Adaptive and Resource-Efficient Rural Area Networks

Slides at: www.cs.bham.ac.uk/~pejovicv/cambridge

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Digital Divide

- A division between those who do and those who do not have access to and the capability to use modern information and communication technologies (ICTs)
- The digital divide is tightly connected with the living standard, health care, economy, education, political freedoms
- Observed from different aspects: gender, age, affluence

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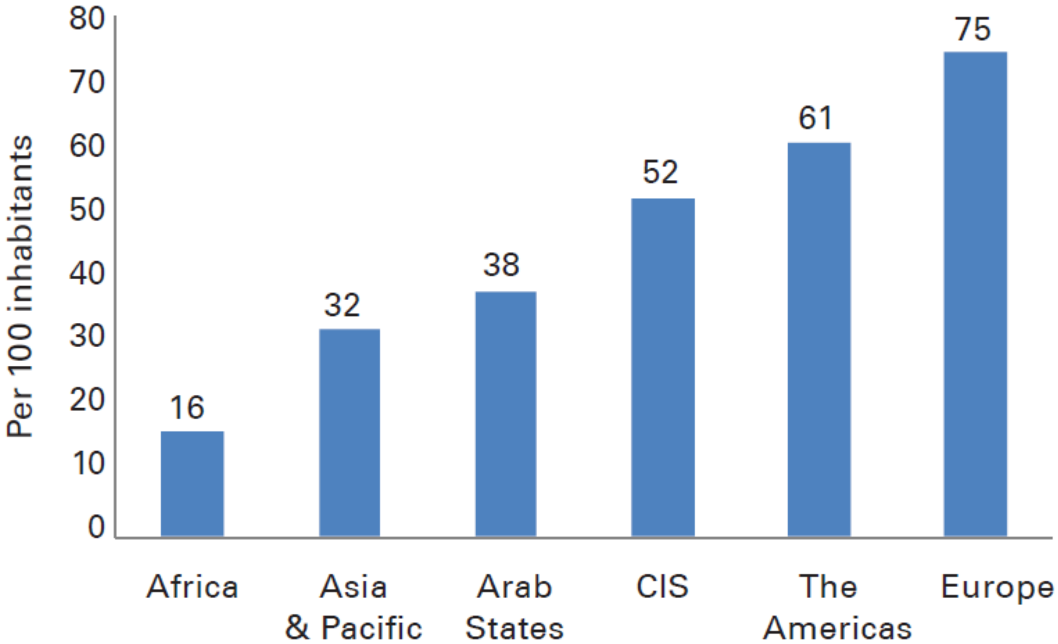
Digital Divide – A Broad View



Internet users per region
Source: ITU 2013

Digital Divide – Causes

Differences between regions that impact ICT adoption:

- Purchasing power – ICTs cost
- Existing infrastructure – ICTs need reliable power supply
- Level of urbanization – ICTs are designed for cities
- Different cultures – the same ICTs might not be suitable for all societies

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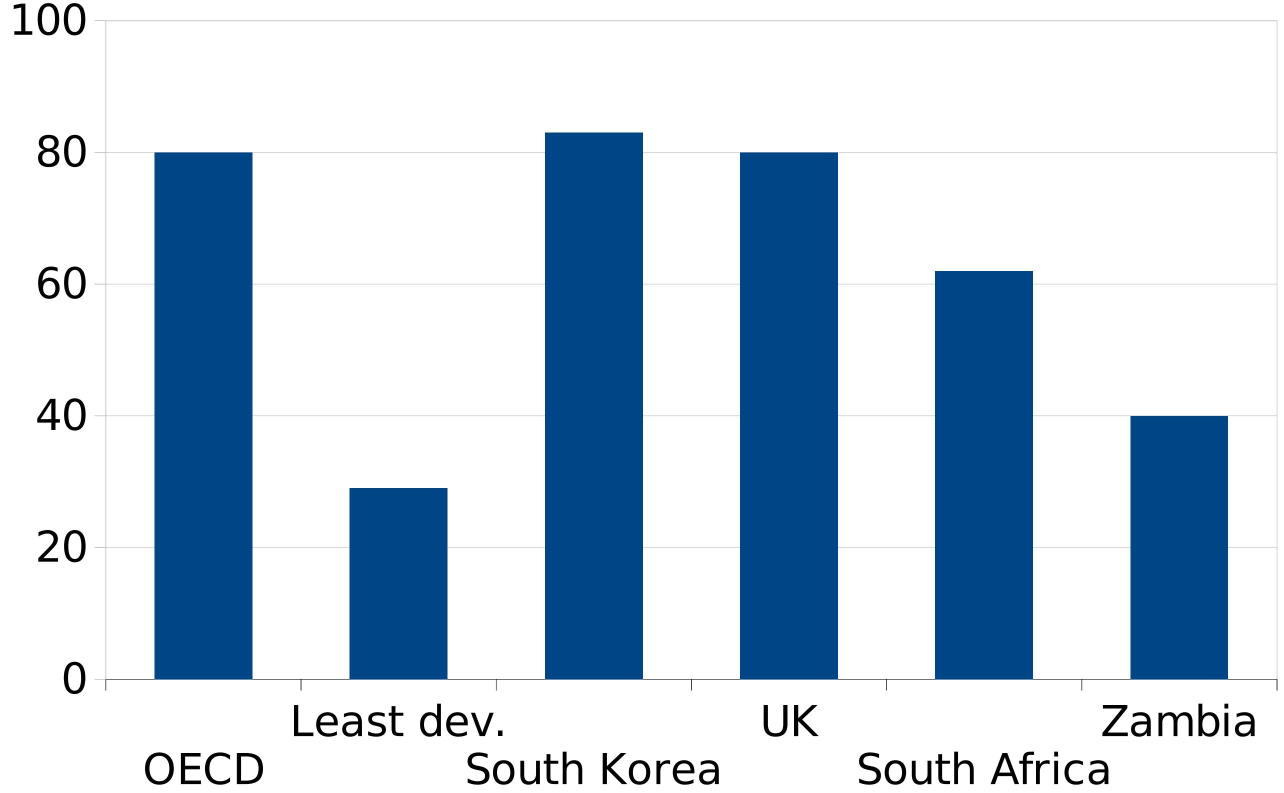
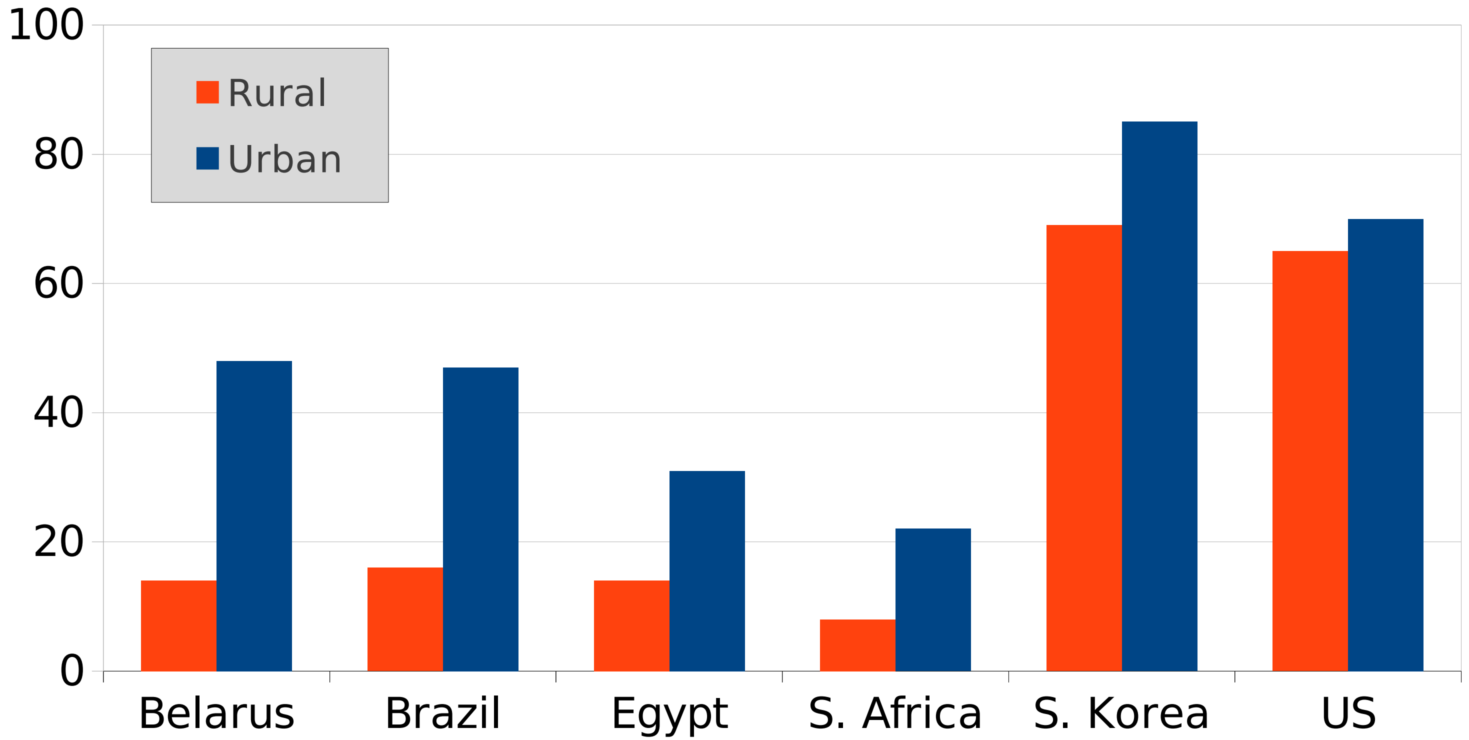
Digital Divide – Urbanisation Levels



Urbanisation level [%]
Source: World Bank

Digital Divide – Rural vs Urban



Population that uses the Internet [%]
Source: ITU

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Existing Solutions

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Existing Problems

Technical

- Poor signal propagation due to vast distances, terrain configuration, vegetation
- Wireless interference, especially in the case of unlicensed solutions
- Lack of reliable electrical energy supply

Socio-economic

- Economic infeasibility of wide area coverage
- Lack of locally relevant online content
- Inability to engage a wider community into the network
- Micro digital divides: castes, genders

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Our view on why rural area connectivity fails

In rural areas a unique set of technical and social challenges are obstacles to Internet penetration.

The essence of the problem lies in a general lack of understanding of rural area dwellers’ needs, and in the development of communication technologies without consideration of unique nuances of rural areas.

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Holistic approach

Investigate existing solutions
identify obstacles and
true needs of our users

Develop technical solutions
with experts from target areas

Investigating Technical and Social Challenges in Rural Areas

Analysis of existing rural wireless networks in Africa (Macha, Zambia and Dwesa, South Africa):

Why Macha and Dwesa?

- Real rural Africa
- Community wireless networks
- Different social settings
- Strong collaboration links through our partners

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Investigating Technical and Social Challenges in Rural Areas

Analysis of existing rural wireless networks in Africa (Macha, Zambia and Dwesa, South Africa):

- Lightweight traffic monitoring system:
  - Packet headers on the satellite gateway
  - Squid proxy logs
- Social surveys
  - Go beyond just anecdotal evidence - quantifiable data
  - Examine Internet usage, legacy communication practices, social aspects of computer networking, quality of service issues

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Investigating Technical and Social Challenges – Key Findings

- The location of Internet access (home/work/internet café) impacts the type of applications used online:
  - Only at-home access allows full-fledged online experience, including active OSN usage, content generation; otherwise deliberate interaction model
- There is a strong locality of interest:
  - The majority of voice-over-IP (VoIP) calls and instant messages (IM) are exchanged within the village
- Network performance and user behavior are tightly intertwined:

s

More about rural area network analysis in our WWW'11 paper

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Develop Technical Solutions

Guidelines:

- Provide at-home Internet access to all
- Support local communication
- Facilitate content generation
- Be resource (electrical energy, satellite bandwidth, wireless spectrum) efficient

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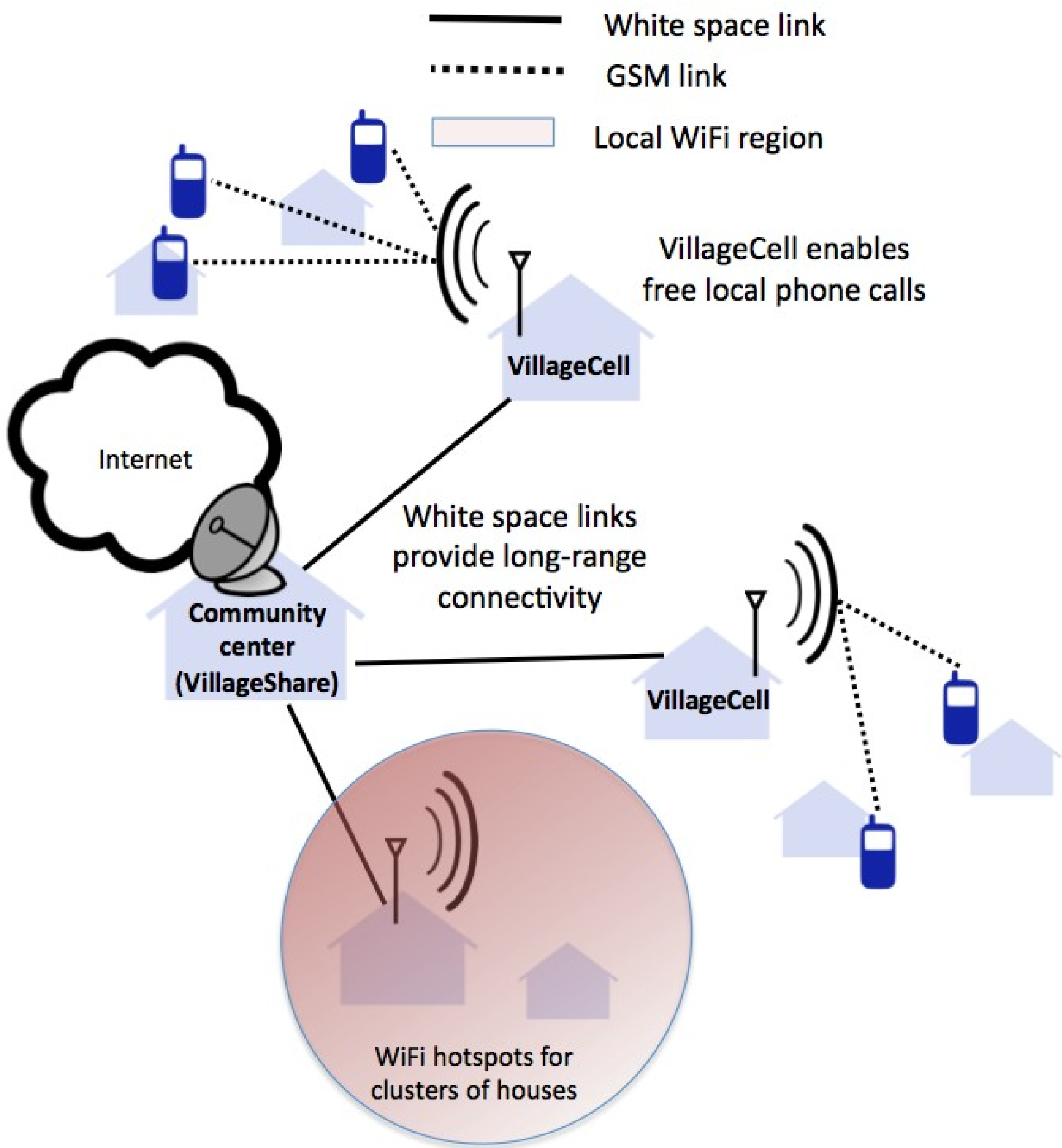
VillageNet



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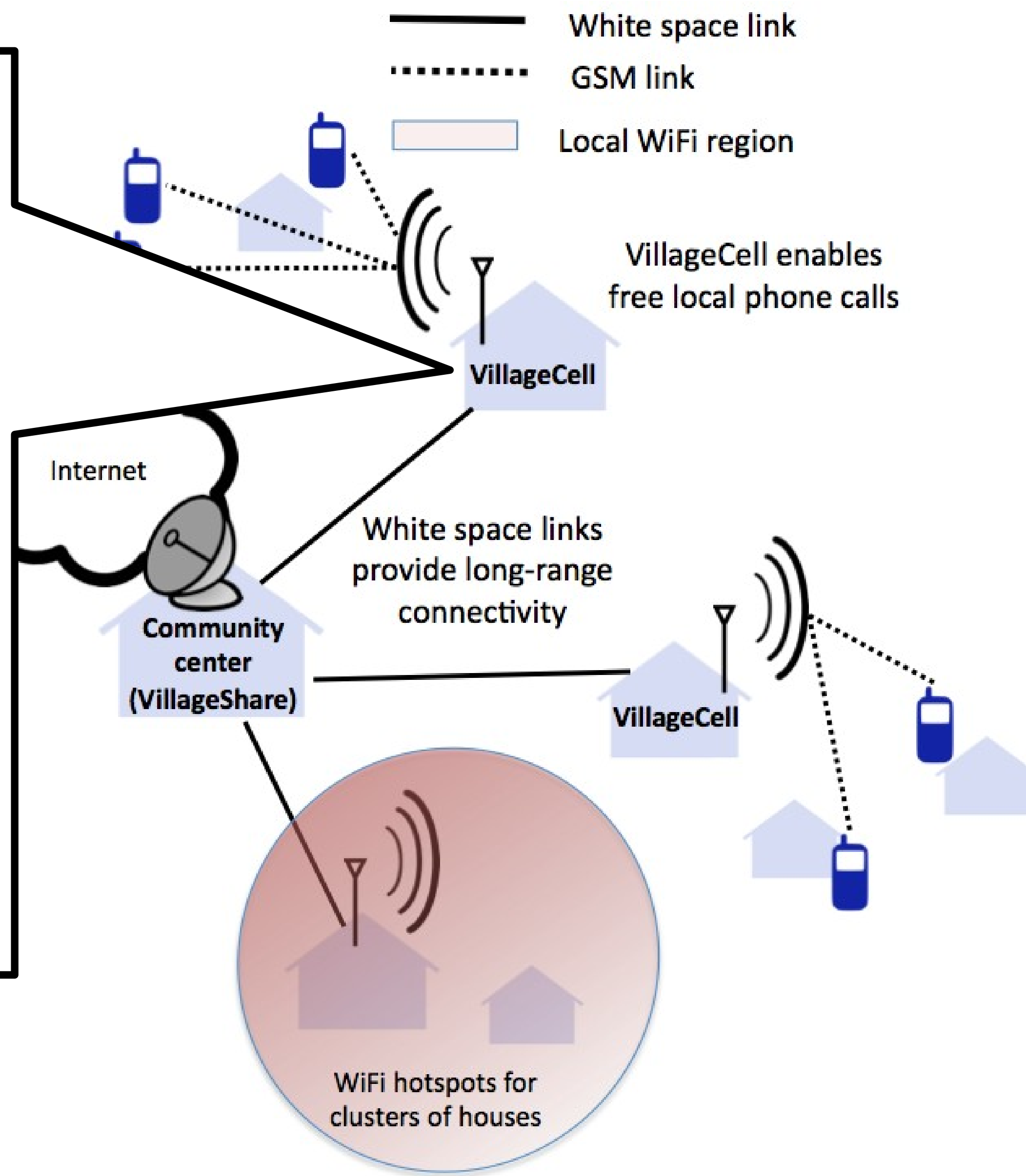
VillageNet

VillageCell

Evolved into *Kwiizya* deployed in Macha, Zambia.

Check: M. Zheleva et al. "Kwiizya…", MobiSys'13



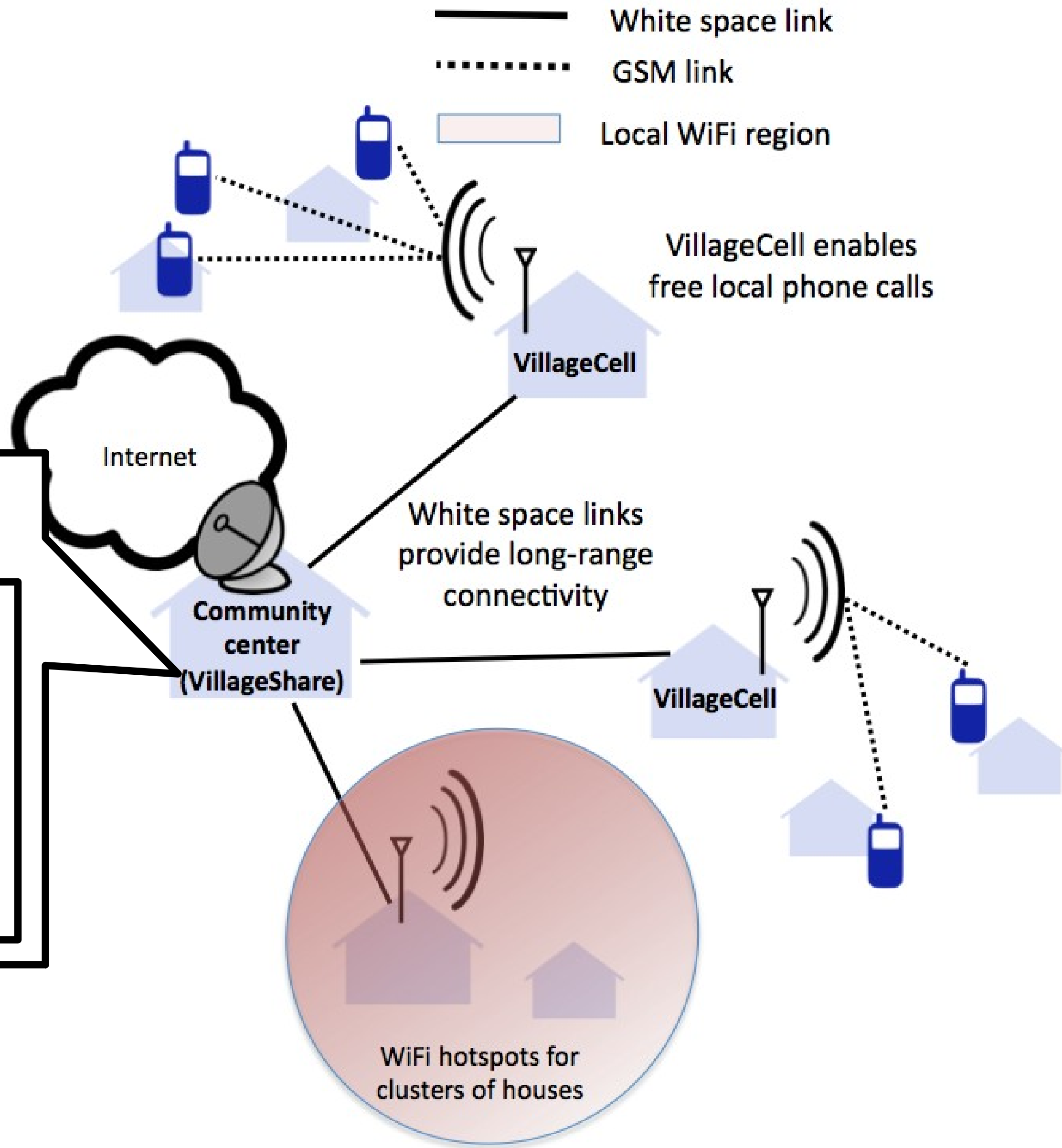
VillageNet

VillageShare

Evolved into *Kwaabana*

deployed in Macha, Zambia and rural Eastern Cape

Check: D. Johnson et al. "Kwaabana...", ACM DEV'13



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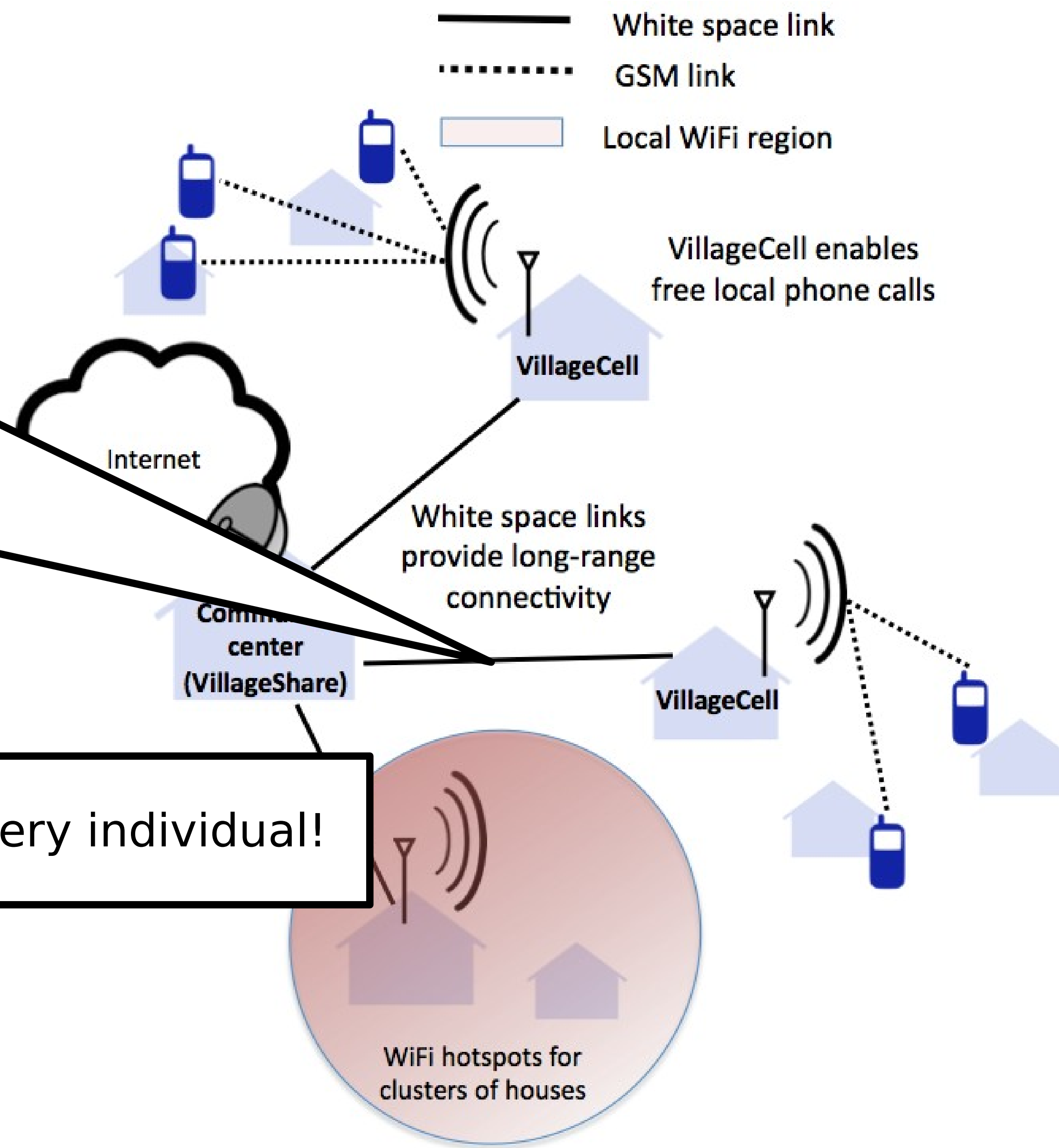
VillageNet

VillageLink

Connect distant locations through outdoor, non line of sight wireless links operating on unlicensed frequencies.



Bring connectivity to every individual!

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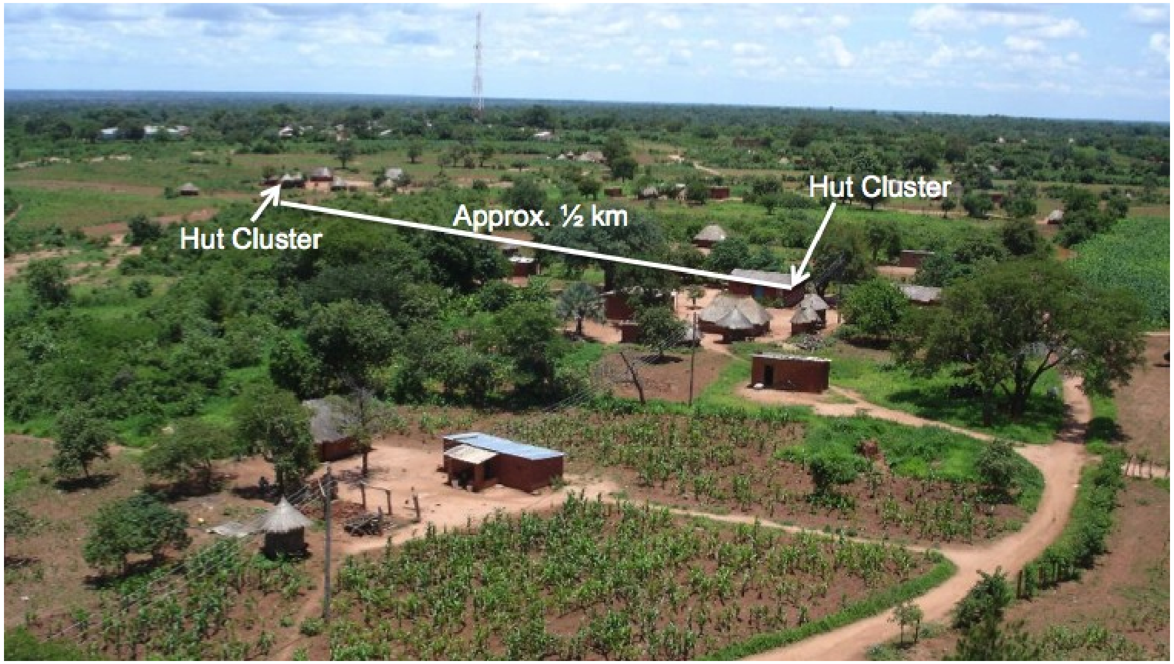
Wide-Area Wireless



Low population density:

- Cell phone towers are not economically viable for low income under-populated areas
- WiFi networks have a limited range and require a line of sight

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New opportunities for rural area connectivity

White spaces:

- Frequency band from roughly 50MHz to 800MHz
- Vacant after TV went digital; potentially unlicensed spectrum
- Excellent propagation properties:
  - Long range (path loss ~ f^2)
  - Not absorbed by vegetation
  - Signal can bend around obstacles

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White Spaces – Issues

- White spaces encompass a few hundreds of MHz of spectrum
- Dynamic range in white spaces:

Technology	f_L (MHz)	f_U (MHz)	D (dB)
802.11 (2.4GHz)	2412	2484	0.26
802.11 (5 GHz)	5170	5700	0.85
GSM 900	935	960	0.23
White spaces	43.25	797.25	25.31

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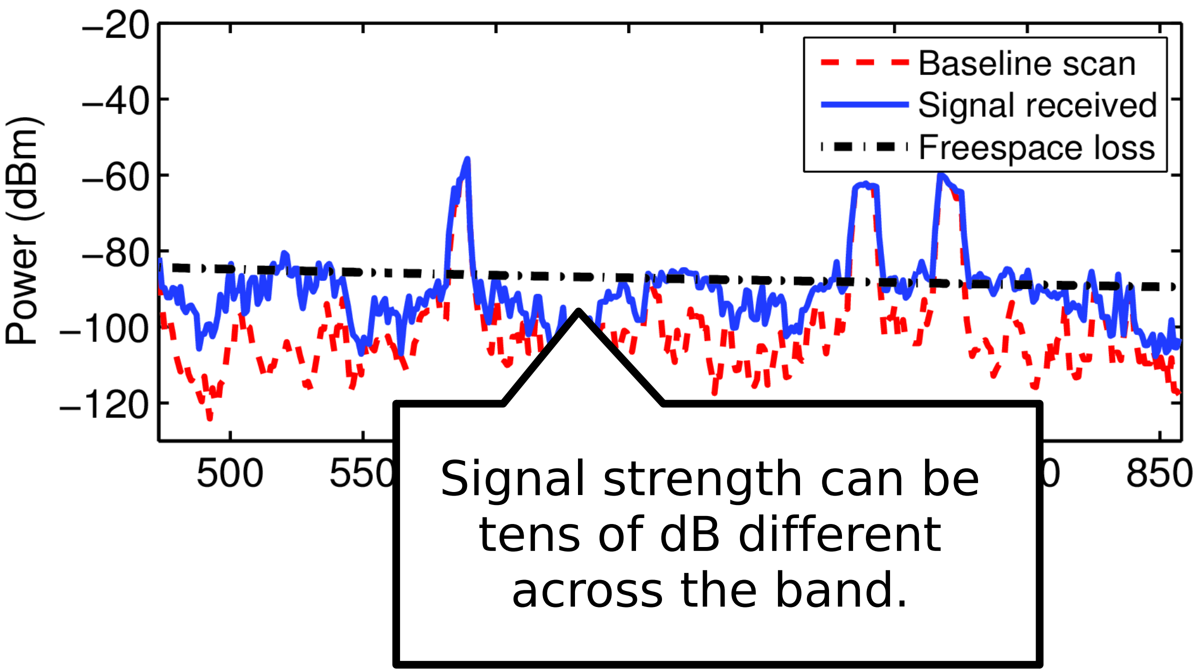
White Spaces – Issues

- White spaces encompass a few hundreds of MHz of spectrum
- Dynamic range in white spaces:

Results from a 3 km long outdoor link in South Africa



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White Spaces – Issues

- White spaces encompass a few hundreds of MHz of spectrum
- Dynamic range in white spaces:

Why is this a problem?

Performance across the frequency b
cannot be described
solely by the propagation theo y

Antenna properties and the environment
determine signal strength at different channels

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White Spaces – Channel Allocation

- We have a limited pool of vacant white space channels
- Network capacity depends on the useful signal strength and the interference (plus noise) strength

How to allocate wireless channels
to network nodes so that
the network capacity is maximized?

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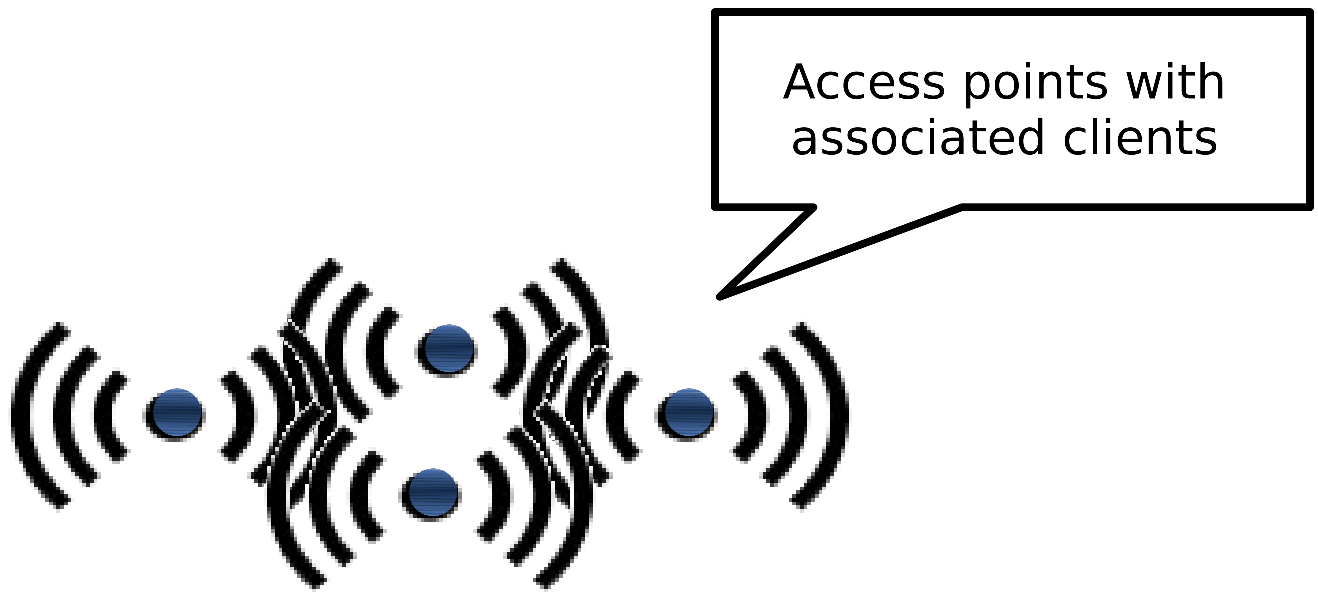
Conventional Network – Channel Allocation

- Signal strength is equal at all frequencies. Channels allocation strives to minimize interference.



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Conventional Network – Channel Allocation

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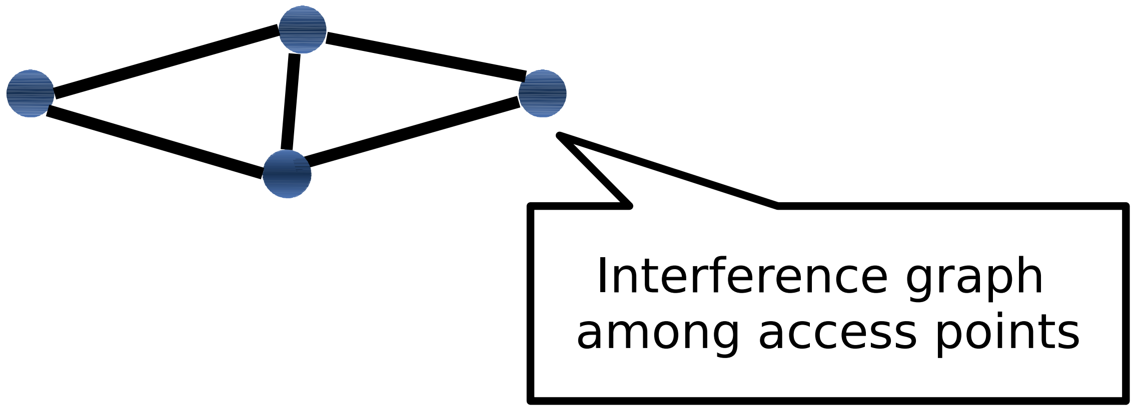
- Graph coloring – assign colors (channels) so that no two nodes that share a link in the interference graph are assigned the same color.



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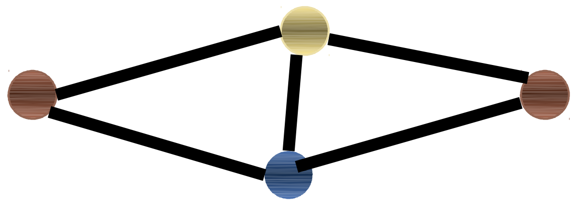

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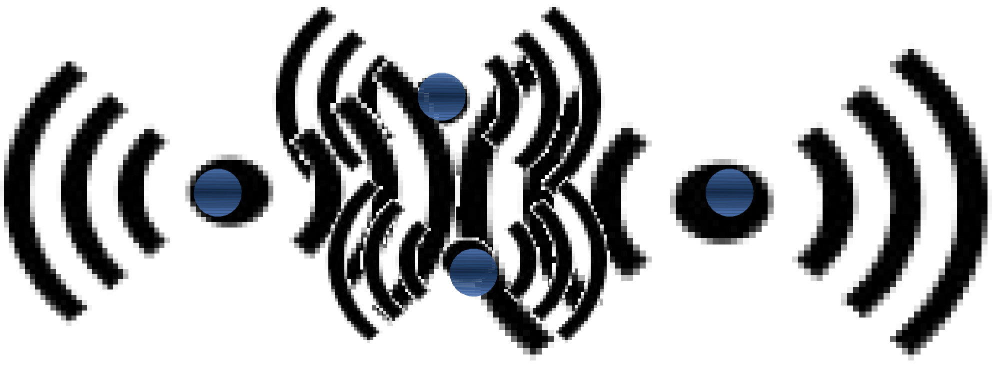
White Space Network – Channel Allocation

- In white spaces signal strength varies over channels, moreover the variation may be different for different pairs of nodes.



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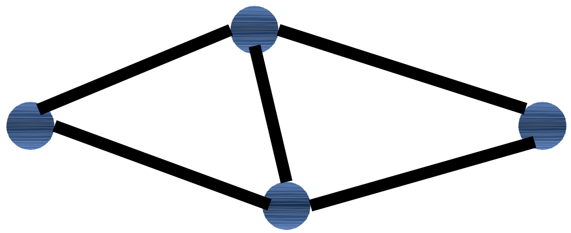

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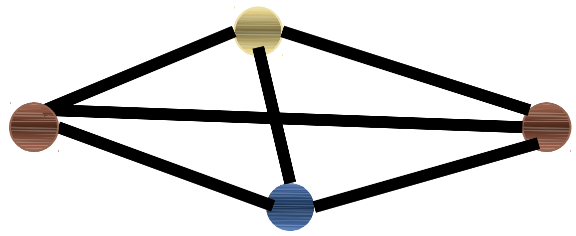

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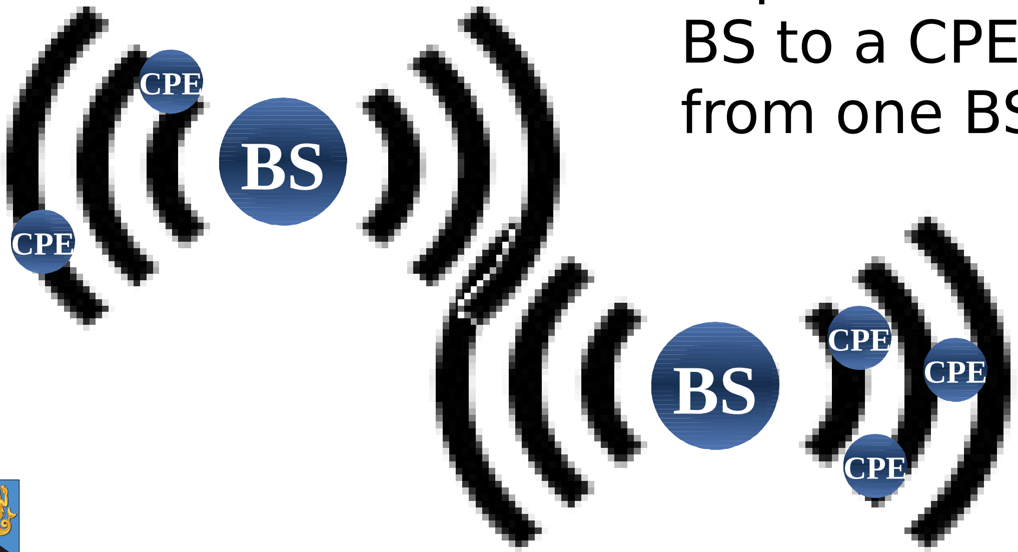
White Space Network – Channel Allocation

Propagation diversity over a wide white space band is highly varying and unpredictable

Even if we were to know propagation over all frequencies for all links, the problem would be intractable

Channel Probing and Medium Access

- Consider a network of base stations (BSs) with multiple associated clients (CPEs)
- BSs select their operating channels and CPS switch to a channel selected by the BS they are associated with



- Selection of the operating channel impacts the signal strength from a BS to a CPE and the interference from one BS to another.

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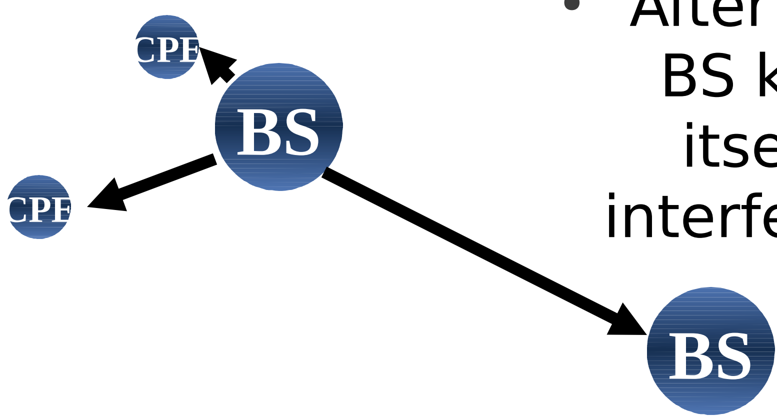
Channel Probing and Medium Access

- We extend the 802.22 protocol with inter-BS and BS-CPE probing.
- A probe is a packet whose content is known to the receiver. By comparing the received probe with the sent one, we can estimate the channel quality. A probe is sent at each available channel.



- After the probing is completed each BS knows channel quality between itself and each of its CPEs and the interference level between itself and each of the neighboring Bss.
- The information is also propagated to the neighboring BSs.

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Channel Allocation Method

- **Gibbs sampling** – obtain samples from a hard-to-sample multivariate distribution
- Draws samples from a multivariate probability distribution: $p(x_1, \ldots, x_N)$
- Sample each of the variables (x_i) in turn from a conditional probability distribution: $p(x_i \mid x_1^j, \ldots, x_{i-1}^j, x_{i+1}^j, \ldots, x_N^j)$
  Do this for each sample j = 1..k
- In the end we have *k* samples from the joint distribution

How is Gibbs sampling connected with channel allocation?

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Channel Allocation Method

1) Probability distribution is related to overall network performance

2) Probability distribution depends on channels allocated to BSs

3) Probability distribution favors states that lead to maximum performance

4) Conditional probability distribution isolates the impact of each of the nodes on the total optimization function

5) Conditional probability distribution can be calculated independently at each of the base stations

If the above conditions hold,
Gibbs sampling of the performance distribution
(over channels at different BSs)
will lead to the optimal channel allocation

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Channel Allocation Method

- Network performance metric:
  - ***Total network capacity C***, under a certain channel allocation ***c*** independently at each of the base stations: $C(c) = \sum_i C_i(c_i) = \sum W \log(1 + SINR_i(c_i))$

Sum of the capacity of each BS-CPE

SINR (signal to interference-plus-noise ratio) is different at different channels for different BS-CPEs due to high variability of propagation in white spaces

- Remember one of the conditions to use Gibbs sampling: *Conditional probability distribution isolates the impact of each of the nodes on the total optimization function*
  - SINR: a single BSs decision on the operating channel affects interference at other BSs, yet we cannot isolate the effect as it is "hidden" behind a log function

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Channel Allocation Method

- Network performance metric, take two:
  - ***Cumulative interference-plus-noise to signal ratio (CINSR):***

$$CINSR(c)=\sum_i \frac{1}{SINR_i(c_i)} = \sum_i \frac{\overset{\textbf{Noise}}{\boxed{N_0W}} + \overset{\textbf{Interference}}{\boxed{\sum_j ch(i,j)PH_{ji}(c_i)}}}{\underset{\textbf{Useful signal}}{\boxed{PH_i(c_i)}}}$$

ch(i,j) is 1 if BS i and BS j operate on the same channel

Channel Allocation Method

- Network performance metric, take two:
  - ***Cumulative interference-plus-noise to signal ratio (CINSR)***
    - Easy to isolate the impact of a single decision on the total metric

$$CINSR_i(c) = \frac{N_0 W}{PH_i(c_i)} + \sum_{j \neq i} ch(i,j)\left(\boxed{\frac{PH_{ji}(c_i)}{PH_i(c_i)}} + \boxed{\frac{PH_{ij}(c_i)}{PH_j(c_i)}}\right)$$

Impact of a local decision on own CINSR

Impact of a local decision on others CINSR

All the information can be calculated locally!

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Channel Allocation Method

- Connect the network performance metric with a probability distribution:
  - The Gibbs distribution:

$$\pi(c) = \frac{e^{-\frac{CINSR(c)}{T}}}{\sum_{c' \in c^N} e^{-\frac{CINSR(c')}{T}}}$$

Favors low CINSR states especially at a low temperature (T)

  - Local Gibbs distribution:

$$\pi_i(c) = \frac{e^{-\frac{CINSR_i(c_i,(c_j)_{j \neq i})}{T}}}{\sum_{c' \in c^N} e^{-\frac{CINSR_i(c_i,(c_j)_{j \neq i})}{T}}}$$

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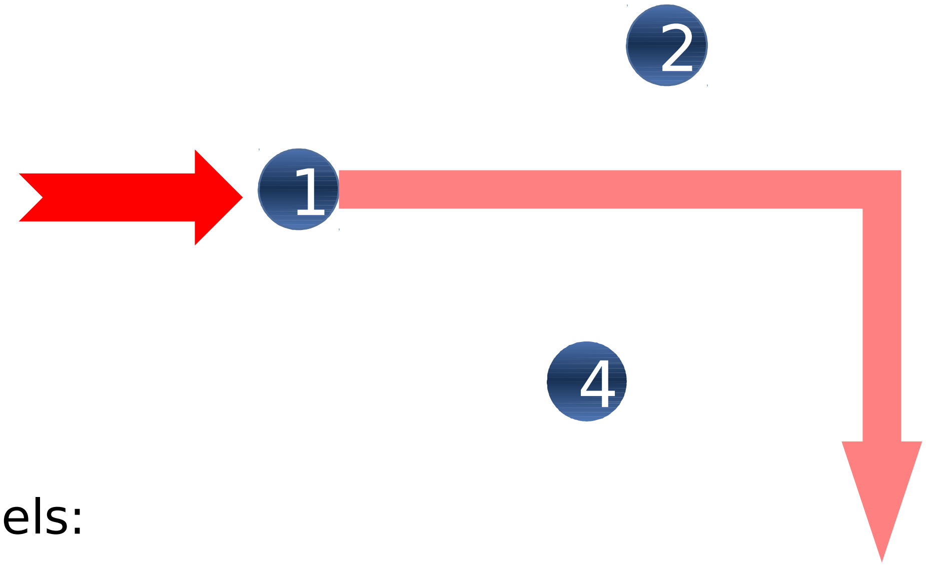
Channel Allocation Method

- Each BS samples its local Gibbs distribution to obtain a preferred channel selection



Available channels:

Channel Allocation Method

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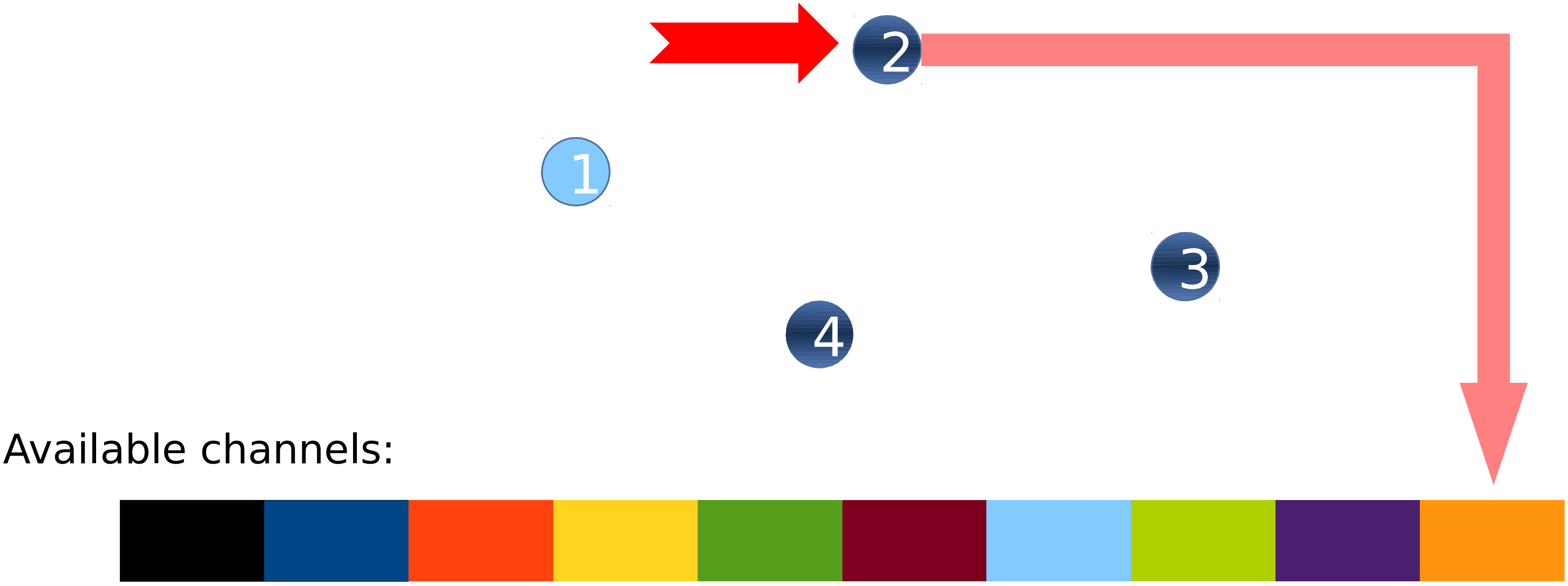

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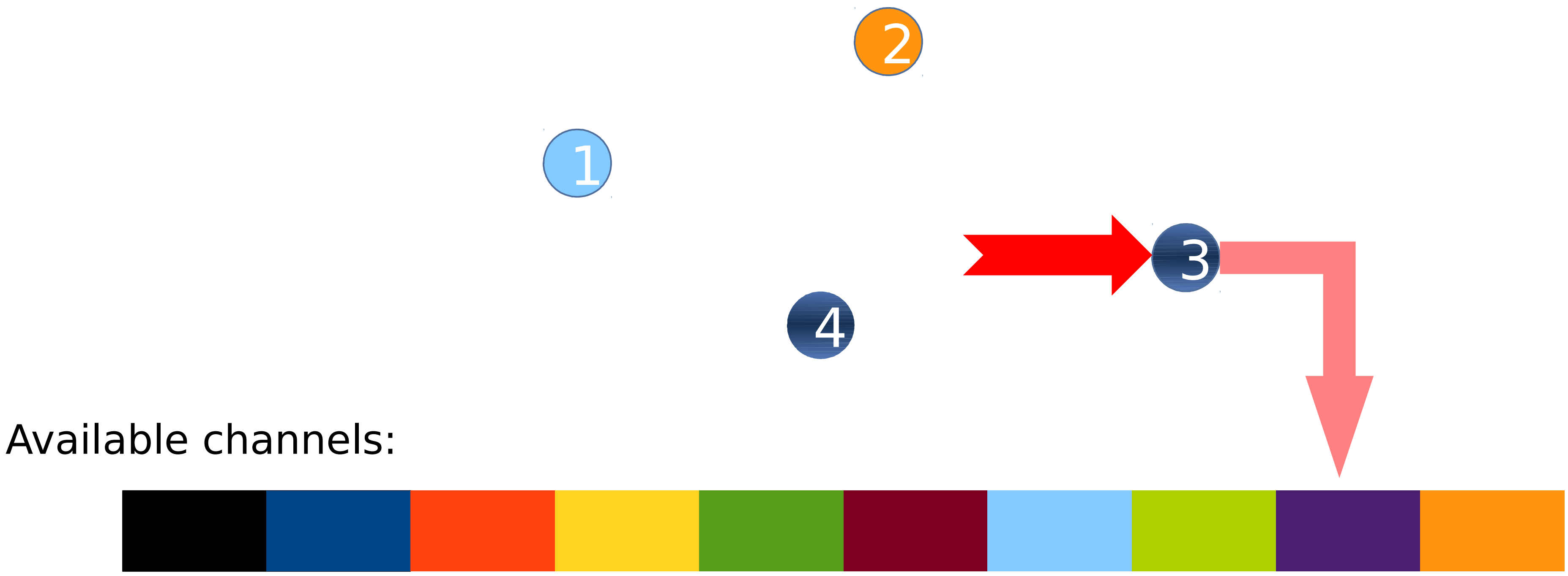

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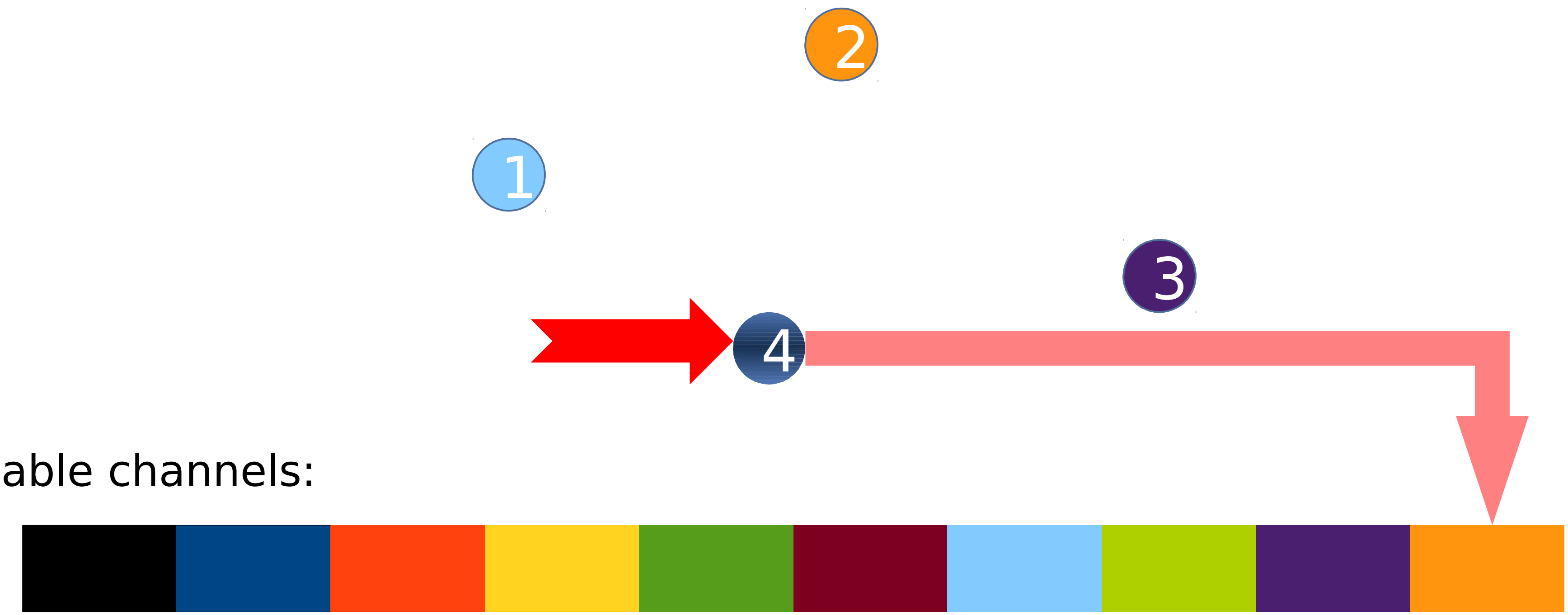

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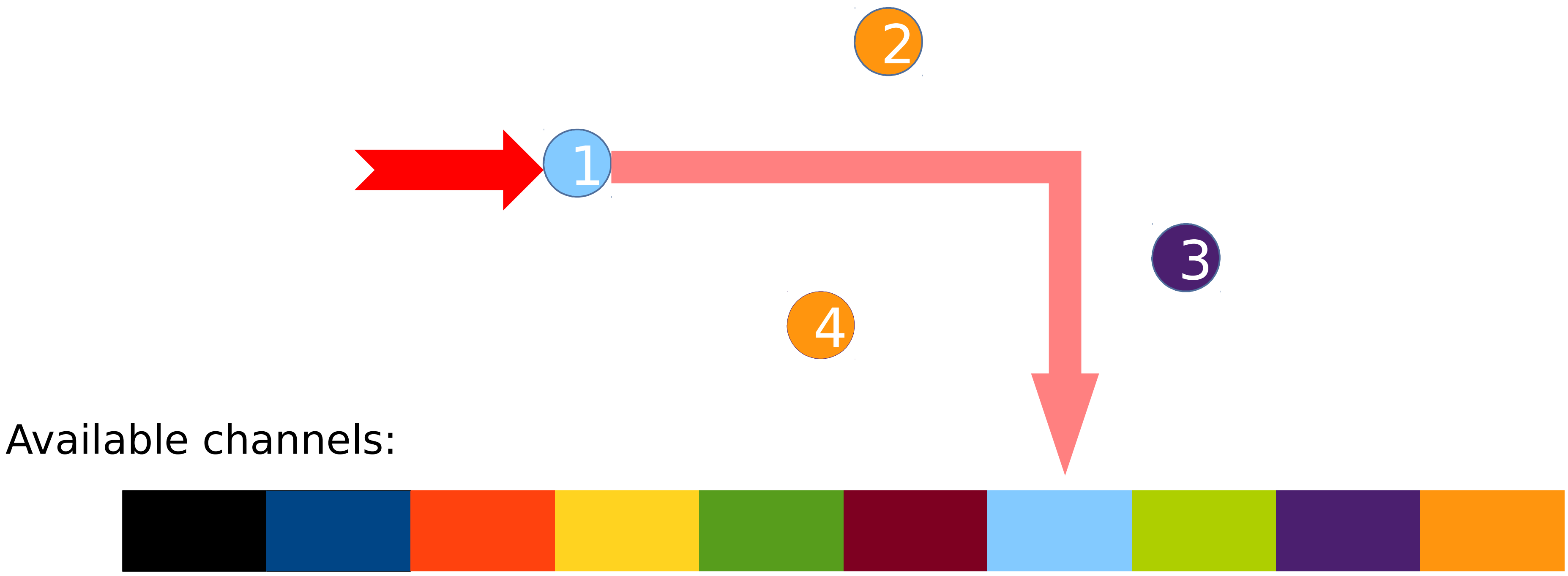

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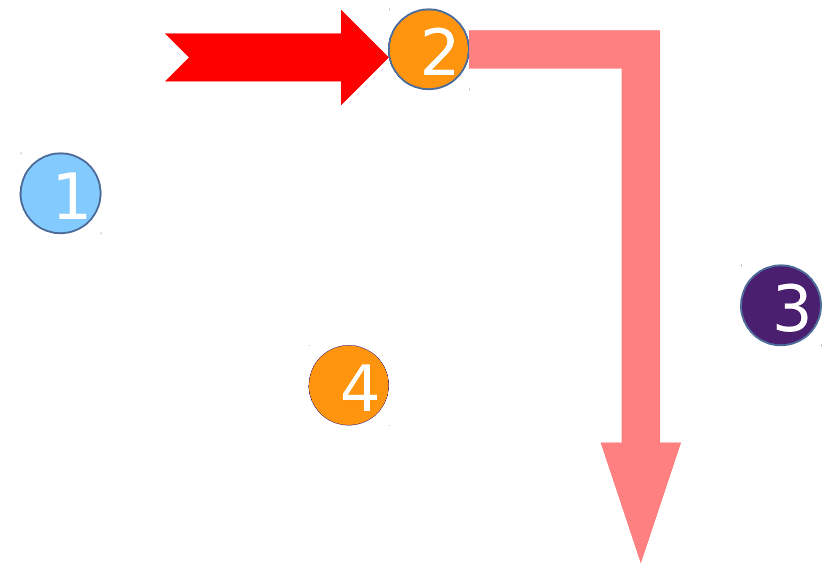

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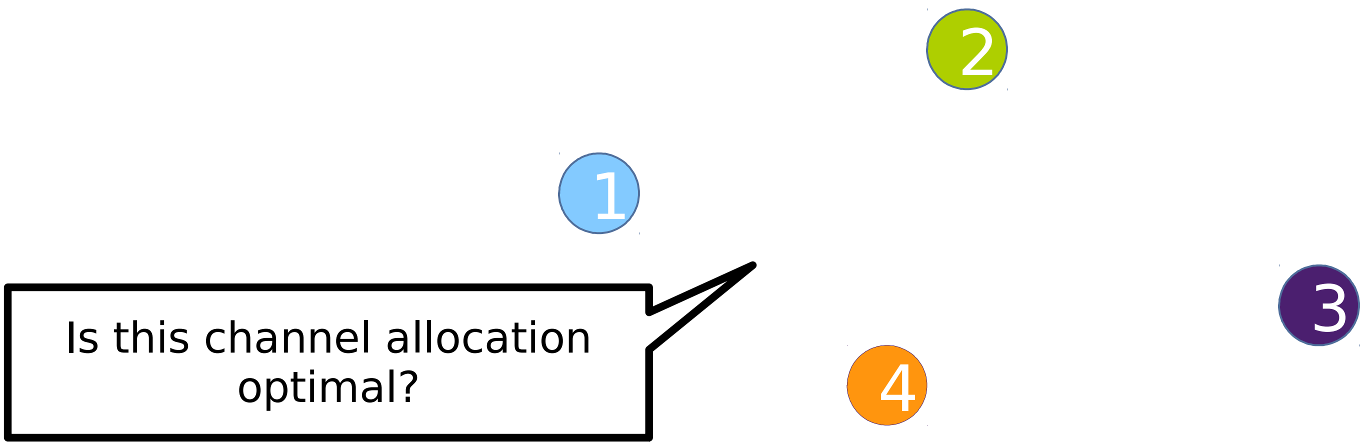
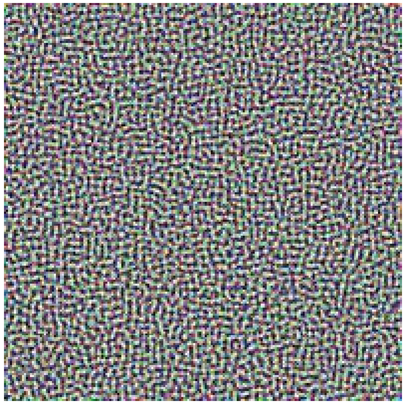
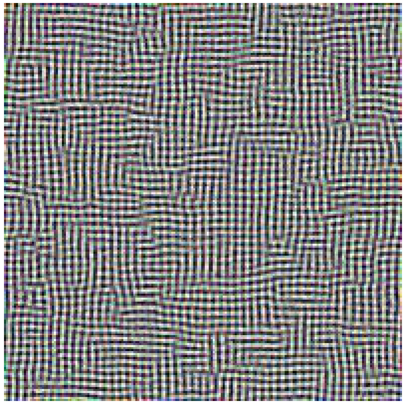


Available channels:

Channel Allocation Method

- The distribution might be such that many states have low energy, and the sampler might get stuck in a channel selection which is good, but not optimal
- **Annealed sampler** – change the temperature (*T*) as the process progresses allows the exploration of a wider solution space:
- Depending on the temperature change schedule we get different results
- Inspiration from annealing in metallurgy





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VillageLink Algorithm

- Distributed channel allocation algorithm (at each node):
  - While time $t < t_{end}$
    - Calculate temperature T at time t (temperature decreases over time)
    - Calculate local $CINSR_i$ for each possible channel decision
    - Calculate and sample local Gibbs distribution $\pi_i(c)$
    - Pick a channel according to the channel sampled from the Gibbs distribution and disseminate that information to neighbors
    - Listen to information about the channel selection of neighbors
  - Switch the wireless interface to the last selected channel

Channel switching does not occur in the loop!

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VillageLink Algorithm

- Properties of the algorithm
  - Distributed algorithm - uses only local computations.
  - Uses propagation profiling results from channel probing.
  - Only the information on the channel that resulted from the sampling process is used in each iteration. True channel switching happens only once at the end of the process.
  - For certain cooling schedules converges towards the globally minimal CINSR. However, there is no guarantee on the number of iterations needed.

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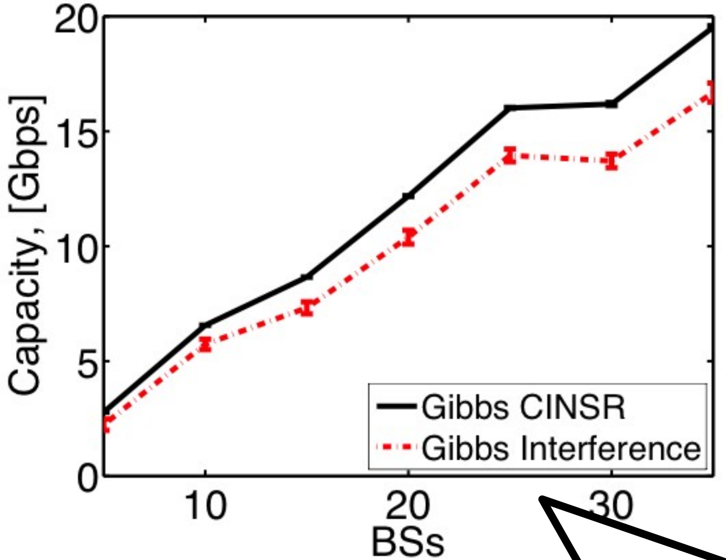
VillageLink – Evaluation

- Simulation setup
  - Propagation in white spaces is influenced by the free space loss, antenna patterns and the environment
    - Propagation calculation takes into account transmission power, antenna gain and the distance between the nodes
    - We closely model antenna irradiation patterns, frequency selectivity and antenna orientation
  - We experiment with a varying number of base stations and available channels
  - We model a wide area with a few TV stations that create varying spectrum availability over the area

VillageLink – Evaluation

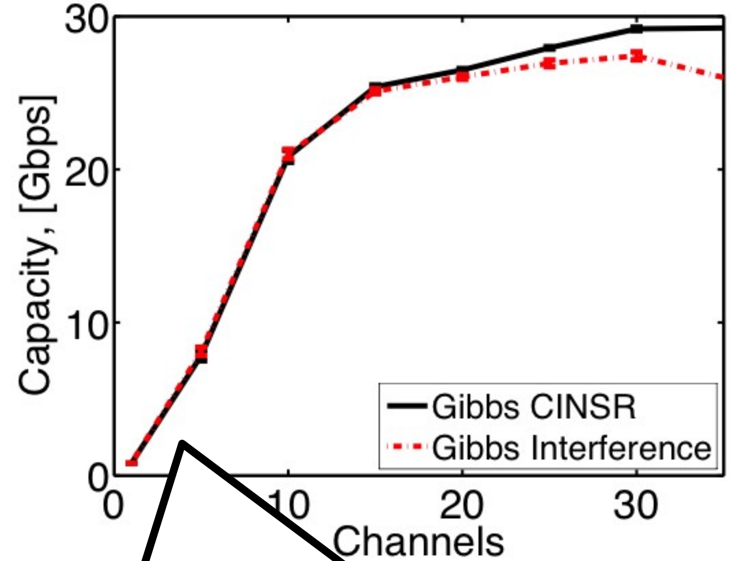
- Is CINSR a good metric?
  - Comparison to the minimal interference metric

Over-provisioned channels
a lot of vacant channels, few BSs



Channel allocation in a rural network is important even when interference is not a problem

Under provisioned channels
a lot of BSs, few channels



Minimizing interference is a good approach if the interference limits the capacity

VillageLink – Evaluation

- Alternatives to VillageLink
  - Least congested channel search (LCCS) – selects the least used channel locally
  - Preferred intra-cell channel allocation (PICA) – selects the channel for which the BS experiences the highest channel gain towards its clients
  - VillageLink minimizes CINSR (cumulative interference plus noise to signal ratio), thus taking into account both preferred channels and interference

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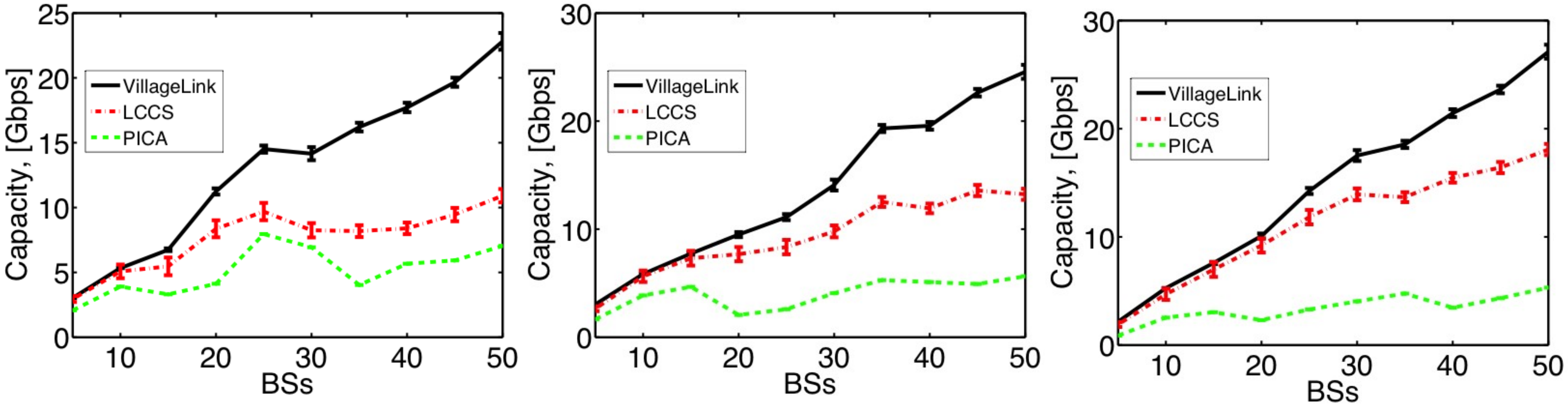
VillageLink – Evaluation

- Total network capacity:

Ten available channels

Fifteen available channels

Twenty available channels



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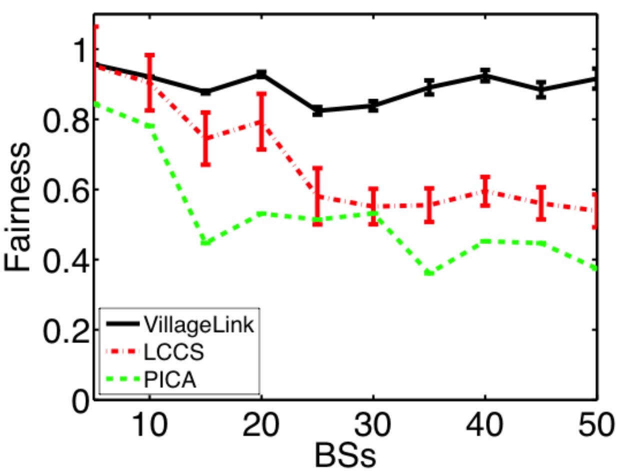
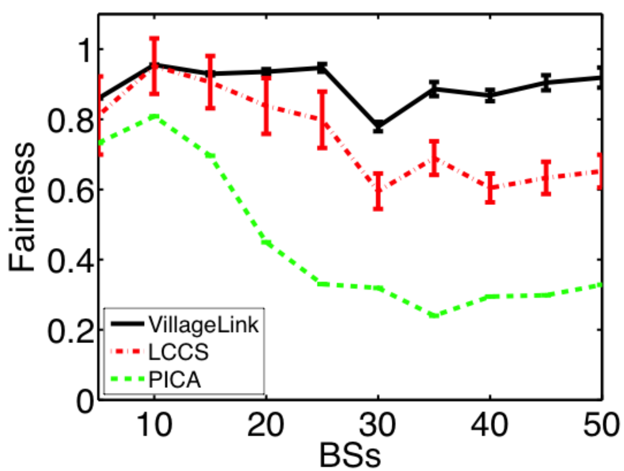
VillageLink – Evaluation

- Fairness (Jain fairness index,
  the closer the value is to 1 the better)

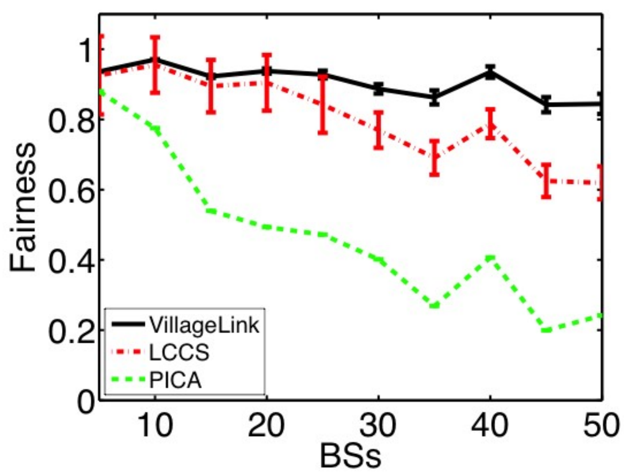
Ten available channels



Fifteen available channels



Twenty available channels



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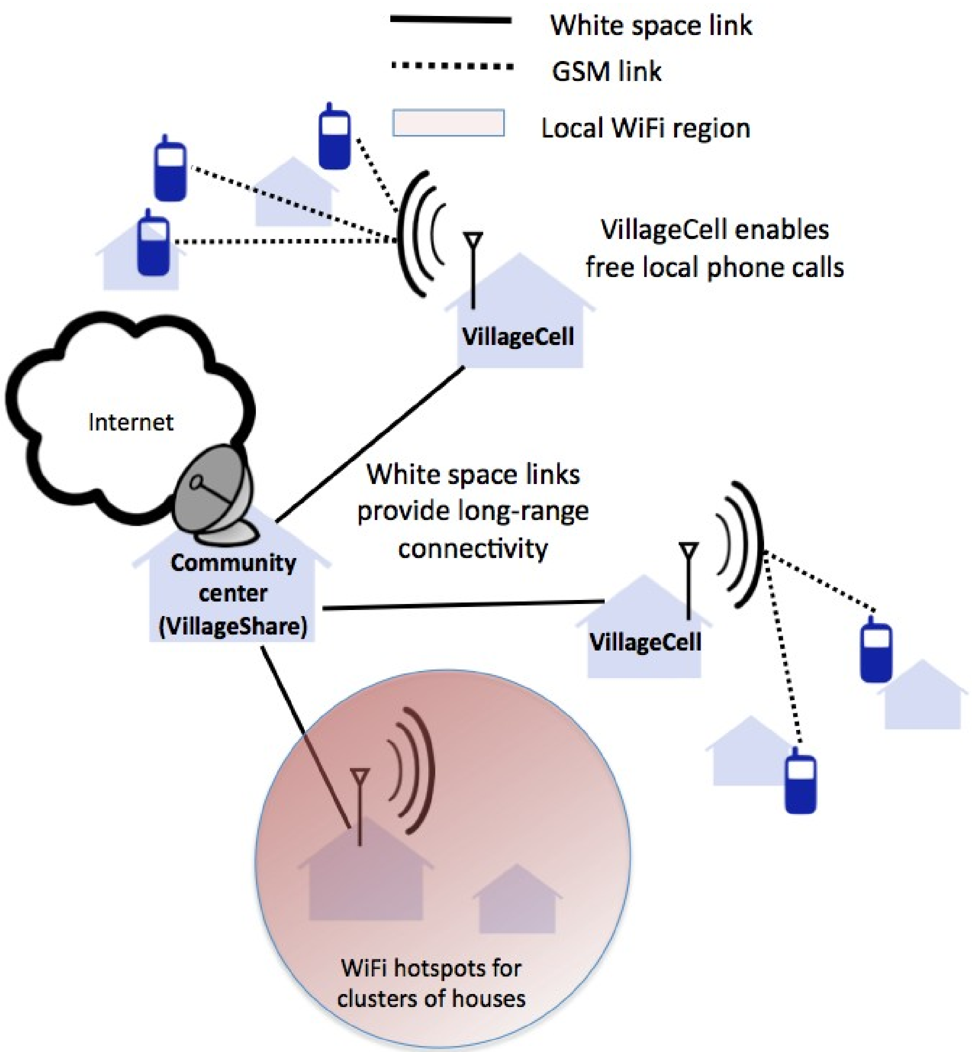
VillageLink – Conclusion

- White space channel allocation algorithm that jointly minimizes interference and maximizes BS-CPE capacity
- A practical solution that requires the minimal number of channel switching events
- VillageLink is an integral part of VillageNet, a set of networking solutions we developed for rural areas that includes our previous work VillageCell and VillageShare



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VillageLink – Future

- System Implementation
  - From simulator to Software Defined Radio
- Deployment
  - Use case for VillageLink
- Licensing
  - White spaces are still a grey zone when it comes to licensing, especially in our target areas

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Collaborators

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- Meraka Institute, South Africa
- LinkNet, Macha, Zambia

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Thank you!

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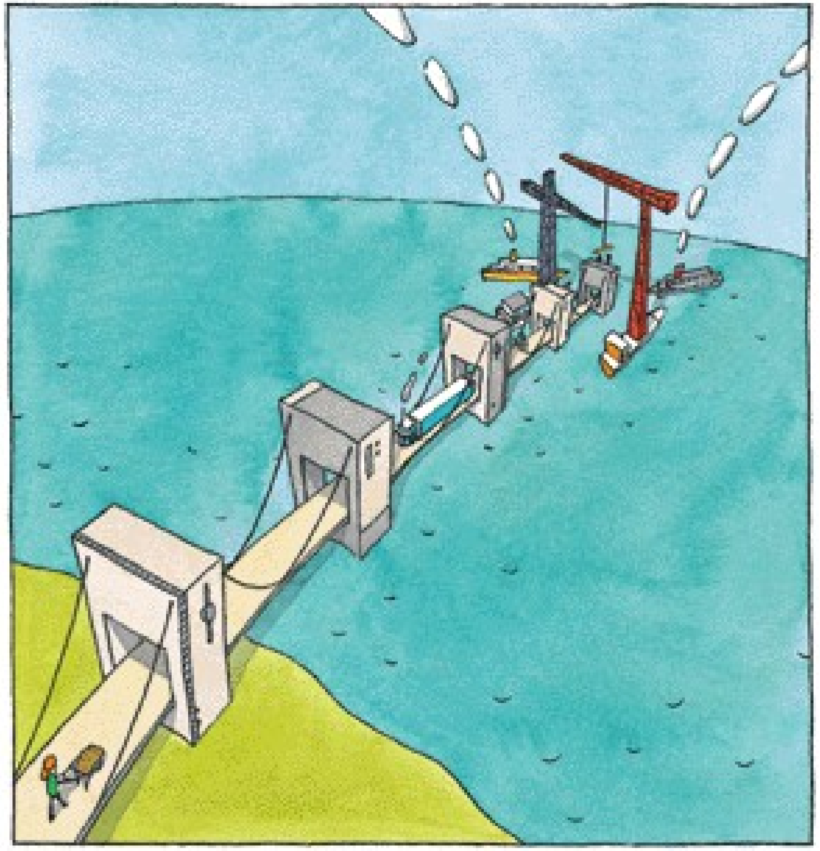
Digital Divide – Rethinking the definition

- A gap between those who do and those who do not have access to ICTs



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Digital Divide – Rethinking the definition

- A variety of inequalities among people's access to ICTs, ability to use ICTs and benefits from using ICTs.

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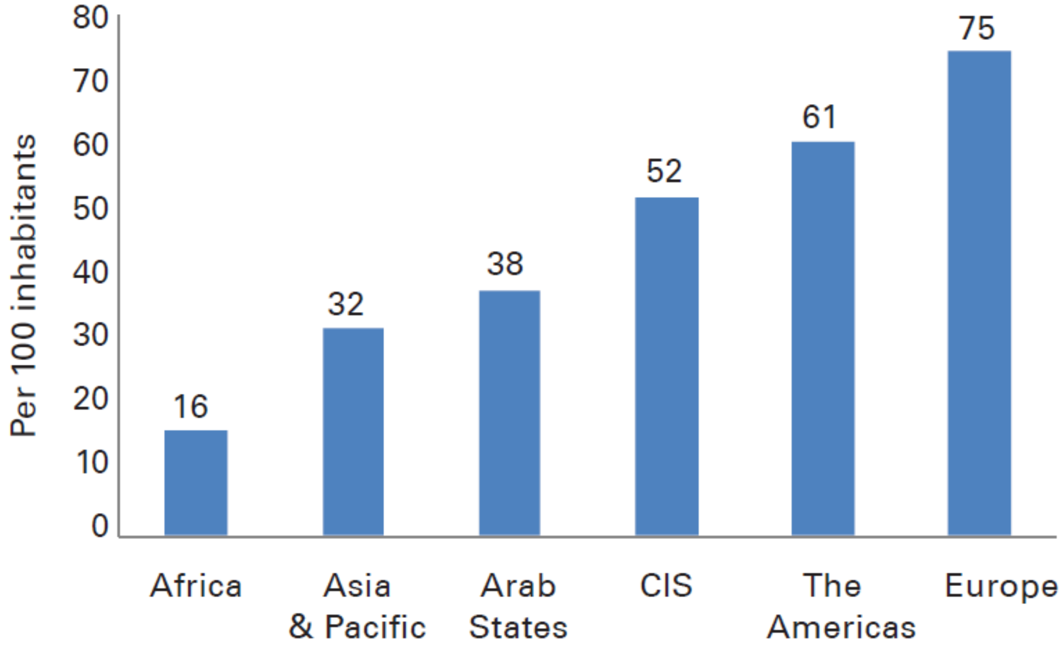
Measuring Success

- This is an over simplified view of the divide



Measuring Success

- A complex metric is necessary
  - Conventional metrics of access do not capture differences in access quality

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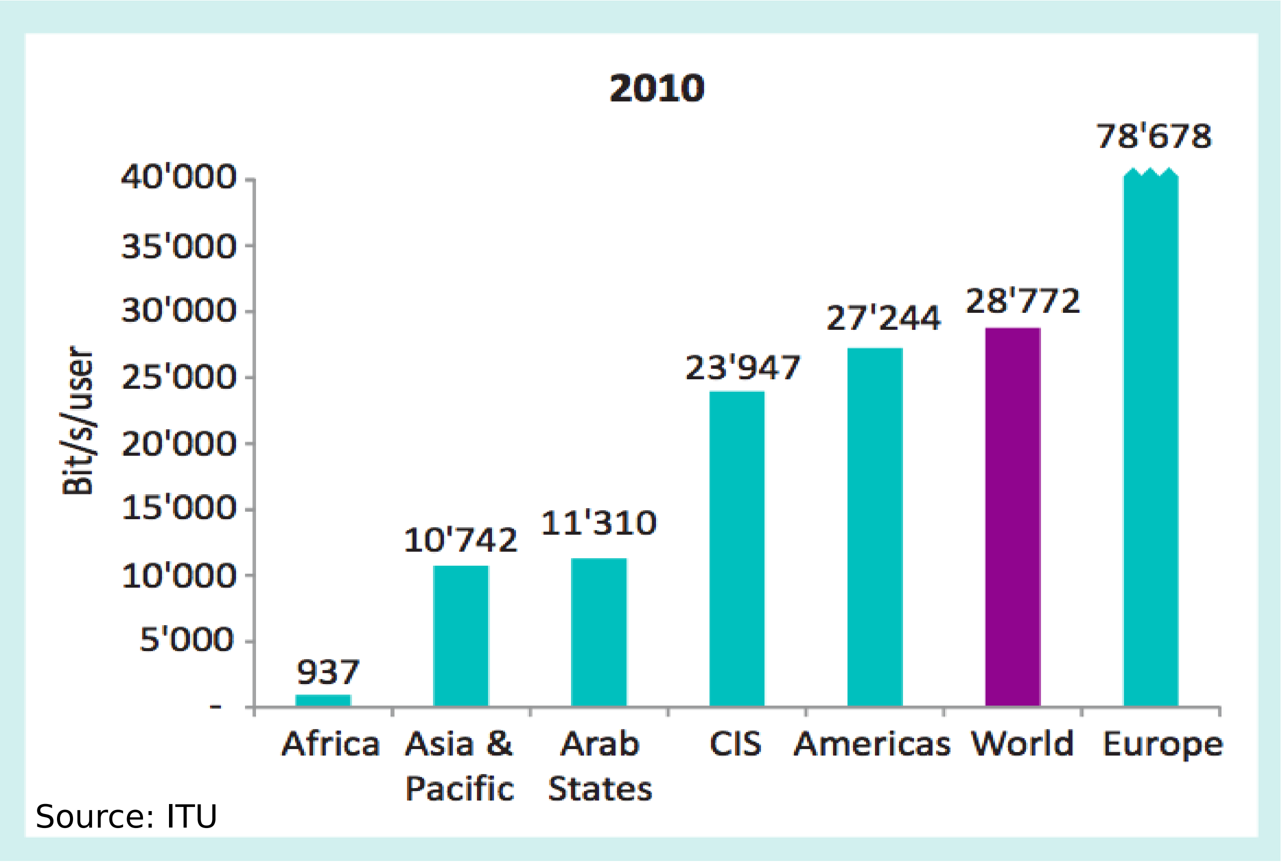
Measuring Success

- Example – Connectivity Speed

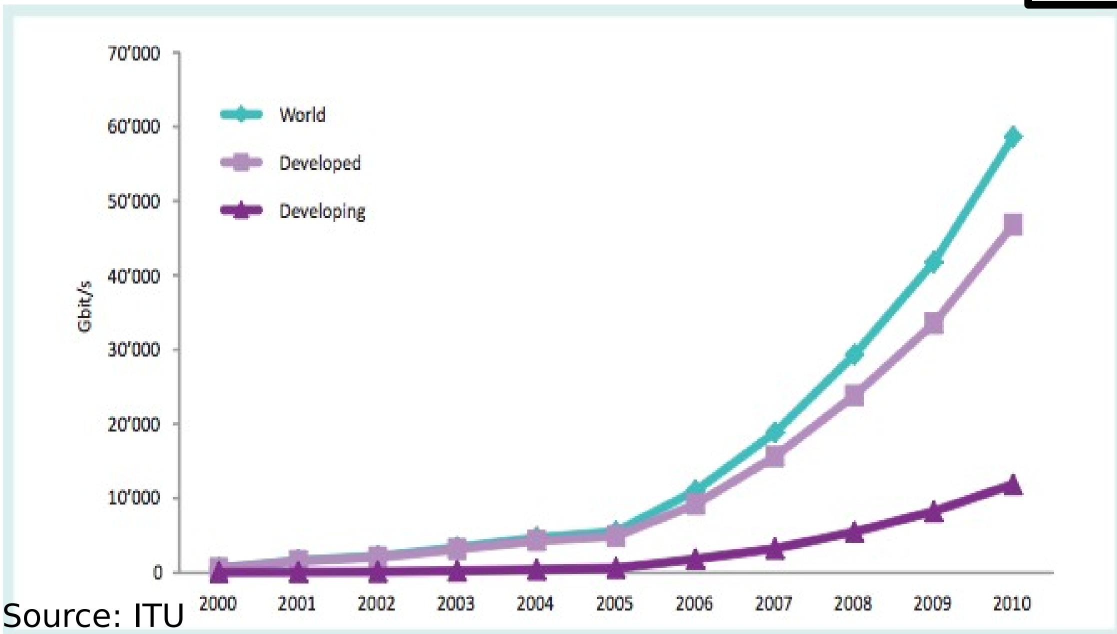


International Internet bandwidth (bit/s per user), by region

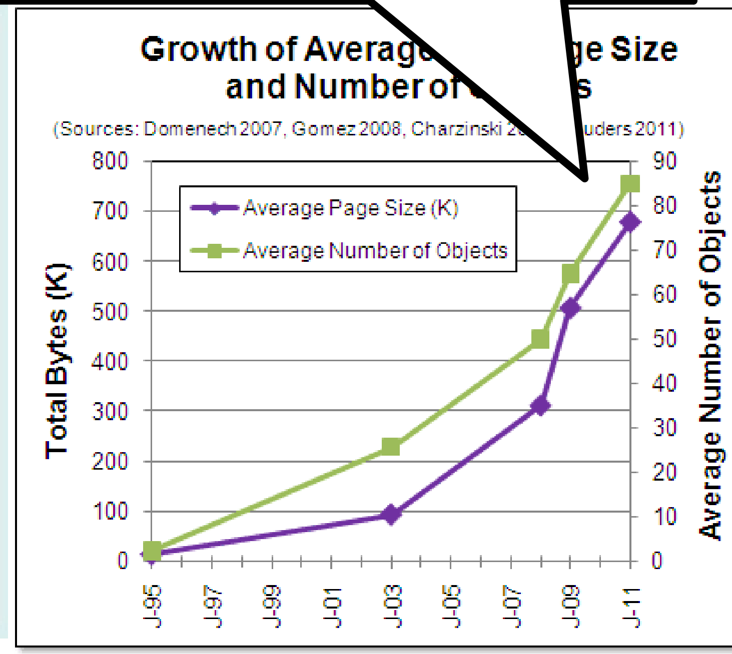
Measuring Success

- Example – Connectivity Spee

The average web page size grew about 50 times in 15 years



Source: ITU



International Internet bandwidth by region

Is the access in the developing world effectively getting worse?

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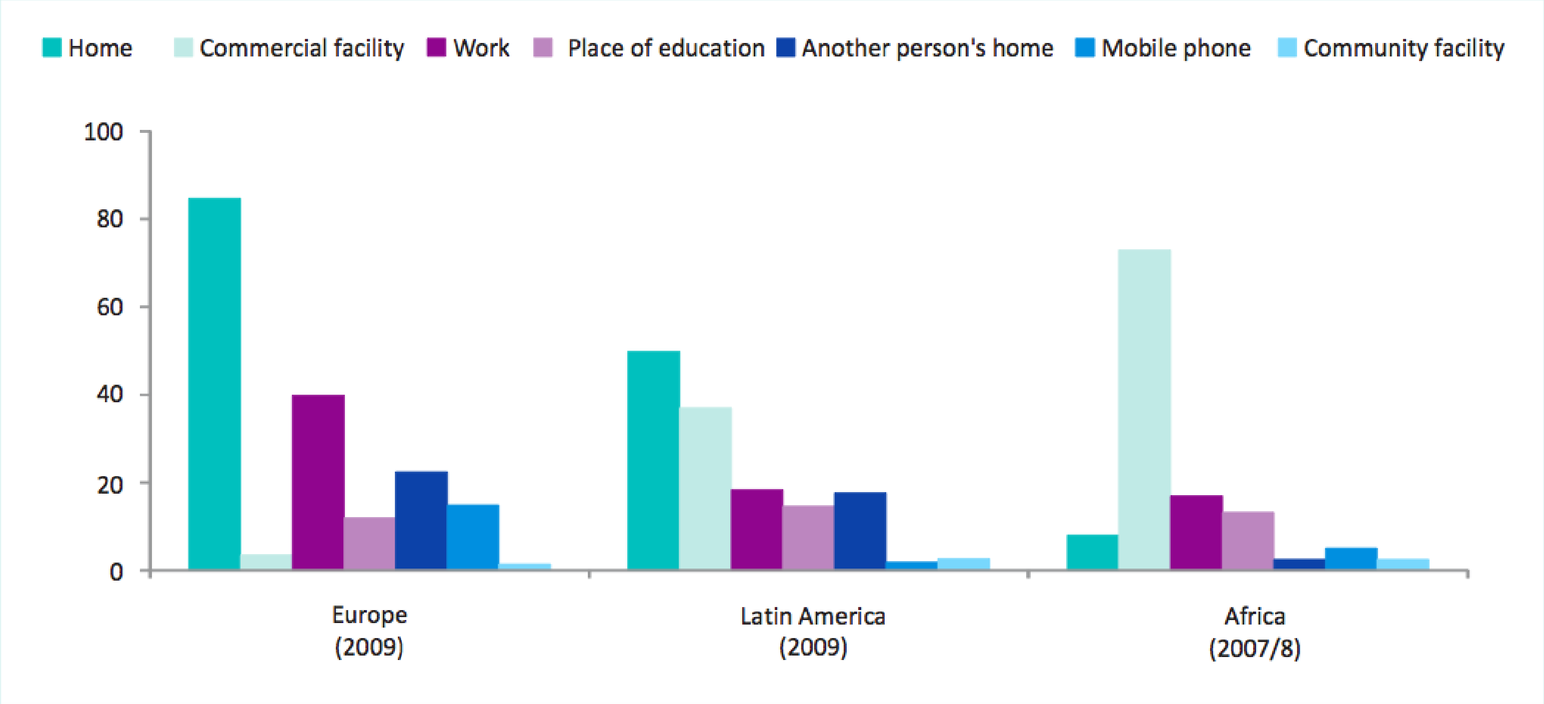
Measuring Success

- Example – Location of Access

Chart 5.9: Location of Internet use aggregated for 17 African countries, 8 Latin American countries and 35 European countries, latest available year



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Measuring Success

- Example – Location of Access
  - Location of access is important:
    - Distance:
      - At home or a long walk to a terminal
    - Availability hours:
      - Any time or business hours only
    - Pre-determining online behavior:
      - Browse the web or prepare emails before the access happens
    - Types of applications used:
      - Some applications are more suited for leisurely at-home access - Facebook

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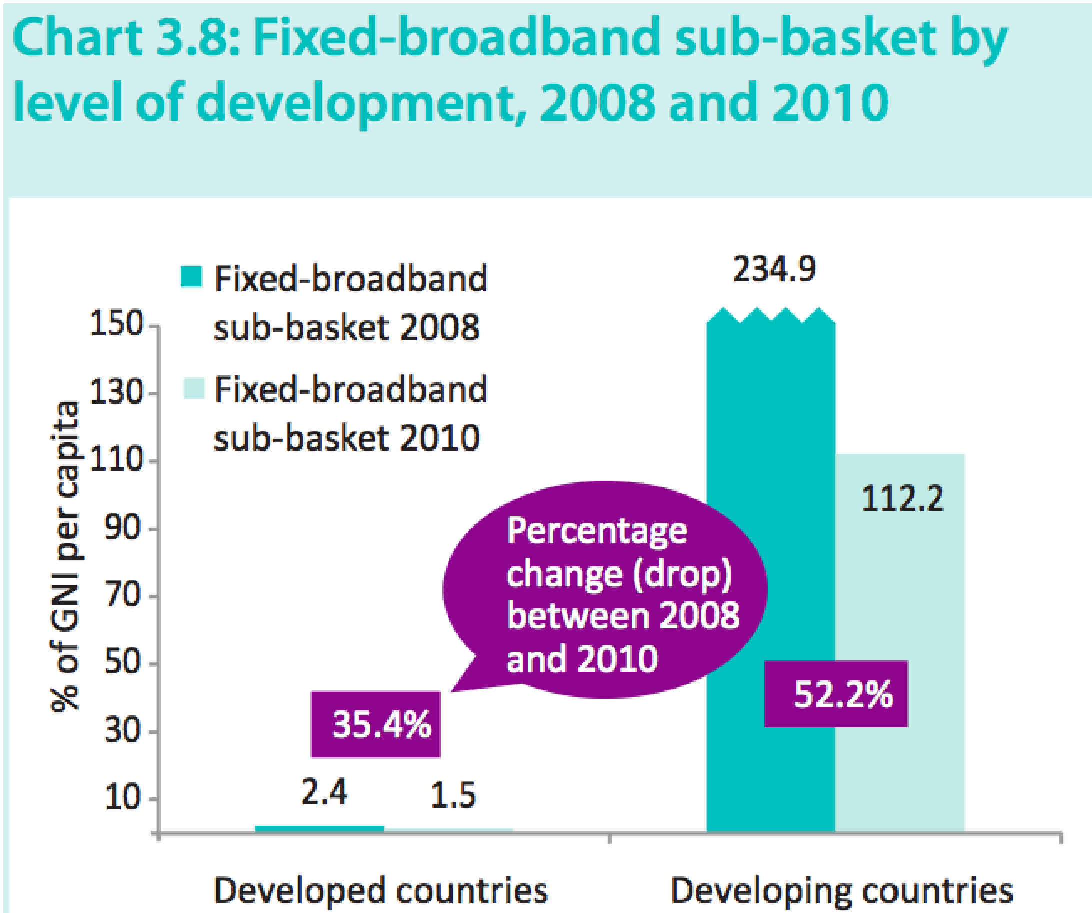
Measuring Success

- Example – Cost of Access



Source: ITU

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Measuring Success

- Cultural and socio-economic affordances of connectivity:
  - Content in local languages
  - Availability of e-Government services
  - e-Commerce
  - Supporting infrastructure: roads, banking (credit cards)
  - Social affordances: connectivity with local and global population; online social networks; networked individualism

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Holistic approach