WhiteHaul: An Efficient Spectrum Aggregation System for Low-Cost and High Capacity Backhaul over White Spaces

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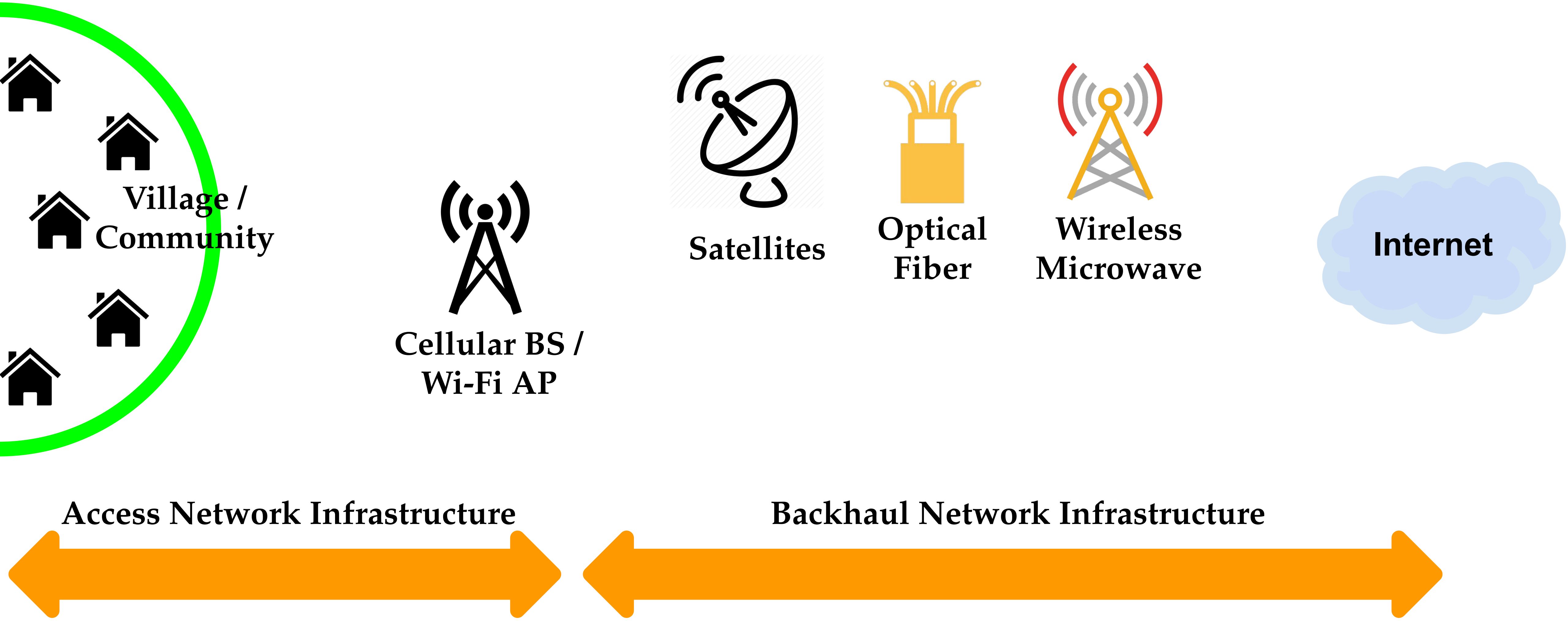
46.4 %   3.4 Billions

Around half of world's population has no Internet access

- Majority of population live in rural areas or low-income regions
- Lacks affordable backhaul network infrastructure
- The traditional ways to connect these remote areas are expensive and have low ROI.

How to reduce the cost of backhaul network infrastructure?



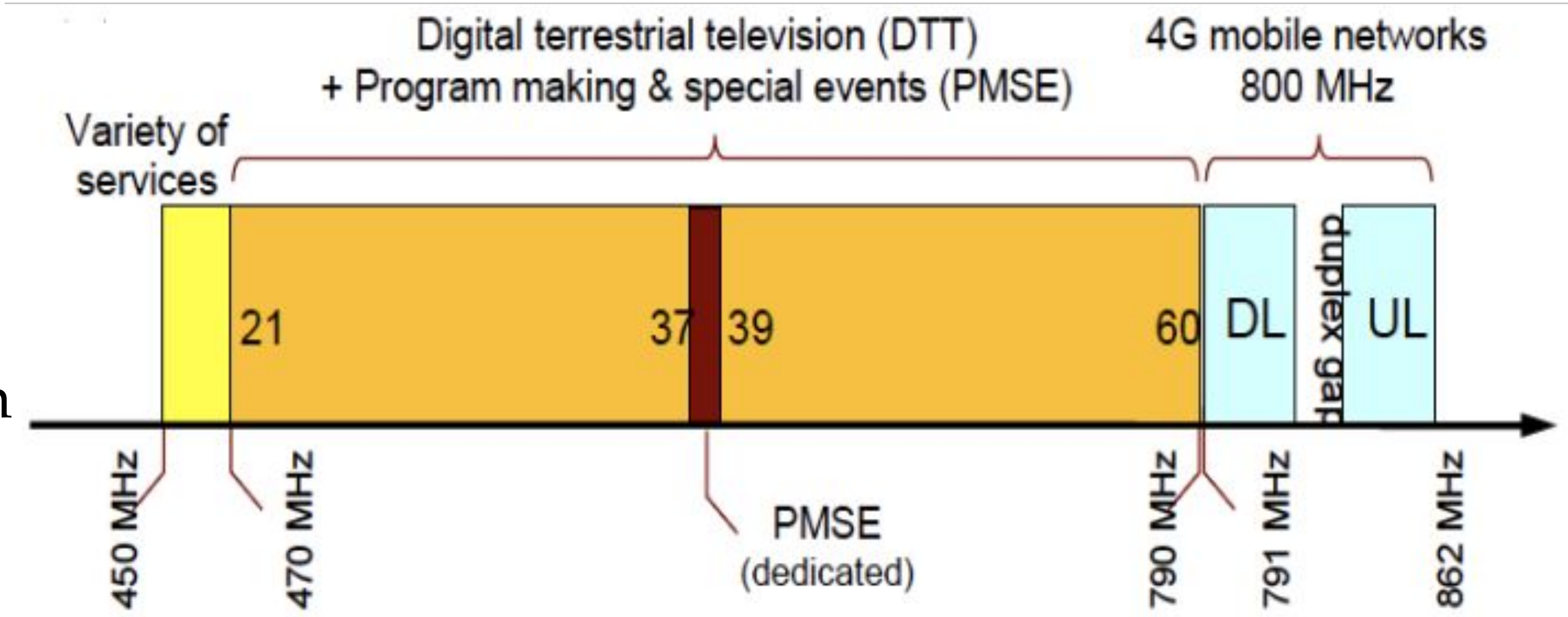
Our Approach: Exploit Spectrum White Spaces

- **Key idea**: Aggregate the unused spectrum portions to provide a low-cost and high capacity backhaul system.

- **TV white spaces (TVWS) spectrum**: unused spaces in UHF TV band

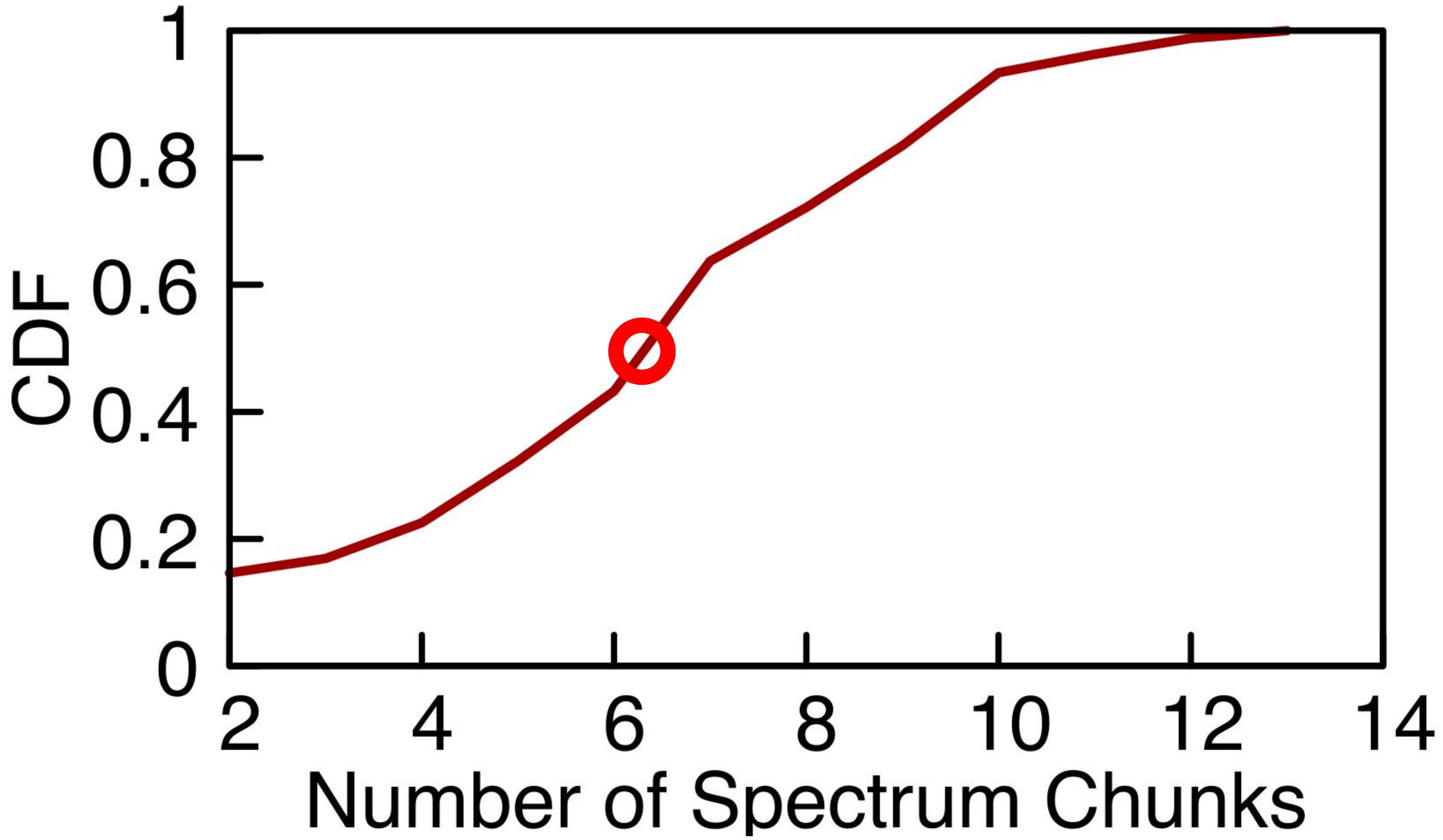
- Costs little
- Ample spectrum (200+MHz) in rural areas
- Excellent propagation characteristics → Longer range or NLoS propagation

UHF TV Band and Adjacent Bands
Source: Ofcom



Challenges and Constraints (1)

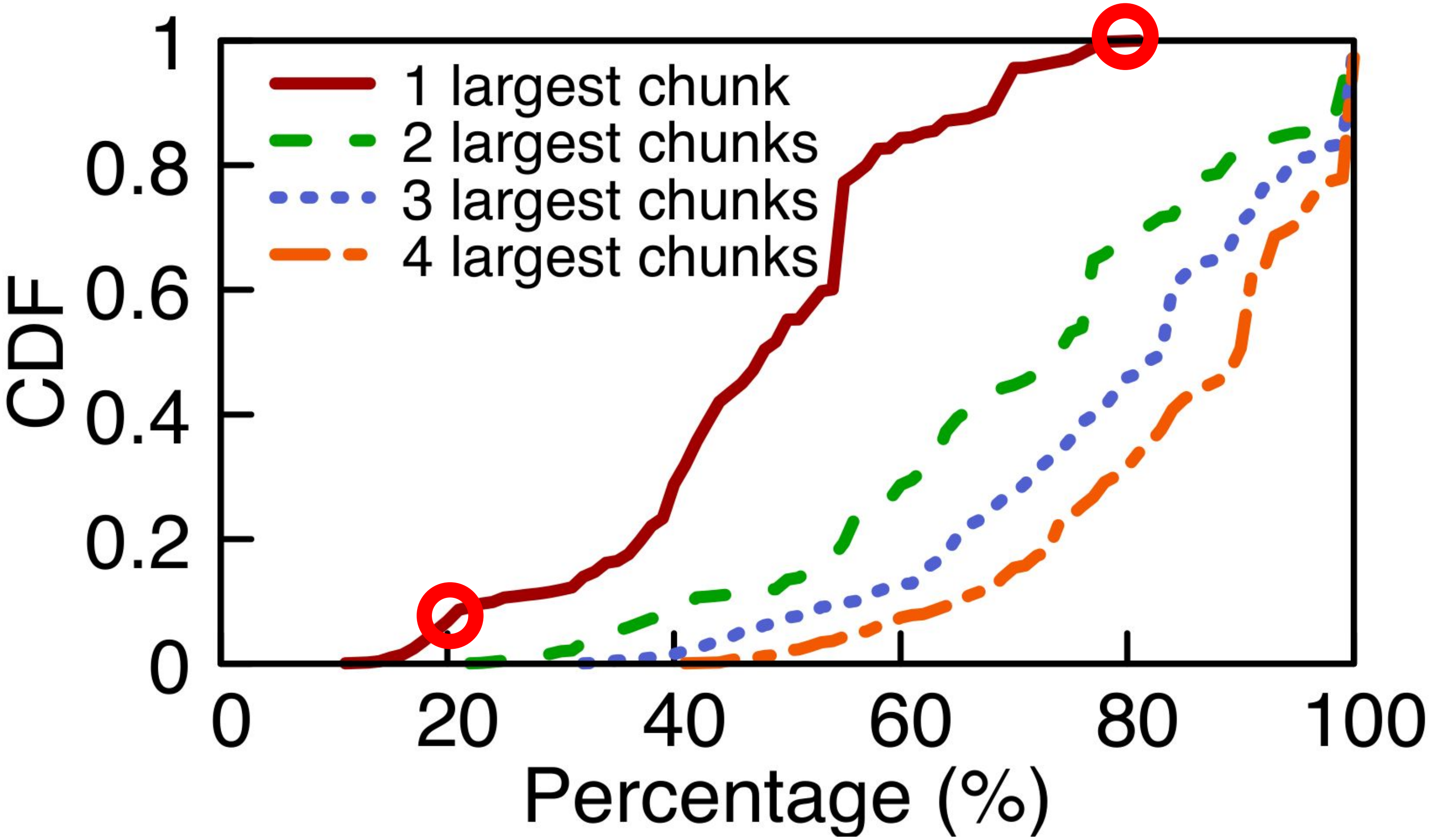
- Individual TVWS channels narrow (6/8 MHz)
- Available spectrum fragmented



TVWS spectrum is fragmented into 6 chunks in 50% of locations (Rural)

Challenges and Constraints (2)

- High degree of diversity in terms of chunk sizes, power asymmetry and interference levels



Diverse spectrum chunks

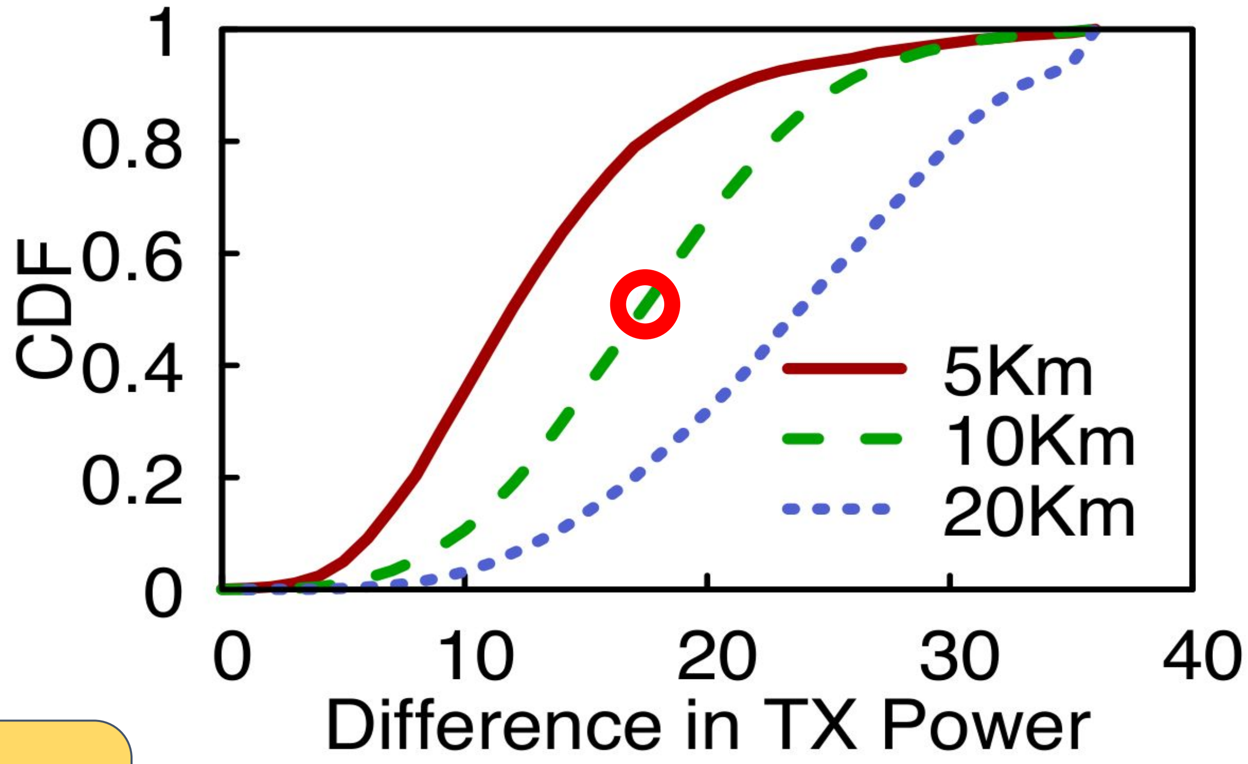
Challenges and Constraints (2)

- High degree of diversity in terms of chunk sizes, power asymmetry and interference levels
- **For example**: TX power on channel #1 can be 20 dBm in one location and 30 dBm in another location.

Power Asymmetry

Different MCS values at endpoints

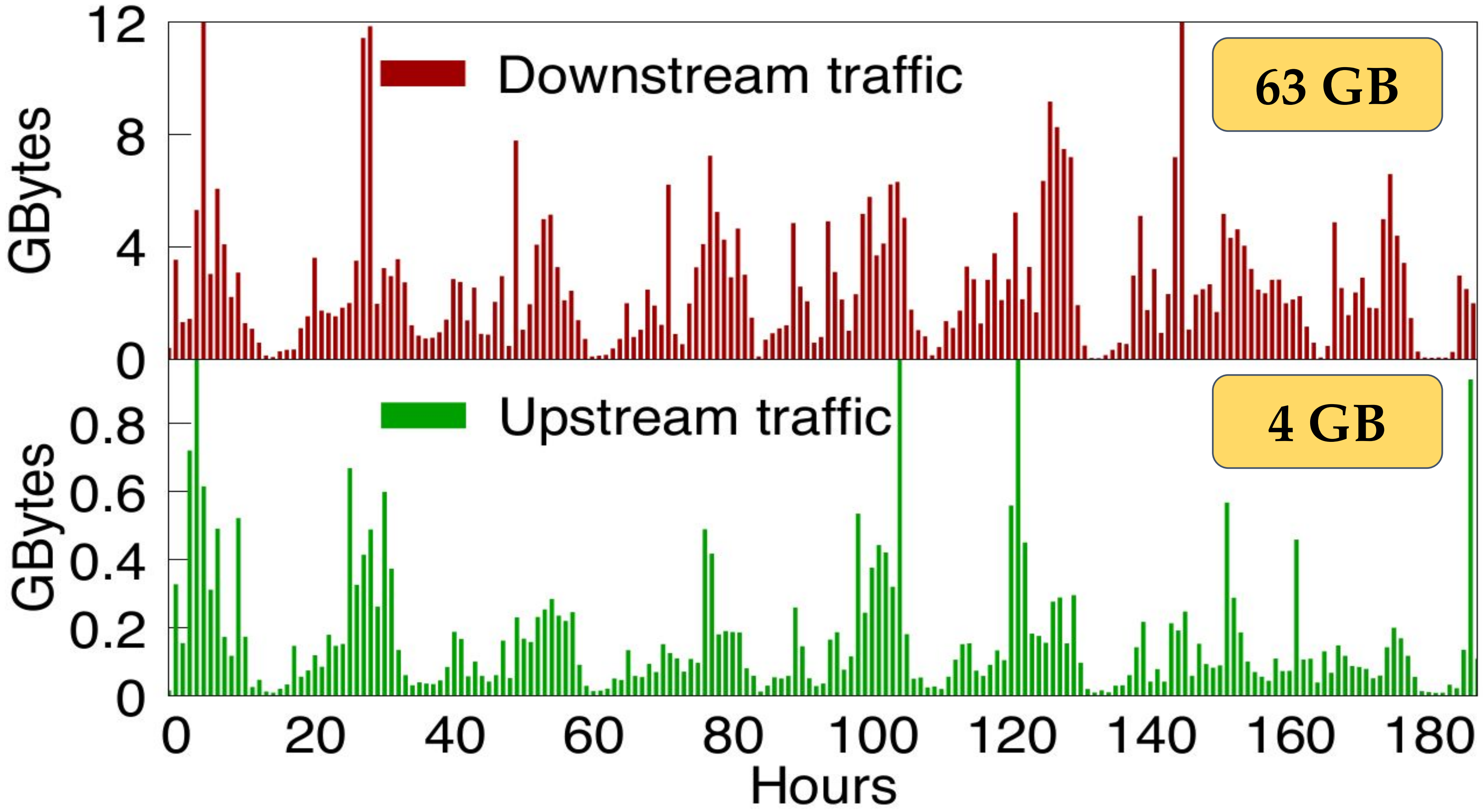
Capacity Asymmetry



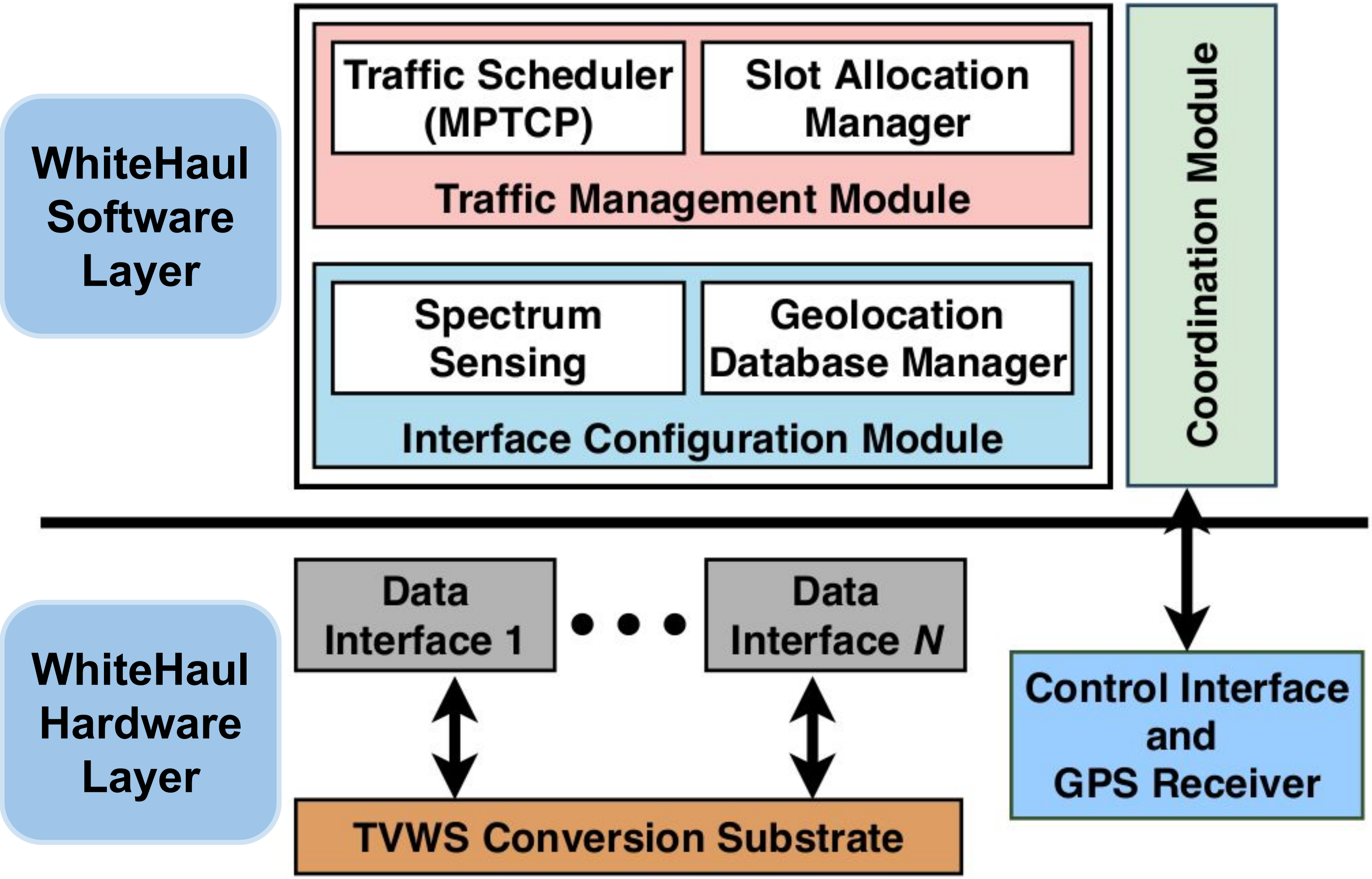
Power asymmetry between link endpoints

Challenges and Constraints (3)

- Backhaul links also exhibit highly asymmetric and time varying traffic



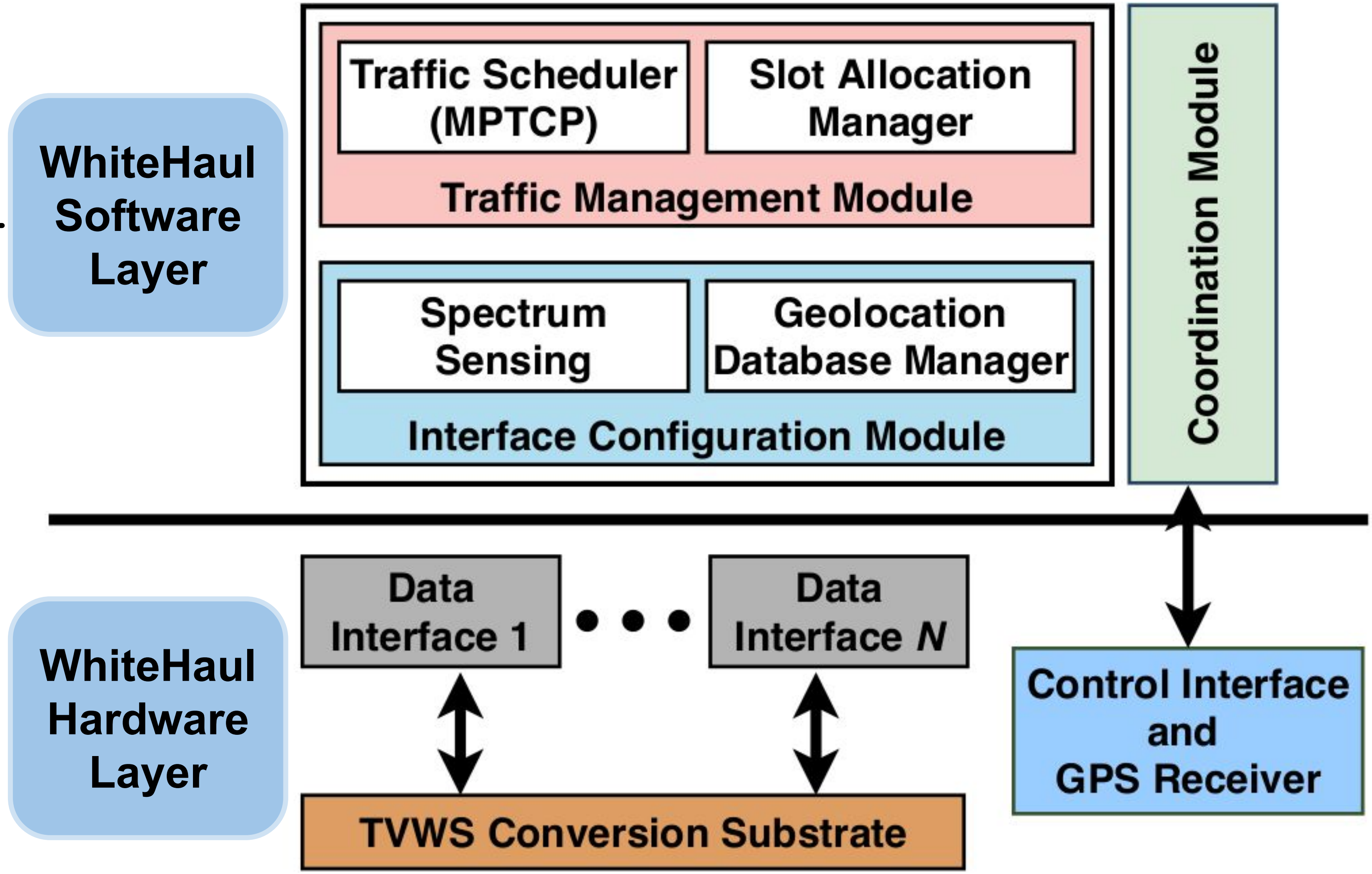
Our Key Contribution: WhiteHaul System



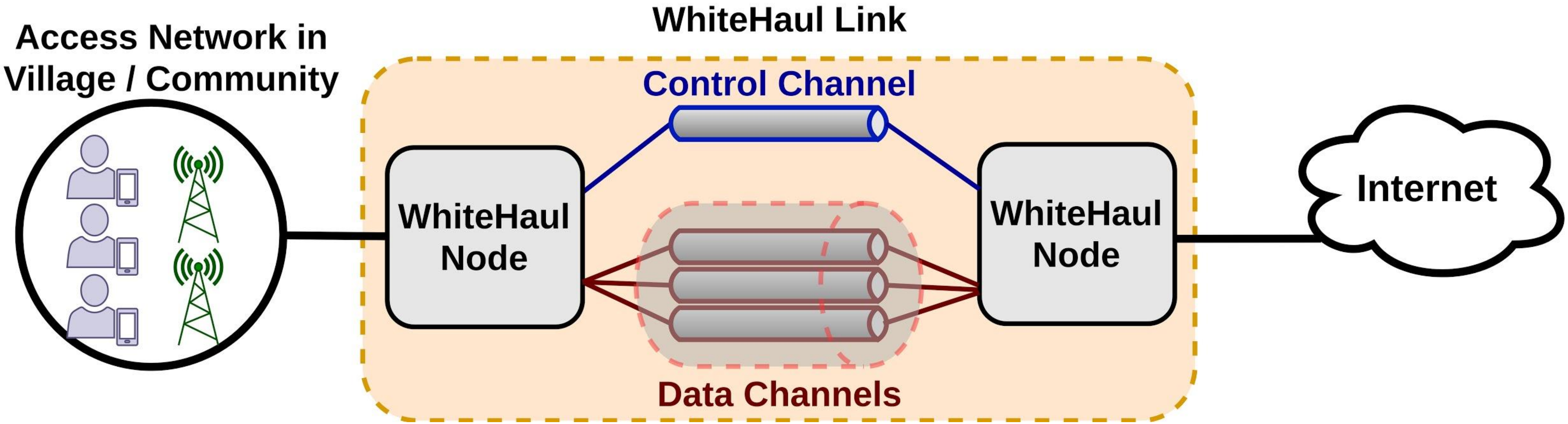
- Combines multiple commodity Wi-Fi cards using a single antenna
- Features a custom-designed frequency conversion substrate for up/down conversion to TV band frequencies

Our Key Contribution: WhiteHaul System

- Leverages MPTCP as a link-level tunnel
- Features a new cross-layer congestion control algorithm for efficient bandwidth utilization
- Adaptive time allocation to handle link capacity/traffic asymmetry



WhiteHaul based Backhaul Illustration



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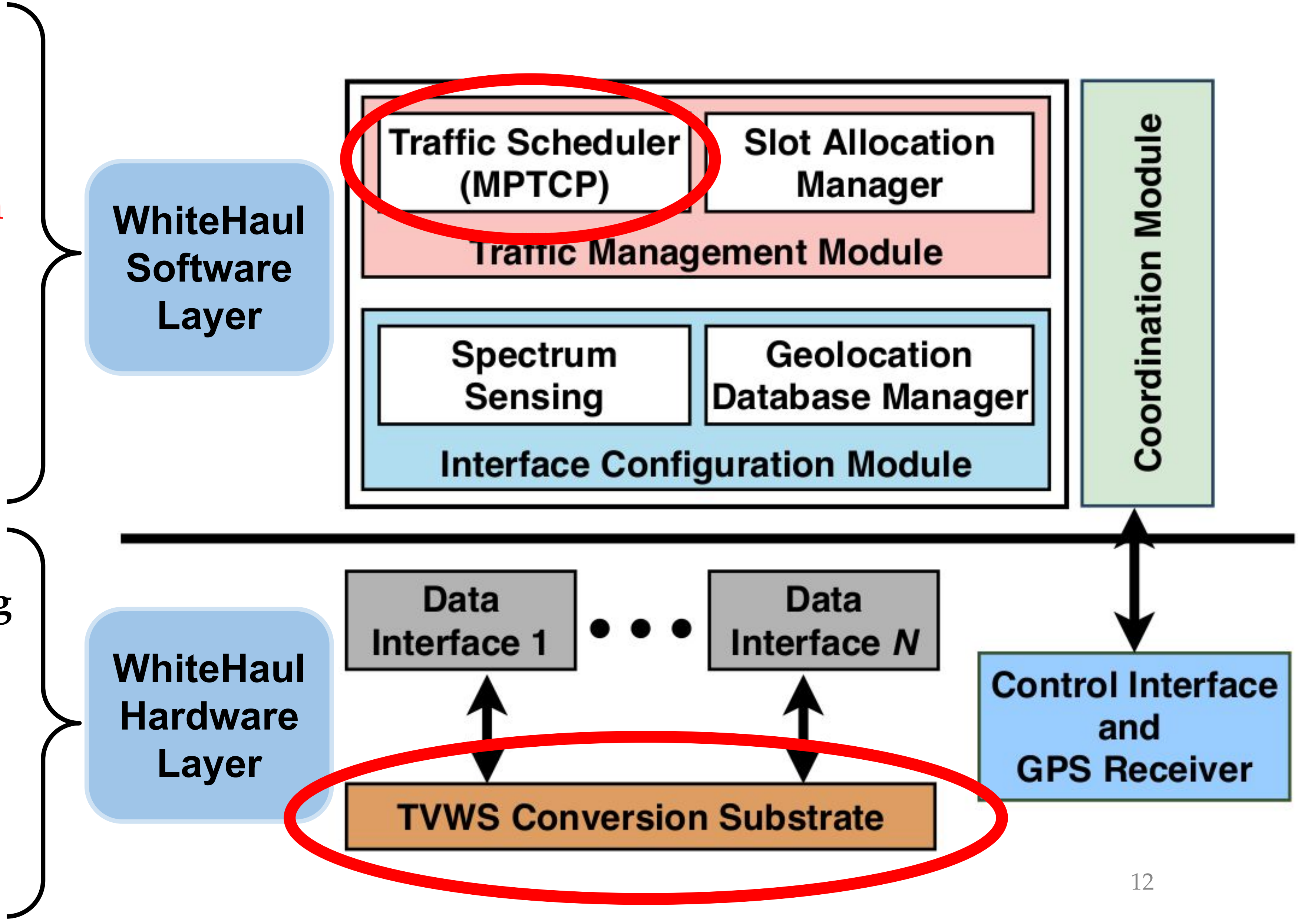
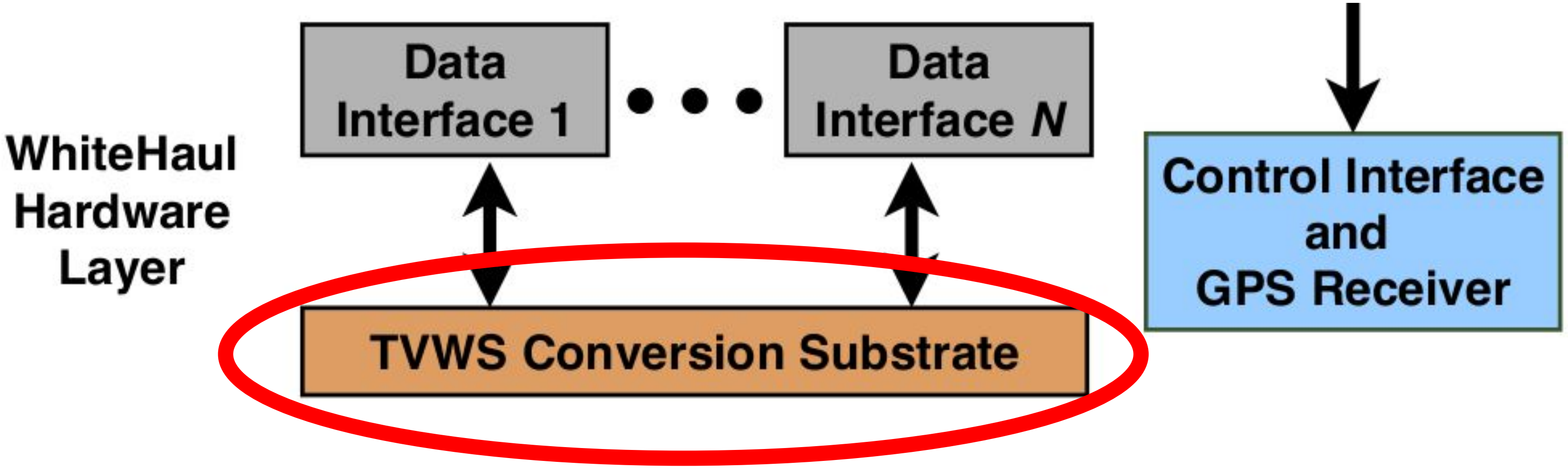
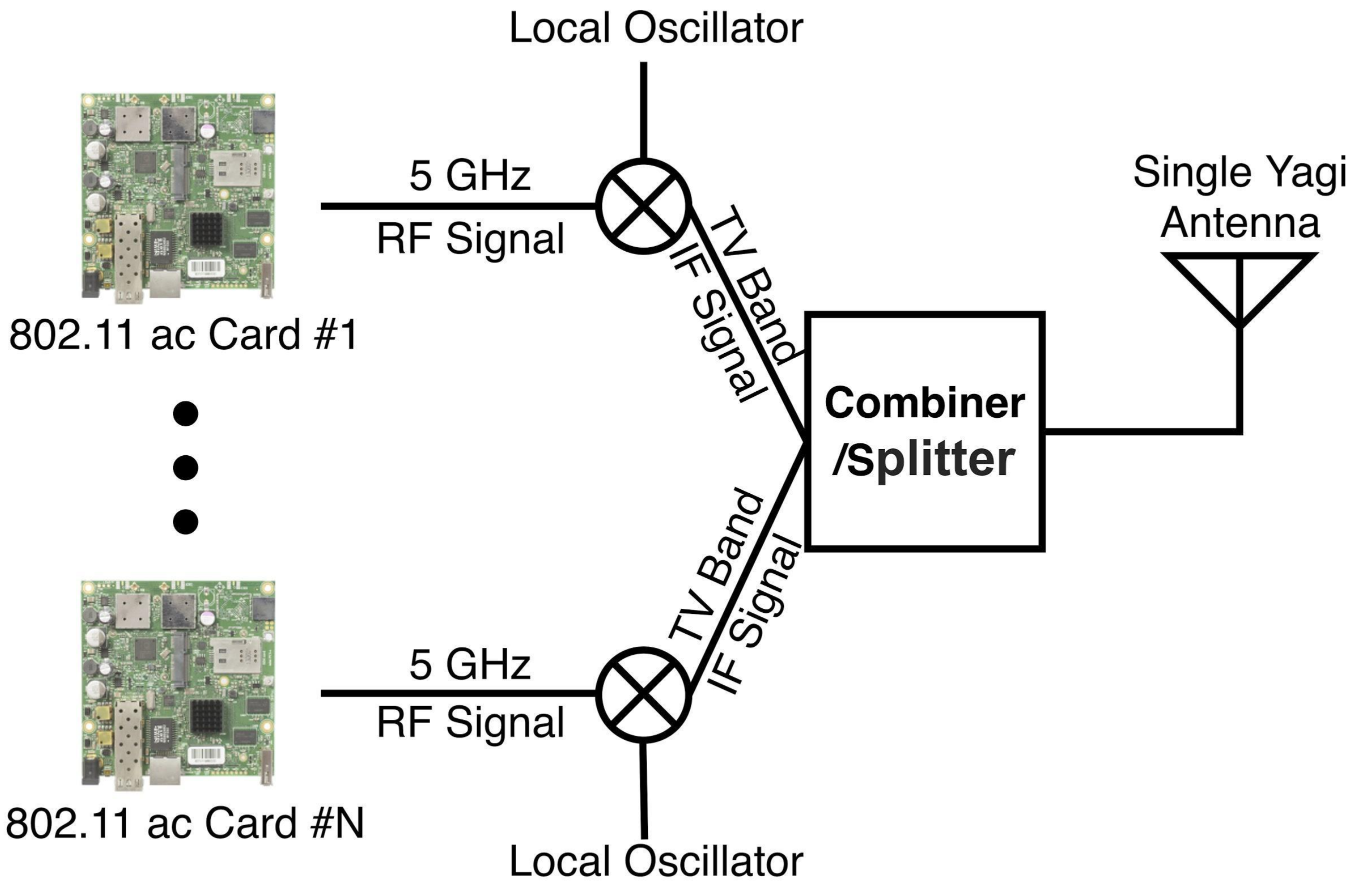


WhiteHaul Hardware Layer

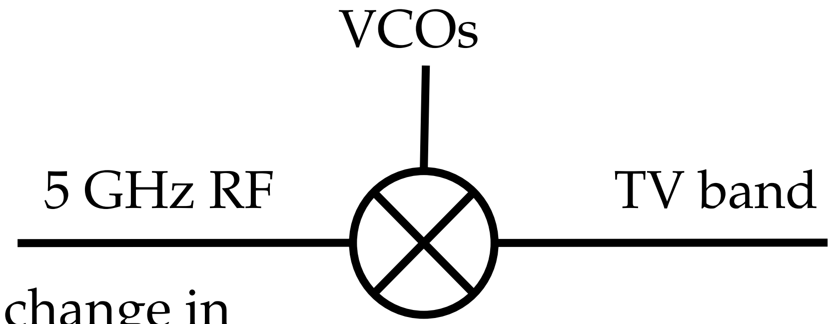


WhiteHaul HW Architecture



- In the HW layer:
    - We use COTS 802.11ac cards
    - Downconvert the 5GHz signal to TV band signal in case of transmission
    - Upconvert the TV band signal to 5GHz in case of reception

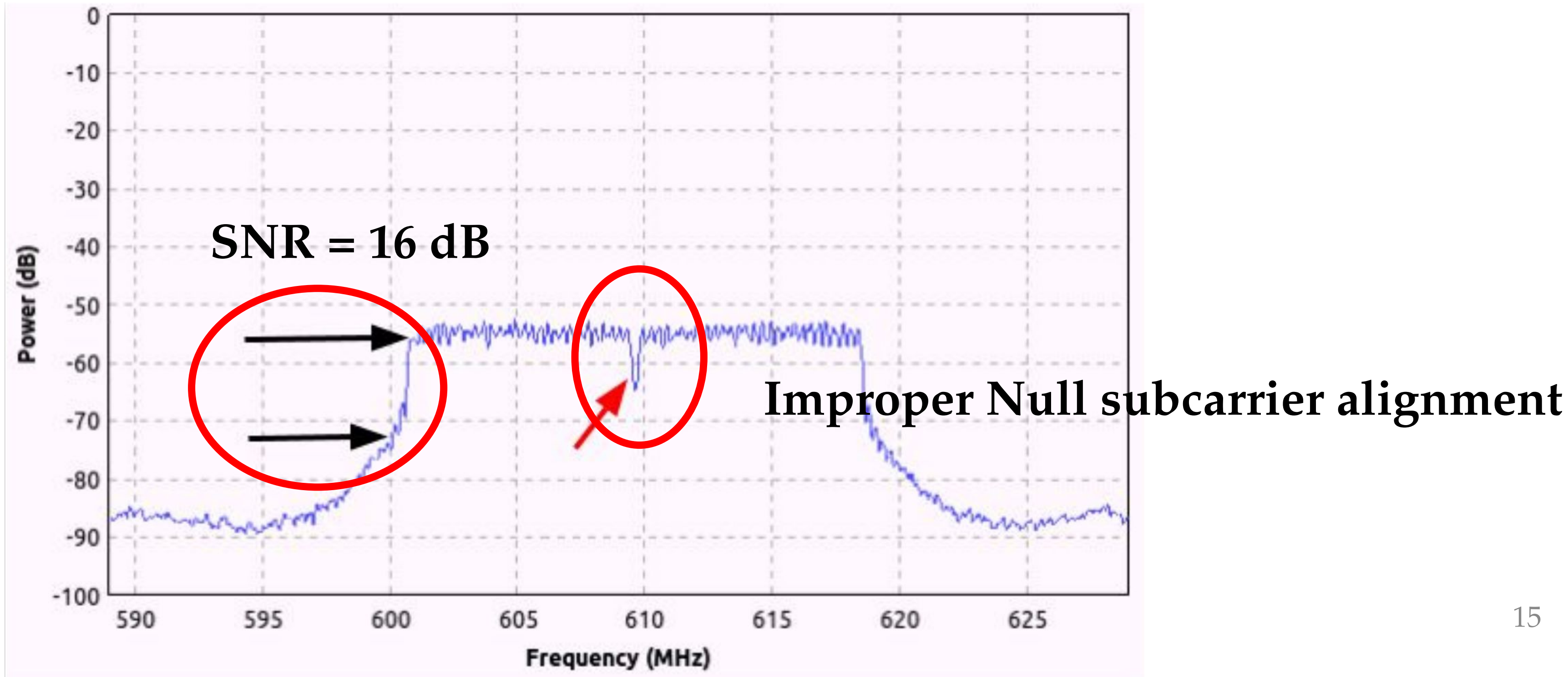
Limitations of Voltage Controlled Oscillators



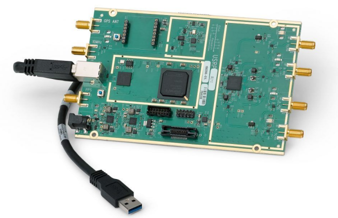
Voltage Controlled Oscillator (VCO) has limitations:

- Low tuning sensitivity ≅ 10 MHz/V
  - Every 1 unit change in the voltage corresponds to 10 MHz change in the center frequency of LO signal

- High nonlinearity → unwanted emissions

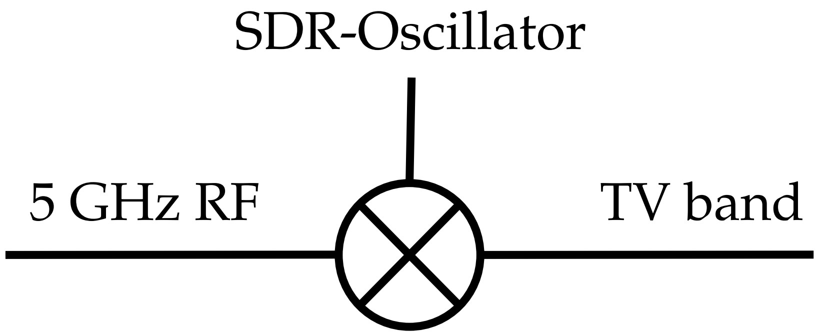


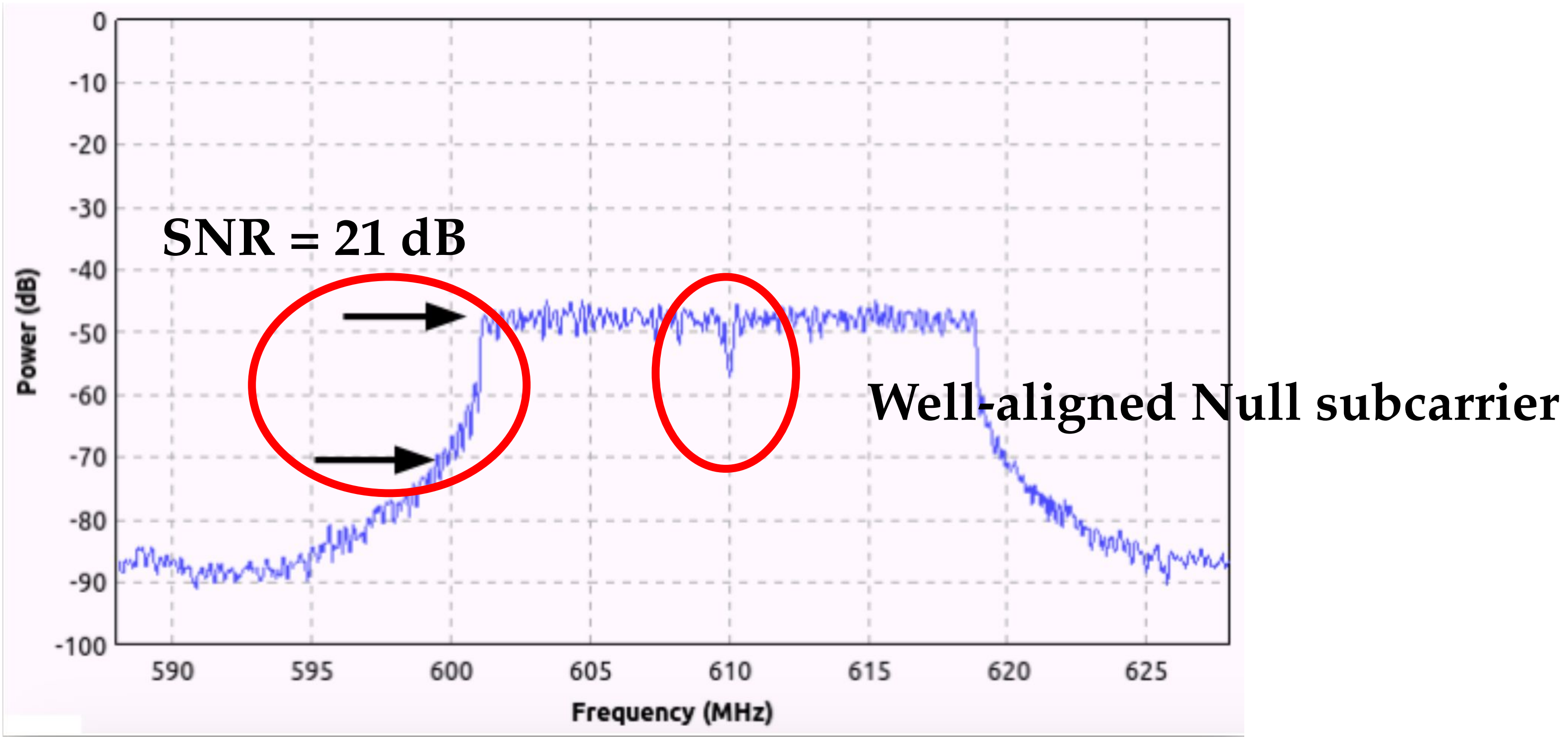
SDR-based Oscillators

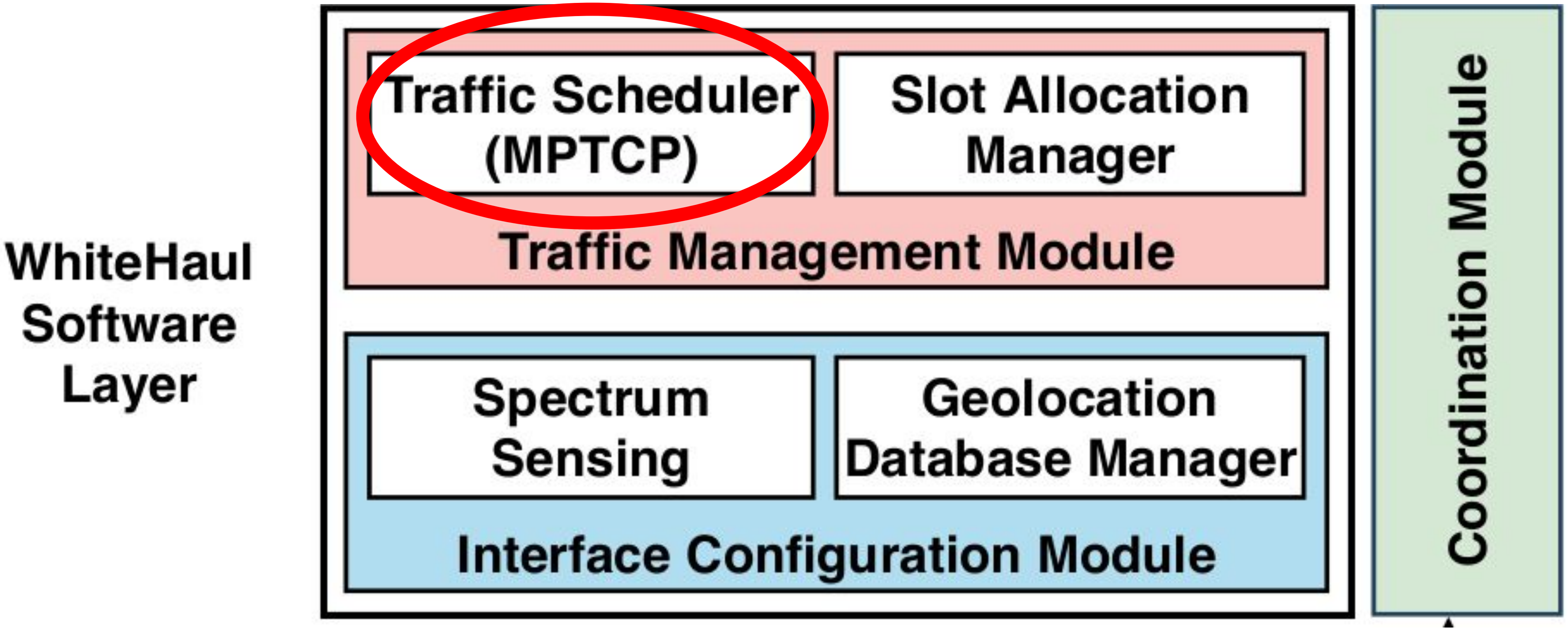


In WhiteHaul HW layer:

- We used SDR unit to generate sinusoidal signal which acts as a LO signal input to the RF mixer
- Flexible LO frequency configuration, up to 1 KHz granularity
- Higher quality of the downconverted signal





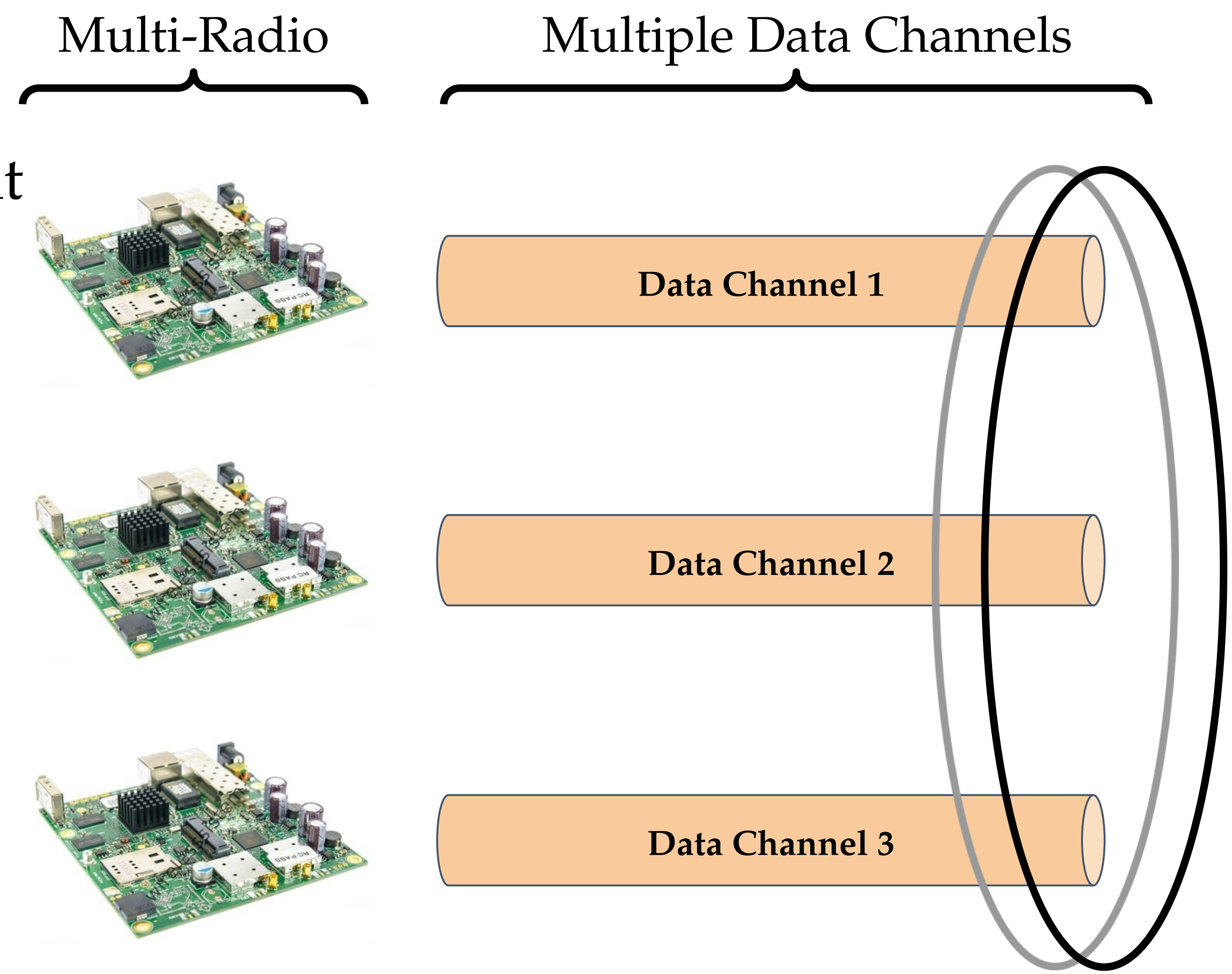


WhiteHaul Software Layer

Traffic Management in WhiteHaul

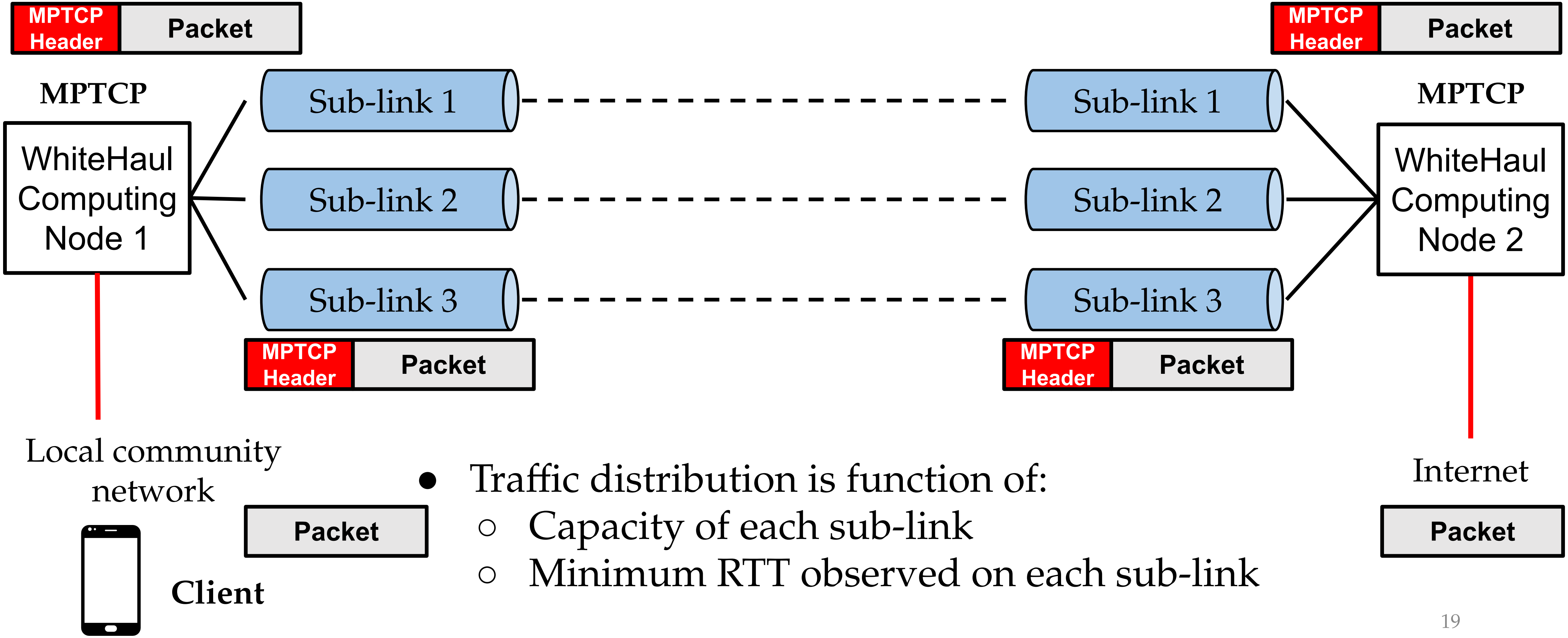
- The main function of the traffic management module is to **glue** different data channels into **one single pipe**
  - Transparent to the end users

- Multi-Path TCP:
  - Reliable data transmission with built-in mechanisms for retransmissions and reordering
  - Flexible distribution of the user traffic across multiple interfaces



MPTCP Traffic Distribution

MPTCP module should be able to estimate the capacity of the underlying interfaces accurately



- Traffic distribution is function of:
  - Capacity of each sub-link
  - Minimum RTT observed on each sub-link

Deficiency of capacity estimation in MPTCP

In our settings:

- No competing flows
- Packet losses mainly link quality related (e.g., NLoS conditions)

MPTCP congestion control algorithms, (LIA, OLIA, CUBIC):

- Packet drops are misleading
- Slow and inaccurate to track the underlying link capacity as it fluctuates

We propose a novel cross layer congestion control for MPTCP

Problem 1: Slow and inaccurate tracking of link capacity
Solution: Explicit feedback from MAC layer

Problem 2: Packet drops are misleading
Solution: Monitor the queuing delay and slow shrinking

Whitehaul ensures that each MPTCP subflow always saturates its underlying capacity

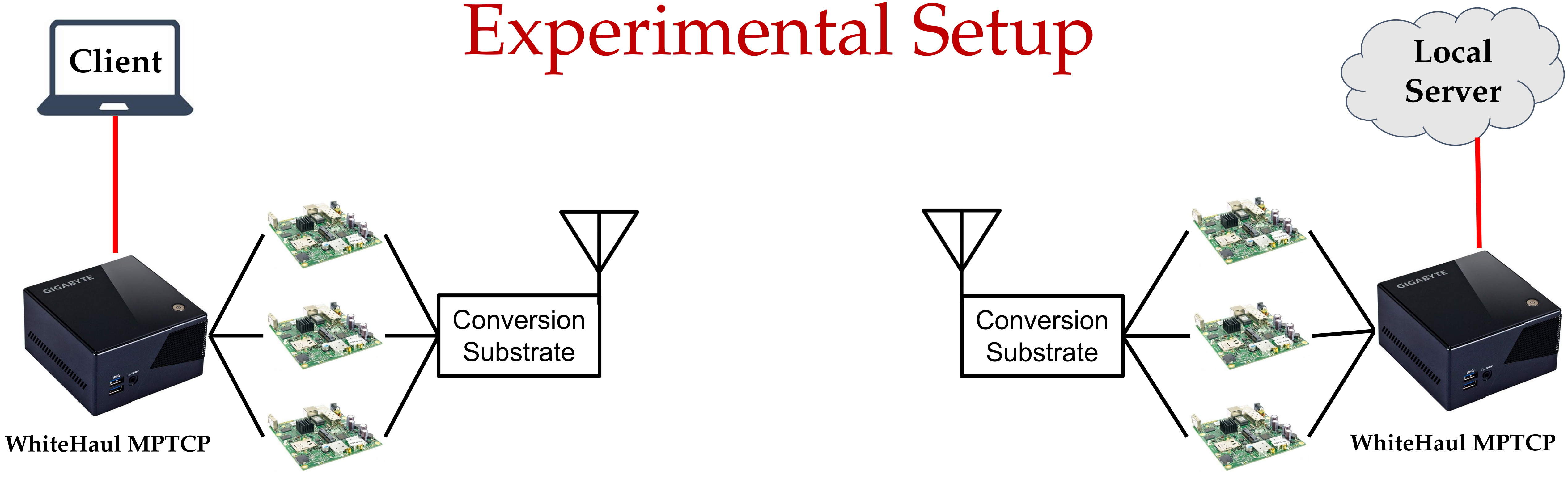
input: Ω_i, is the target window for $subflow_i$
input: λ_i, is the delay budget for $subflow_i$
input: α_i, is the increase weight for $\texttt{cwnd}_i$

CongestionAvoidance($subflow_i$)
  if *A new window of data begins* **then**
    aqd $\leftarrow$ AvgQueueingDelay($subflow_i$)
    /* Update α_i */
    if $aqd \leq \lambda_i$ **then**
      if $cwnd_i \geq \Omega_i$ **then**
        $\alpha_i \leftarrow 1$
      else
        $\alpha_i \leftarrow 100$
    else
      $\alpha_i \leftarrow 1$
    /* Periodic cwnd reduction */
    if $aqd > \lambda_i$ & $cwnd_i > \Omega_i$ **then**
      $cwnd_i \leftarrow \Omega_i$
      $ssthresh_i \leftarrow cwnd_i$
  /* Response to new ACKs */
  if $cwnd_i \geq ssthresh_i$ **then**
    $cwnd_i \leftarrow cwnd_i + \alpha_i / cwnd_i$
  else
    tcpInSlowStart()

/* Response to 3 duplicate ACKs */
DecreaseCWND($subflow_i$)
  $cwnd_i \leftarrow max(cwnd_i - (cwnd_i * 0.1), 2)$

WhiteHaul Evaluation Based on Prototype Implementation

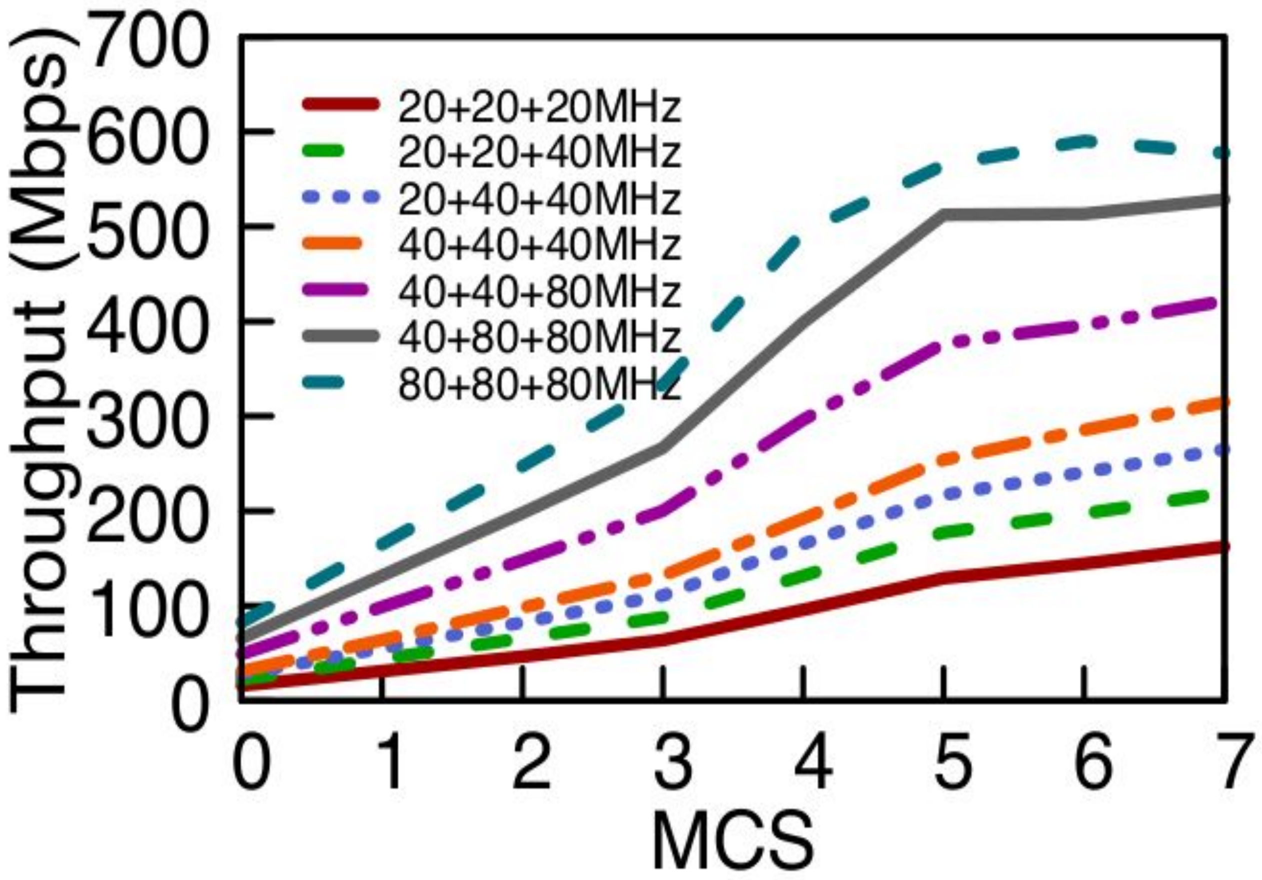
Experimental Setup



1. Two Ubuntu 16.04 small form factor PCs are running WhiteHaul SW layer including WhiteHaul MPTCP
2. Six Mikrotik 802.11ac cards attached to the two SFF PCs, with GbE interfaces
3. WhiteHaul conversion substrate at both sides down/up convert the 5GHz/TVWS signals
4. A client laptop used to generate a iperf TCP traffic is attached to one WhiteHaul node
5. The other WhiteHaul node is directly connected to the local server through one of its GbE ports

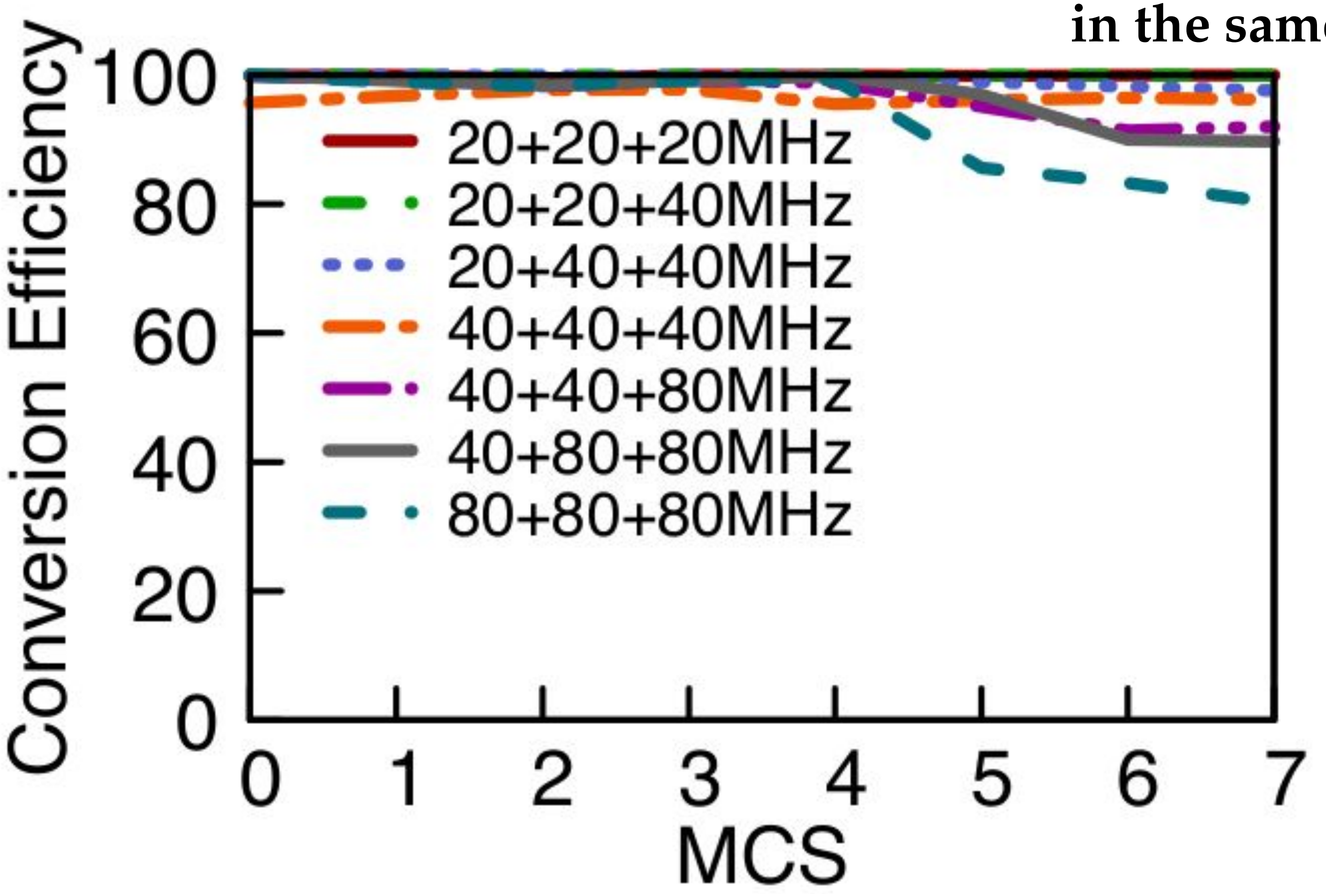
Maximum Throughput

- **3 contiguous spectrum chunks = 240 MHz → Achieves nearly 600 Mbps**



Conversion Efficiency

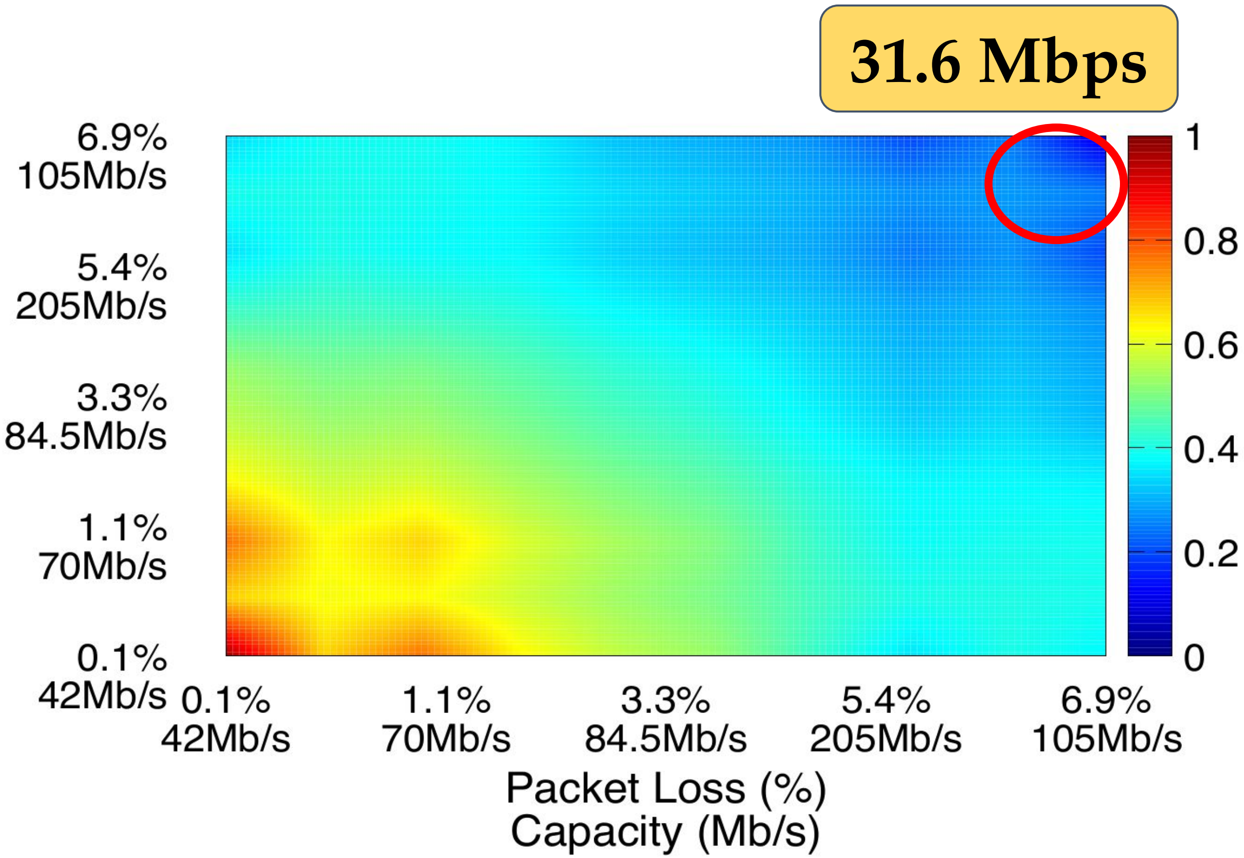
$$\text{Conversion Efficiency} = \frac{\text{Throughput achieved in TVWS after conversion process}}{\text{Throughput achieved on 5GHz band in the same setup}} \%$$

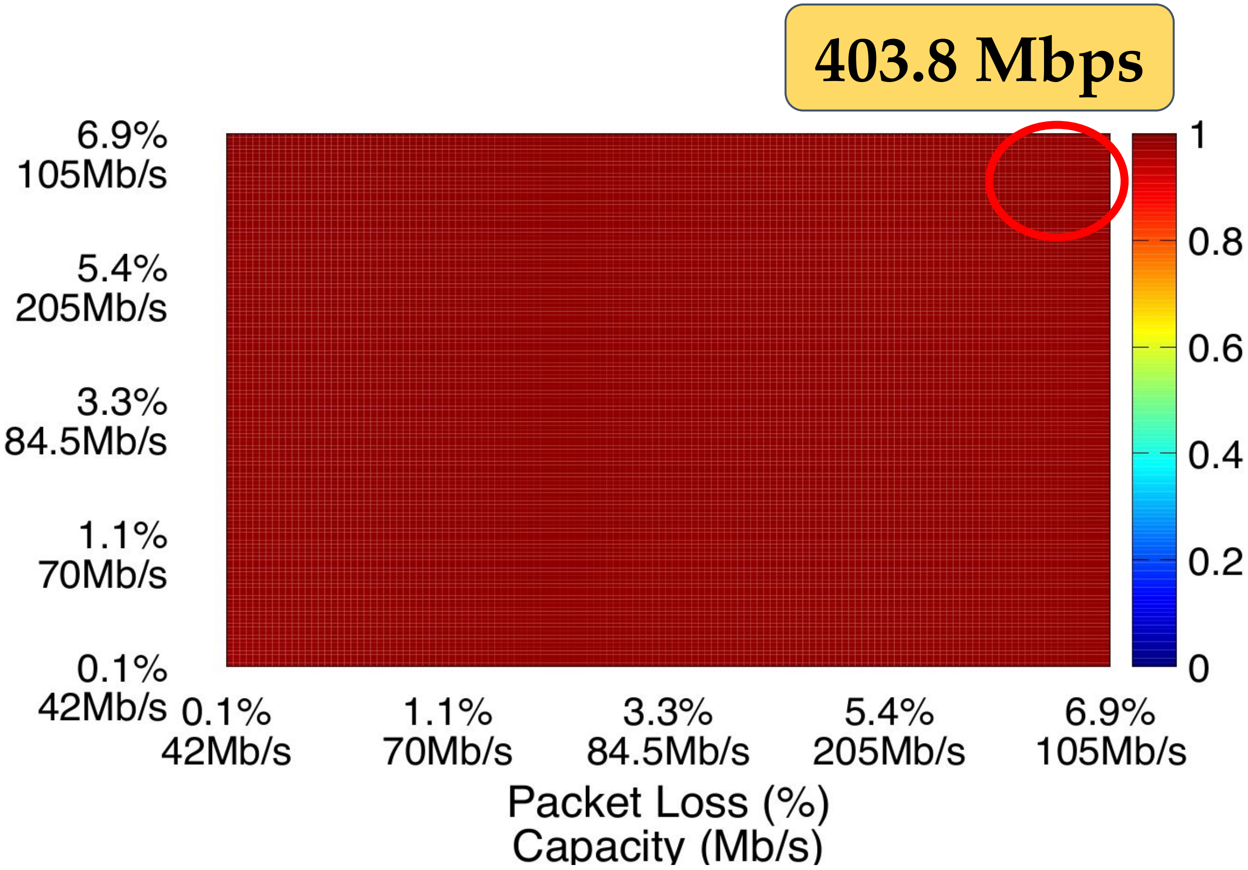


- Conversion substrate achieves 96-99% efficiency across all MCS values
- That drops to 89% in case of 80+80+80 combination due to the limited Inter-channel separation

WhiteHaul MPTCP Performance

- **WhiteHaul outperforms CUBIC by order of magnitude**





WhiteHaul Cost Analysis

	Spectrum Bandwidth	Capacity	Cost
WhiteHaul	80 MHz	210 Mbps	1585 USD
	160 MHz	420 Mbps	3205 USD
	240 MHz	630 Mbps	4555 USD
Carlson	24 MHz	70 Mbps	5297 USD
Redline	20 MHz	60 Mbps	5000 USD
Adaptrum	8 MHz	23 Mbps	5000 USD

Future Work

- Real-world trials

- Examining WhiteHaul wider applicability beyond the TVWS spectrum

Summary

- WhiteHaul TVWS based backhaul system design:
  - TVWS conversion substrate to efficiently handle multiple non-contiguous chunks of spectrum with multiple commodity Wi-Fi cards and single antenna
  - MPTCP as a link-level tunnel along with a novel cross-layer congestion control algorithm
- Extensive evaluation using prototype implementation of WhiteHaul in different configurations and in various scenarios:
  - Achieves nearly 600Mbps throughput using single polarized antenna
  - Can go beyond 1Gbps with a dual-polarized antenna at marginal additional cost
- Also present extensive analysis of TVWS spectrum characteristics from a backhaul use case perspective