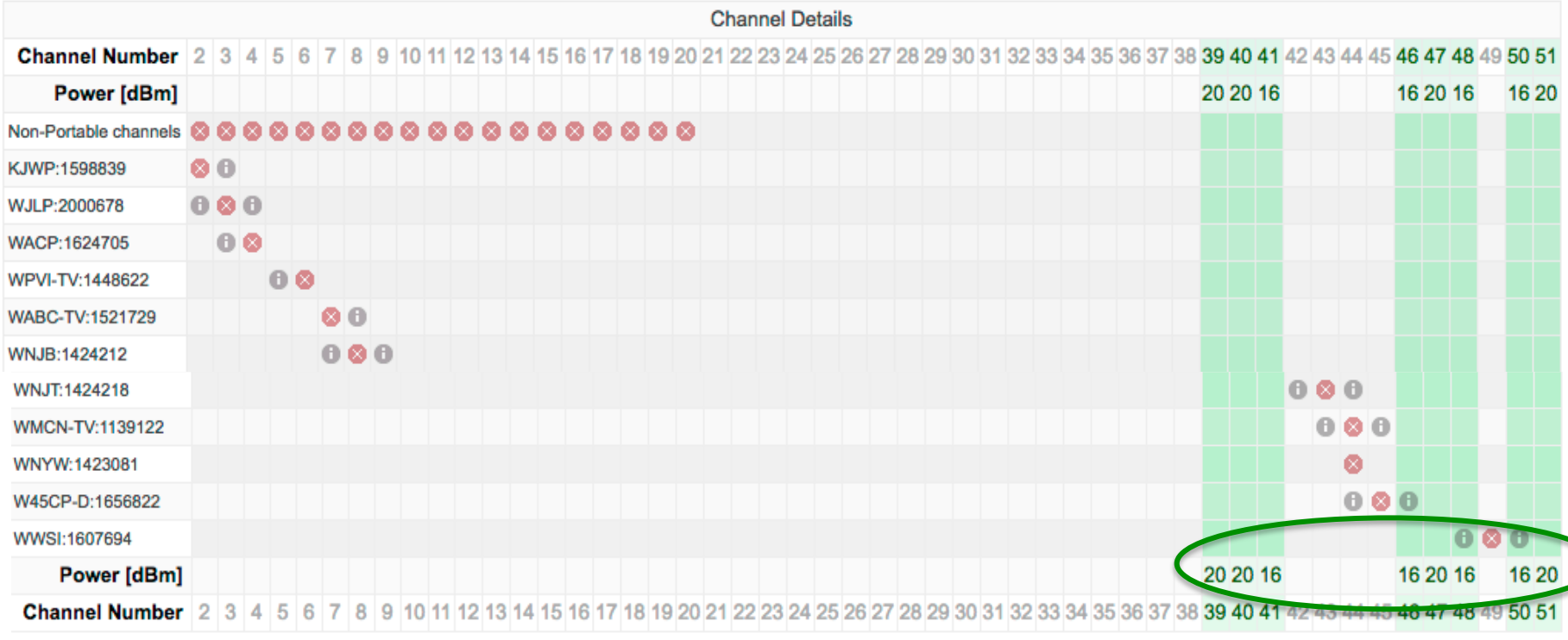
**Available Spectrum: 3 Channels (18 MHz)**




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