VillageLink: Wide-Area Wireless Coverage

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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
Digital Divide

Internet users per region

Source: ITU 2013
Digital Divide – Rural vs Urban

Population that uses the Internet [%]

Source: ITU
Almost 3 billion people live in rural areas of the developing world. They are the most Internet-deprived layer of the society.
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.
Holistic Approach

Investigate existing solutions, identify obstacles and true needs of our users

Develop technical solutions with experts from target areas
Investigating Challenges in Rural Area Connectivity

- Analysis of the existing rural-area networks in Africa:
  - Satellite-based WLAN
  - Lightweight traffic monitoring system:
    - Packet headers on the satellite gateway
    - Squid proxy logs
  - Social surveys

More on rural area network analysis in our WWW'11 paper
Investigating 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:
  - People share files via USB drives when the network is congested
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
**VillageNet**

**VillageCell**

Enables free local mobile phone calls via off-the-shelf open-source solutions.

It requires no modification to the existing GSM handsets and SIM cards.

More in our ICTD'12 paper
VillageNet

VillageShare

Improves content generation and sharing in a village via a local file sharing application.

Enables extra upload capacity via time-delayed uploads.

More in our ACM DEV'12 paper
VillageNet

VillageLink

Connect distant locations through outdoor, non line of sight wireless links operating on unlicensed frequencies.
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
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 $\sim f^2$)
    - Not absorbed by vegetation
    - Signal can bend around obstacles
White Spaces – Issues

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

<table>
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<th>Technology</th>
<th>$f_L$ (MHz)</th>
<th>$f_U$ (MHz)</th>
<th>$D$ (dB)</th>
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<td>White spaces</td>
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</tr>
</tbody>
</table>
White Spaces – Issues

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

Results from a 3km long outdoor link in South Africa

- Signal strength can be tens of dB different across the band
White Spaces – Issues

Performance across the frequency band cannot be described solely by the propagation theory.

Antenna properties and the environment determine signal strength at different channels.

Why is this a problem?
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?
Conventional Network – Channel Allocation

- Signal strength is equal at all frequencies. Channels allocation strives to minimize interference.
Conventional Network – Channel Allocation

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- Interference graph + graph colouring
Conventional Network – Channel Allocation

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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.

Access points with associated clients
White Space Network – Channel Allocation

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- Minimizing interference with graph coloring does not work anymore. The graph depends on channel selection.
White Space Network – Channel Allocation

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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.
VillageLink

• **Distributed** channel allocation for white spaces
VillageLink

- **Distributed** channel allocation for white spaces
- Profile white space propagation with **probing**

After the probing is completed each BS knows the channel quality between itself and each of its CPEs and the interference level between itself and each of the neighboring BSs.

Information exchanged among neighbouring BSs.
VillageLink

- **Distributed** channel allocation for white spaces
- Profile white space propagation with **probing**
- **Gibbs sampling** for channel selection
  - Obtain samples from a hard-to-sample multivariate distribution: \( p(x_1, \ldots, x_N) \)
  - Sample each of the variables \( x_i \) in turn from a conditional probability distribution: \( p(x_i | x_1^j, \ldots, x_{i-1}^j, x_{i+1}^j, \ldots, x_N^j) \)
  - Do this for each sample \( j = 1..k \)
  - In the end we have \( k \) samples from the joint distribution \( p(x_1, \ldots, x_N) \)

\( X_s \) represent channels allocated to BSs.

We use a probability distribution that favours low-interference, high-capacity network state.
VillageLink

- **Distributed** channel allocation for white spaces
- Profile white space propagation with **probing**
- **Gibbs sampling** for channel selection
  - For $P$ we use Gibbs distribution:
    \[ \pi(c) = \frac{e^{-\frac{\text{CINSR}(c)}{T}}}{\sum_{c' \in c^N} e^{-\frac{\text{CINSR}(c')}{T}}} \]
- We develop a metric:
  \[ \text{CINSR}(c) = \sum_i \frac{1}{\text{SINR}_i(c_i)} = \sum_i \frac{N_0 W + \sum_{j \neq i} \text{ch}(i,j) \text{PH}_{ji}(c_i)}{\text{PH}_i(c_i)} \]
VillageLink

- **Distributed** channel allocation for white spaces
- Profile white space propagation with **probing**
- **Gibbs sampling** for channel selection
- **Annealed sampler** to ensure that the solution space is well explored
  - Parameter $(T)$ change: convergence vs exploration
  - Inspiration from metallurgy
VillageLink

- **Distributed** channel allocation for white spaces
- Profile white space propagation with **probing**
- **Gibbs sampling** for channel selection
- **Annealed sampler** to ensure that the solution space is well explored
- **Channel switching** happens only **once**, before that BSs exchange the desired channel selection, but do not physically switch channels
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
VillageLink – Evaluation

Ten available channels

Fifteen available channels

Twenty available channels
VillageLink in VillageNet

- **VillageLink:**
  - Provide at-home access for all
  - Spectrum efficient
  - Max capacity
  - Min interference
  - Autonomous BSs

- **Future work:**
  - SDR implementation
  - Integration with VillageNet
  - White space licensing?
Thank you!

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Slides, related papers:
www.cs.bham.ac.uk/~pejovicv/COMSNETS.php
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 $C/NSR_i$ 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
Gibbs Sampling Conditions

- Probability distribution is related to overall network performance
- Probability distribution depends on channels allocated to BSs
- Probability distribution favors states that lead to maximum performance
- Conditional probability distribution isolates the impact of each of the nodes on the total optimization function
- Conditional probability distribution can be calculated independently at each of the BSs
Gibbs Sampling Metric

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

- Network performance metric:
  - Cumulative interference-plus-noise to signal ratio (CINSR):
    \[
    CINSR(c) = \sum_i \frac{1}{SINR_i(c_i)} = \sum_i \frac{N_0W + \sum_{j \neq i} ch(i, j)PH_{ji}(c_i)}{PH_i(c_i)}
    \]

- Easy to isolate the impact of a single decision on the total metric:
  \[
  CINSR_i(c) = \frac{N_0W}{PH_i(c_i)} + \sum_{j \neq i} ch(i, j) \left( \frac{PH_{ji}(c_i)}{PH_i(c_i)} + \frac{PH_{ij}(c_i)}{PH_j(c_i)} \right)
  \]
VillageLink – Evaluation

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

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

Minimizing interference is a good approach if the interference limits the capacity.
Almost 3 billion people live in rural areas of the developing world. They are the most Internet-deprived layer of the society.

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