FRACTEL: A Fresh Perspective on (Rural) Mesh Networks

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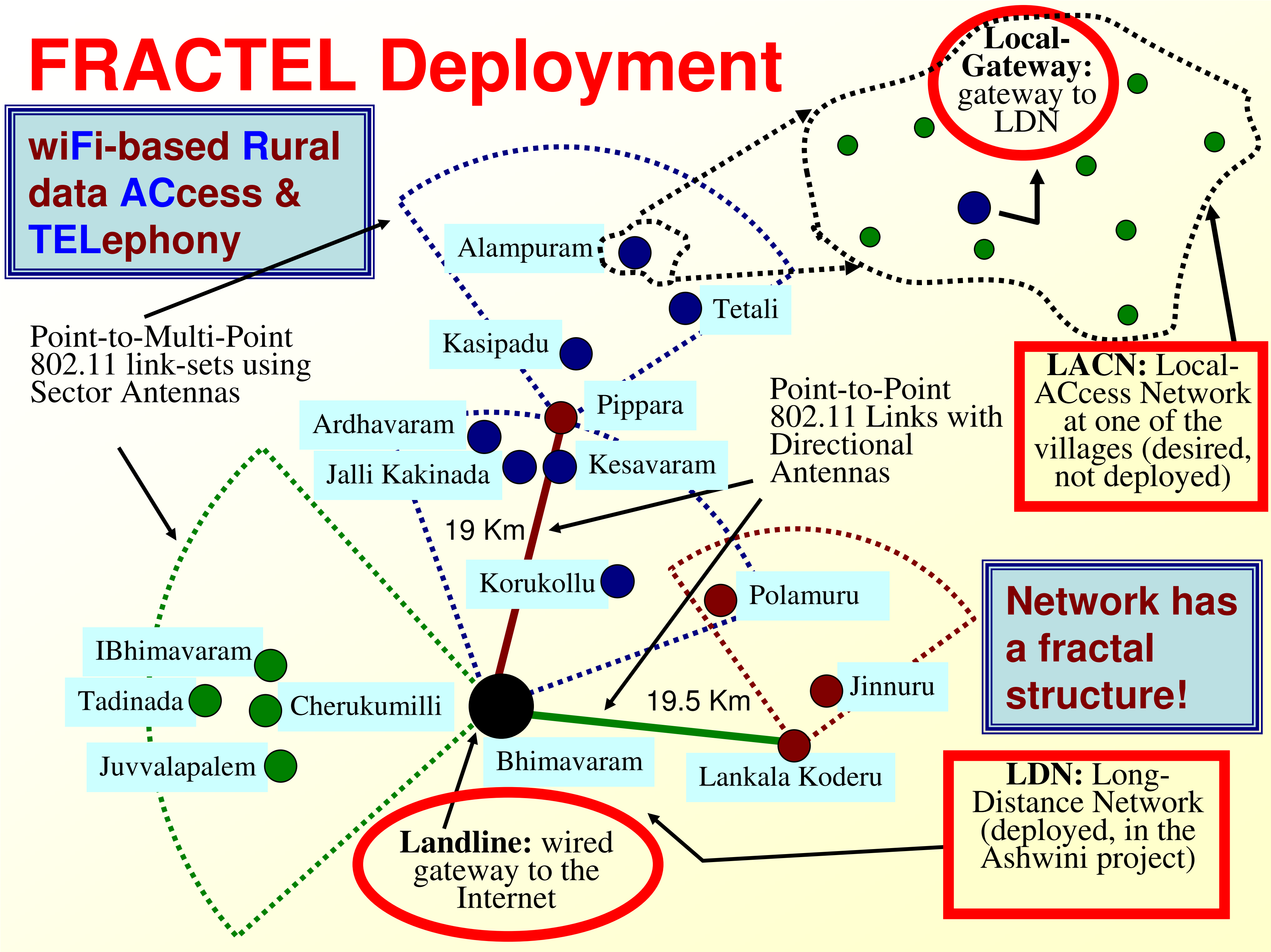
FRACTEL Deployment



FRACTEL Goals

- Support a variety of applications:
  - HTTP/FTP
  - Voice over IP
  - Video-conferencing based, real-time
- Quality of Service is necessary
- Scalable operation:
  - Deployment for a few hundred nodes in a district

Outline

- FRACTEL problem setting
- Link abstraction in FRACTEL
- TDMA operation in FRACTEL
- TDMA implementation challenges
- Conclusion

FRACTEL Problem Setting

1. Network architecture
   - Long-distance versus local-access links
     - Antenna type
     - Mounting height
   - Expected network expanse
2. Nature of traffic

FRACTEL Network Arch. (1 of 3)

Long-distance links

- Few km to tens of km

Antenna types:

- High-gain directional antennas: 24-27dBi
  - 8^{o} beam-width
  - P2P links
- Sometimes 17-19dBi sector antennas
  - 30^{o}-90^{o} beam-width
  - P2MP link-set
- Cost: $100 or so

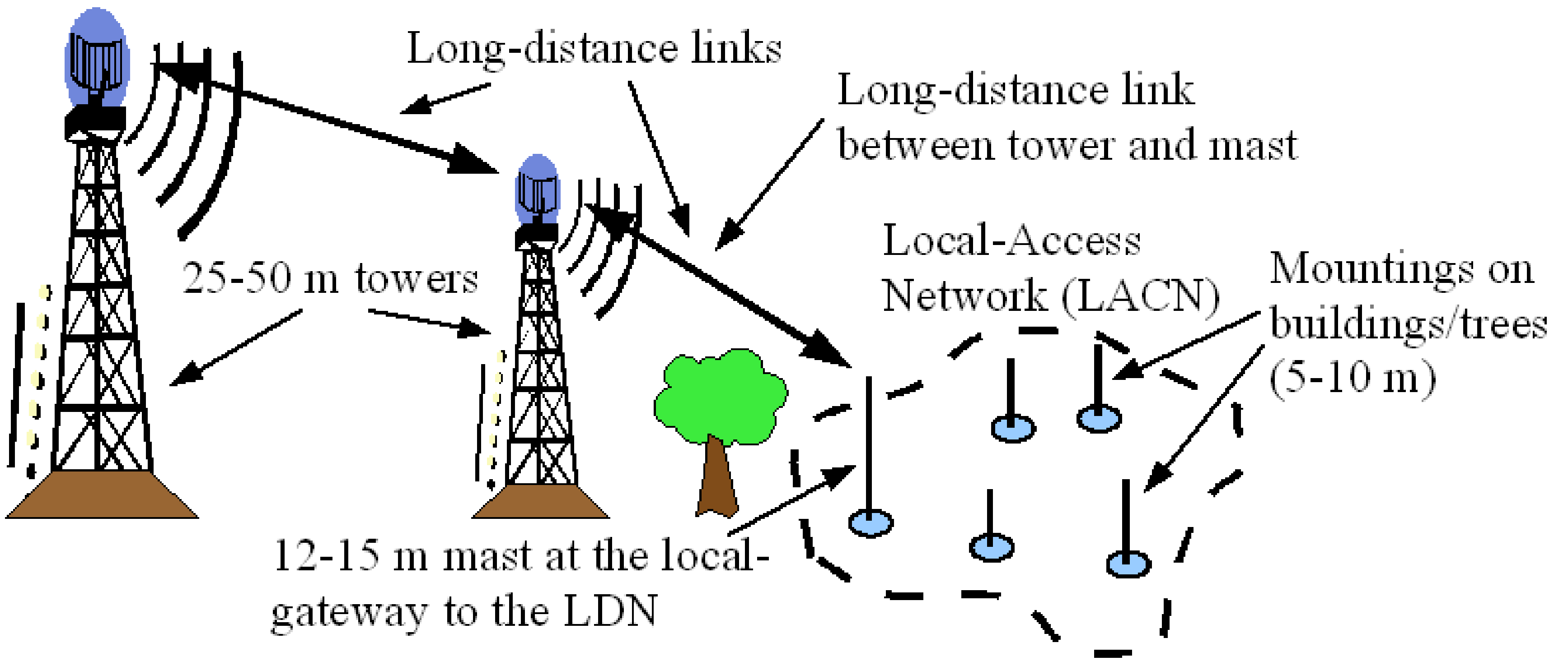
Local-access links

- Few 100 metres

Antenna types:

- Omni-directional antennas: 8dBi
- Or Cantennas: 10dBi
- Cost: $10-15
- Light-weight: easy mounting
- No alignment procedures

FRACTEL Network Arch. (2 of 3)



Long-distance links

Antenna mounting:

– 25-50m tall towers: high cost, planned

– 12-15m masts can be used at one end

Local-access links

Antenna mounting:

– Mounted on buildings, trees, etc.

– 5-10m at most

FRACTEL Network Arch. (3 of 3)

Network Expanse:

1. District expanse: 20-30km radius
2. One point of wired connectivity within each district
3. 10-20km long-distance links

1+2+3 → most districts can be covered within 2 hops of the landline

Nature of Traffic in FRACTEL

1. Traffic to/from landline
   - E.g. video-conferencing between landline and villages
2. Traffic between villages and the Internet, via landline

We expect traffic between two villages to be a small fraction

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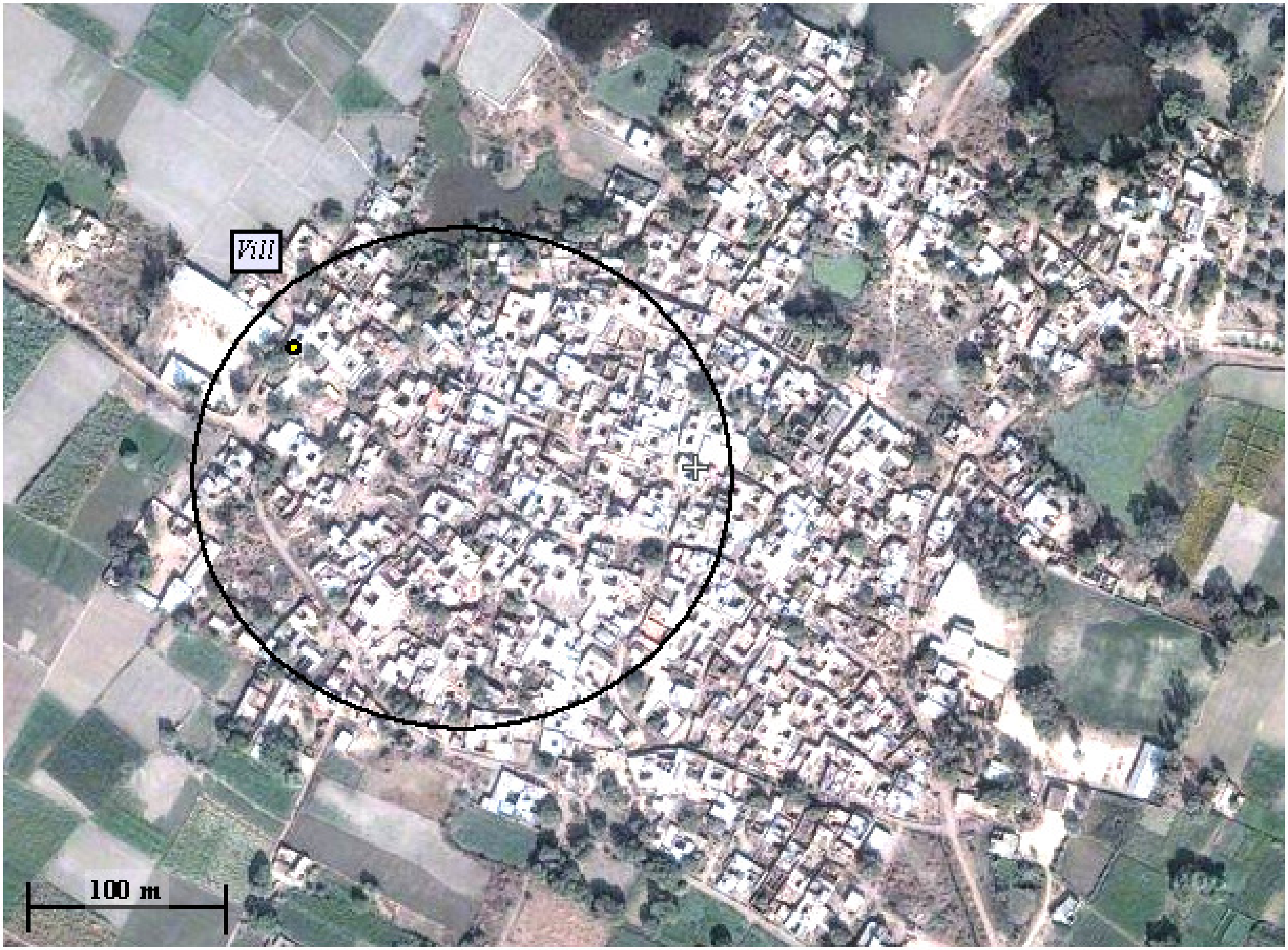
Link Abstraction: Background

- Link behaviour critical for predictable performance
- Link abstraction:
  - Either link exists or does not
  - That is, 0% packet reception, or ~100%
  - Abstraction holds in wired networks
- Roofnet study:
  - Outdoor WiFi mesh, Boston/Cambridge area
  - Most links have intermediate loss rates, between 0% and 100%
  - *No link abstraction!*

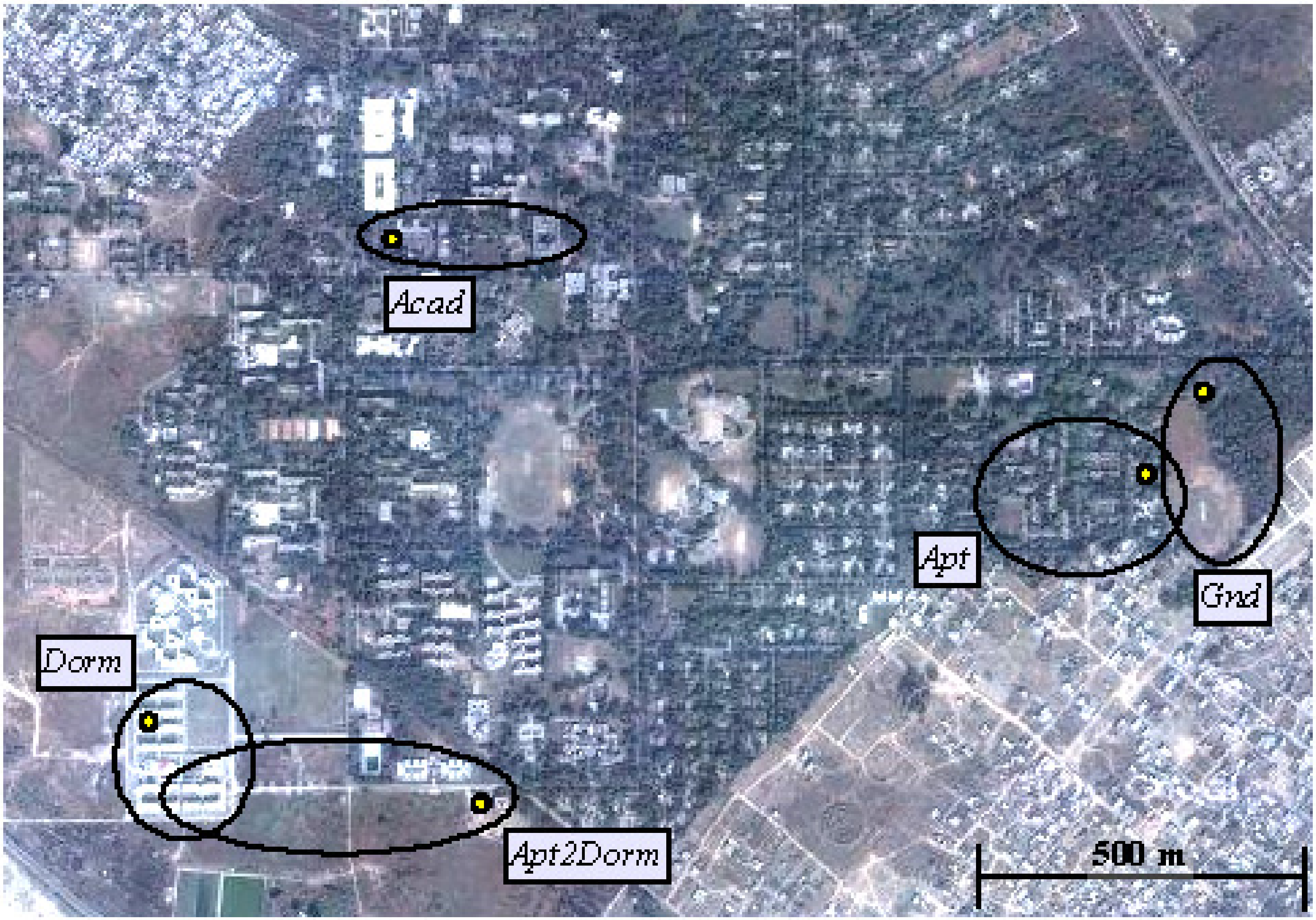
Link Abstr.: DGP, Roofnet, FRACTEL

	Typical link distances	**Network architecture**	**Environment**	**Multipath effects**	**SNR or RSSI**	**External interference**	**Link abstraction**
Long-distance mesh networks (e.g. DGP)	Up to few tens of kms	High gain directional & sector antennas on tall towers or masts	Rural setting studied in depth	Effect not apparent	Has strong correlation with link quality	Affects links performance	Valid
Rooftop mesh networks (e.g. Roofnet)	Mostly < 500 m	Mostly omni-directional antennas on rooftops	Dense urban setting studied in-depth	Reported as a significant component	Not useful in predicting link quality	Reported as not significant	Not valid
FRACTEL	Mostly < 500 m	Would like to avoid tall towers	Rural, campus, residential	*To be determined*	*To be determined*	*To be determined*	*To be determined*

FRACTEL Measmt. Study: Amaur



FRACTEL Measmt. Study: IITK



Measurement & Analysis Results

Strong correlation between error rate and RSSI

Intermediate loss rates: due to interference, not multipath

No interference ➔ link abstraction can be made to hold: based on RSSI threshold, variability window

Using links with intermediate loss rates ➔ unstable behaviour

Results contrary to Roofnet

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  - Spatial reuse
  - TDMA in the LDN
  - TDMA in the LACNs
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TDMA in FRACTEL

CSMA/CA inefficient, unpredictable in multi-hop settings

TDMA is an alternative, explored in prior literature

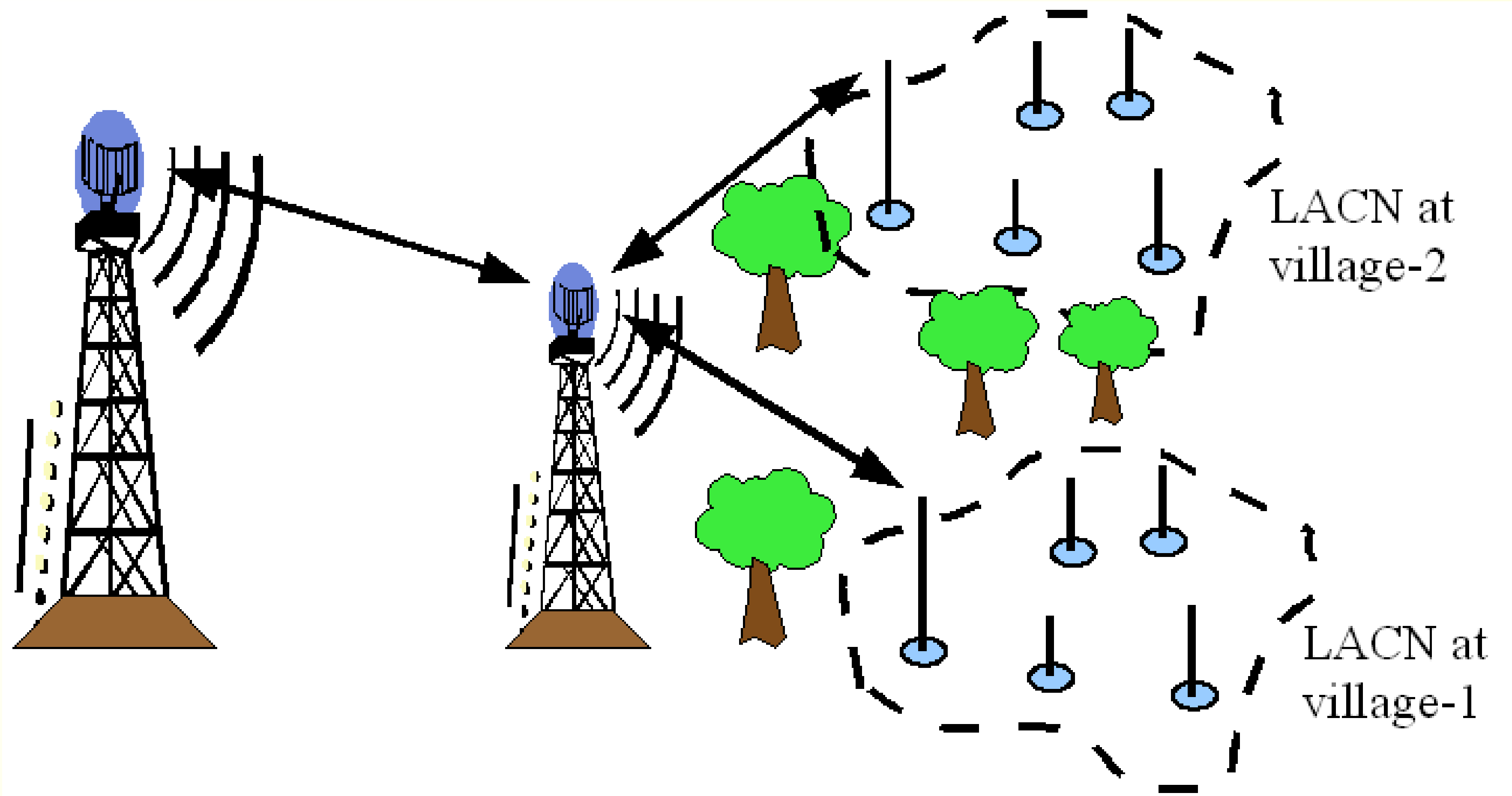
For each link, allocate time-slot, channel: a (ts_i, c_j) tuple

Interfering links cannot have the same (ts_i, c_j) allocation
== node colouring in the interference graph

Recent formulations: routing is a variable too
Other inputs: expected traffic pattern, number of radios
➔ Complex formulation, solution

Is the nature of the problem different in FRACTEL?

Spatial Reuse in FRACTEL



O1: ***the LDN, and the LACNs at each village are independent of one another (i.e. non-interfering)***

➔ Consider the LDN, and each LACN independently

Allocating (ts_i, c_j) in the LDN

The issue of routing

Most traffic is to/from landline

+

Few multi-path routing opportunities in the LDN

→

Topology has a natural tree structure

↓

O2: ***the issue of routing can be ignored during time-slot, channel allocation***

Allocating (ts_i, c_j) in the LDN

Terminology

- Consider only two-hop LDN trees for now
  - Hop-1 nodes: one-hop from the landline
    - Connected to landline by hop-1 links
  - Hop-2 nodes: two-hops from the landline
    - Connected to hop-1 nodes by hop-2 links
- We need to colour the links
  - With minimum possible number of colours

Allocating (ts_i, c_j) in the LDN

Lower bound

All hop-1 links are mutually interfering

→ Allocate different colours for each hop-1 link

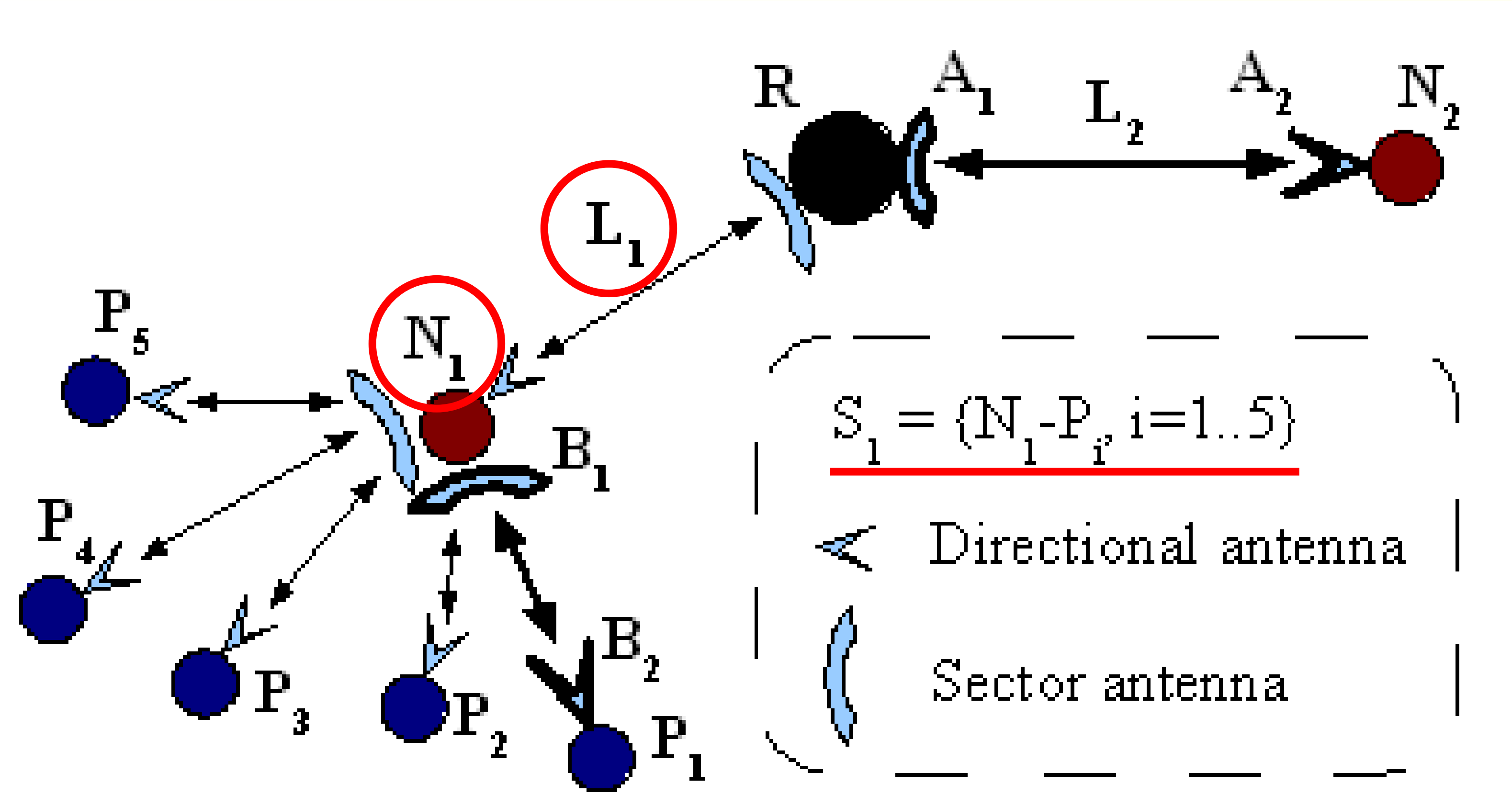
→ Lower bound on number of colours necessary

?

→ Is the same number of colours sufficient?

Allocating (ts_i, c_j) in the LDN

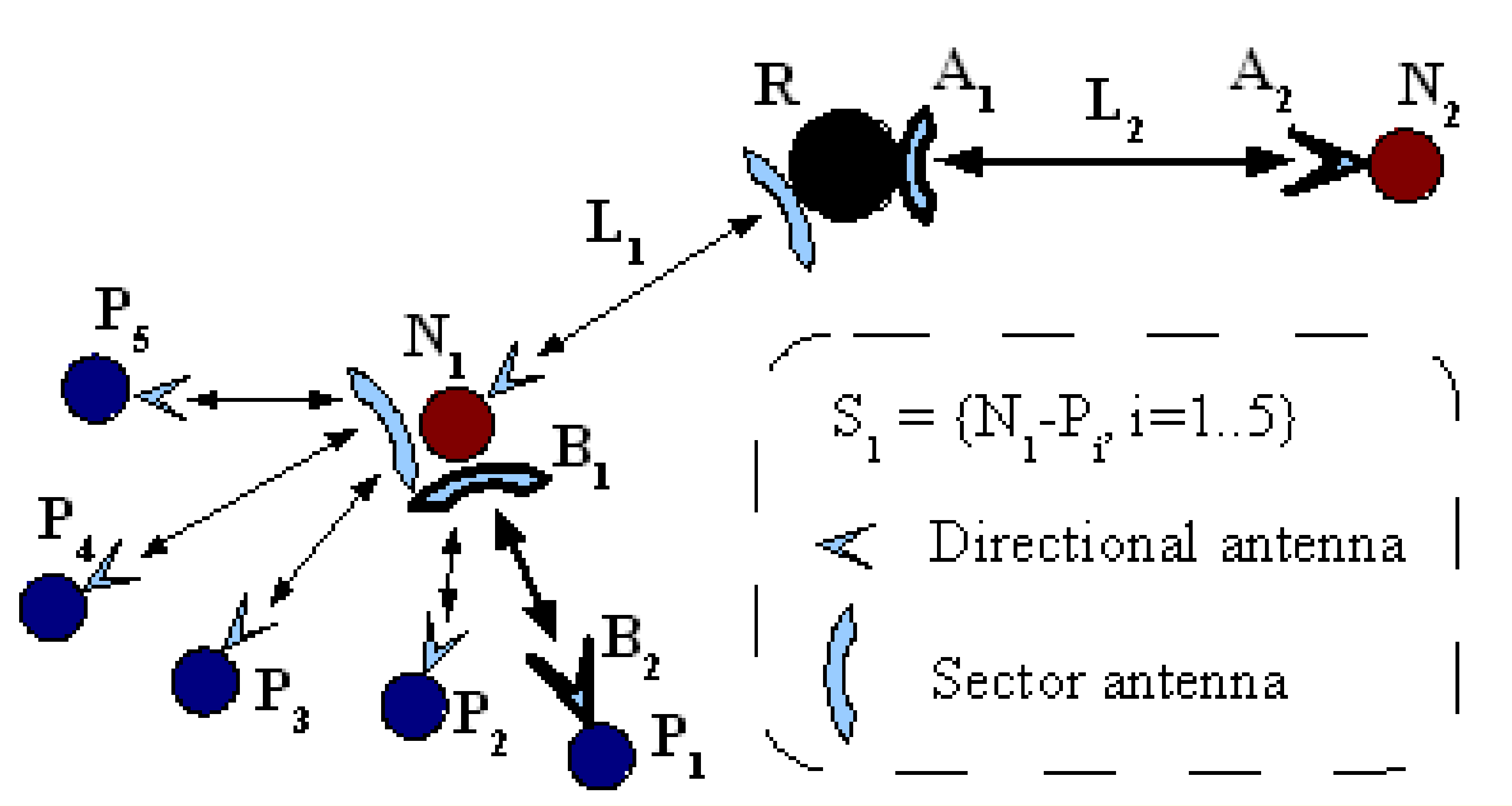
Notation, bottleneck constraint



L_i allocated one slot → S_i needs only one slot

Allocating (ts_i, c_j) in the LDN

Colouring hop-2 links: illustration



S_1 and L_2 are non-interfering

➔ S_1 can be given the same colour as L_2

Allocating (ts_i, c_j) in the LDN

<u>Bipartite perfect matching</u>

For each S_i, several non-interfering L_j will exist

Bipartite perfect matching:

For each S_i, choose a non-interfering L_j

And allocate S_i the same colour as L_j

Polynomial algorithms exist for bipartite perfect matching

Allocating (ts_i, c_j) in the LDN

Further generalization & open issues

Handling non-uniform traffic demands:

Count traffic requirement in units of *b* Kbps

Li has traffic requirement of *k* units

➔ Consider it as *k* different links

Will work if requirement is not too skewed

Open issues:

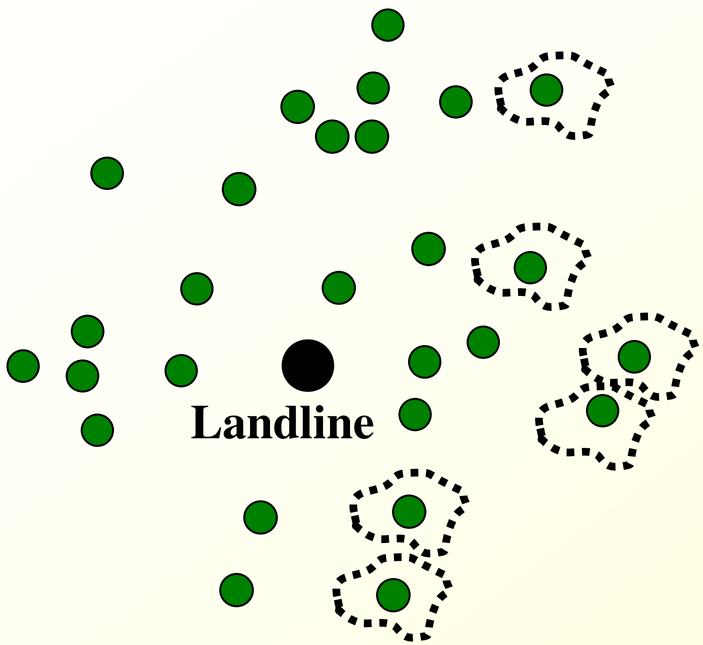
Extending the approach to trees of depth 3

Consideration of 2P:

Is 2P possible with sector antennas?

Allocating (ts_i, c_j) in the LACNs

The idea



C = total capacity in one channel of operation

k = number of orthogonal channels

LG_i = local gateway at $LACN_i$

C_i = total traffic to/from $LACN_i$, via LG_i

T = total number of LACNs

Uniform traffic requirements ➔ $C_i = kC/T$

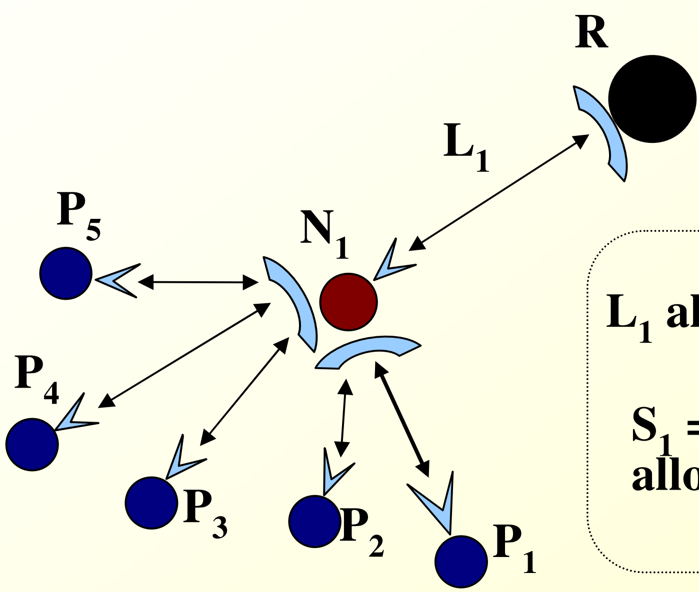
Large T, small k ➔ $C_i << C$ ➔ O3

O3: for each LACN, the long-distance link at its local-gateway is the bottleneck

➔ Enough slack for scheduling within each LACN

Allocating (ts_i, c_j) in the LACNs

<u>An independent channel for each LACN</u>



L_1 allocated (ts_{i1}, c_{j1})

$S_1 = \{N_1\text{-}P_i, i=1..5\}$ allocated (ts_{i2}, c_{j2})

At most <u>two channels</u> for long-distance links at <u>hop-1</u> nodes

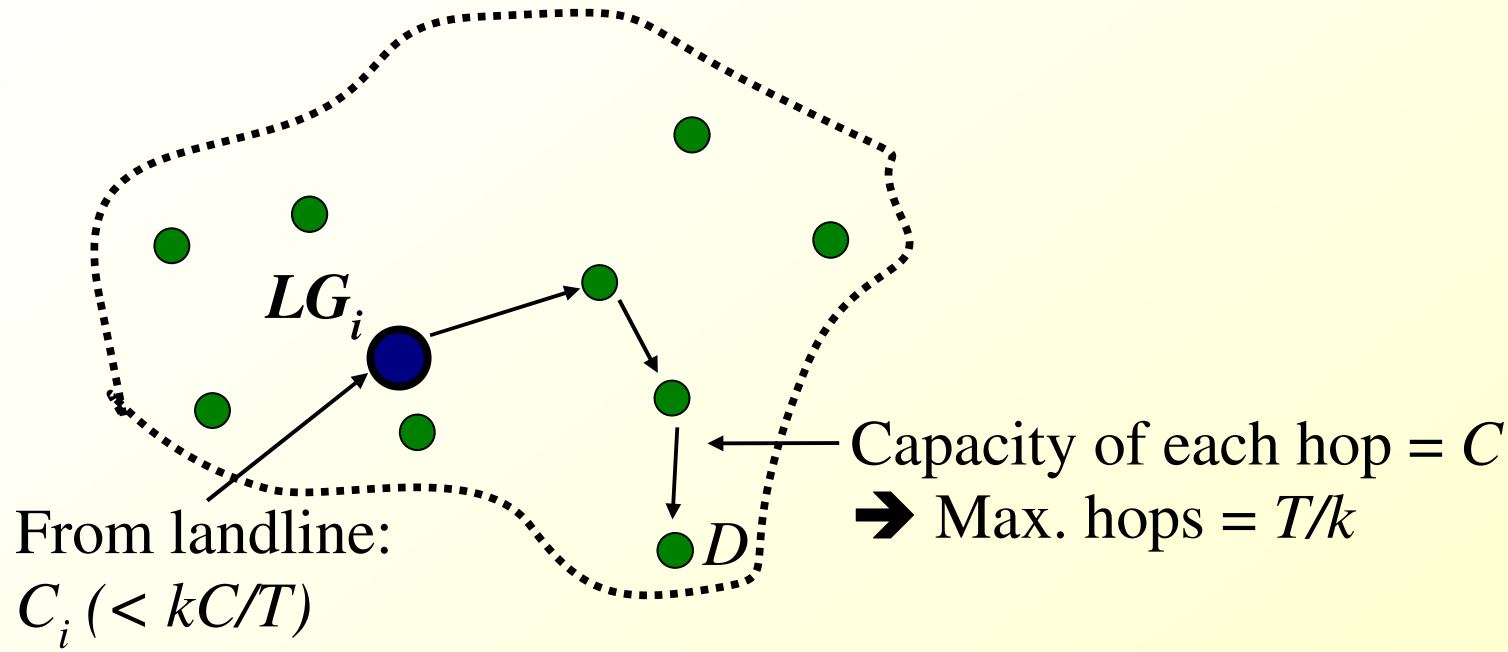
Only <u>one channel</u> for long-distance link at <u>hop-2</u> nodes

➔

<u>O4:</u> we have at least one channel entirely free for *$LACN_i$*

Allocating (ts_i, c_j) in the LACNs

<u>Supporting up to *T/k* hops</u>



Time taken for *B* bytes over *h* hops = *h x B/C*

Time taken for B bytes to arrive over the LDN at $LG_i = B/C_i$

= *T/k x B/C*

➔ up to *T/k* hops can be supported without any spatial reuse

Allocating (ts_i, c_j) in the LACNs

Some remarks

- Similar arguments apply for scheduling any mix of uplink/downlink traffic
- Some numbers:
  - Say, $T = 30$, $k = 3$ ➔ $30/3 = 10$ hops can be supported!
  - Typical village expanse < 1km
  - Link lengths: few hundred metres
    ➔ LACN only 3-4 hops in practice
- Challenge: how to do scheduling at a fine granularity (per-packet)?
  - There are other challenges too…

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TDMA Implementation Challenges

1. How to achieve time synchronization, in a potentially large network?
2. We need dynamic scheduling:
   - In FRACTEL, traffic patterns will be dynamic
   - Only a subset of nodes may be active at a time
3. In each LACN, we need fine granularity scheduling, depending on source/ destination of packet

Strategies to Address the Challenges

- Use the hierarchical structure of the network
- Use centralized algorithms for synchronization and scheduling
- Use a multi-hop connection-oriented link layer
- Use fine-granularity scheduling in each LACN

The four strategies fit in well with one another

Addressing the Challenges (1/3)

Simplifying synchronization:

Recall O4: we have an entire channel of operation for each LACN

➔ No need to synchronize $LACN_i$ with LDN, or with $LACN_j$

Multi-hop connection-oriented link layer:

- How exactly does LG_i know when to schedule for *D*?
- Use the notion of traffic flows at the MAC/routing layer
  - Similar to 802.16 connections
  - Can be used to categorize traffic: voice, video, ftp/http
  - Categorization helps in scheduling
- Connection state is maintained at LG_i as well as the landline

Addressing the Challenges (2/3)

Multi-hop framing:

- LG_i repeatedly schedules multi-hop downlink/uplink frames
- Note: we have a lot of leeway for framing overheads
  - We estimated *T/k* hops = *30/3 = 10* hops possible
  - But only 3-4 hops need to be supported in practice

Link-layer ARQ:

- Link abstraction ➔ ~0% error rates
- Hence we can have link-layer ACKs over multiple hops
  - Fits in well with multi-hop framing mechanism and connection-oriented link layer

Addressing the Challenges (3/3)

Centralized scheduling & synchronization:

- *LG_i* handles scheduling, synchronization in *$LACN_i$*
- Landline handles scheduling, synchronization in the LDN
  - LDN aware of traffic during flow setup
  - Can handle dynamic scheduling

Centralized approach is valid design choice:

- Fault tolerance is not an issue since anyway we have a tree structure
- Scaling is not a concern too, since we have used hierarchy

Open Technical Issues

- What exactly will be the multi-hop framing mechanism?
  - What will be the overheads?
  - Small frames may be needed for lower delay: overheads for small frames?
- How exactly can we schedule each category of traffic?
- How can we achieve multi-hop synchronization using off-the-shelf 802.11 hardware?
  - Current 802.11 hardware supports single-hop synchronization with minimal error (4 micro-sec)
- Dynamic channel/time-slot allocation:
  - We do not want to disrupt a functional network
  - How to achieve dynamic scheduling with minimal disruption?

Conclusion, Wider Applicability

Conclusion:

- FRACTEL: mesh network deployment in rural settings
  - Several properties warrant a specific consideration rather than a generic approach
- Take-away lesson: consideration of deployment specifics will likely change the nature of the problem

Wider applicability:

- Our discussion has been centered around 802.11b/g
  - 802.11a band has been delicensed recently in India
- Our observations also likely apply to 802.16 networks:
  - Network architecture, pattern of spatial reuse
  - Scheduling in the presence of bottleneck links
  - Use of hierarchy, centralized approach