Network Modeling and Analysis of a Public Safety Broadband Network

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National Institute of Standards and Technology

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Demonstration Network Stakeholder Meeting

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Motivation and Objectives

- Evaluate the performance of LTE technologies and their use in the nationwide public safety network
- Provide insights on the performance trends and trade-offs
  - Understand the factors that affect performance
- Define common performance metrics and develop modeling approach:
  - Use off-the-shelf (commercial and publicly available) network planning and simulation tools
  - Develop additional models and measurement tools as needed

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Outline

Part I: Modeling Coverage and Capacity of a Public Safety Broadband Network

Part II: Modeling a Nationwide Public Safety Broadband Network

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Overview of Part I: Modeling Coverage and Capacity

- Definition of Coverage
  - Metric (signal strength, signal-to-interference ratio)
  - Criteria (data rate, coverage probability)
  - Area covered vs. population covered
- Definition of Capacity
- Modeling Approach
- Sample analyses of coverage/capacity by
  - Traffic load
  - 5 MHz vs. 10 MHz bandwidth
  - Number of sites

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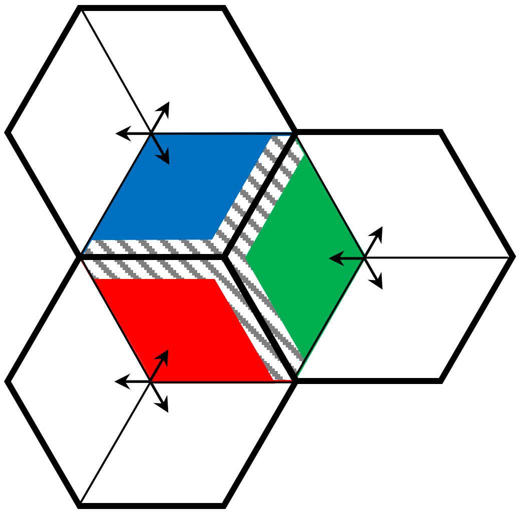
Coverage Definition

Percentage of the target area for which

Coverage Metric ≥ Threshold value ← Coverage criterion

Possible coverage metrics:

- Reference Signal Received Power (RSRP)
  - Provides an upper bound on actual coverage
  - Neglects the effect of intercell interference from other-cell traffic and control signals
- Signal-to-Interference-plus-Noise Ratio (SINR)
  - Accounts for intercell interference on the uplink (UL) and downlink (DL)
  - Depends on the traffic load



The threshold value is a function of the data rate and coverage probability of interest.

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Coverage Data Rate

- A higher data rate requires a larger threshold value in the coverage criterion.

Examples:

DL Data Rate	Required Modulation-Coding Scheme*	RSRP Threshold†	DL SINR Threshold†
192 kb/s	MCS 0	-108.7 dBm	11.5 dB
768 kb/s	MCS 6	-101.4 dBm	18.9 dB

* Required modulation-coding schemes assume an allocation of 4 resource blocks per sub-frame and two-layer spatial multiplexing.

† Thresholds include a fade margin for 95% coverage probability.

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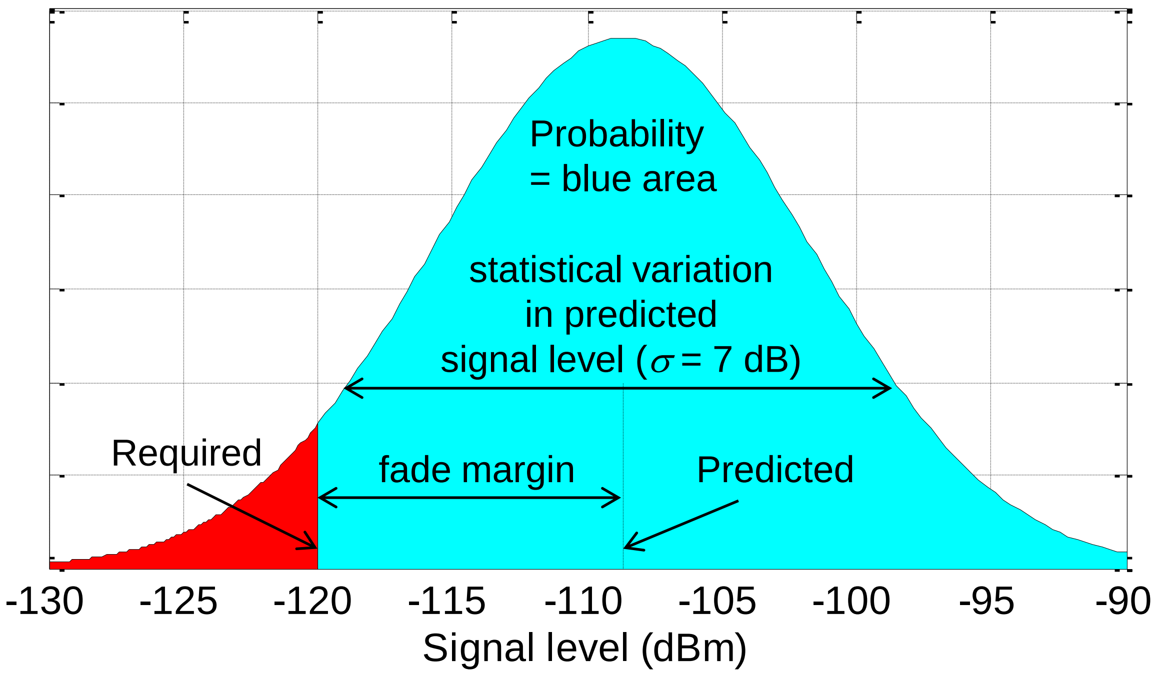
Coverage Probability

- Probability that the signal level at a given location exceeds the minimum required level



95% probability $\Rightarrow$ 11.5 dB fade margin
85% probability $\Rightarrow$ 7.3 dB fade margin

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Coverage Definition
Area vs. Population

- Area Coverage
  - Percentage of target area that satisfies the coverage criterion (“covered area”)
- Population Coverage
  - Percentage of total population in target area that is located in covered area
  - Based on a population distribution (e.g., census tract data)
  - Adjustments for time-of-day/seasonal migration

Capacity Definition

While *coverage* can account for intercell interference, it doesn't account for resource (bandwidth) limitations. A *capacity* metric is needed.

Possible capacity metrics:

- Maximum amount of traffic that can be supported (b/s)
  - Normalized by bandwidth (b/s/Hz)
- Maximum number of users that can be served

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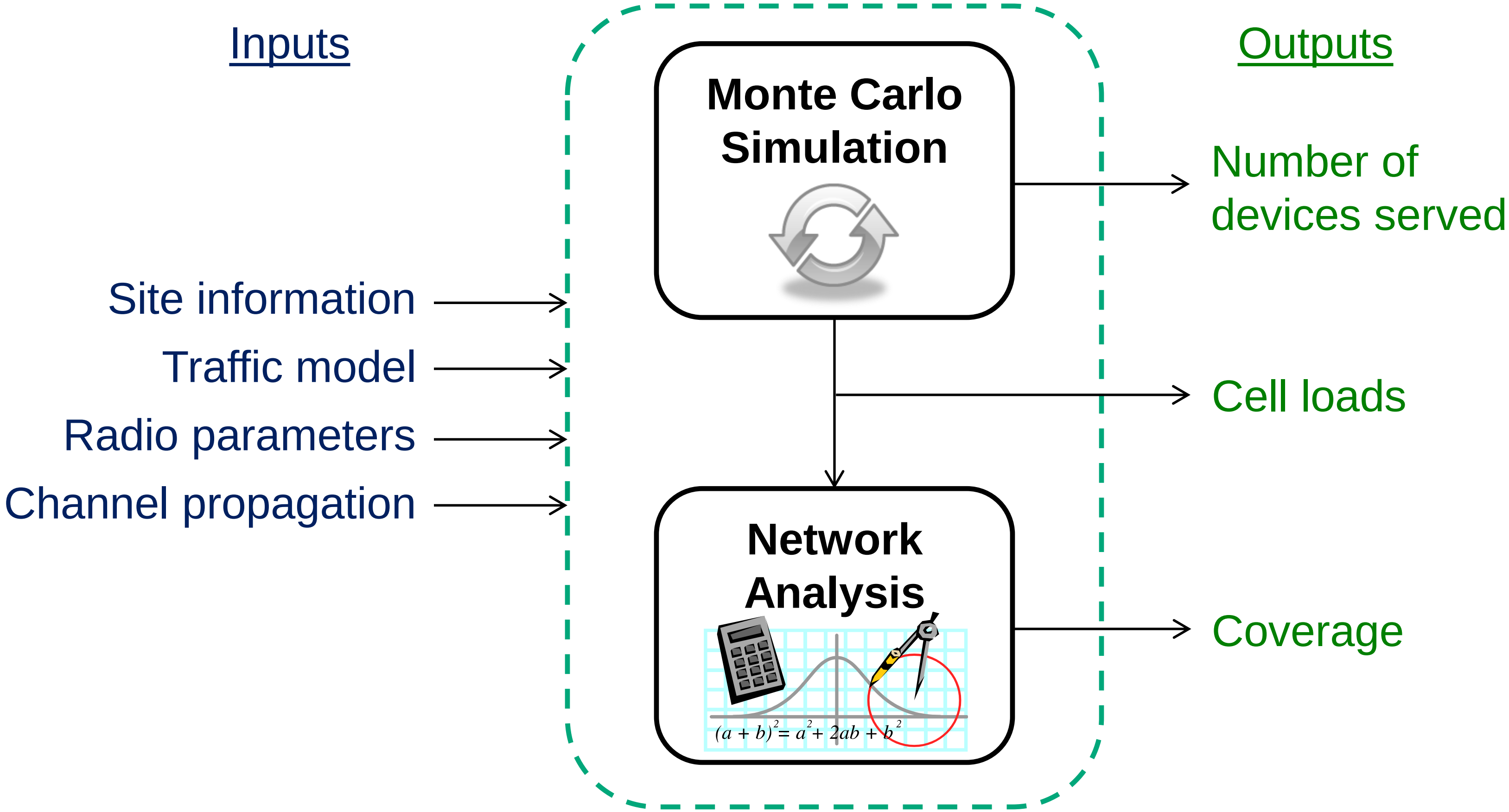
Modeling Approach



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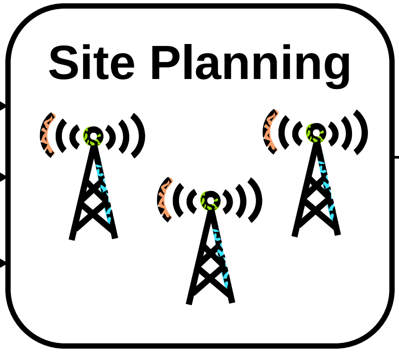
Greenfield Planning

Inputs

Service requirements
- Coverage
- Data rate

Traffic model



Output

Site locations

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Sources of Uncertainty

- Channel propagation model
  - Tuned vs. untuned: Variations in coverage predictions of up to 15% were observed between tuned and untuned models in the Boulder demonstration network.
- Modeling of intercell interference

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Specifics of this Modeling Exercise

- Areas modeled

	Area (km^2)	Population	# Sites
Adams County, Colorado	3,097	445,475	14
King/Pierce/Snohomish Counties, Washington (Seattle area)	15,527	3,439,800	Not given — greenfield planning done

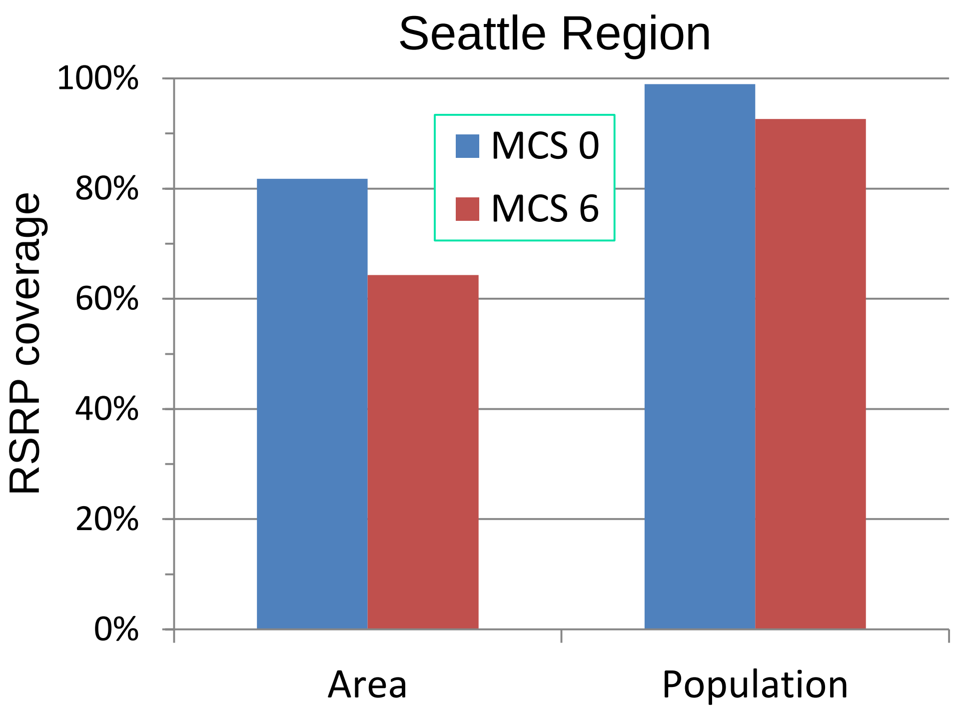
- Network planning tools used*
  - Mentum Planet v5.3
  - AIRCOM ASSET v7.0.0
- Network configurations were not optimized.

*DISCLAIMER: The full description of the procedures used in this presentation requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST, or are recommended by NIST, or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

Outline of Sample Results

- RSRP coverage
  - Impact of data rate requirement
- SINR coverage
  - Light traffic model vs. Heavy traffic model
  - Number of devices
  - 5 MHz vs. 10 MHz
  - Number of sites
- Cell load and Number of terminals served
  - Number of devices
  - 5 MHz vs. 10 MHz
  - Number of sites

RSRP Coverage
Data Rate Requirement



Settings
91 sites 4 W/MHz/ant. 95% probability

- Coverage decreases with the data rate requirement
  - MCS = Modulation-Coding Scheme
  - Higher MCS supports a higher data rate
- Population coverage is easier to achieve than area coverage, generally
- RSRP coverage does not explicitly include the effects of other-cell traffic.

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Traffic Model Examples

- “Heavy” traffic model based on FCC cell-edge data rate requirement
  - A device receives 768 kb/s DL and transmits 256 kb/s UL (assuming DL MCS≥6 and UL MCS≥5)
  - Assume every on-duty user carries such a device, and it transmits with some activity factor
- “Light” traffic model based on the Minneapolis Bridge Collapse scenario (Scenario III) described in the FCC white paper, “The Public Safety Nationwide Interoperable Broadband Network: A New Model for Capacity, Performance and Cost,” June 2010.
  - Seven applications, each with its own UL/DL data rate, activity factor, and user penetration rate (see next slide) (assuming DL MCS≥0 and UL MCS≥0)
  - Excluding command unit video

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Traffic Models
Data Rates and Activity Factors

Type of device	% of PS users carrying device	Uplink data rate (kb/s)	Downlink data rate (kb/s)	% of time device transmits	% of time device receives
Heavy Traffic Model					
768/256-kb/s	100%	256	768	50%	50%
*Light Traffic Model**					
Mobile Video Camera	25%	256	12	10%	5%
Data File Transfer CAD/GIS	87%	50	300	15%	5%
VoIP	100%	27	27	5%	15%
Secure File Transfer	12%	93	93	5%	5%
EMS Patient Tracking	6%	30	50	10%	5%
EMS Data Transfer	6%	20	25	25%	5%
EMS Internet Access	6%	10	90	10%	5%

* Based on the Minneapolis Bridge Collapse scenario defined in “The Public Safety Nationwide Interoperable Broadband Network: A New Model for Capacity, Performance and Cost,” FCC White Paper, June 2010, Exhibit 9, p. 26, excluding “command unit video.”

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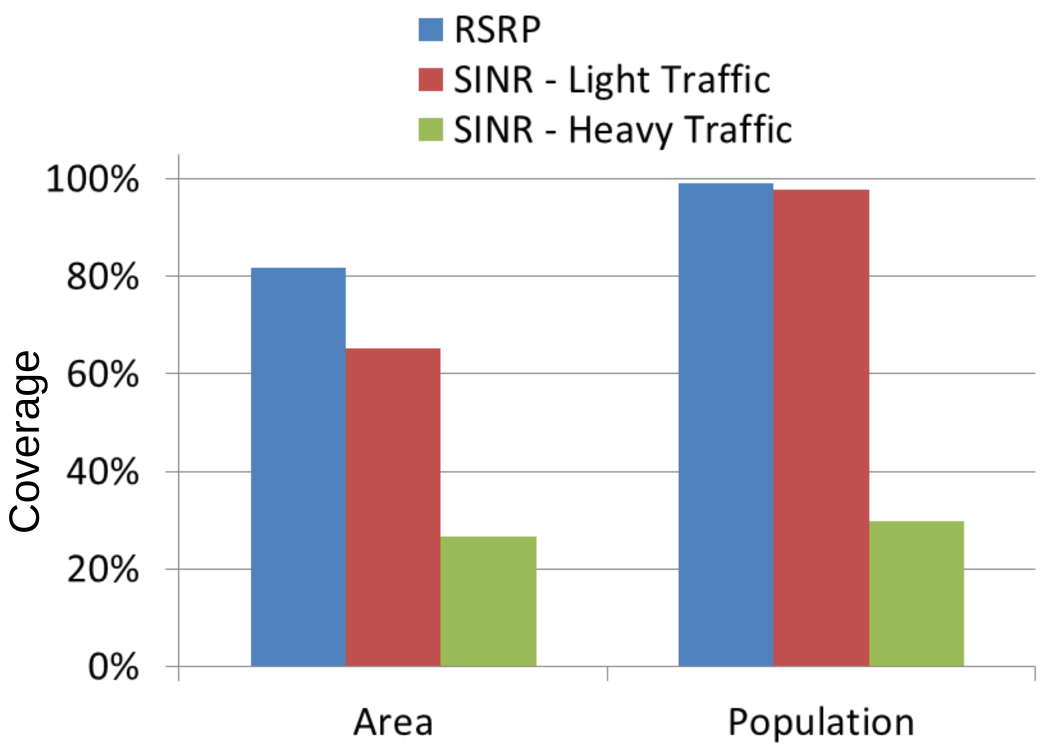
Offered Load

Example: # on-duty PS users = 300

Type of device	# of PS users carrying device	# of actively transmitting devices	Uplink offered load (kb/s)	Downlink offered load (kb/s)
Heavy Traffic Model				
768/256-kb/s	300	**150**	**38,400**	**115,200**
Light Traffic Model				
Mobile Video Camera	75	8	1,920	45
Data File Transfer CAD/GIS	261	39	1,958	3,915
VoIP	300	45	405	1,215
Secure File Transfer	36	2	167	167
EMS Patient Tracking	18	2	54	45
EMS Data Transfer	18	5	90	23
EMS Internet Access	18	2	18	81
Total of Light Traffic Model:		**103**	**4,612**	**5,491**

Traffic is distributed proportionally to population density (2010 census tract data).

Impact of Traffic on Coverage
Seattle Region



Settings
91 sites 10+10 MHz 4 W/MHz/ant. 95% probability

- Coverage decreases with increasing traffic
  - Traffic generates intercell interference
  - Intercell interference lowers the SINR, shrinking coverage
  - Heavy traffic model also has a higher data rate requirement (stricter coverage criterion)

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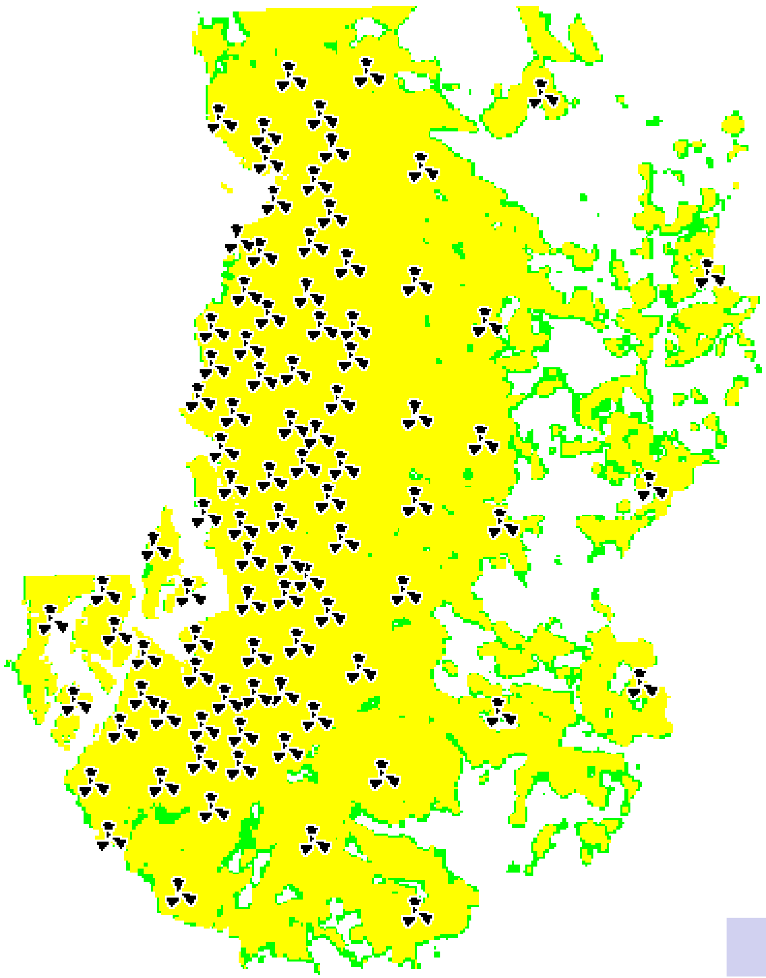
RSRP Coverage Probability Maps

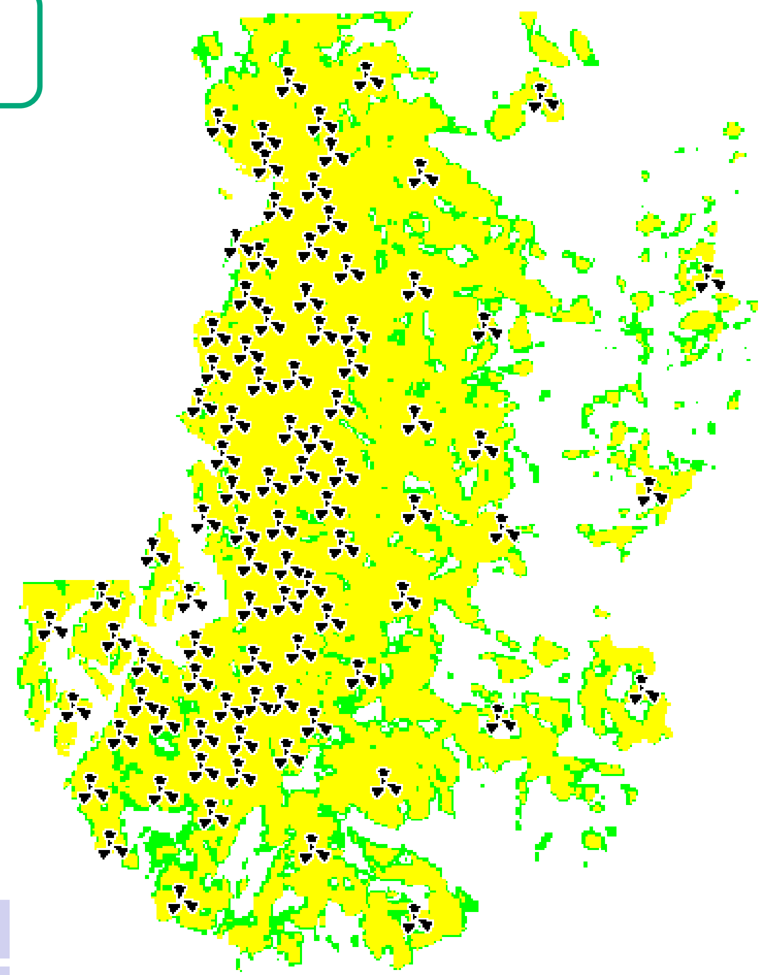
Seattle Region



MCS0

Green	85%
Yellow	95%

Settings
91 sites 4 W/MHz/ant.



MCS6

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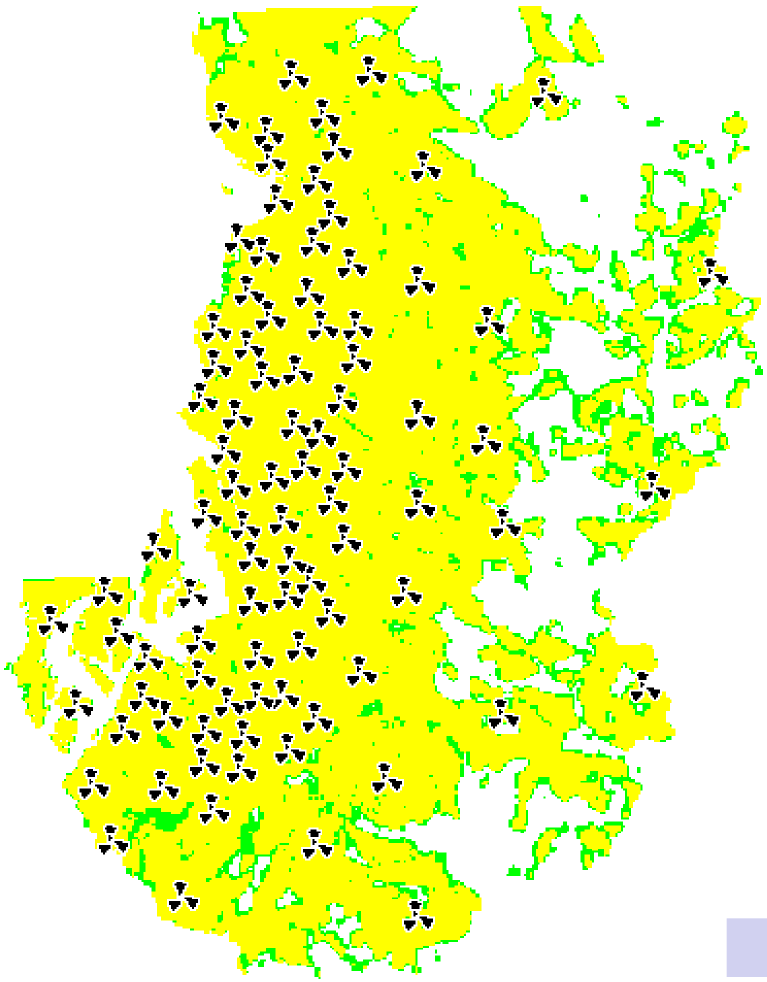
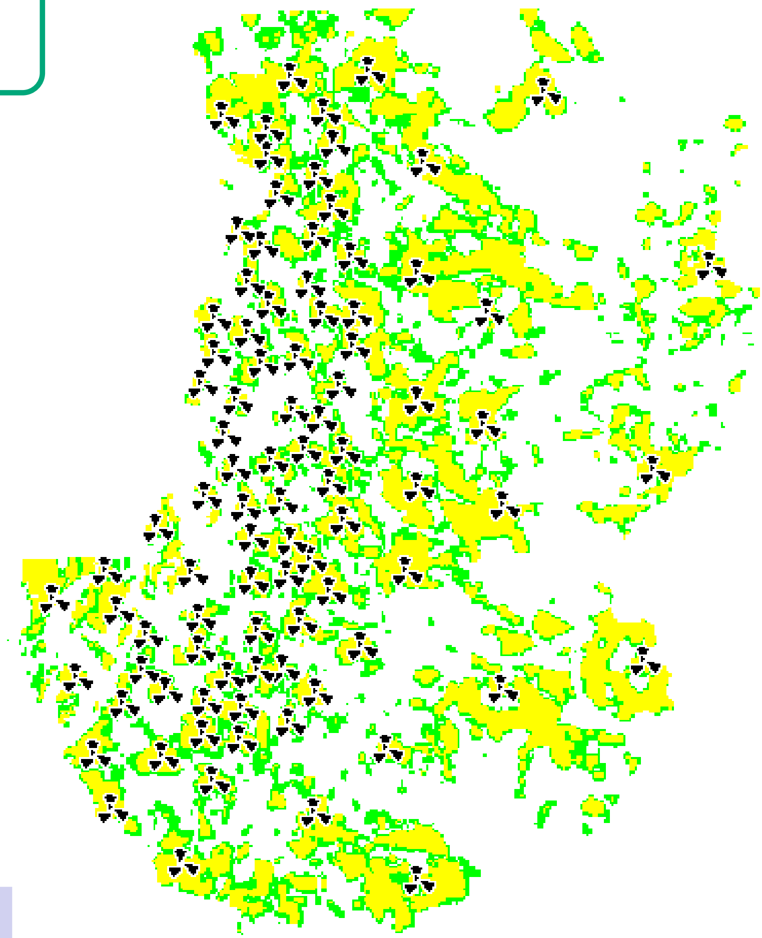
SINR Coverage Probability Maps
Seattle Region

85% (green)	
95% (yellow)	



Light Traffic Model



Heavy Traffic Model

Settings
91 sites 10+10 MHz 4 W/MHz/ant.

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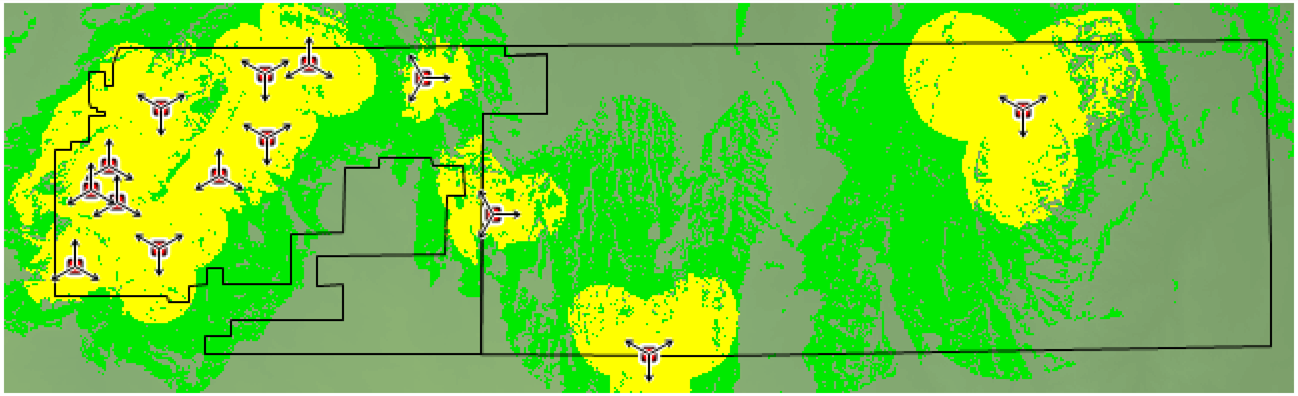
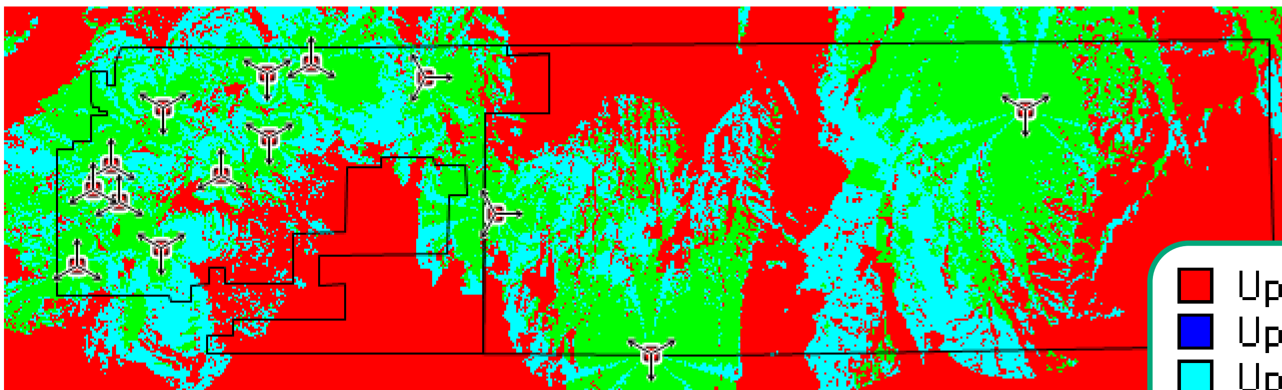
95% Coverage Probability Maps

Adams County

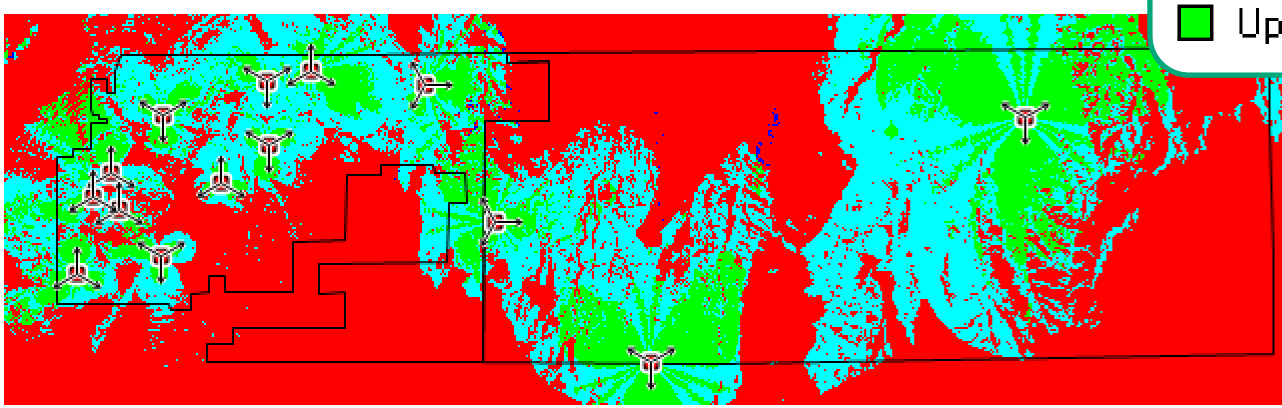
RSRP Coverage



SINR Coverage - Light Traffic Model



SINR Coverage - Heavy Traffic Model



Settings
14 sites 10+10 MHz 2 W/MHz/ant.

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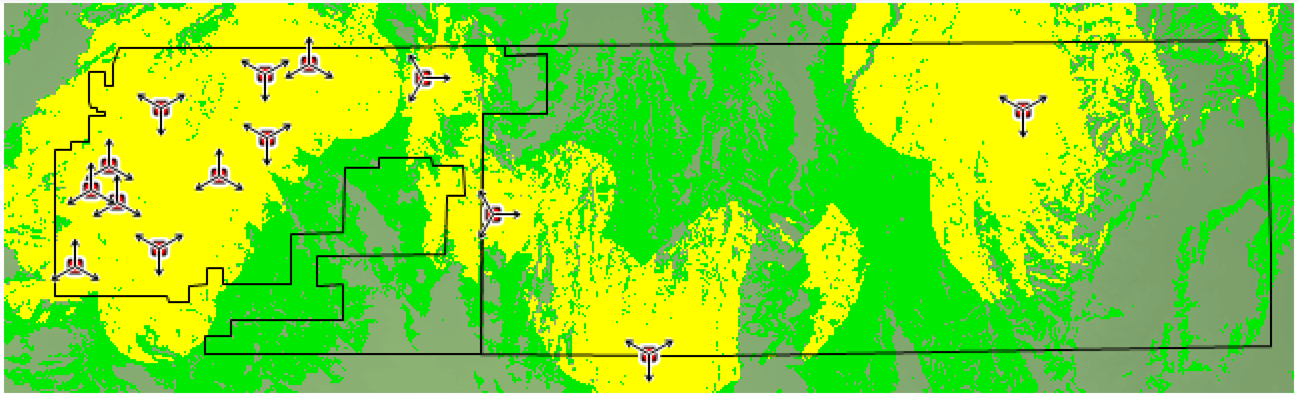
85% Coverage Probability Maps

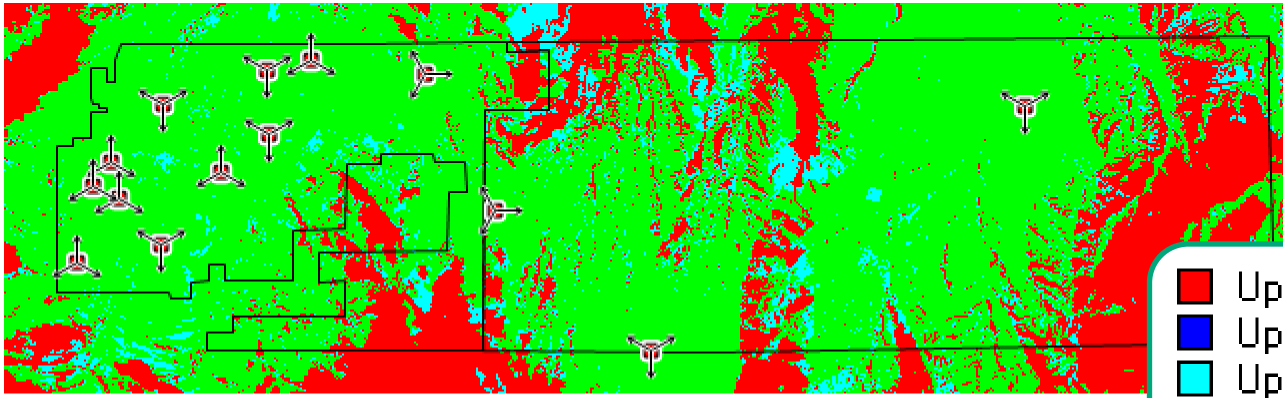
Adams County

RSRP Coverage



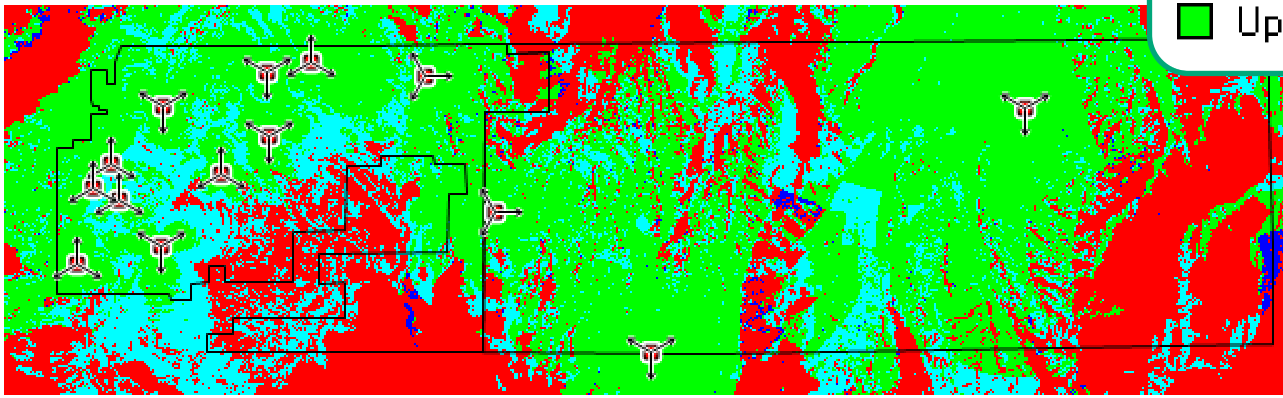
- MCS 0
- MCS 6

SINR Coverage - Light Traffic Model



- Uplink Fail, Downlink Fail
- Uplink Fail, Downlink OK
- Uplink OK, Downlink Fail
- Uplink OK, Downlink OK

SINR Coverage - Heavy Traffic Model



Settings
14 sites 10+10 MHz 2 W/MHz/ant.

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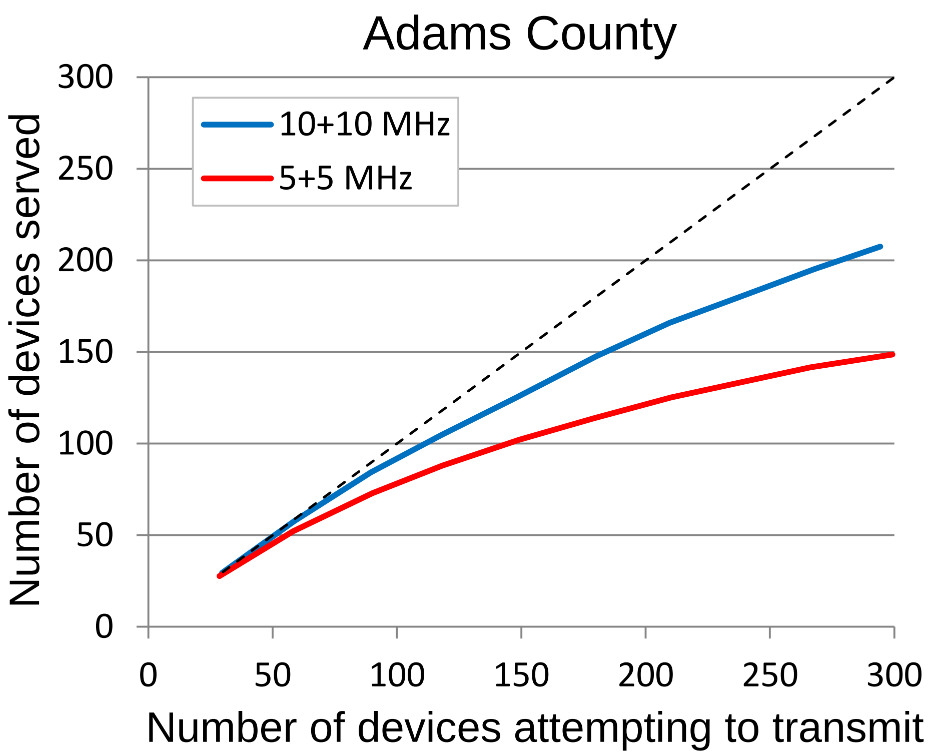
Number of Devices Served



Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model

- As traffic load increases, interference and capacity limitations take hold
- Benefits of additional bandwidth are more apparent under equal load (next slide)

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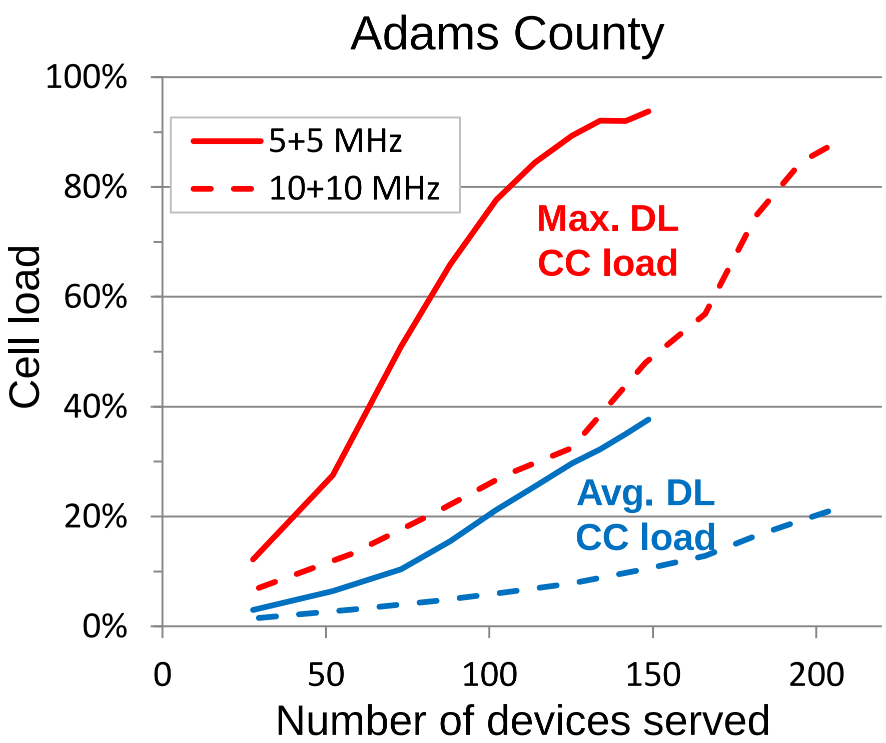
Cell Load vs. Number of Devices



Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model

- Cell load increases with the number of devices served
- Additional bandwidth lowers cell load
  - Twice the number of resource blocks available
  - Lower intercell interference permits higher, more spectrally-efficient MCS
- For a given average cell load, doubling the bandwidth doubles the # devices that can be served

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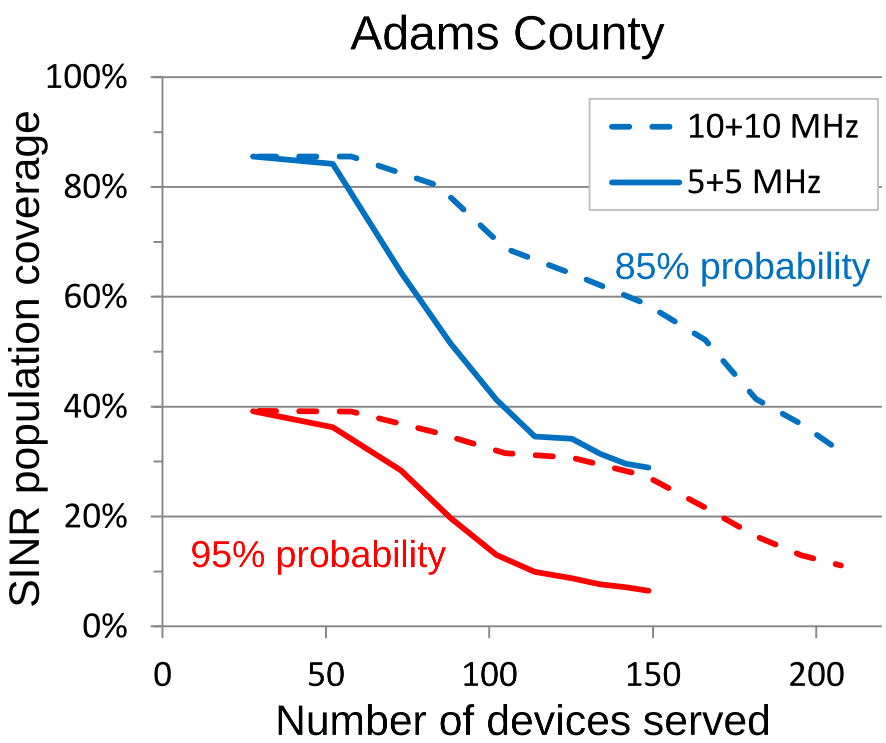
Coverage vs. Traffic Load



Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model

- Coverage decreases with increasing load
- Additional bandwidth improves coverage
  - Lowers intercell interference
- Coverage probability has a significant impact on the coverage value
  - Higher coverage probability requirement requires a larger fade margin

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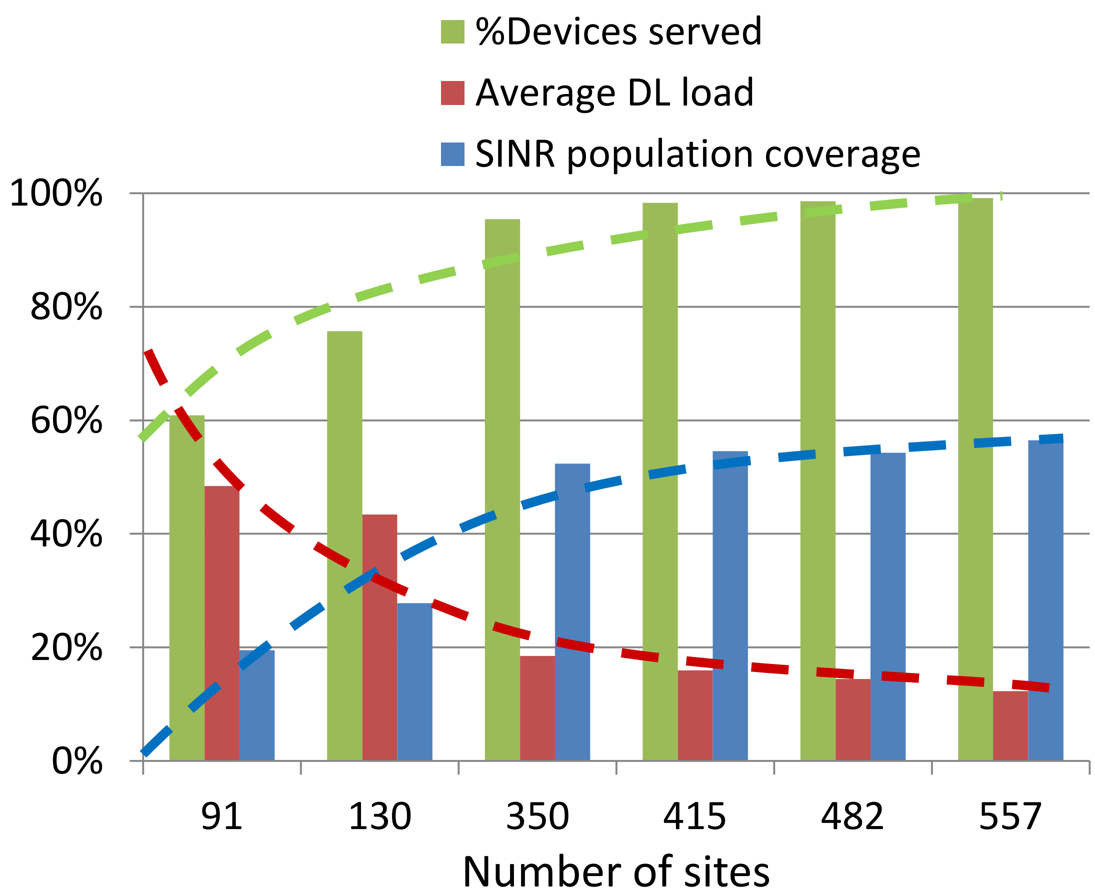
Increasing the Number of Sites
Seattle Region



- Adding more sites increases the % devices served, decreases sector load, and improves coverage
- Diminishing returns with greater number of sites
  - Note: Site configurations not optimized

Settings
5+5 MHz 4 W/MHz/ant. Heavy traffic model 95% coverage probability

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Main Take-Away Points

- Coverage depends on
  - Data rate requirement
  - Coverage probability requirement (fade margin)
  - Traffic load (because of intercell interference)
- Traffic model descriptors
  - # Devices and their geographic distribution
  - Data rates
  - Activity factors
- Both coverage and capacity predictions depend on the channel propagation model. Ideally, the model should be tuned with measurement data.

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Questions?

Modeling a Nationwide
Public Safety Broadband Network

Overview of Part II: Modeling a Nationwide Network

- Nationwide modeling approach
  - Classification by terrain and population density
  - Analysis of representative sample areas
  - Extrapolation to larger areas
- Preliminary results
  - Classification for the continental US
  - Illustration of site placement
  - Sample results for a class/subdivision
- Areas of further study

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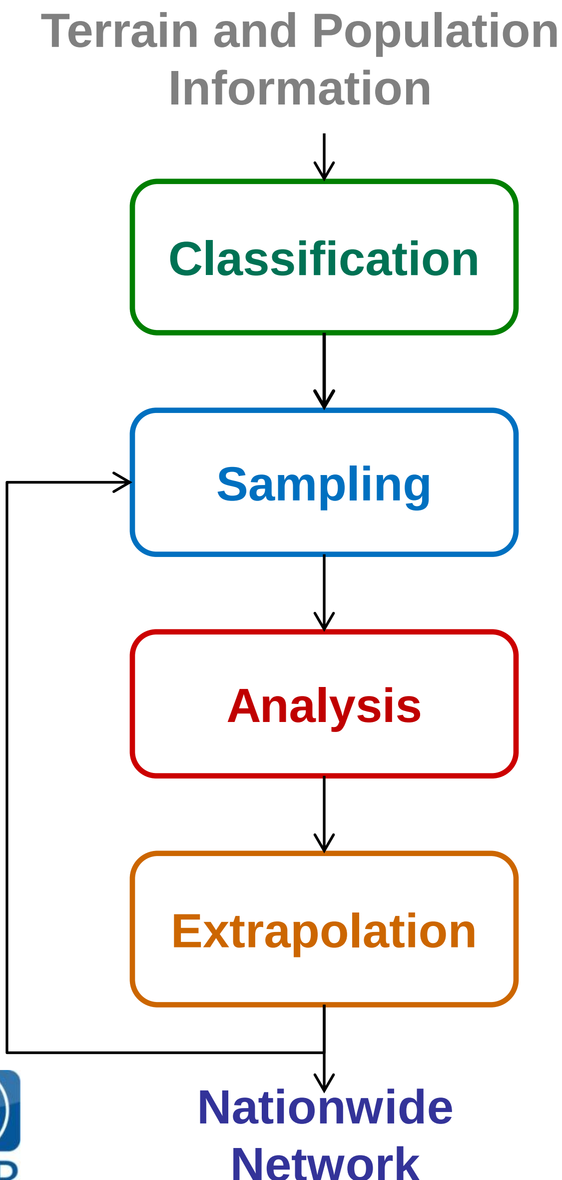
Nationwide Modeling Approach



Divide the entire geographic area into fixed size subdivisions and group subdivisions with similar characteristics together to form classes

Identify subdivisions to analyze

Conduct a detailed analysis of the selected subdivisions

Use results of detailed analysis for all classes and scale to the entire geographic area.

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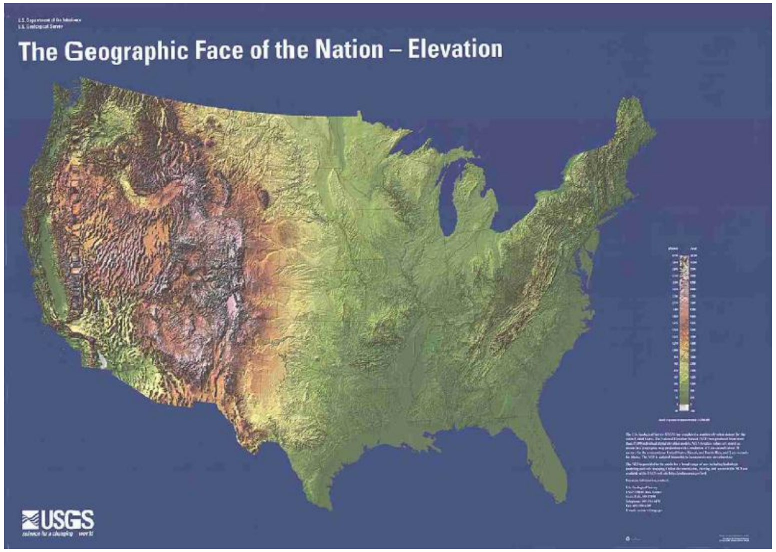
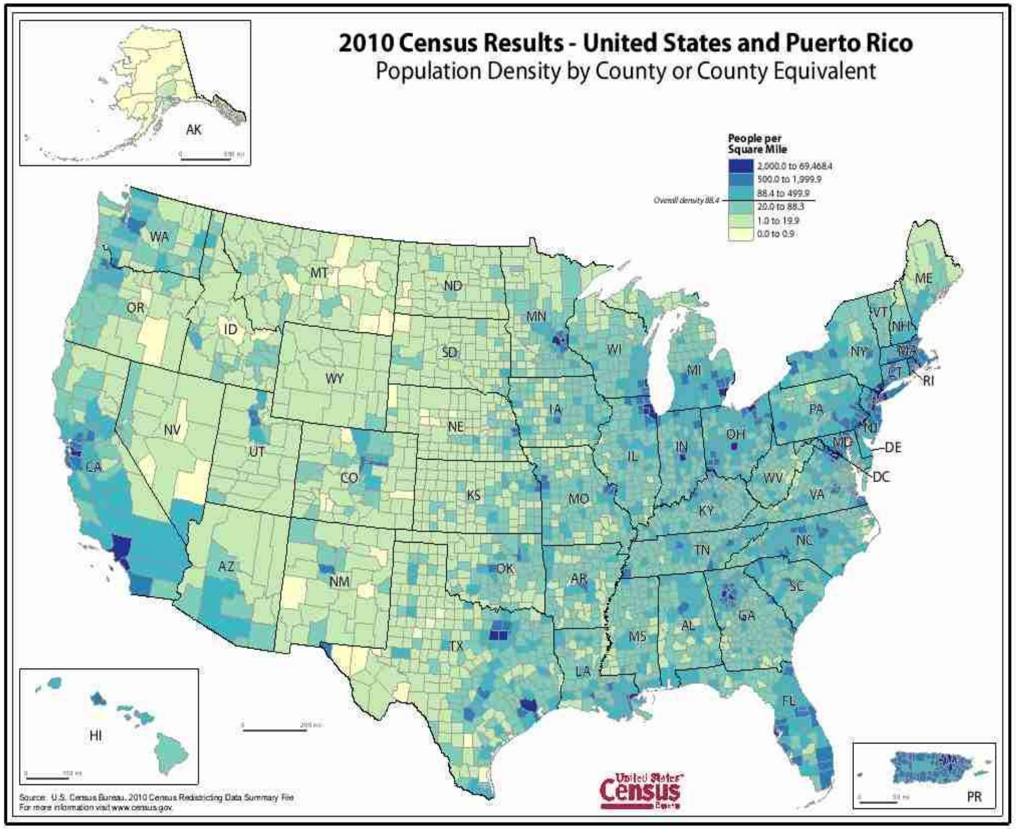
United States Terrain and Population Density Maps

Terrain affects signal propagation



Number of public safety users depends on population density



Deployment needs vary by region

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Classification

Inputs

Elevation →
Census Data (2010) →
Density threshold →
Algorithm parameters →

Partition into subdivisions

Clustering
Identify subdivisions with similar characteristics

Outputs

→ Grid
→ Classes

Sampling

Inputs

List of all subdivisions (belonging to a class)

Current and target error rate

Sampling

Outputs

Selected subdivisions to analyze

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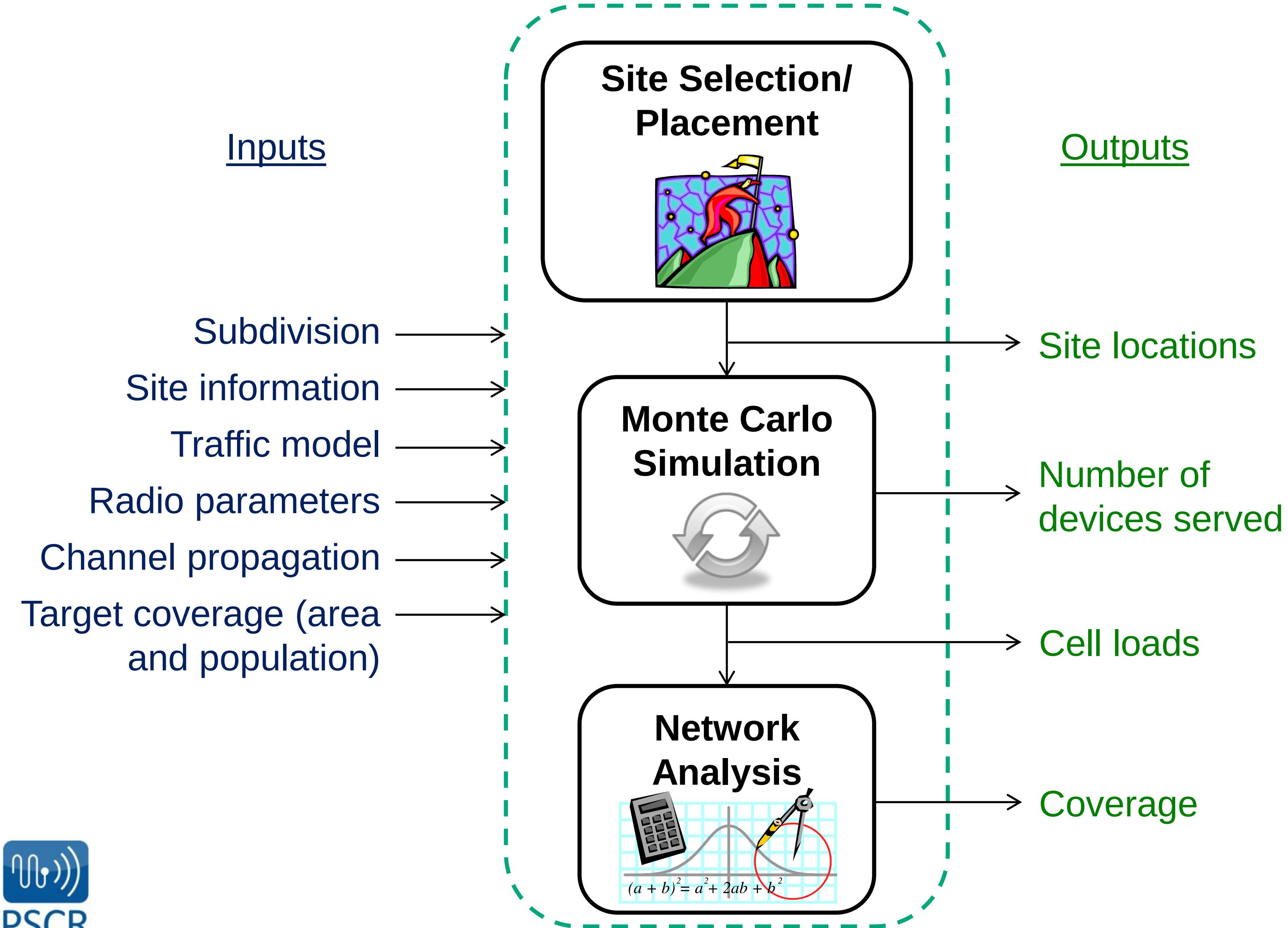
Analysis

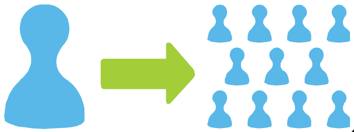

Inputs
Subdivision
Site information
Traffic model
Radio parameters
Channel propagation
Target coverage (area and population)
Site Selection/ Placement
Monte Carlo Simulation
Network Analysis
$(a + b)^2 = a^2 + 2ab + b^2$
Outputs
Site locations
Number of devices served
Cell loads
Coverage

Extrapolation

Inputs

Classification results →
Sampled subdivision results →

Class Extrapolation



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Nationwide Extrapolation

Outputs

Number of sites
Area coverage
Population coverage

Total number of sites
Area coverage
Population coverage

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Preliminary Results

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Areas of further study

- Consider the effects of additional input parameters:
  - Building clutter information
  - Population migration (time-of-day/ seasonal adjustments)
  - Population/user growth (5-year, 10-year estimates)
  - Traffic models (eg. day-to-day versus incident)
- Develop more accurate simulation models
  - Refine channel propagation models
  - Investigate interference coordination
  - Validate simulation models
- Obtain more complete information:
  - Number and distribution of public safety users
  - Site locations
  - Network equipment parameters (eNodeB, subscriber units)

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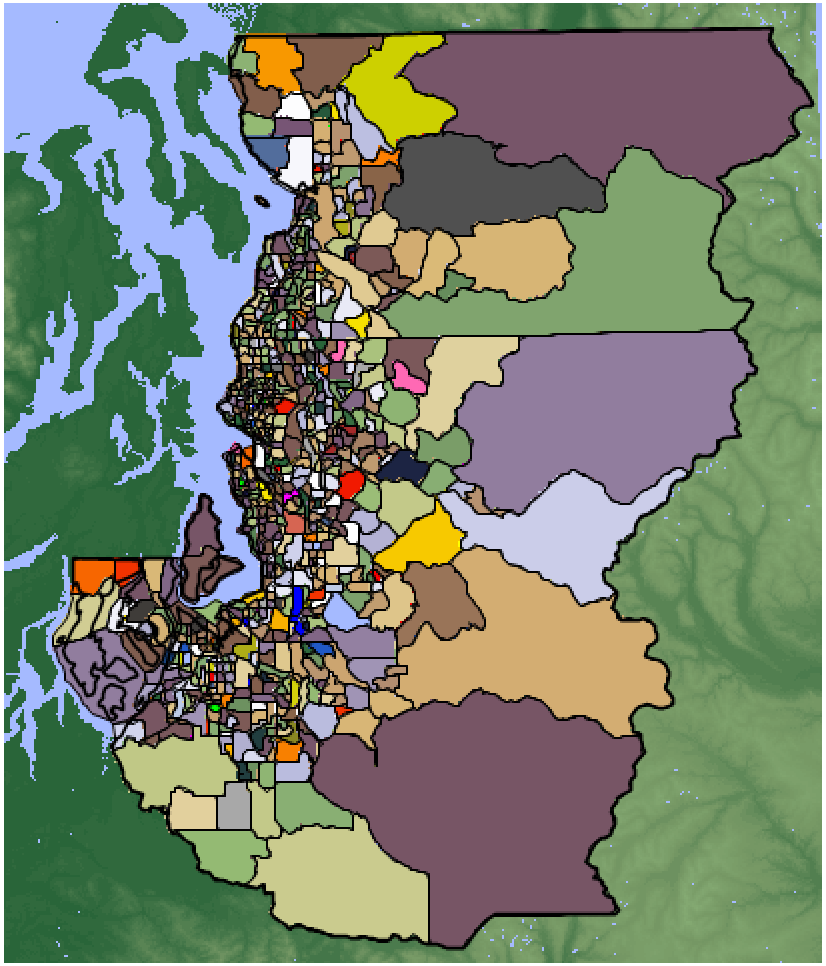
Questions?

Appendix

King/Pierce/Snohomish Counties, Washington

Area	15,527 km^2
2010 Population	3,439,800
Sites	Not given — greenfield planning done



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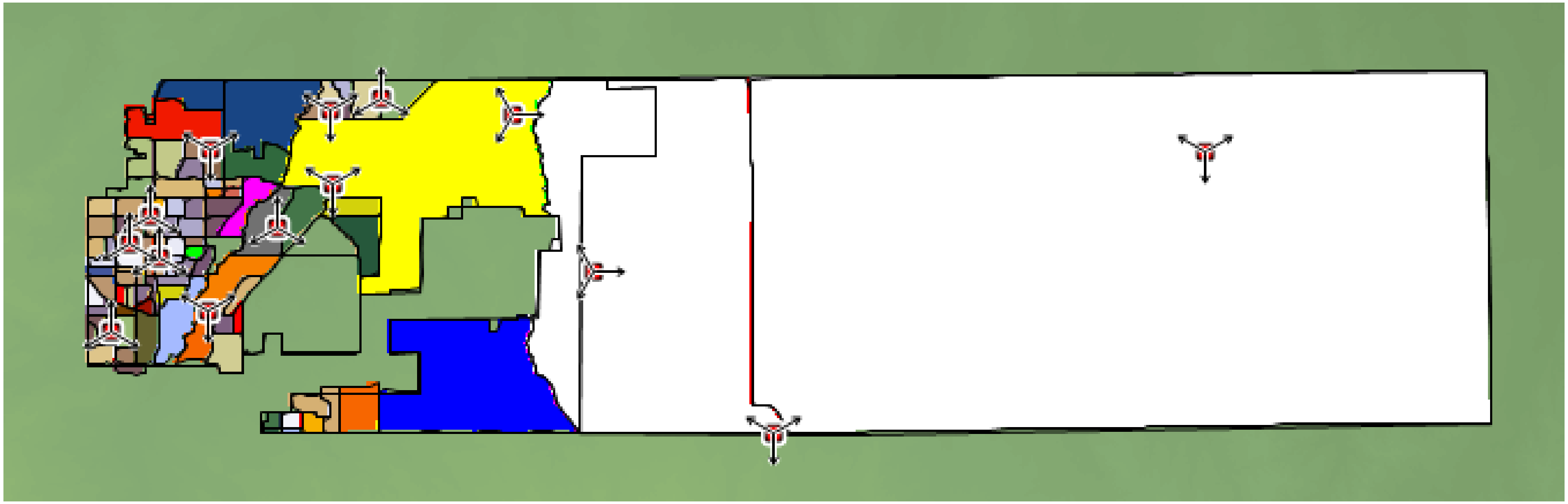
Adams County, Colorado



Area	2010 Population	# Sites
3,097 km^2	445,475	14

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Modeling Assumptions
Seattle Region

System	Bandwidth	5+5 MHz
	Center frequencies	765.5 MHz DL, 795.5 MHz UL
eNodeB	Sector antenna	2 × Andrew LNX-6515DS-VTM, 65° HBW, 16.7 dBi
	Tx power	2 × 20W
	Noise figure	2.5 dB
	Cable/connector losses	2.5 dB
User Equipment	Antenna	1 Tx, 2 Rx, omnidirectional, –4 dBi
	Rx height	1.5 m
	Tx power	23 dBm
	Noise figure	12 dB
Channel Propagation	CRC-Predict Model (untuned)	
	Slow fading std dev	7 dB
	Penetration loss	0 dB (outdoor)
ICIC	Hard frequency reuse	

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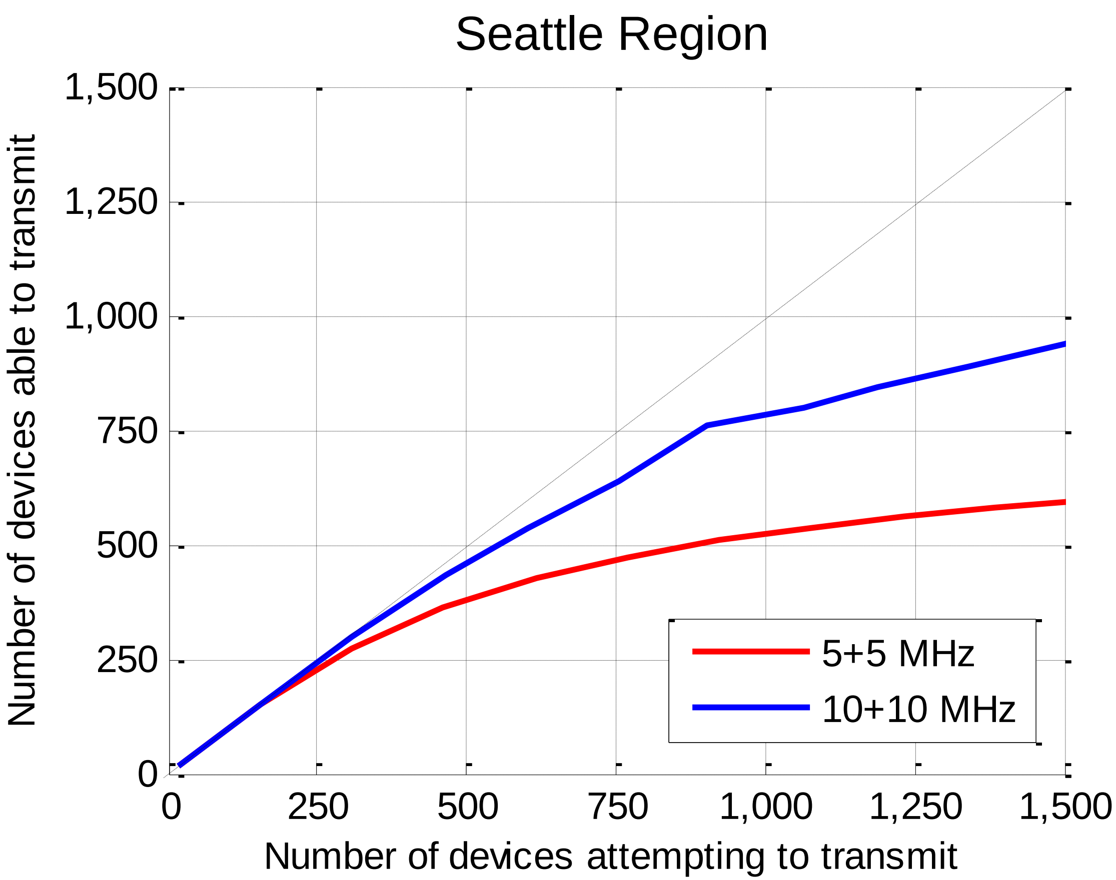
Modeling Assumptions
Adams County

System	Bandwidth	5+5 MHz
	Center frequencies	765.5 MHz DL, 795.5 MHz UL
eNodeB	Sector antenna	Andrew DBXNH-8585B-VTM, 87° HBW, 14.4 dBi
	Tx power	2 × 10W
	Noise figure	2.5 dB
	Cable/connector losses	0.5 dB
User Equipment	Antenna	1 Tx, 2 Rx, omnidirectional, –4 dBi
	Rx height	1.5 m
	Tx power	23 dBm
	Noise figure	12 dB
Channel Propagation	ASSET Standard Macrocell 3 tuned with Boulder demonstration network Table Mountain 1 measurements	
	Slow fading std dev	7 dB
	Penetration loss	0 dB (outdoor)
ICIC	Soft frequency reuse with 70%/30% cell-center/cell-edge bandwidth split	

Sample Link Budget

	UL Traffic	DL RS
# RBs	4	
Req SINR for 768/256-kb/s (dB)	-0.09	7.37
Noise figure (dB)	2.5	12
Occupied bandwidth (Hz)	720,000	15,000
Required signal strength (dBm)	-113.0	-112.9
Tx antenna gain (dBi)	-4	14.4
Rx antenna gain (dBi)	14.4	-4
Cable/connector loss (dB)	0.5	0.5
Cell-edge coverage probability	95.0%	
Slow fading std dev (dB)	7	
Slow fading margin (dB)	11.5	
Handoff gain (dB)	2.8	
Fixed IoT (dB)	3	
Max tx power (dBm)	23	40.0
RS power (dBm)		15.2
MAPL (dB)	134.2	126.5
RSRP design threshold (dBm)	**-109.1**	**-101.4**

Number of Devices Served



Settings
91 sites 4 W/MHz/ant. 768/256-kb/s traffic model

- As traffic load increases, interference and capacity limitations take hold.
- For a given *percentage* of devices served, doubling the bandwidth doubles the number of devices served.

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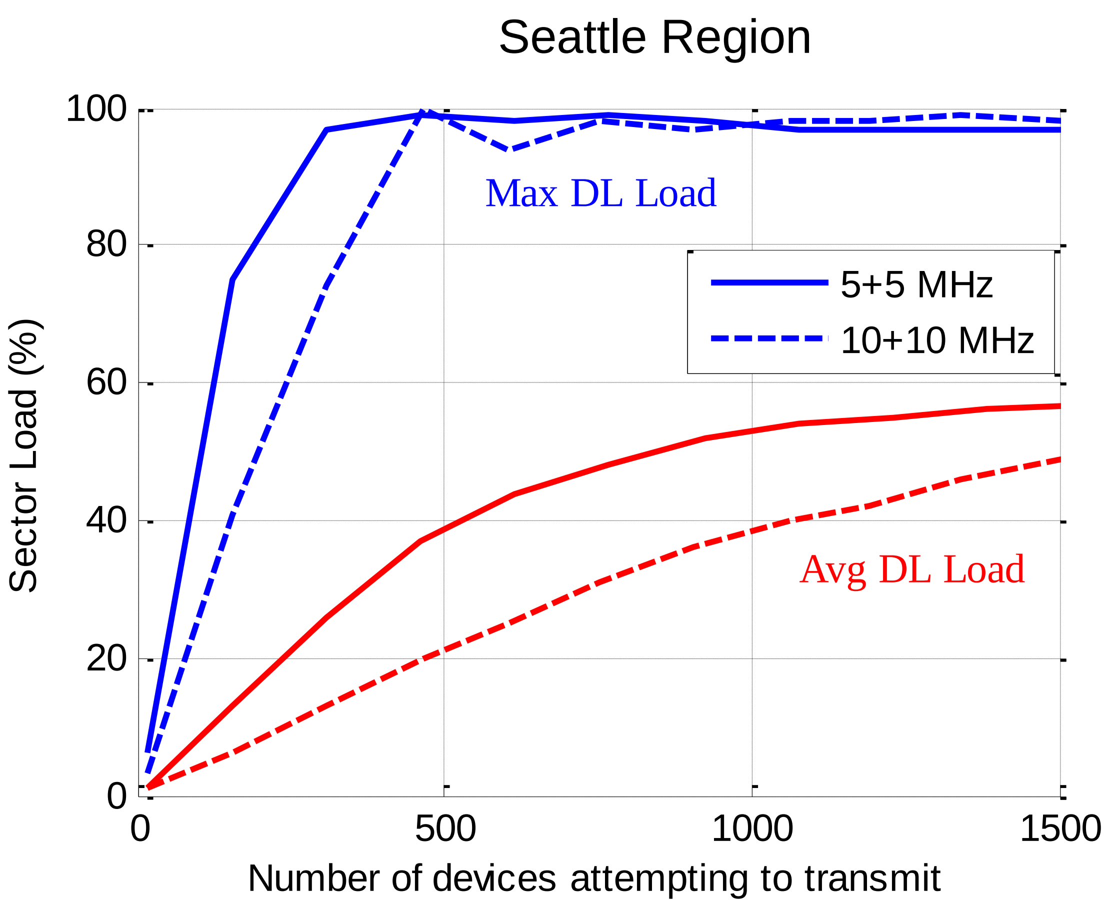
Cell Load vs. Number of Devices



Settings
91 sites 4 W/MHz/ant. 768/256-kb/s traffic model

- Cell load increases with the number of transmitting devices
- Additional bandwidth lowers cell load
  - Twice the number of resource blocks
  - Resulting lower intercell interference permits higher, more spectrally-efficient MCS

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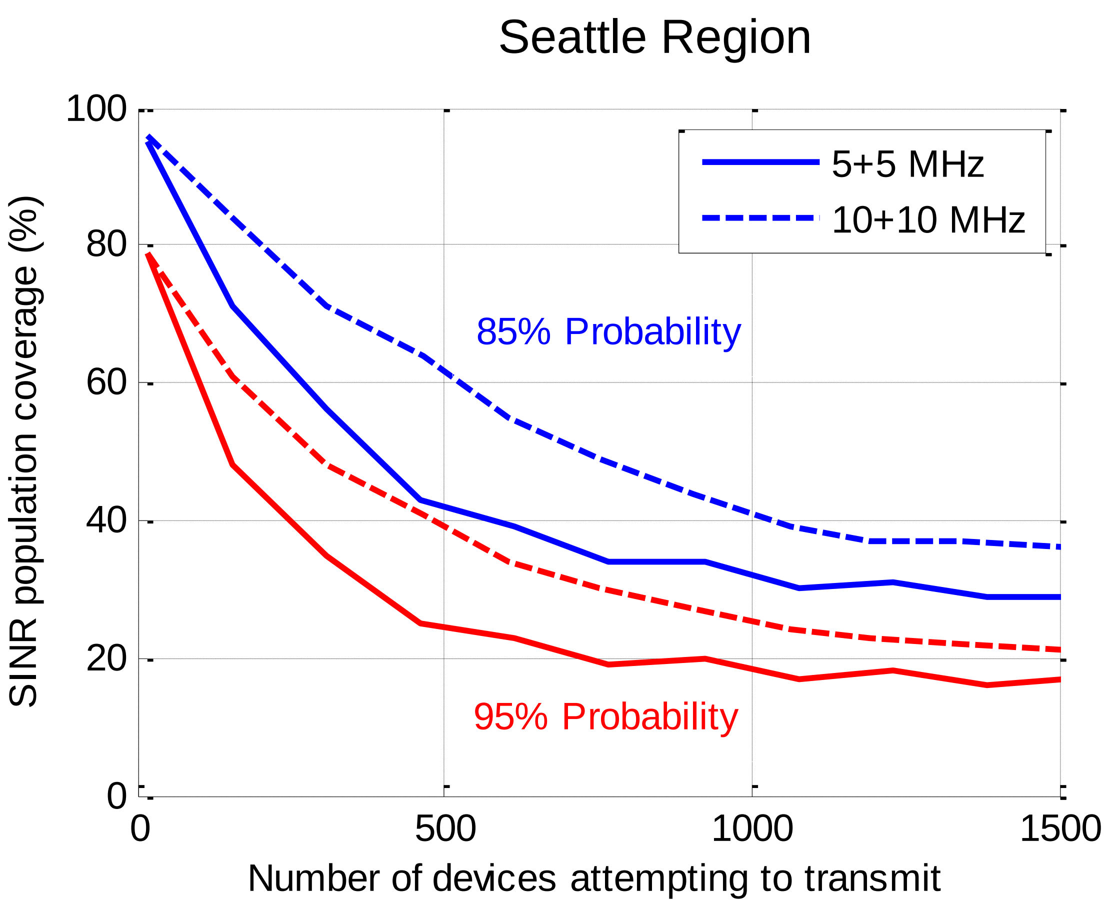
Coverage vs. Traffic Load



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- Coverage decreases with increasing load
- Additional bandwidth improves coverage
  - Lowers intercell interference
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  - Higher coverage probability requirement requires a larger fade margin

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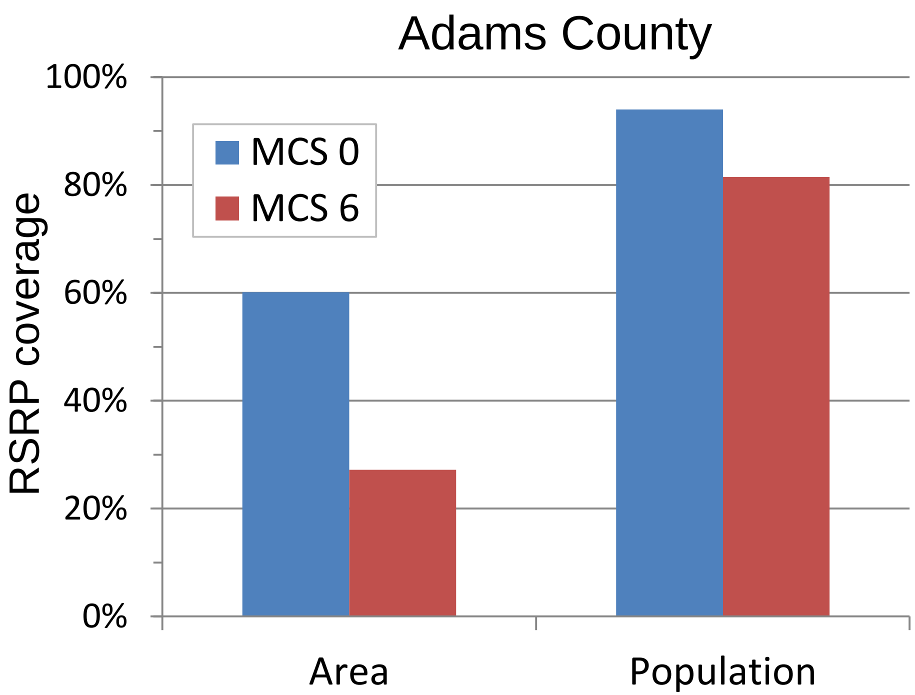
RSRP Coverage
Data Rate Requirement



Settings
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- Coverage decreases with the data rate requirement
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  - Higher MCS supports a higher data rate
- Population coverage easier to achieve than area coverage, generally

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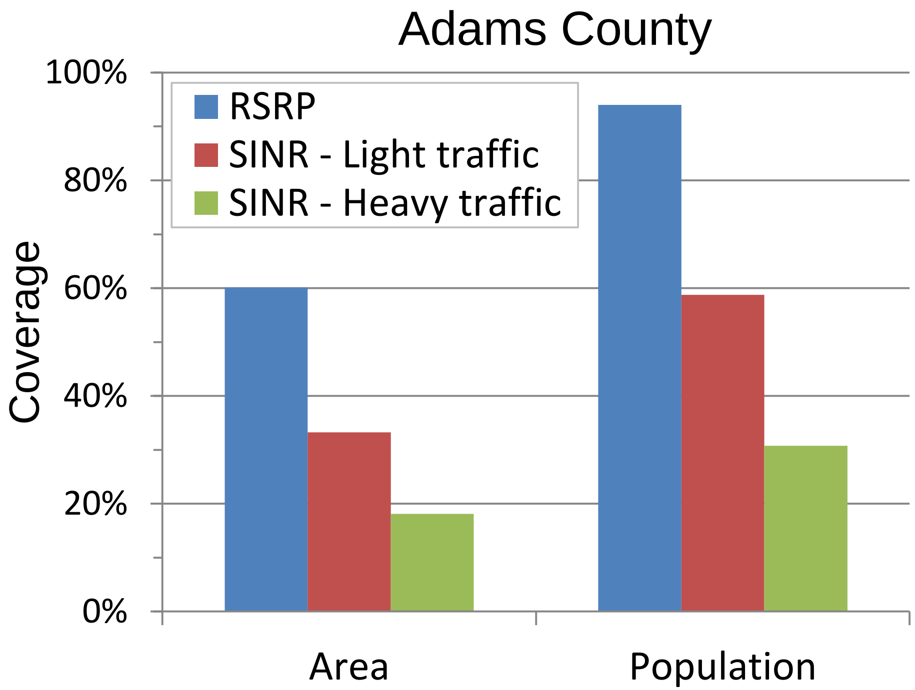
Impact of Traffic on Coverage

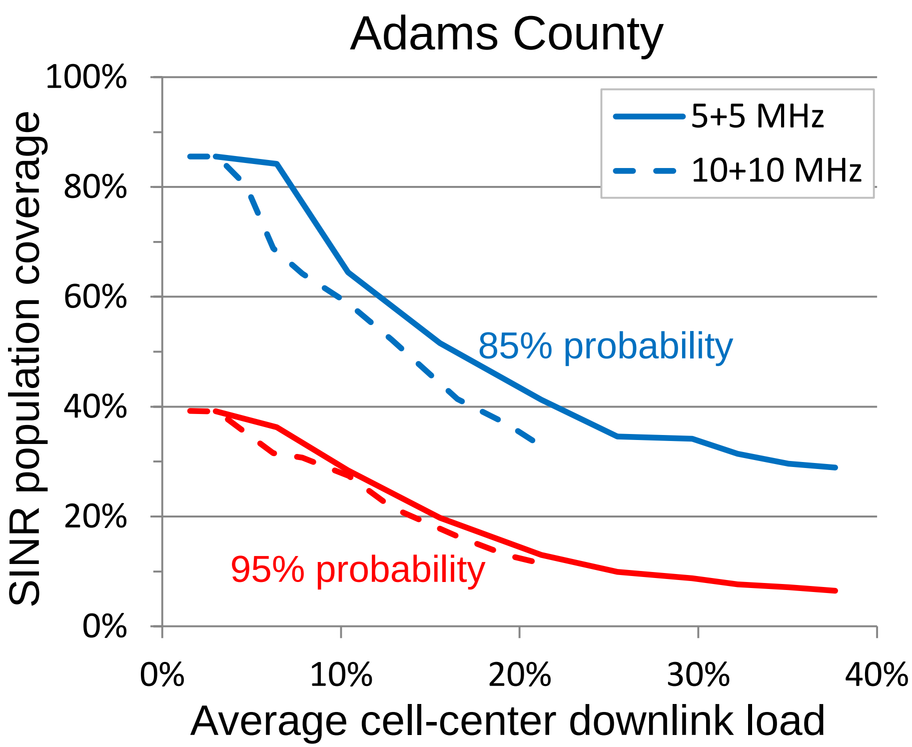


Settings
14 sites 10+10 MHz 2 W/MHz/ant. 95% probability

- Coverage decreases with increasing traffic
  - Traffic generates intercell interference
  - Intercell interference lowers the SINR, shrinking coverage
  - Heavy traffic model also has a higher data rate requirement (stricter coverage criterion)

PSCR

Coverage vs. Cell Load

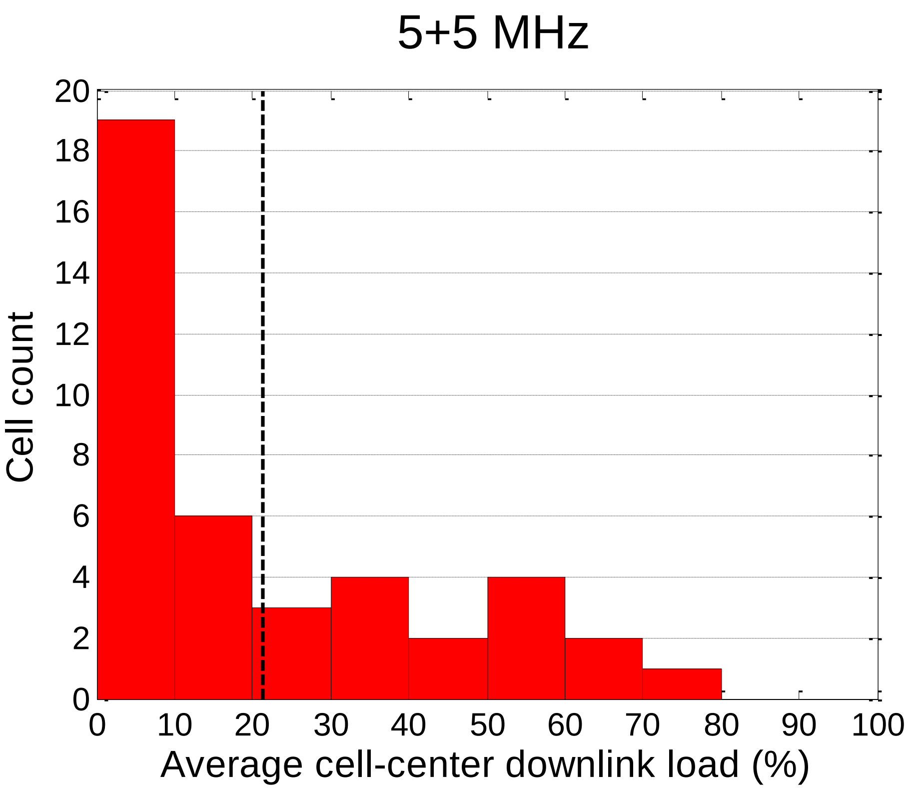


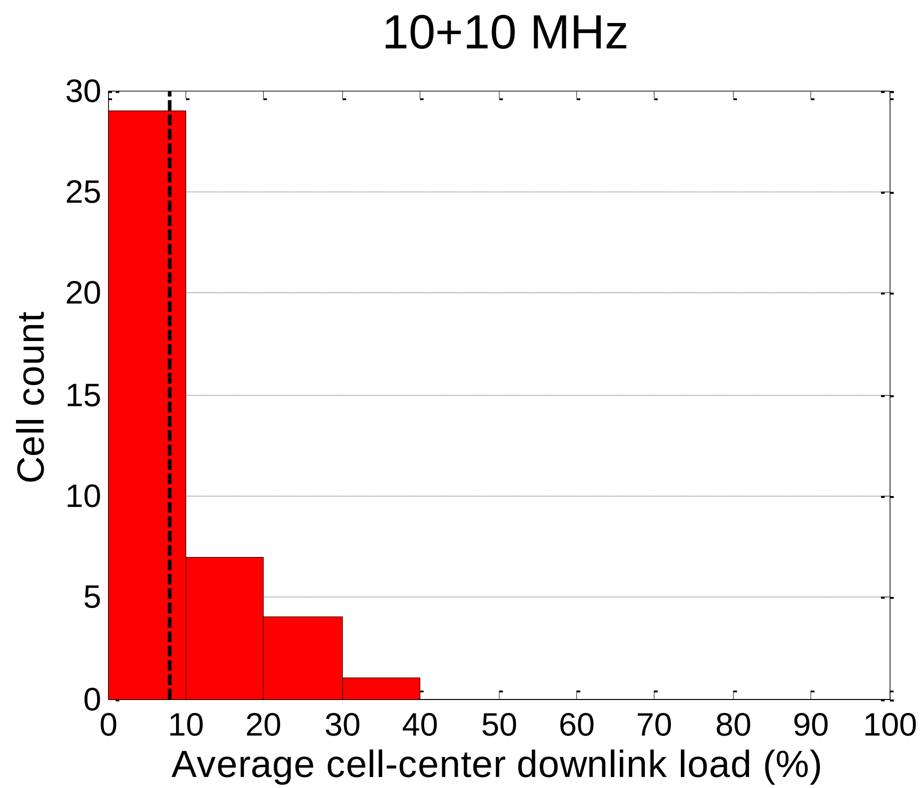
Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model

- Coverage decreases with increasing load
- Coverage probability has a significant impact on the coverage value
  - Higher coverage probability requirement requires a larger fade margin

PSCR

Downlink Cell-Center Loads
Adams County



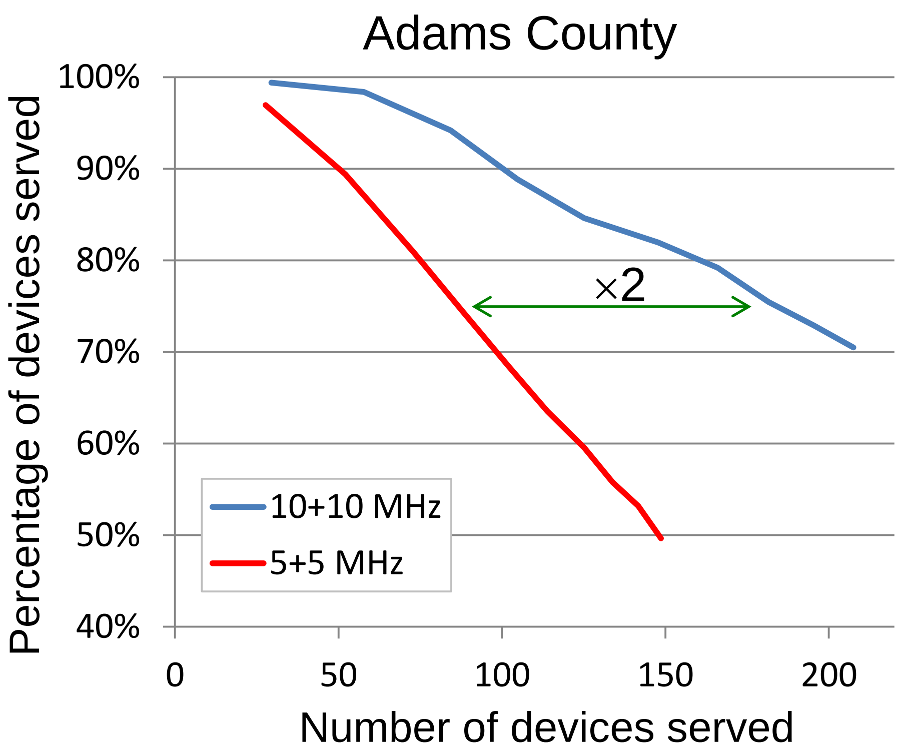


Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model 150 devices

- Distribution of cell loads shifted lower with greater bandwidth

PSCR

Number of Devices Served



Settings
14 sites 2 W/MHz/ant. 768/256-kb/s traffic model

- For a given percentage of devices served, doubling the bandwidth doubles the number of devices served.