Mesh Networks Alliance
IEEE 802.11 TGs Proposal submission

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Joint ComNets – Philips proposal

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This version has been edited for publication as PDF file at ComNets, RWTH Aachen University.

Some animations may not be displayed correctly in PDF format.

Please see http://802wirelessworld.com for the original version in PowerPoint format.

Abstract

The Mesh Networks Alliance (MNA) describes MAC layer enhancements to IEEE 802.11 to provide efficient methods for Mesh WLAN. It offers a flexible design, which coexists with legacy 802.11 devices on a single channel. MNA reuses standard 802.11 technology such as Contention Free Period (CFP), Beacon frames and Transmission Opportunity (TXOP). Furthermore, the Mesh Networks Alliance offers a security concept for the distribution of 802.11i keys.

Mesh Networks Alliance

Mesh WLAN MAC

Recombining 802.11 and its amendments

IEEE 802.11s PAR requirements

1. **The proposed amendment shall be** an extension to the IEEE 802.11 MAC**.**
2. **The amendment will define an architecture and protocol for providing an IEEE 802.11 ESS Mesh […] to create an** IEEE 802.11 Wireless Distribution System
3. **[…] over self-configuring** multi-hop **topologies.**
4. **An ESS** Mesh is functionally equivalent to a wired ESS**, with respect to the STAs relationship with the BSS and ESS.**
5. **A** target configuration is up to 32 devices **participating as AP forwarders in the ESS Mesh.**
6. **The** amendment shall utilize IEEE 802.11i **security mechanisms, or an extension thereof**
7. **[…] in which all of the APs are** controlled by a single logical administrative entity **for security.**
8. **The amendment shall allow the use of** one or more IEEE 802.11 radios **on each AP in the ESS Mesh.**

802.11s MAC design requirements

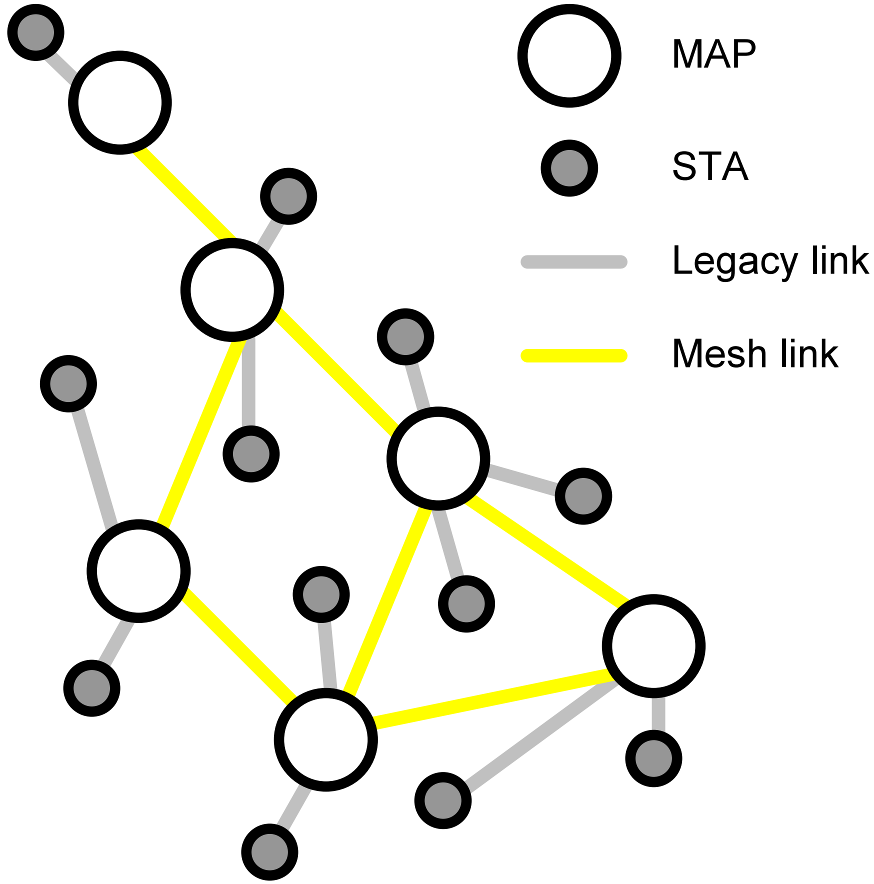
- **Seamless integration of**
  - Legacy 802.11 stations (STAs) *AND*
  - 802.11s Mesh Points (MPs)
- **Fully downwards compatible**
  - No changes to existing STAs needed
  - Need to mitigate interference from legacy to Mesh WLAN

- **Support for 1 or more radios**
- **Capability to operate Mesh *AND* legacy STAs on single channel**
- **Extension for multi-channel operation**

1. **Solve single channel case**
2. **Extend for multi-channel case**

The need for interference awareness

- **Mesh Points (MPs), Mesh APs (MAPs) and stations co-located**
- **Shared radios possible**
  - Mesh traffic
  - Basic Service Set traffic
- **Mutual interference**
- **Disproportionateness of reception and interference range, see 11-04/1075r0**



Single channel Mesh WLAN

- **Mesh & STAs share wireless medium**
- **802.11 legacy STAs very aggressive**
  - Problem for TGe
    - EDCA prioritization over DCF impossible

→ **Highly efficient solution for coexistence needed**

- **802.11 Contention Free Period (CFP)**
  - No access by STAs
  - STAs respect all CFPs, incl. neighboring [9.3.2.2, 802.11, 1999]

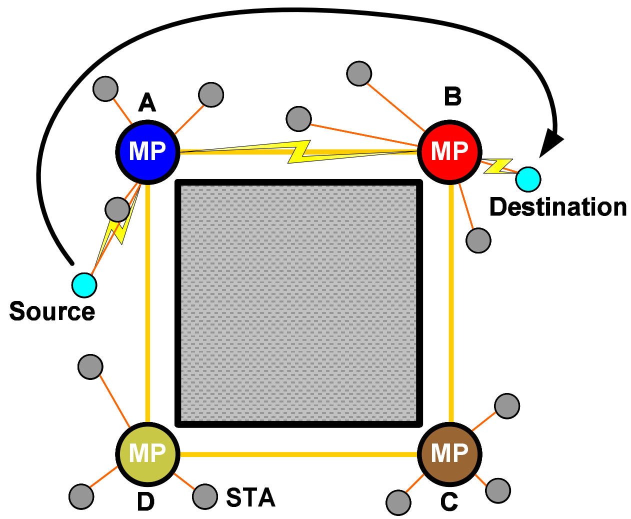
→ **CFP as exclusive resource for Mesh**
  - Divided into equal Transmission Opportunities (TXOPs: 802.11e concept)

Seamless Mesh & legacy WLAN integration

- **Contention Period**
  - Up-/Downstream
  - Random 802.11 CSMA/CA access
    - HCCA, EDCA, DCF
  - Fully legacy compatible
- **Contention Free Period**
  - Scheduled access
  - Highly efficient
  - Optimal spatial frequency reuse

Example

1. **BSS, STA → AP**
2. **Mesh, MP → MP**
3. **BSS, AP → STA**

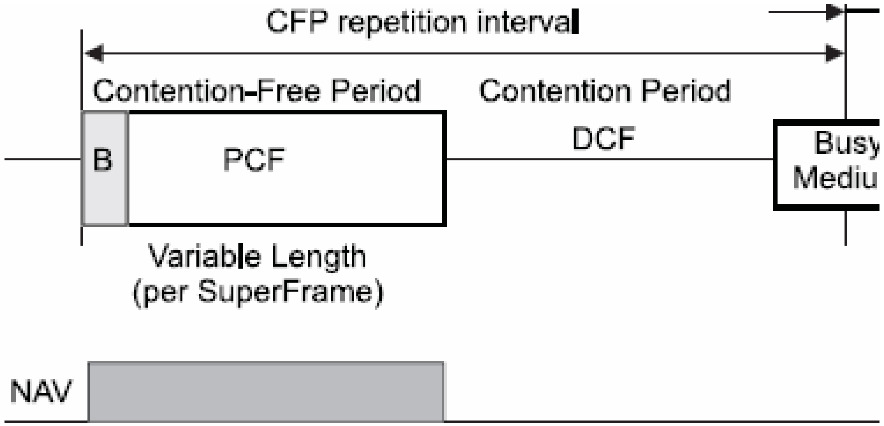


802.11 Contention Free Period (CFP)

- **APs *MUST* transmit beacon frames [11.1.1.1, 11.1.2.1, 802.11, 1999]**

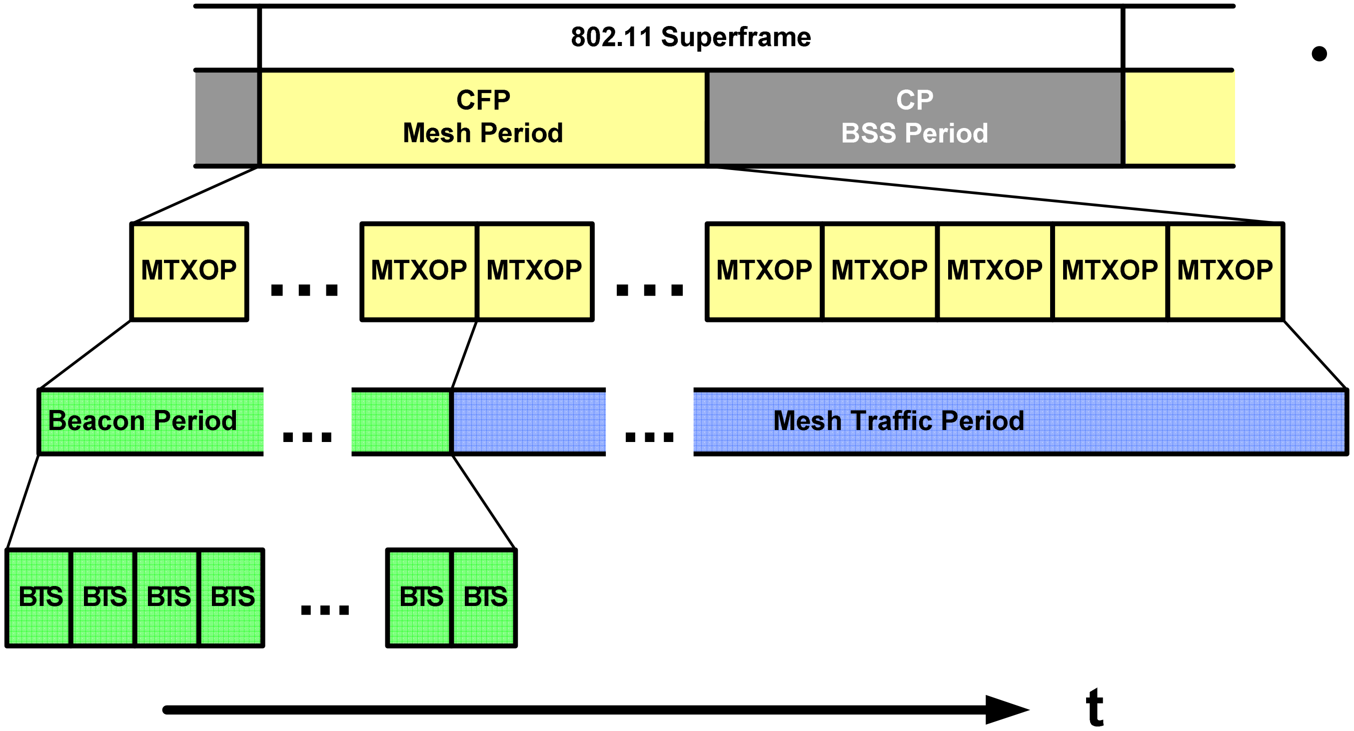
  → Mesh APs *MUST* transmit beacon frames
- **Use beacon frames to announce CFP**

  "All stations inherently obey the medium access rules […] and they set their NAV at the beginning of each CFP." [9.3, 802.11, 1999]
  - Silence 802.11 legacy STAs → Enable exclusive resource for Mesh WLAN
  - Extend beacon frames to coordinate Mesh WLAN



- **Coordinate beacon transmissions**
  - Beacon Period (BP)
- **Coordinate Mesh data exchange**
  - Mesh Traffic Period (MTP)

Structured Contention Free Period (CFP)



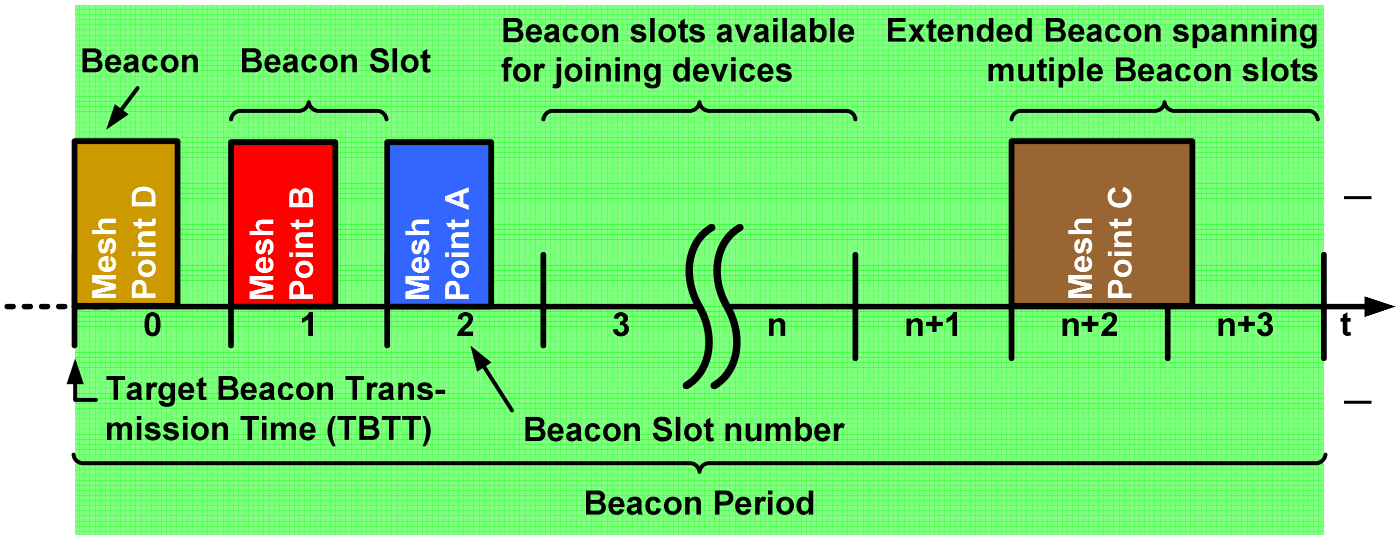
- **CFP reserved for Mesh**
  - Divided into Mesh Transmission Opportunities (MTXOPs)

- **Beacon Period (BP) for coordination**
  - MTXOPs divided into Beacon Transmission Slots (BTSs)
- **Mesh Traffic Period (MTP) for data exchange**

Beacon Period (BP)

Beacon Period – Mesh Coordination

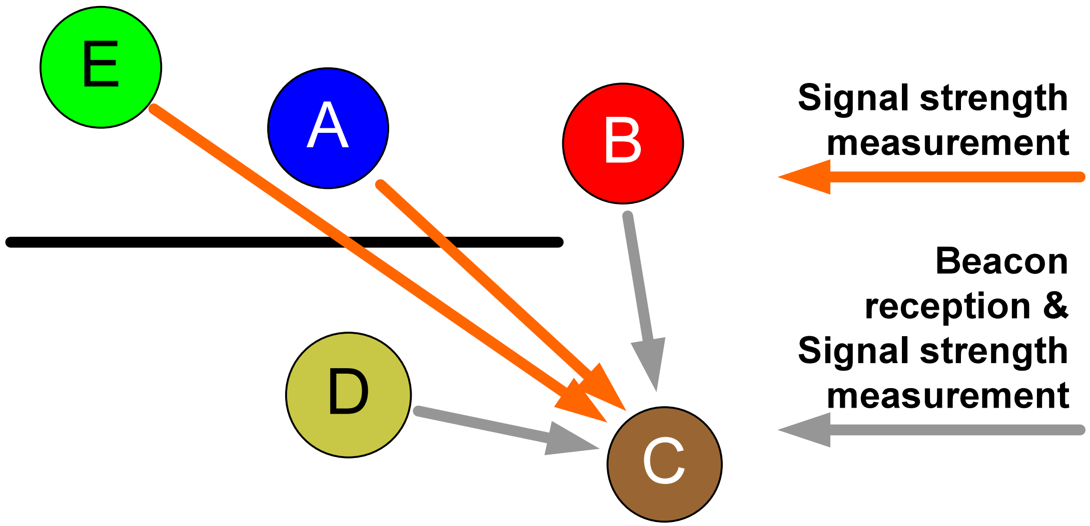
- **MPs subsequently send beacons**
  - Beacon Period Access Protocol (BPAP)
    - Beacon Transmission Slots
    - Resolves beacon collisions
    - Enable MPs to join Mesh



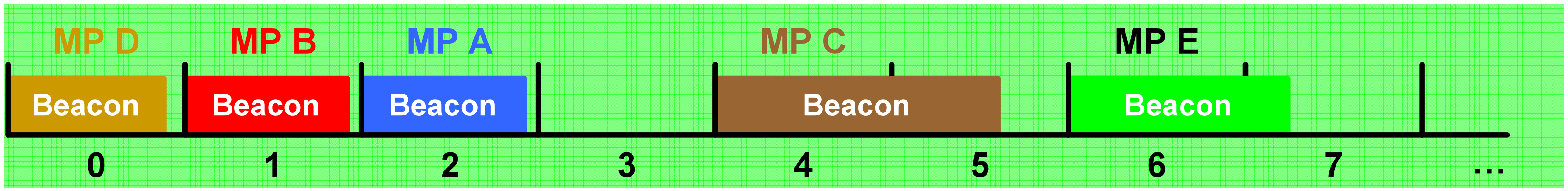
- **Coordinate Mesh Traffic Period (MTP)**
- **Beacon**
  - Carries neighborhood information
  - Signal strength measurement
  - Synchronization

Measurements during Beacon Period

- **Example: MP C**
  - Receives beacon from B & D
  - A & E out of reception range
    - Attenuation from wall

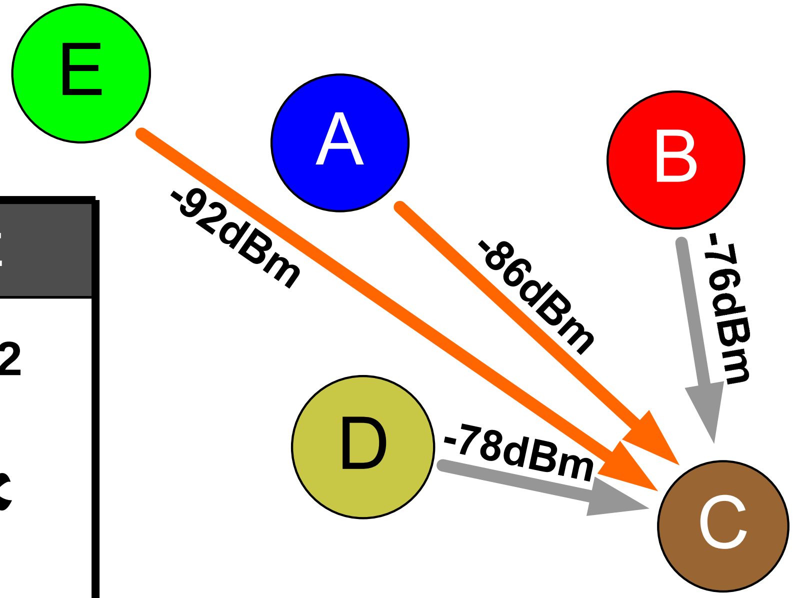


- **Receive beacon information if possible**
- **Measure signal strength for all Beacon Transmission Slots**



Neighborhood as seen by MP C

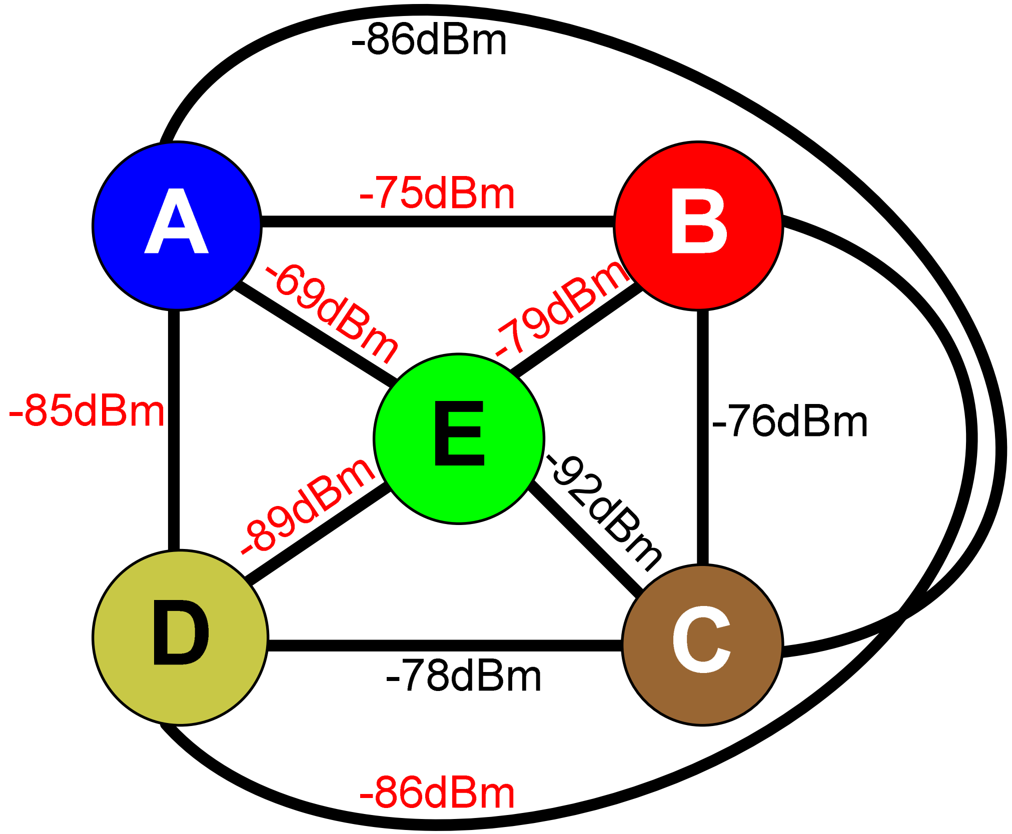
Device	A	B	D	E
RSSI (dBm)	-86	-76	-78	-92
Beacon received	✘	✓	✓	✘
MPs announced in beacon	✘	A, C, D, E	B, C	✘
MPs announcing this MP	B, C, E	A, C, D	B, C, D	A, B, C



- **Direct and indirect neighborhood**

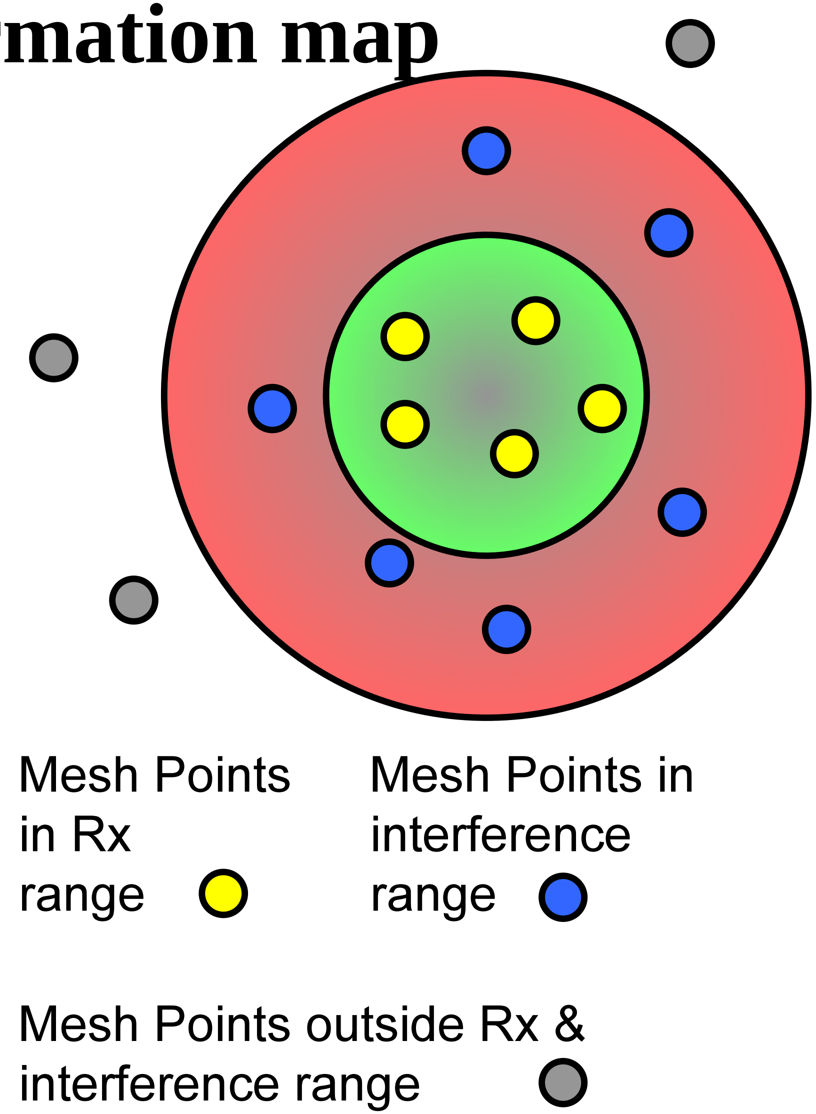
Received Signal Strength Graph

- **Received signal strengths as seen by MP E**
- **Direct edges: Measurement**
- **Other edges: Neighbor's neighbor RSSI**



Neighborhood information map

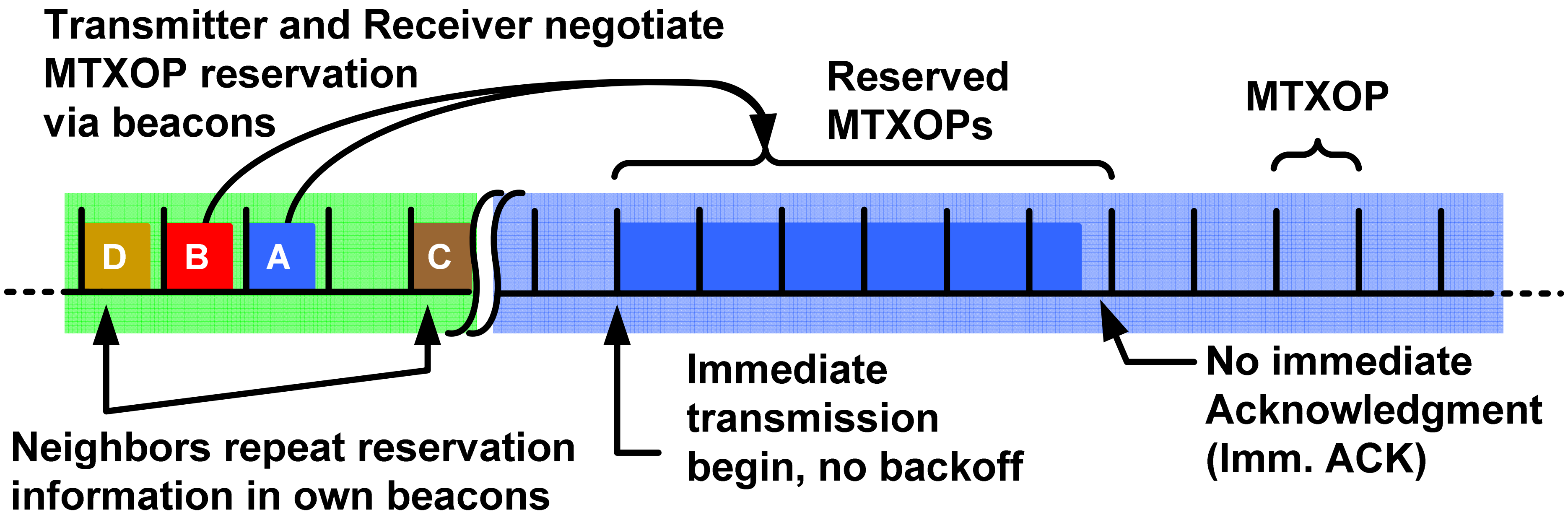
- **Beacons send at most robust PHY mode**
  - Reception close to interference range
- **Mesh Points (MPs) store neighborhood information**
- **→ Neighborhood table**



Data Transmission
Mesh Traffic Period (MTP)

MTP – Data exchange

- **Distributed Reservation Controlled Access (DRCA)**
  - Mesh Points reserve MTXOPs via Beacon
  - Beacons inform neighbors about own transmission
  - Neighbors repeat MTXOP reservations
  - Collision free access

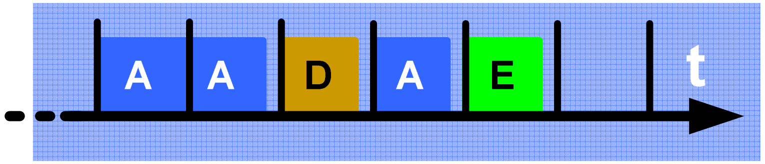


MTP – Interference awareness

- **No immediate Acknowledgment**
  - Prevent transceiver turnaround
  - No interchange of transmitter & receiver role
    - Predictable interference
    - Reliable channel use
- **Spatial frequency reuse**
  - Transmitter & receiver negotiate MTXOP usage
  - Concurrent (simultaneous) transmission enabled

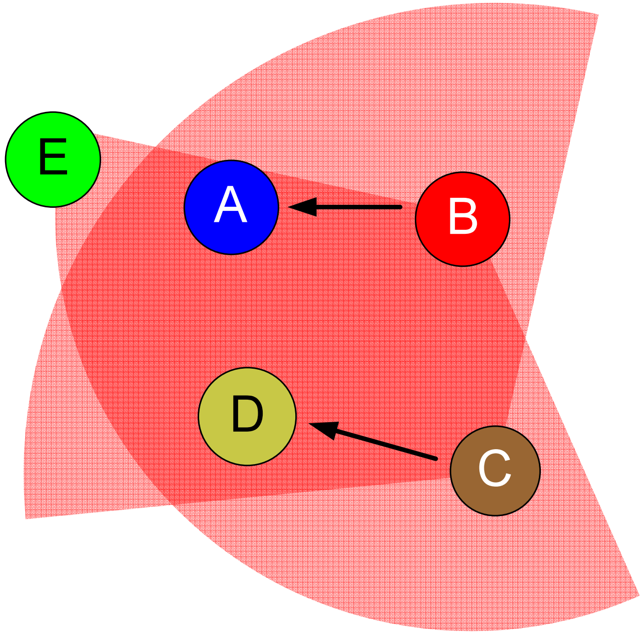
- **MTXOP occupation list**
  - Stored in every Mesh Point
  - Local view of channel availability
  - Prevent collisions
  - Enable prioritization

MTXOP	0	1	2	3	4	…
Receiver	B	B	C	C	A	…
Transmitter	A	A	D	A	E	…

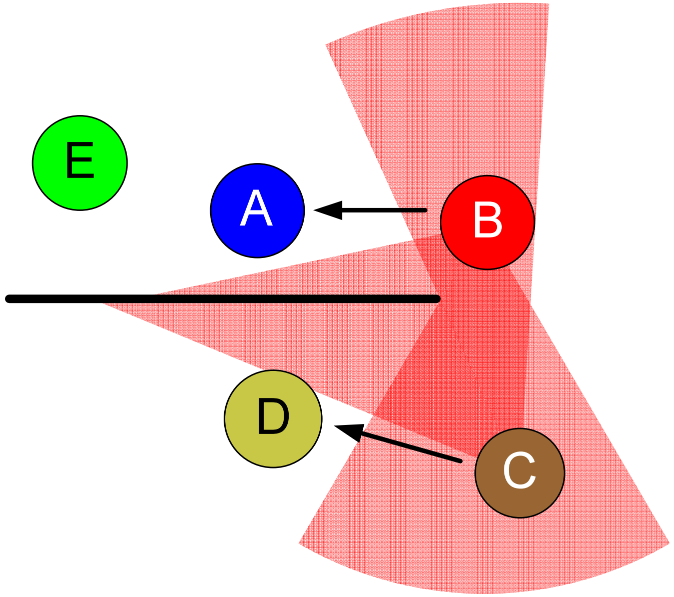


Environmental impact on interference

- Mutual interference
- Subsequent, sequential transmissions



- Wall attenuates signals
- Concurrent, simultaneous transmissions enabled

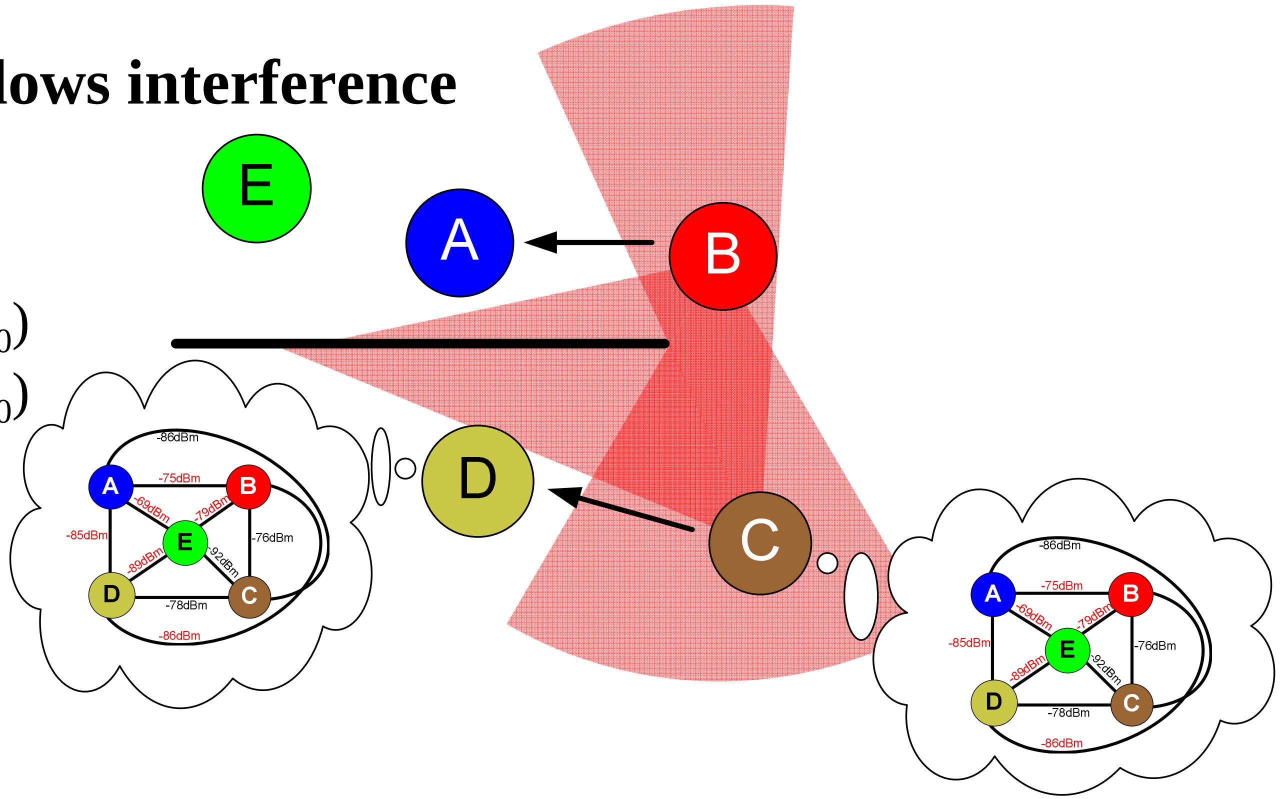


- **Interference aware Mesh Points**
  - Predict, detect and use opportunities for concurrent transmissions

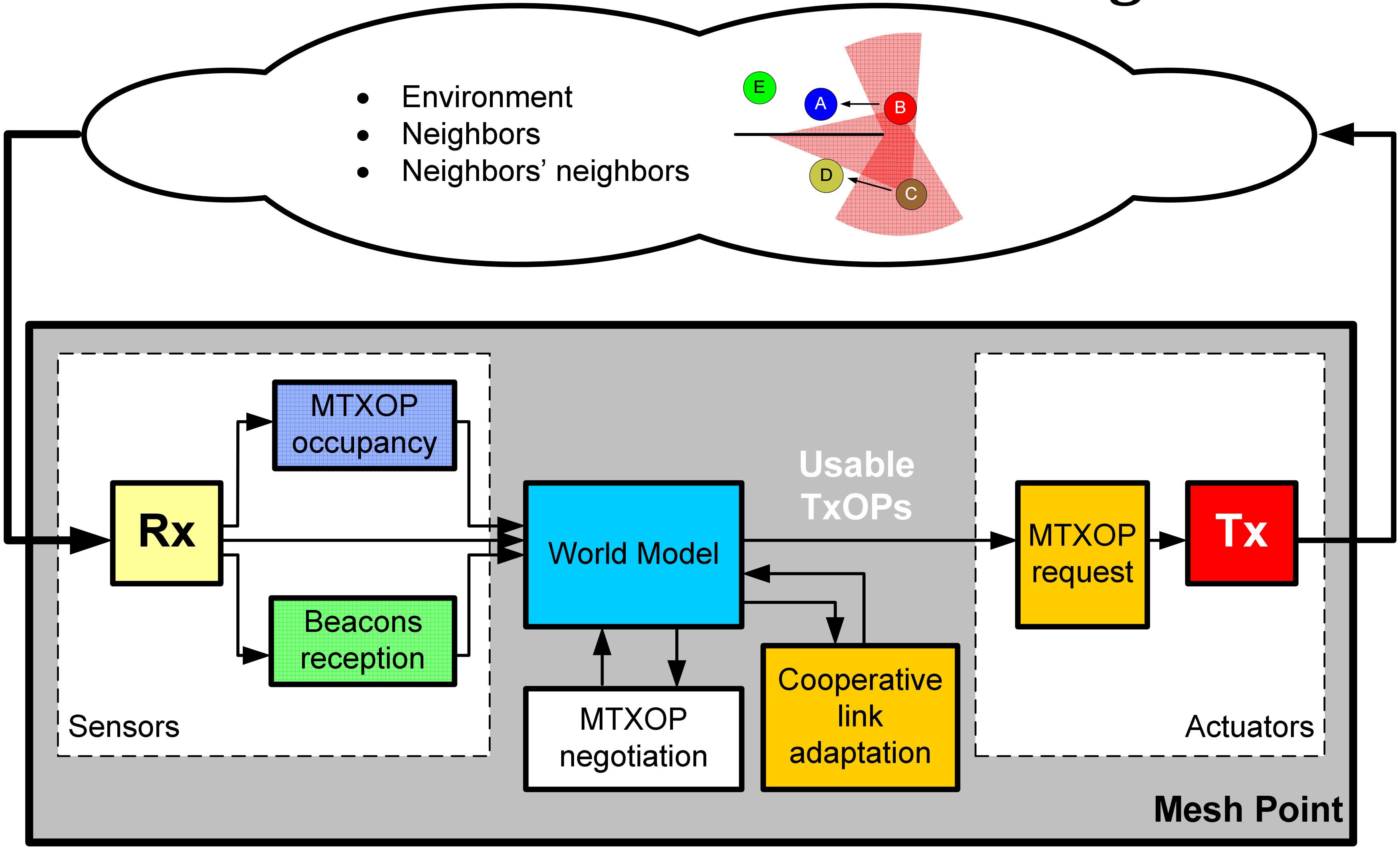
Channel quality prediction

- **Devices learn via beacon frames about other data transmissions**
- **RSSI graph allows interference prediction**
- **Example:**
  - Tx (B→A, t_1-t_0)
  - Tx (C→D, t_1-t_0)

→ Prediction needed

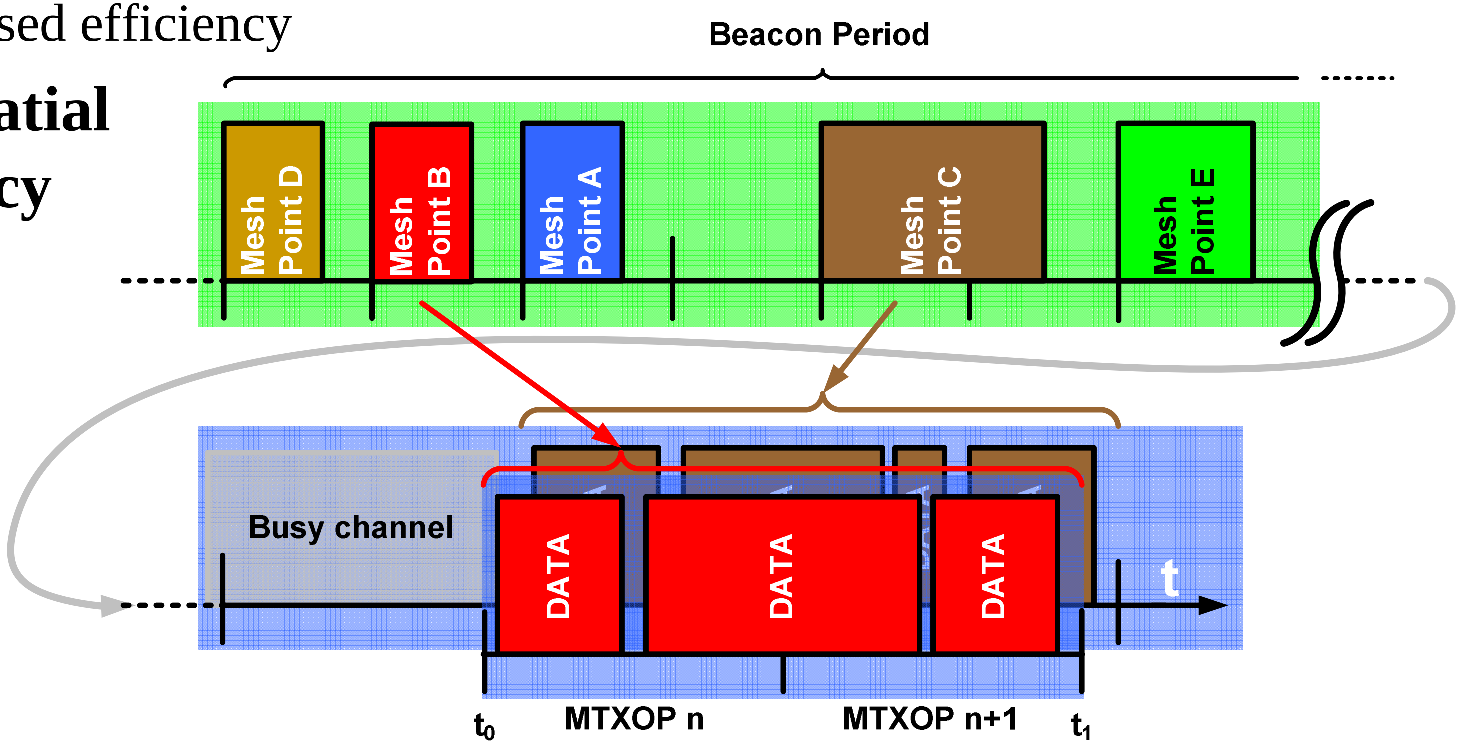


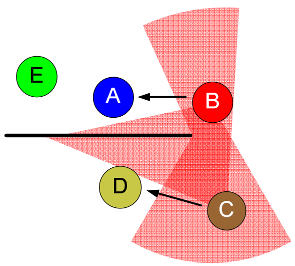
Interference aware scheduling



Concurrent transmissions

- **Simultaneous channel usage**
  - Increased efficiency
- **High spatial frequency reuse**
- **Interference prediction**
  - Via world model

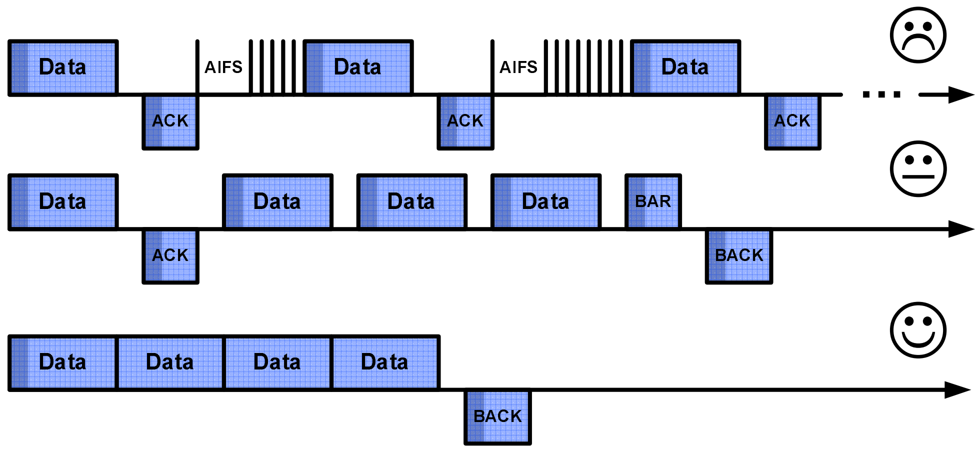




MTP – Block ACK, Frame Aggregation

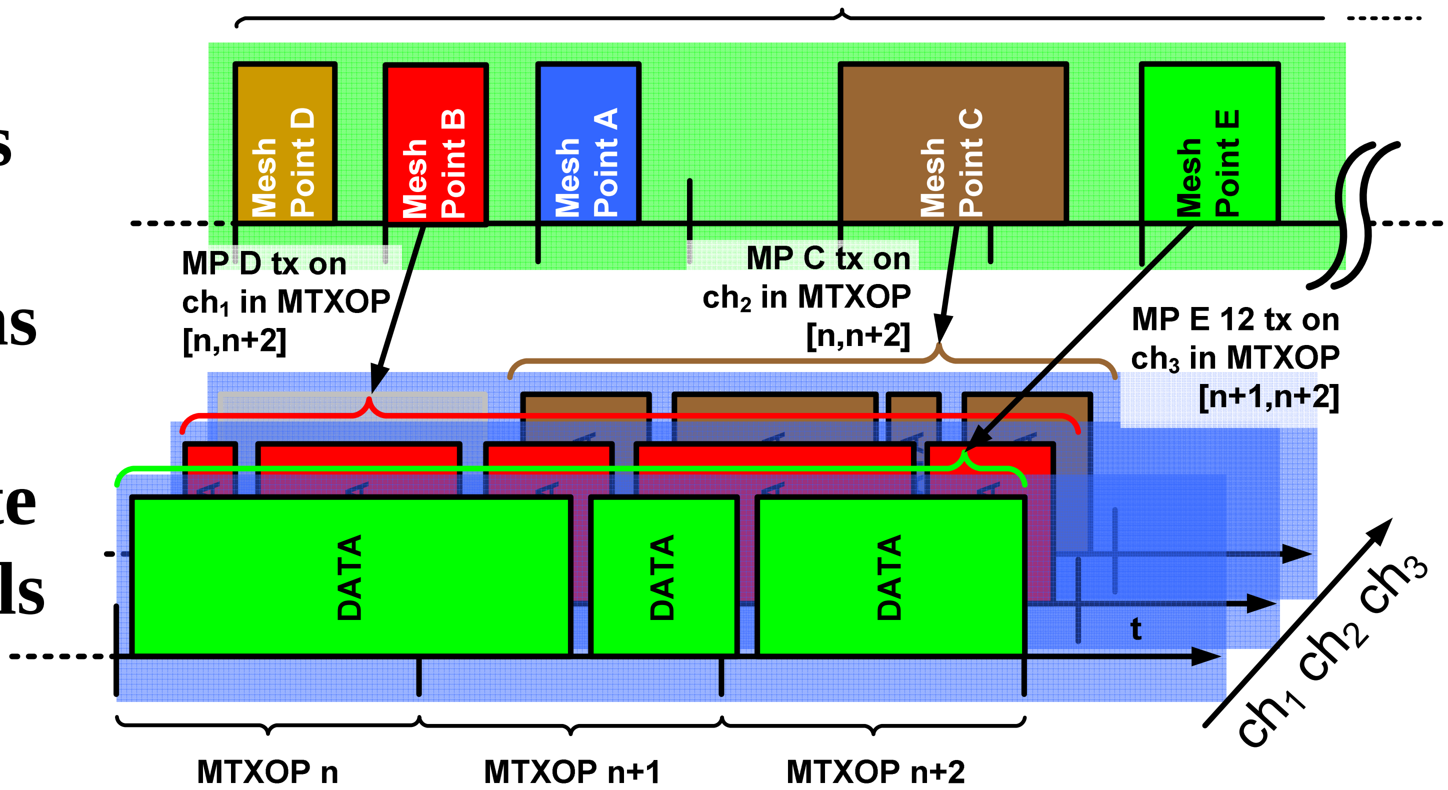
- **Block ACK**
  - 802.11e
  - TCP window oriented
  - Delayed ACK
- **Implicit ACK**
  - Piggybacked to DATA
- **Explicit ACK**
  - Separate MTXOP

- **Frame Aggregation**
  - Reuse TGn solution
  - Optional enhanced variant
  - Safe multiple frame headers
  - Important for efficiency



Multi channel data transmission

- Beacon carries channel information
- Simul-taneous trans-missions on separate channels



Additional MAC details

- Congestion control
- Cooperative link adaptation
- Dynamic channel selection
- Channel measurement reports
- BSS channel separation

→Scalable solution

→Adapts to available hardware functionality

→Flexible and extensible

Mesh Networks Alliance

Mesh WLAN Security

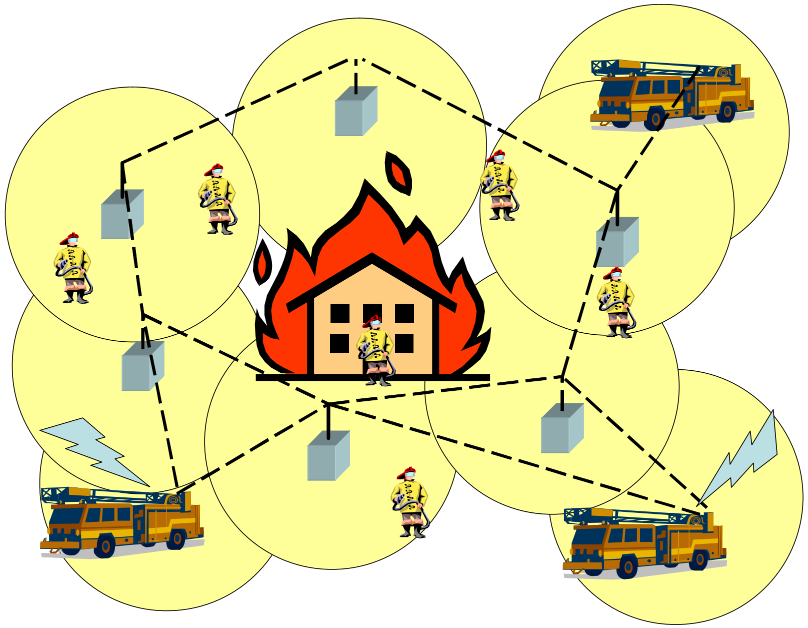
Abstract

This presentation describes the Deterministic Pairwise Key Pre-Distribution Scheme (DPKPS) for 802.11s.

The DPKPS enables *any* pair of mesh points to establish a pairwise key to protect their communication independently of the network topology and membership. Node authentication, revocation as well as identity-based access control are also enabled.

The DPKPS provides a power conserving, reliable and timely security solution. Mesh points can *directly* protect communications. These properties make the DPKPS to cover a wide span of WLAN usage scenarios and to perfectly cover WLAN mesh ad-hoc-like deployments.

IEEE 802.11s Mesh WLAN



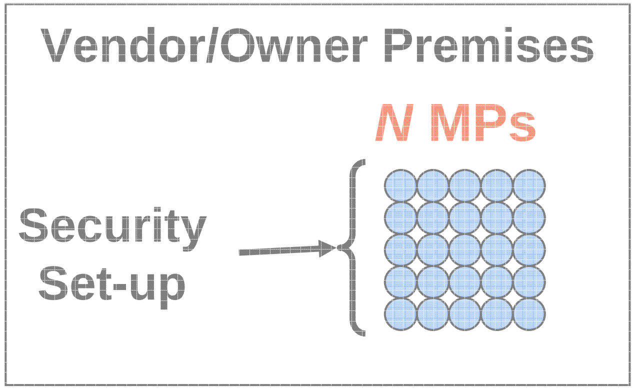
- **Low-cost, easily deployable, high performance network**
- **Low susceptibility to vandalism**
- **Mobile mesh points (MP) and mesh APs**
  - Flexible mesh point roles
  - Dynamic network topology
- **Network self-configuration and self-management**
- **Power conservation**

DPKPS enables secure Mesh WLANs

- **Any-to-any *direct* pairwise (unique symmetric) key establishment**
- **Supports node authentication and revocation, and communication confidentiality and integrity**
- **Supports secure multicast group formation**
- **Supports security in big-scale resource-constrained MeshWLANs (e.g. sensor networks)**
  - Scalability
  - Computational, communication and storage efficiency
  - Robustness and resiliency against MP captures

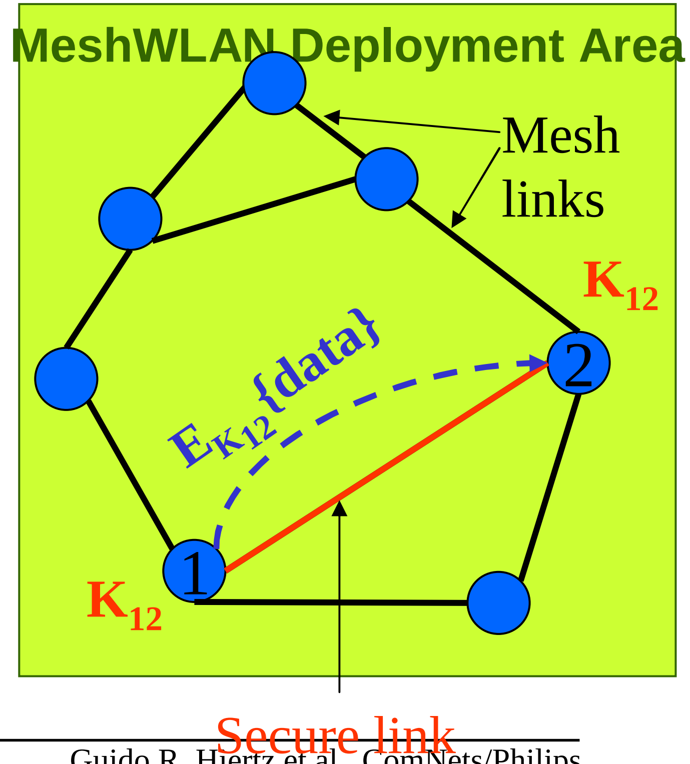
DPKPS Use Model

1. **Security Set-up Phase**
   – Keying material is stored in each MP using a ***combinatorial distribution*** method



2. Secure (Dynamic) Network Formation
   – ***Any pair*** of MPs (which establish a mesh link) can derive a pairwise key from the pre-distributed keying material (e.g. MPs 1 and 2 on picture)

3. Communication/Data Exchange Phase
   – MPs use pairwise keys for data encryption/integrity and/or node authentication.



Overview of Security Set-Up in DPKPS

- **Background**
  - Polynomial-based Key Distribution
  - Finite Projective Plane (FPP)
- **DPKPS Polynomial Pre-Distribution**
- **Motivation for Combinatorial Polynomial Pre-Distribution**
- **Implementation in Low-resource MPs**

Polynomial-based Key Distribution (after Blundo et al.)

- Share length: λ times the size of a key log*q* bits
- Number of shares *q* (>> λ)
- λ-resilient, i.e. λ +1 shares needed to recover original polynomial

– λ-degree polynomial over F*q*

$$f(x, y) = f(y, x)$$

– Each MP ***i*** gets a polynomial share

***MP* 1**	***MP* 2**	**…..**	***MP q*-1**
$f(1, y)$	$f(2, y)$		$f(q-1, y)$

– Generation of ***pairwise key*** K_{ij} for MPs ***i***, ***j***

$$K_{ij} = f(i, j) = f(j, i)$$

Finite Projective Plane (FPP)

– Set S of n^2+n+1 elements: 1, 2, … n^2+n+1 (n prime power)

Example n=2: S = {1, 2, 3, 4, 5, 6, 7}

– Arrangement of S in n^2+n+1 blocks of $n+1$ elements :

Example n=2:

$$\begin{Bmatrix}1\\2\\4\end{Bmatrix}\begin{Bmatrix}2\\3\\5\end{Bmatrix}\begin{Bmatrix}3\\4\\6\end{Bmatrix}\begin{Bmatrix}4\\5\\7\end{Bmatrix}\begin{Bmatrix}1\\5\\6\end{Bmatrix}\begin{Bmatrix}2\\6\\7\end{Bmatrix}\begin{Bmatrix}1\\3\\7\end{Bmatrix}$$

– Any pair of blocks has **1** *common* element

DPKPS Polynomial Pre-Distribution

– n^2+n+1 λ'-degree polynomials over F*q* (*n* prime power)

Example n=2: $\mathbf{F_1(x,y), F_2(x,y),\ldots F_7(x,y)}$

– Each MP ***i*** gets ***n*+1** polynomial shares mapped to FPP blocks

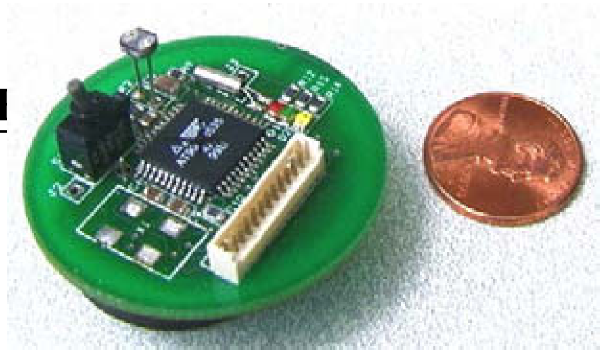
$$\begin{array}{ccccccc}
MP\ 1 & MP\ 2 & \cdots & MP\ (q-1)/(n+1) & MP\ 1+(q-1)/(n+1) & \cdots & MP\ \sim nq \\
\left\{\begin{matrix} F_1(1,y) \\ F_2(1,y) \\ F_4(1,y) \end{matrix}\right\} &
\left\{\begin{matrix} F_1(2,y) \\ F_2(2,y) \\ F_4(2,y) \end{matrix}\right\} & \cdots &
\left\{\begin{matrix} F_1\,(q-1)/(n+1),y) \\ F_2((q-1)/(n+1),y) \\ F_4((q-1)/(n+1),y) \end{matrix}\right\} &
\left\{\begin{matrix} F_2(1+(q-1)/(n+1),y) \\ F_3(1,y) \\ F_5(1,y) \end{matrix}\right\} & \cdots &
\left\{\begin{matrix} F_1(q-1,y) \\ F_3(q-1,y) \\ F_7(q-1,y) \end{matrix}\right\}
\end{array}$$

Shares distributed using block 1

……………………

Why *Combinatorial* Pre-Distribution of Polynomials?

- **Increased computational efficiency ($\lambda' < \lambda$) without decreasing resiliency**
- **Increased scalability $N \approx nq$**
- **Increased resiliency against oblivious attacker (who captures nodes randomly)**



Implementation in Motes (after Liu et al.)

- 4Mhz, 8-bit CPU
- 128KB Flash, 4KB EEPROM and 4KB RAM
- 40Kbits/second
- Running on batteries

– t λ'-degree polynomial over **F*q*'**

$$f_1(x,y), f_2(x,y), \ldots f_t(x,y)$$

$$t = \log q / \log q'$$

– λ'-degree t-polynomial-set over **F*q*'**

$$F(x,y) = f_1(x,y) \| f_2(x,y) \| \ldots \| f_t(x,y)$$

– $F(x,y)$ generates keys of log*q* bits

– Computationally efficient operations modulo *q*' (*q*' << *q*)

Mesh Networks Alliance
Simulation results on MAC performance

802.11s requirements on simulations

- **“Call for proposals” (11-04/1430r122) → Mandatory documents: “Comparison Categories and Informative Checklists” (11-04/1175r10)**
- **11-04/1175r10: “AD2 – Simulation and/or experimental methodology: Any proposal submission that includes simulation results must include a description of the simulation methodology used for mesh simulations. The simulation methodology documentation should provide enough information to, in principle, reproduce the simulation (e.g., including node positions, traffic and propagation model (including PHY assumptions), packet sizes, etc.).”**

802.11 simulation challenges

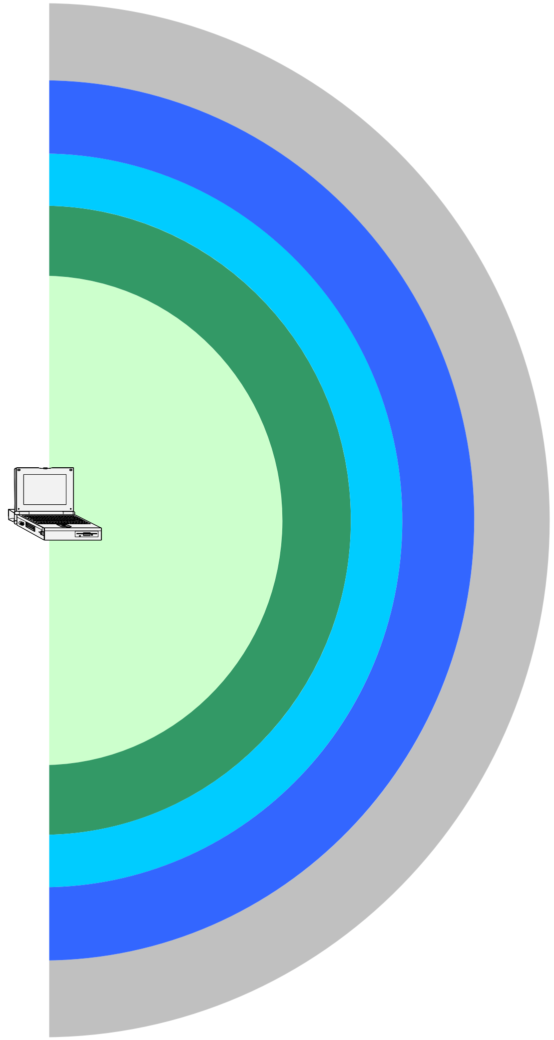
- **Performance (throughput, delay etc.) depends on**
  - Amount of stations
  - Offered traffic per station
  - Medium Access parameters (CWmin, DIFS, AIFS)
  - Clear Channel Assessment
    - Neighboring interference
    - Preamble detection
    - Sensitivity level
  - Received power
    - Transmitted power
    - Antenna configuration
    - Distance between transmitter and receiver
    - Obstacles, attenuation
    - Propagation path
  - Packet Error Rate
    - PHY mode
    - Received Power
    - Carrier To Interference ratio
    - Receiver noise

Channel model considerations

1. DATA reception
2. RTS,CTS, ACK … @BPSK ½
3. CCA (1), busy tone detection
4. CCA (2), OFDM preamble detection
5. Interference

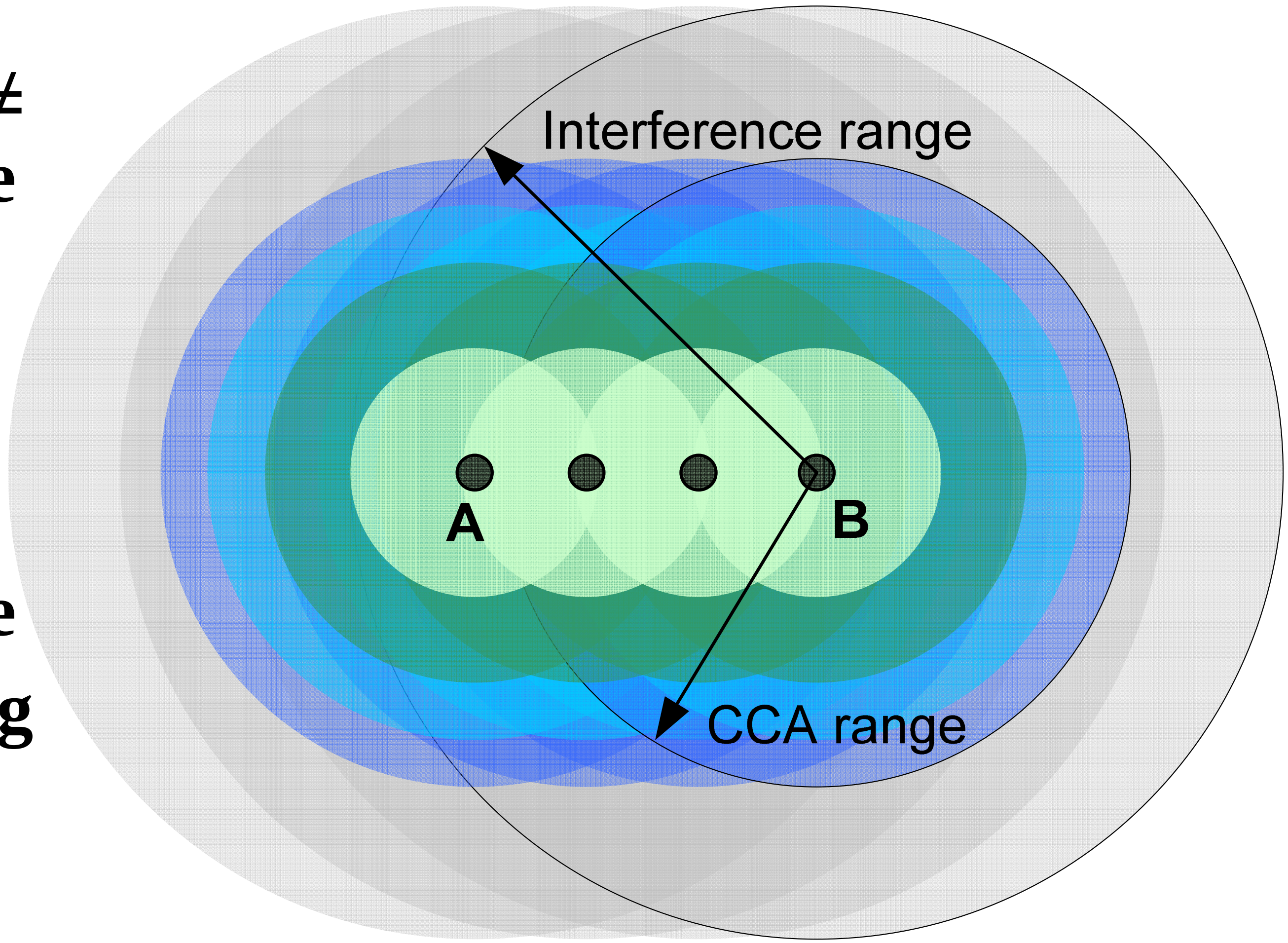
Ranges

- Reception
- RTS/CTS
- CCA (1)
- CCA (2)
- Interference



Need for detailed channel model for Mesh WLAN

- Rx ≠ CCA ≠ interference range
- Multiple neighbors
- Mutual interference
- Overlapping BSSs



Simulation Environment – Channel model

- **Path loss model**

$$P_{Rx} = \frac{P_{Tx}}{d^{\gamma}} \cdot \left(\frac{c}{f_c \cdot 4\pi} \right)$$

  - P_{Tx}: transmission power
  - d: distance between transmitter and receiver
  - γ: damping factor, depending on scenario, incorporating antenna gains, reflection, scattering
    - γ = 2: Free space attenuation
    - γ > 2: More realistic path loss, LOS/NLOS, indoor/outdoor environments
    - **Here: γ = 3.5**
  - f_c: center frequency
    - **Here: f_c = 5GHz**

Simulation Environment – Channel model

- **Additional obstacles (e.g. walls, doors)**
  - Attenuation is subtracted from P_{Rx} (in dB)
- **Carrier over Interference ratio (CoI)**
  - Carrier (C) = $P_{Rx,\ wanted}$
  - Interference (I) = $P_{Rx,\ unwanted,\ i}$
    - i interferer, $i \geq 0$
  - Noise (N)
    - Thermal environment noise, **Here: N = -95 dBm**

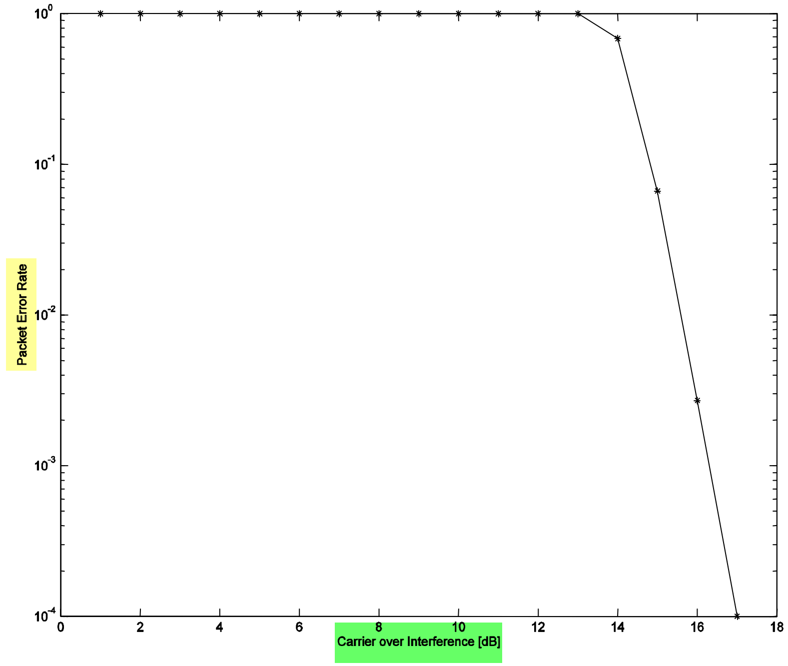
$$CoI = \frac{P_{Rx,wanted}}{N + \sum_i P_{Rx,unwanted}}$$

Simulation Environment – PHY layer model

- **Modeling packet error probability**

$$p(error) = f(P_{Rx,wanted}, CoI, Packetlength, PHY - Mode)$$

- Minimal $P_{Rx,\ wanted}$
  - Sensitivity (see .11a standard)
  - Depending on PHY-Mode
- Link level mapping (Packet Error Rate vs. CoI)
  - Tables derived from real hardware measurements
  - Parameterized by
    - PHY-Mode
    - Packet length
  - Complementary PER, see example figure



Simulation Environment – PHY layer

- **Clear Channel Assessment**
  - IEEE 802.11a
  - 5GHz, OFDM PHY
  - Busy detection for
    - Any Rx signal > -62 dBm
    - Valid OFDM preamble, Rx level > -82 dBm

Simulation scenario set-up

- **Single radio, single frequency channel Mesh WLAN**
  - 20dBm transmission power
- **Offered traffic: Constant Bit Rate (CBR)**
- **802.11a, OFDM PHY, QPSK½ (12Mb/s)**
- **MNA parameters**
  - MTXOP duration 256 µs
- **EDCA parameters**
  - TxOP 2048 µs
  - Backoff settings, see 802.11e, Draft 13

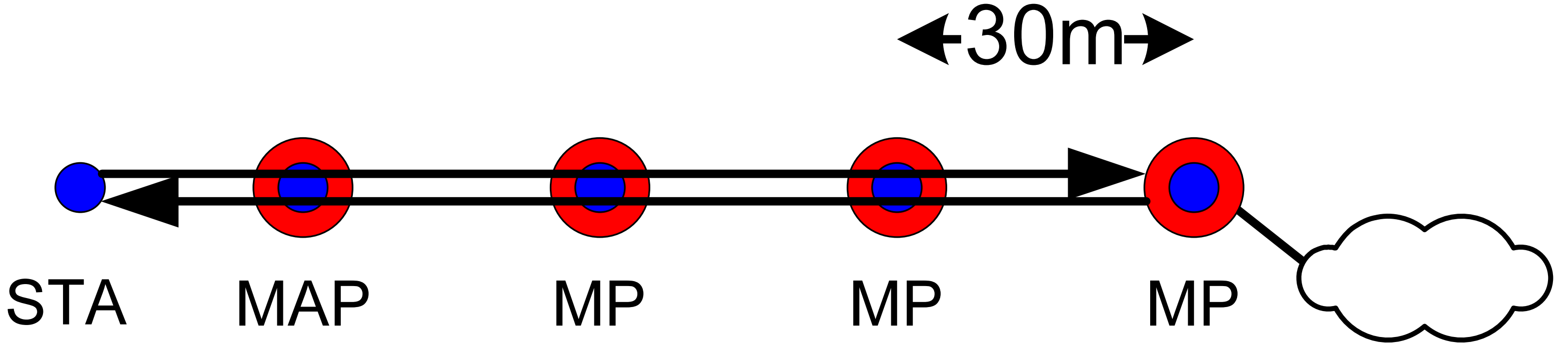
Priority	CWmin	CWmax	AIFS/µs
0 (Best Effort)	15	1023	43
7 (Voice)	3	7	34

Performance evaluation

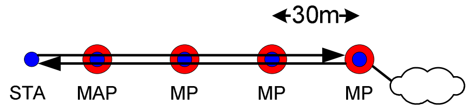
- AP ⇔ STA traffic according to DCF/EDCA
- Final and/or initial hop always uses DCF/EDCA
  - Data delivery from/to STA, BSS traffic
- Traffic in Mesh WLAN
  - DCF/EDCA vs. MNA proposal
- All performance values are end-to-end
  - E.g. MP → MP → STA
- Cumulative (system) throughput is sum of end-to-end throughput

Basic scenario 1 – Multi-hop route

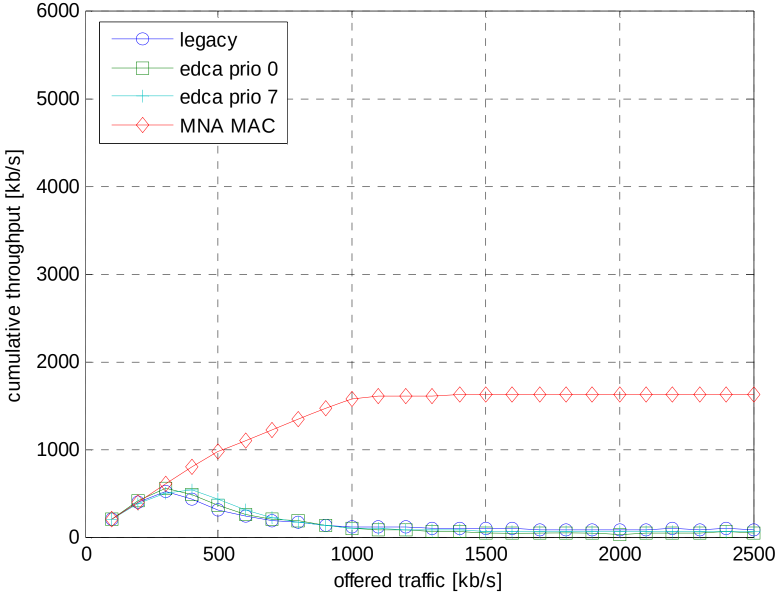
- **4 hop route**
  - Duplex data transmission
  - STA attached to MP
  - Final MP as gateway to Internet
  - ~20ms – 23ms Superframe duration



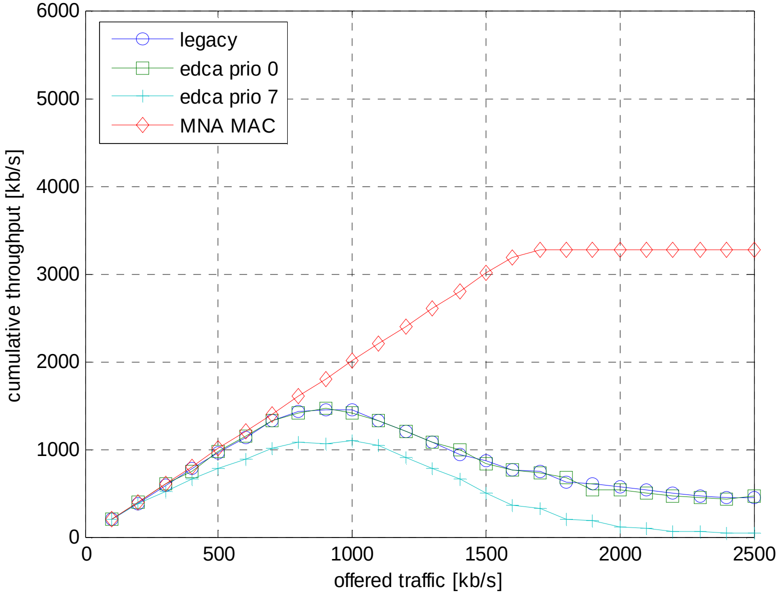
4 hop route – Simulation results



- Cumulative throughput, packet size 80 B

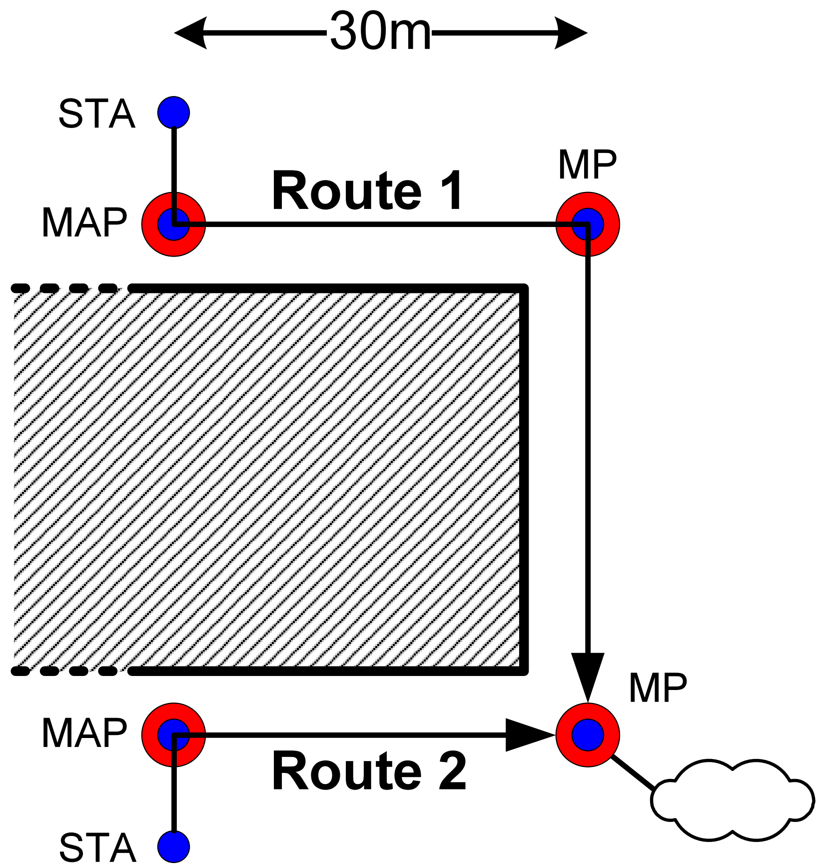


- Cumulative throughput, packet size 1500 B

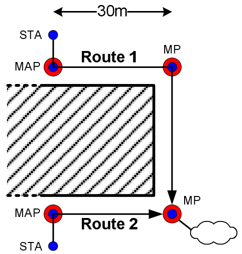


Public access scenario

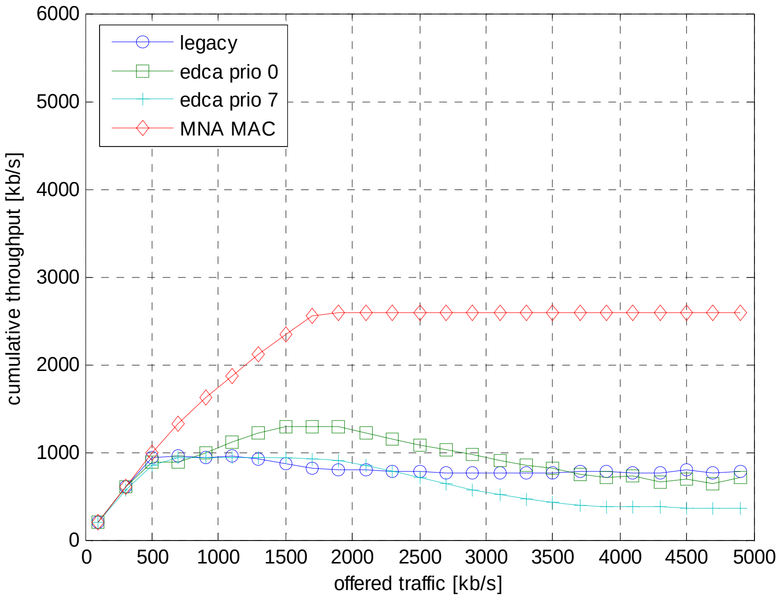
- **Building attenuates signal: 100 dB**
- **Uplink traffic sent from STAs to Internet**
  - 3 hop route
    - STA → MAP → MP → MP
  - 2 hop route
    - STA → MAP → MP
- **~13ms – 20ms Superframe duration**



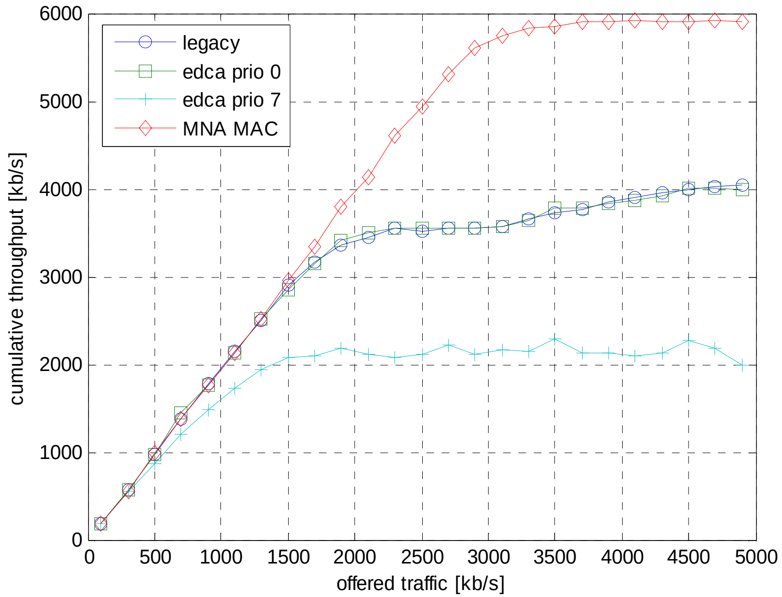
Block scenario – Simulation results



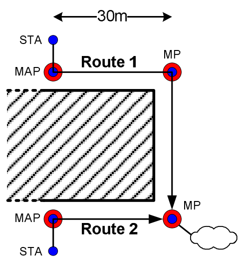
- Cumulative throughput, packet size 80 B



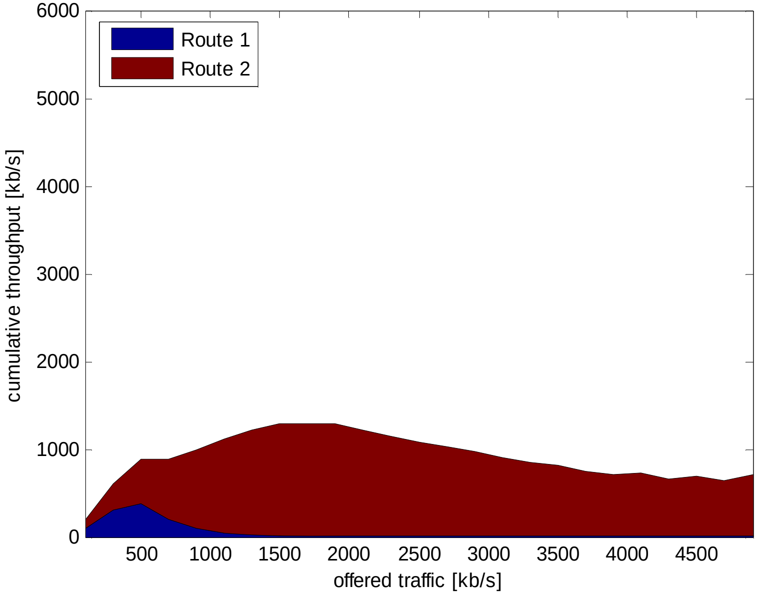
- Cumulative throughput, packet size 1500 B

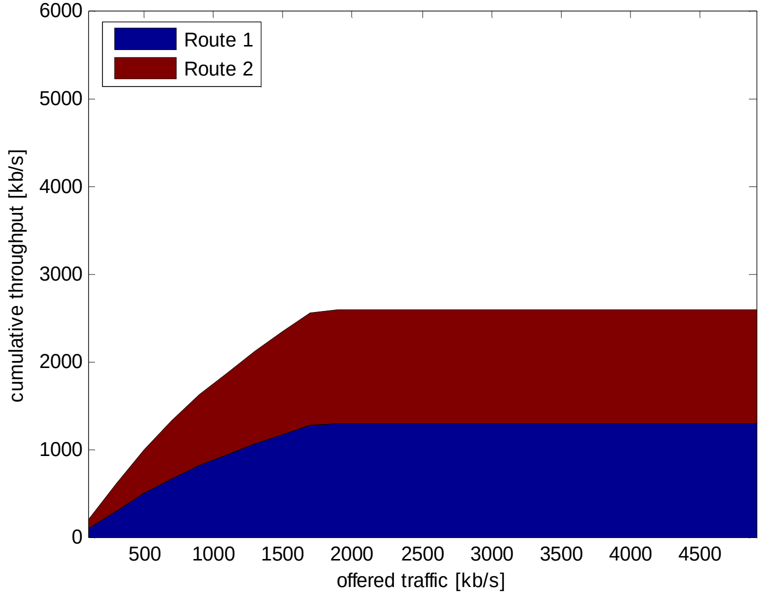


Block scenario – Simulation results

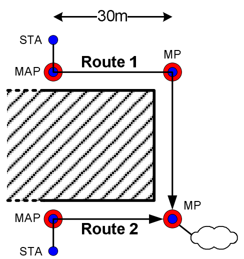


- EDCA (prio. 0), throughput per route, packet size 80 B
- MNA MAC, throughput per route, packet size 80 B

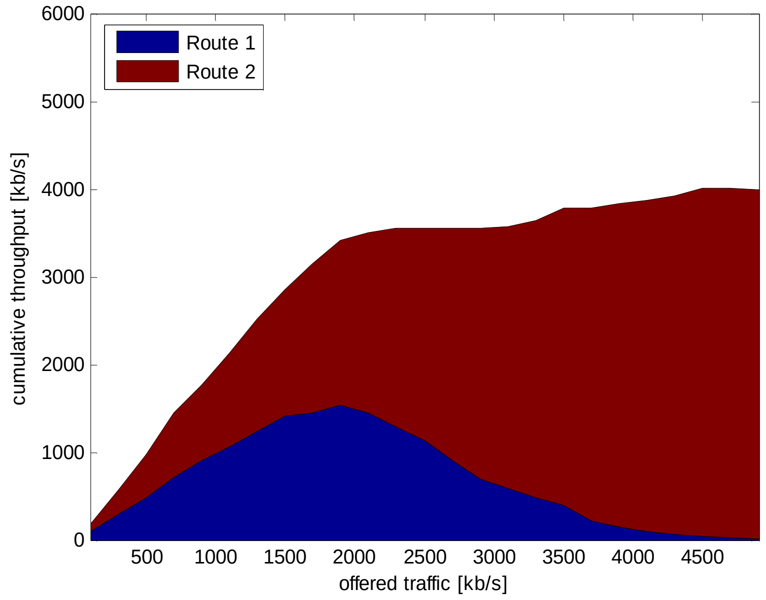


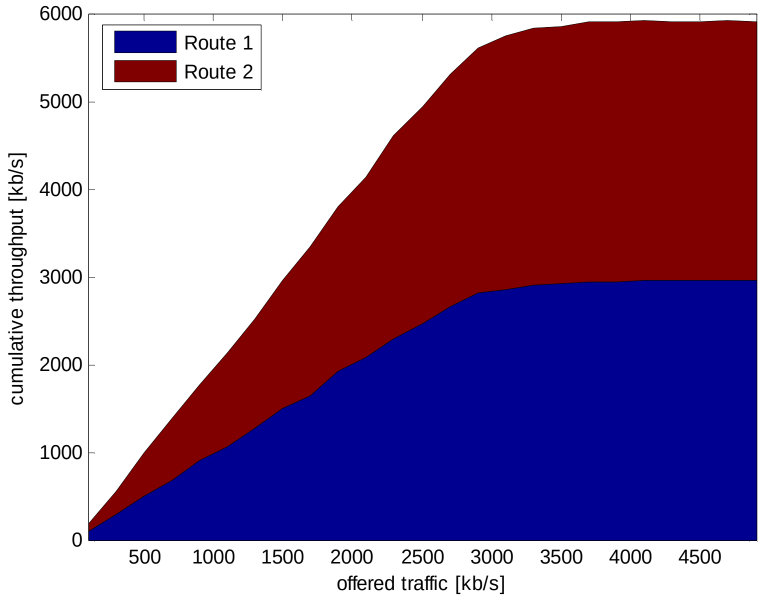


Block scenario – Simulation results



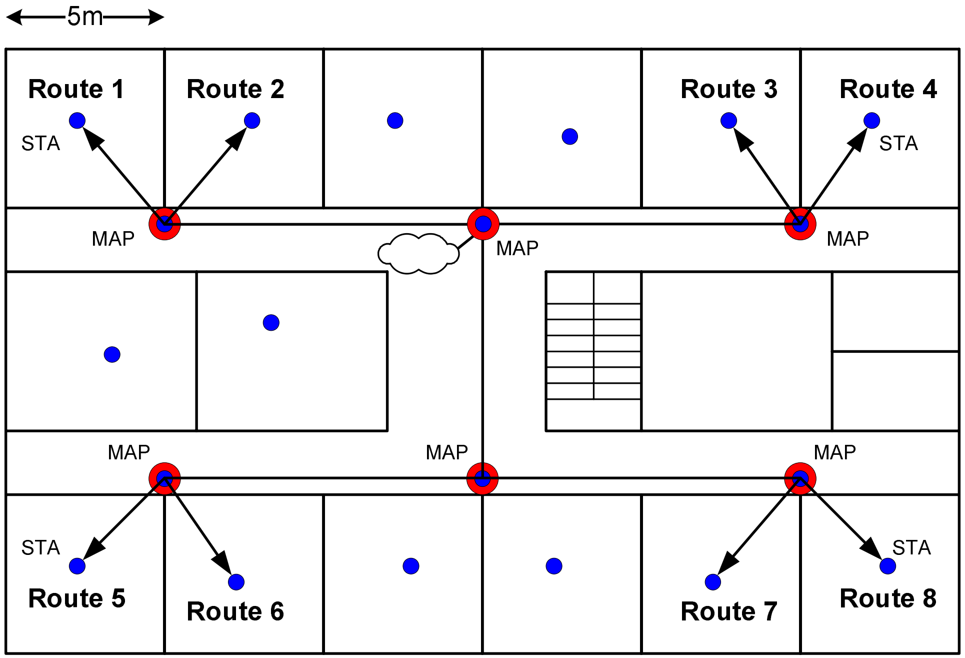
- EDCA (prio. 0), throughput per route, packet size 1500 B
- MNA MAC, throughput per route, packet size 1500 B



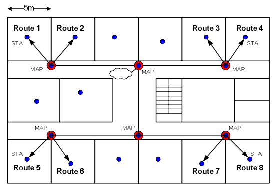


Office scenario

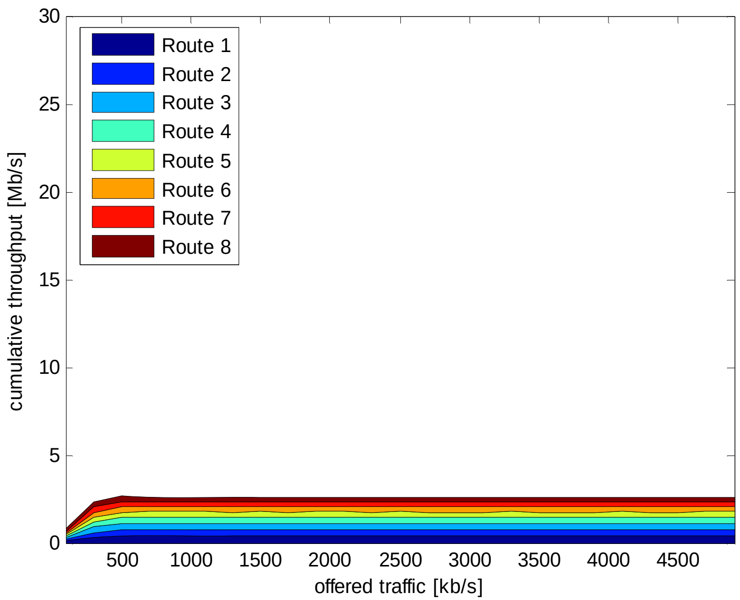
- **Offered traffic: CBR**
  - Downlink routes
- **OFDM PHY, 64QAM¾ (54Mb/s)**
- **~12ms – 19ms Superframe duration**
- **EDCA parameters**
  - See page 48
- **Attenuation**
  - Walls: 13 dB

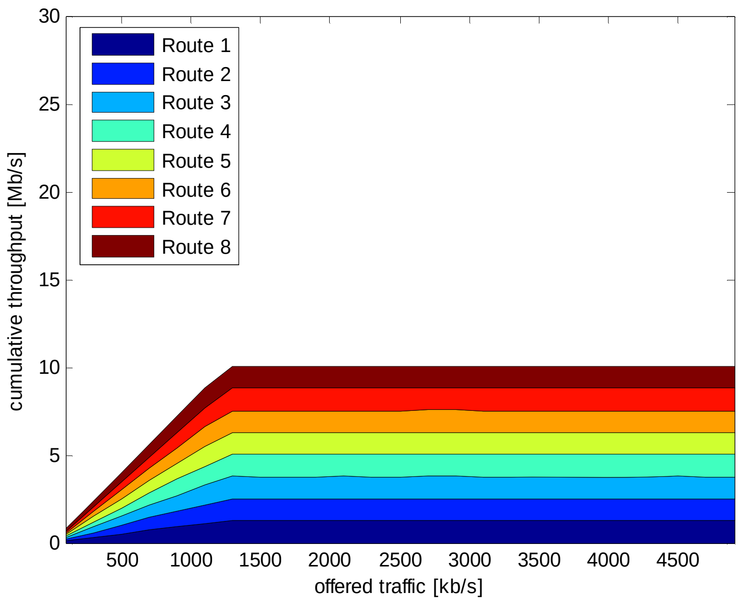


Office scenario – Simulation results

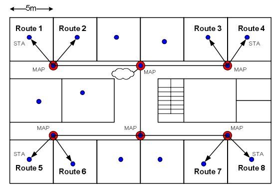


- **EDCA (prio. 0), throughput per route, packet size 80 B**
- **MNA MAC, throughput per route, packet size 80 B**

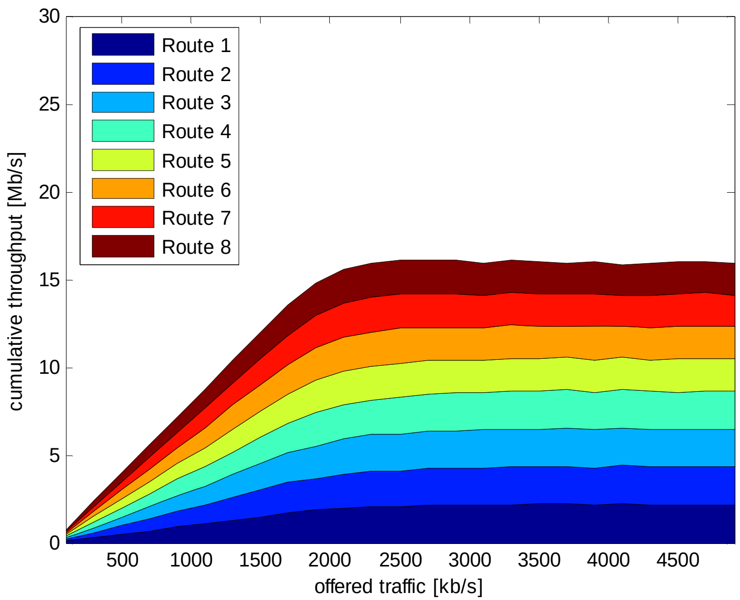




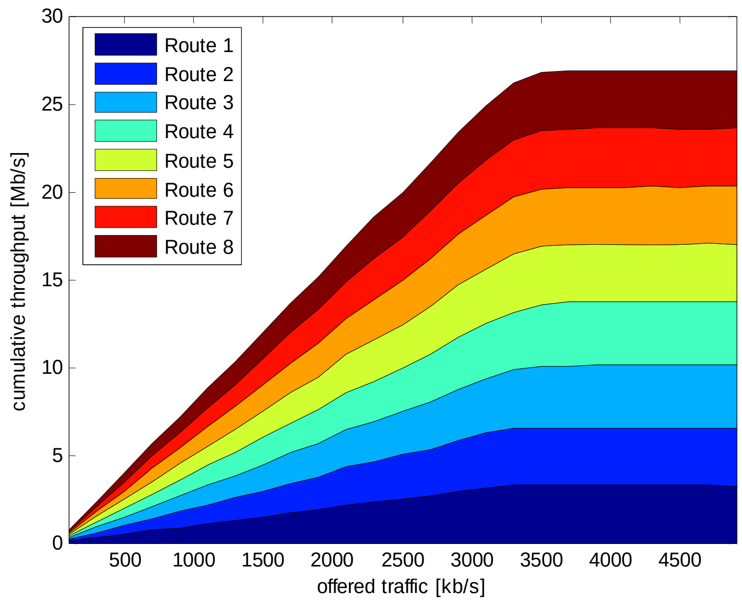
Office scenario – Simulation results



- **EDCA (prio. 0), throughput per route, packet size 1500 B**

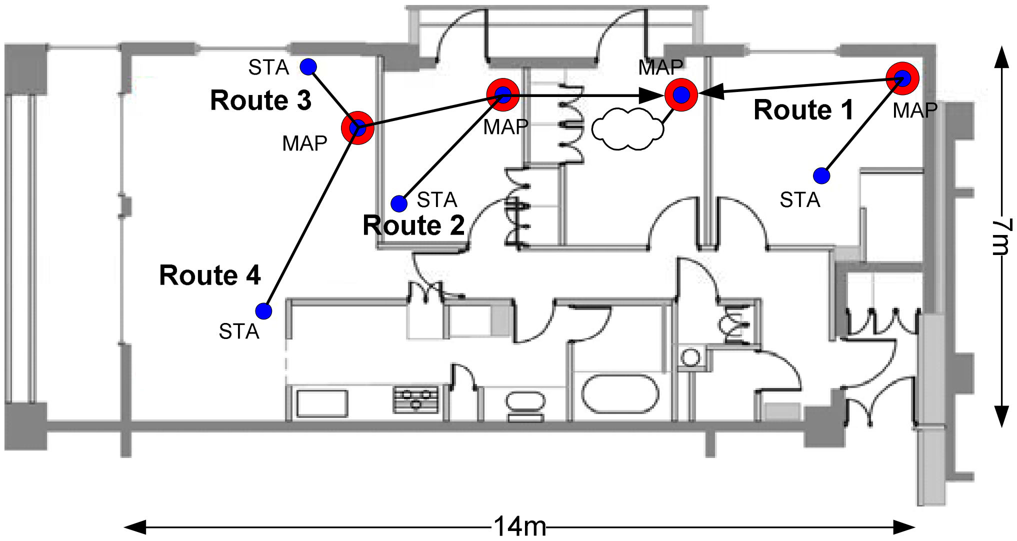


- **MNA MAC, throughput per route, packet size 1500 B**

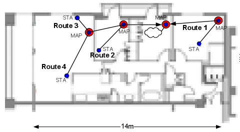


Residential scenario

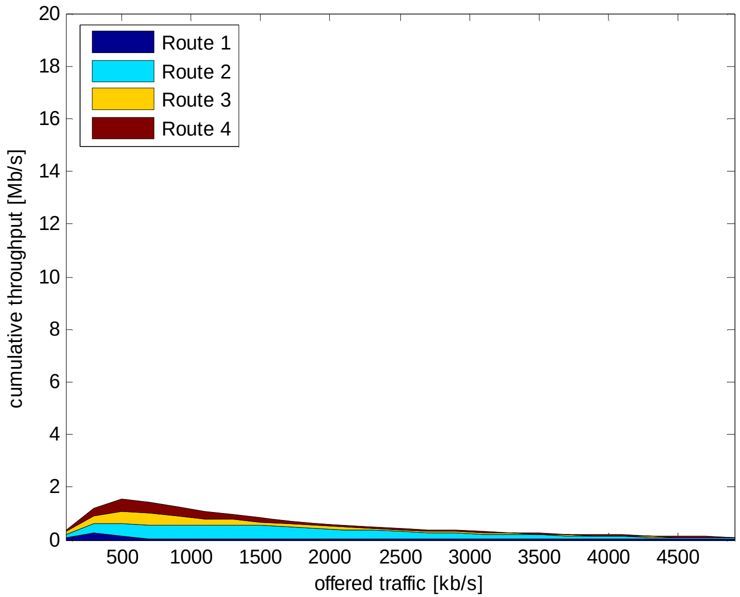
- **Offered traffic: CBR**
  - Uplink routes
- **OFDM PHY, 64QAM¾ (54Mb/s)**
- **~15ms – 22ms Superframe duration**
- **EDCA parameters**
  - See page 48
- **Attenuation**
  - Walls: 10 dB
  - Doors: 3.5 dB

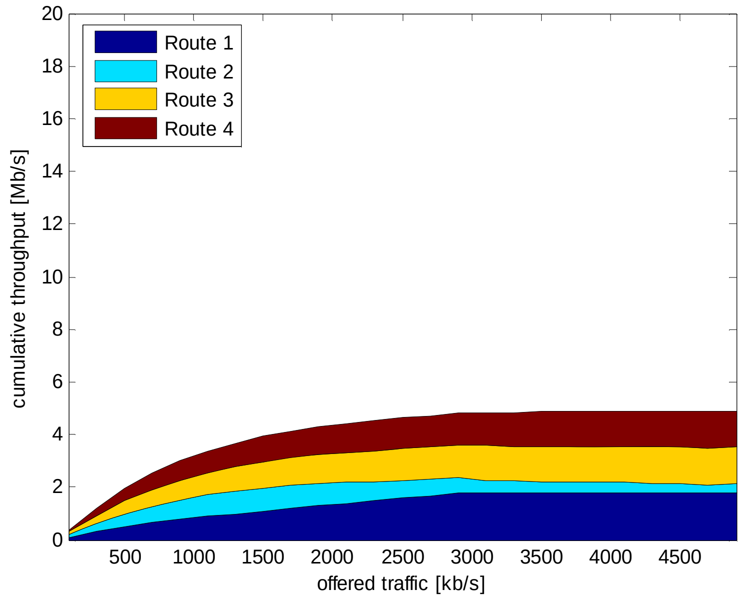


Residential scenario – Simulation results

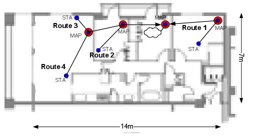


- EDCA (prio. 0), throughput per route, packet size 80 B
- MNA MAC, throughput per route, packet size 80 B

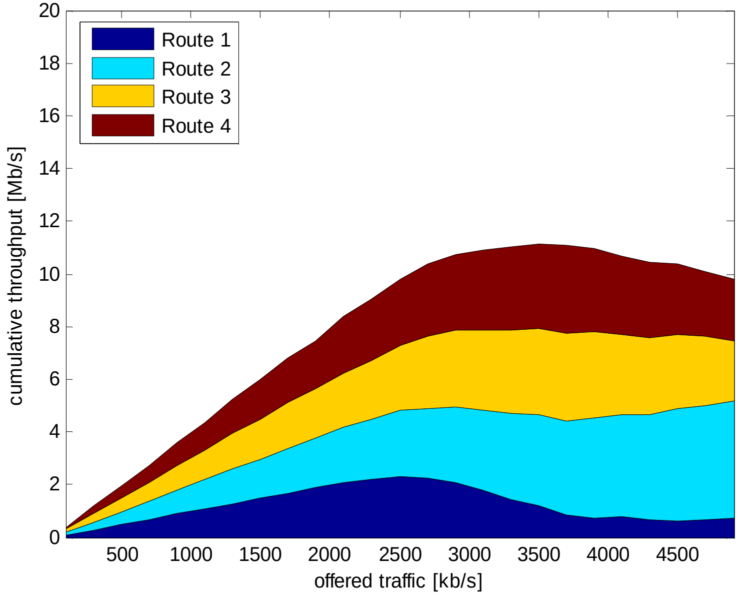


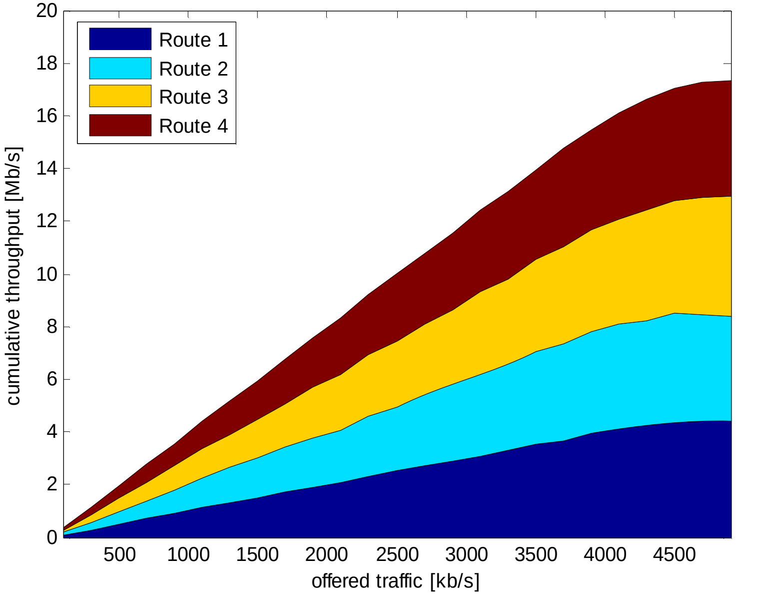


Residential scenario – Simulation results



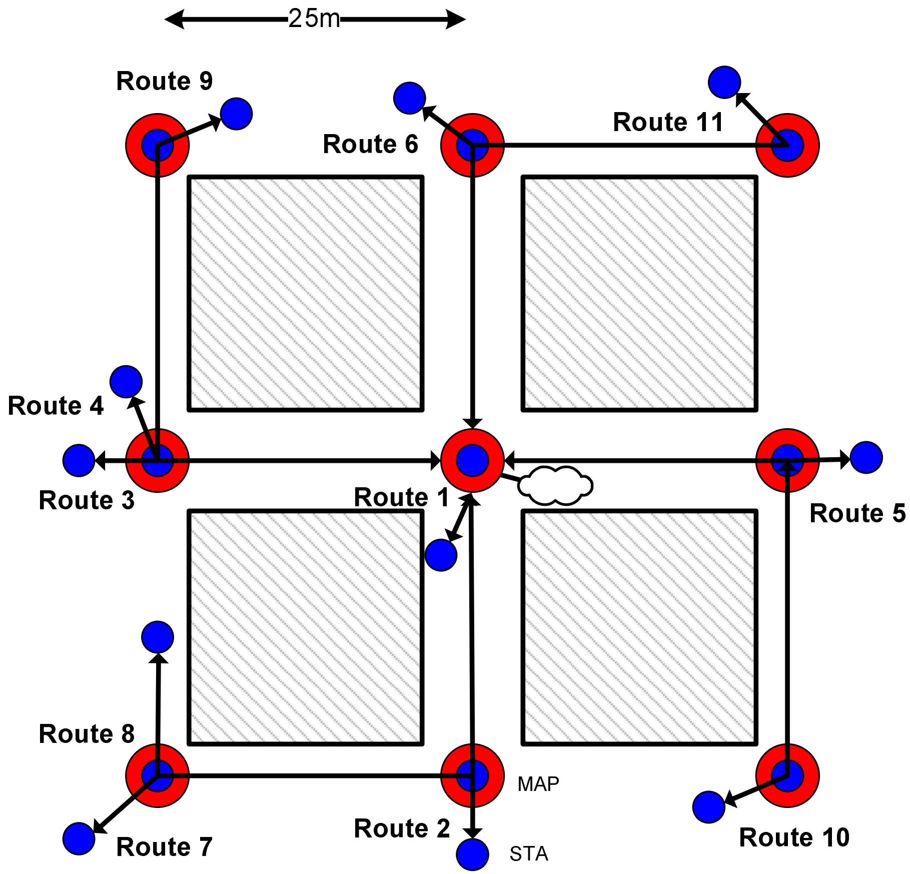
- EDCA (prio. 0), throughput per route, packet size 1500 B
- MNA MAC, throughput per route, packet size 1500 B



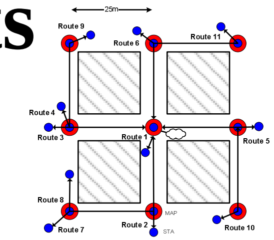


Outdoor scenario

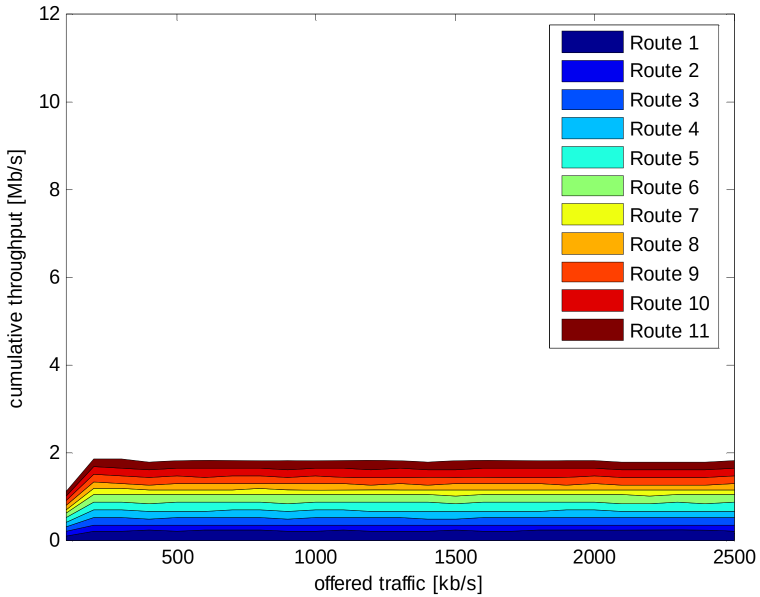
- **Offered traffic: CBR**
  - Downlink routes
  - Uplink routes
- **OFDM PHY, QPSK¾ (18Mb/s)**
- **~12ms – 15ms Superframe duration**
- **EDCA parameters**
  - See page 48
- **Attenuation**
  - Walls: 11 dB



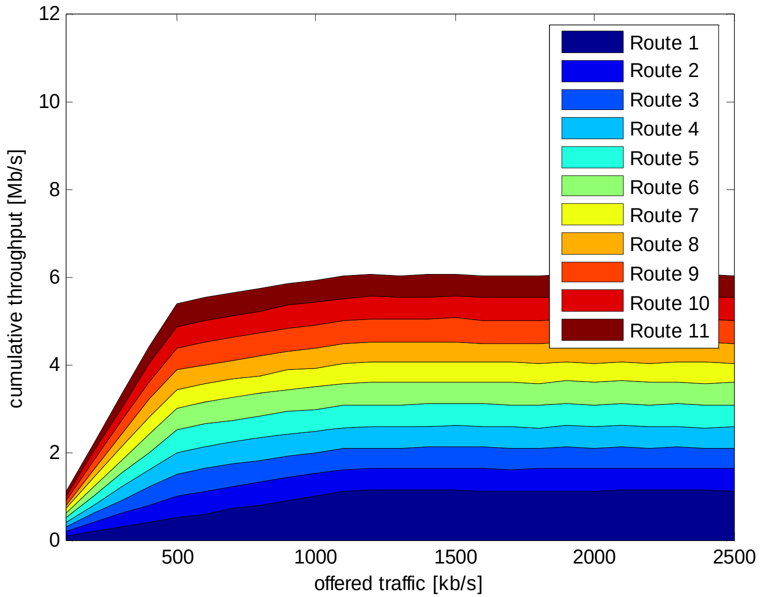
Outdoor scenario – Simulation results Downlink



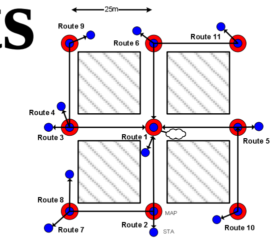
- EDCA (prio. 0), throughput per route, packet size 80 B



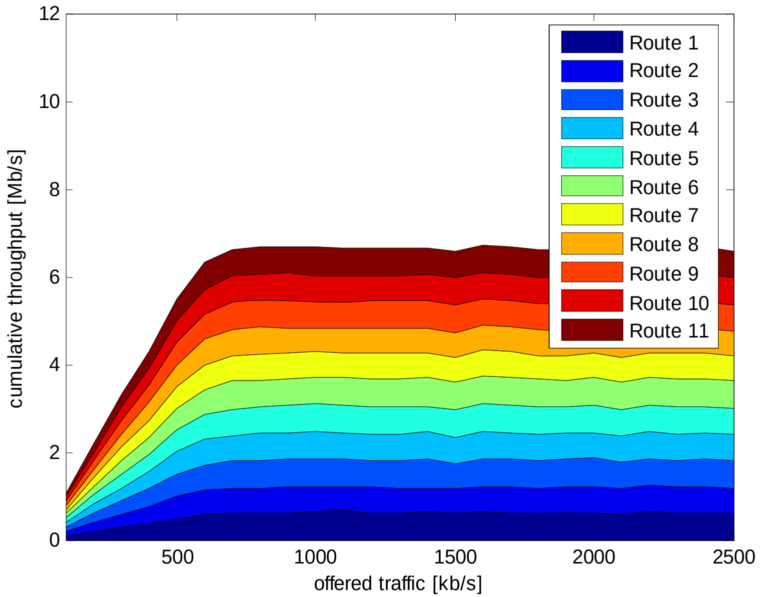
- MNA MAC, throughput per route, packet size 80 B

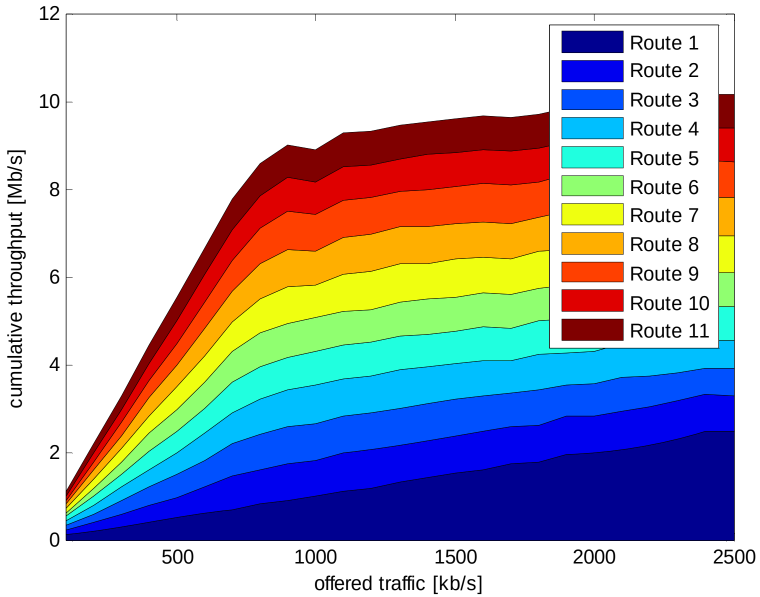


Outdoor scenario – Simulation results Downlink

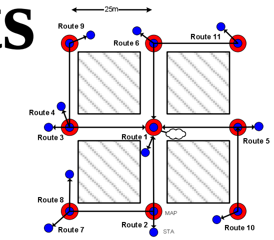


- **EDCA (prio. 0), throughput per route, packet size 1500 B**
- **MNA MAC, throughput per route, packet size 1500 B**

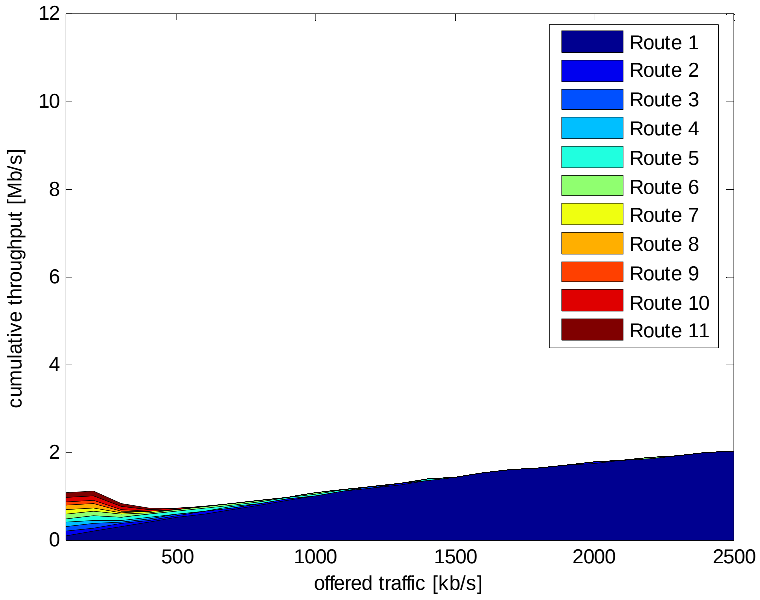


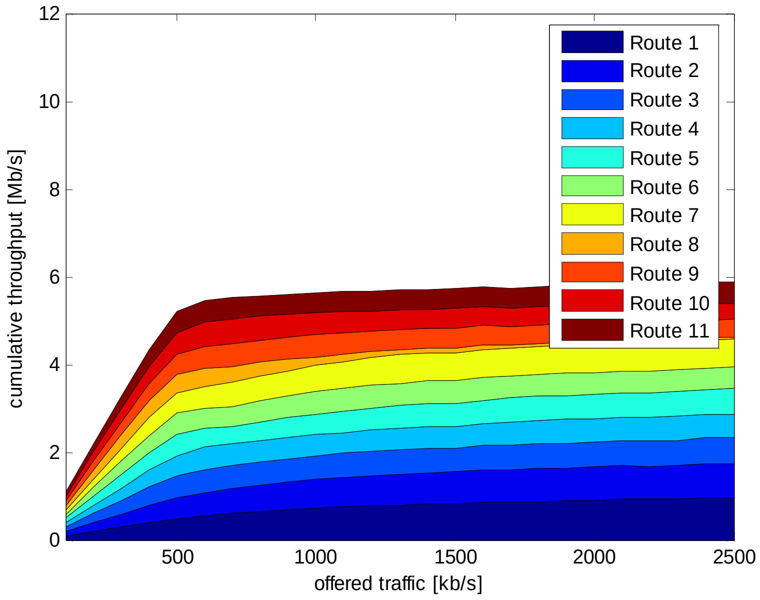


Outdoor scenario – Simulation results Uplink

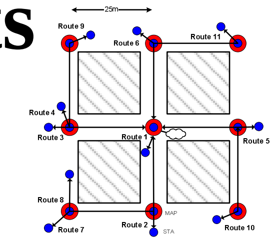


- EDCA (prio. 0), throughput per route, packet size 80 B
- MNA MAC, throughput per route, packet size 80 B

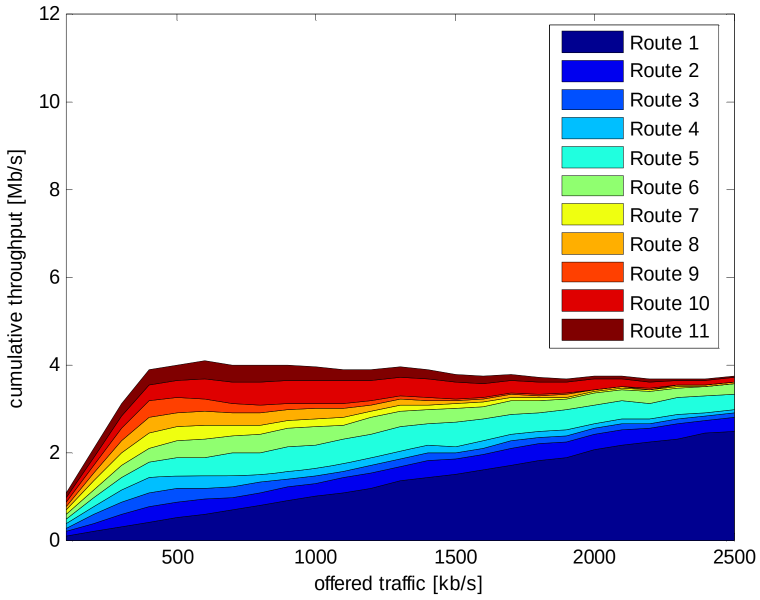


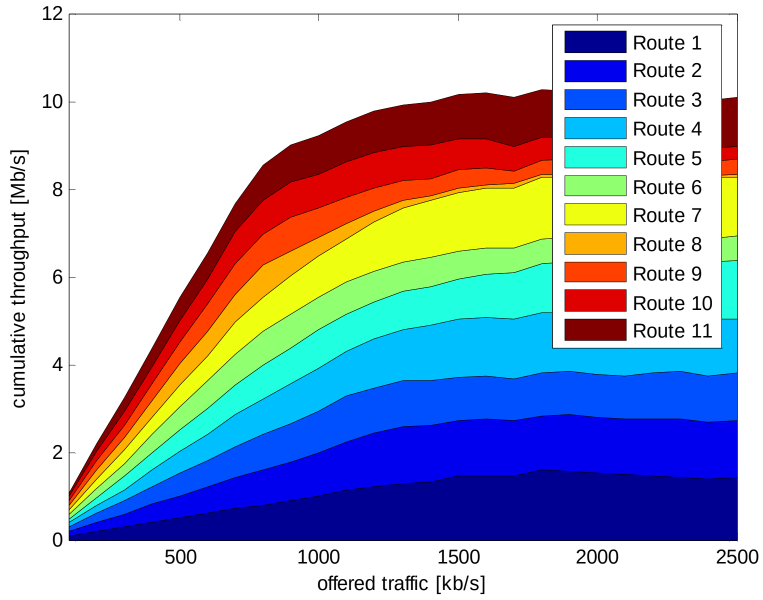


Outdoor scenario – Simulation results Uplink



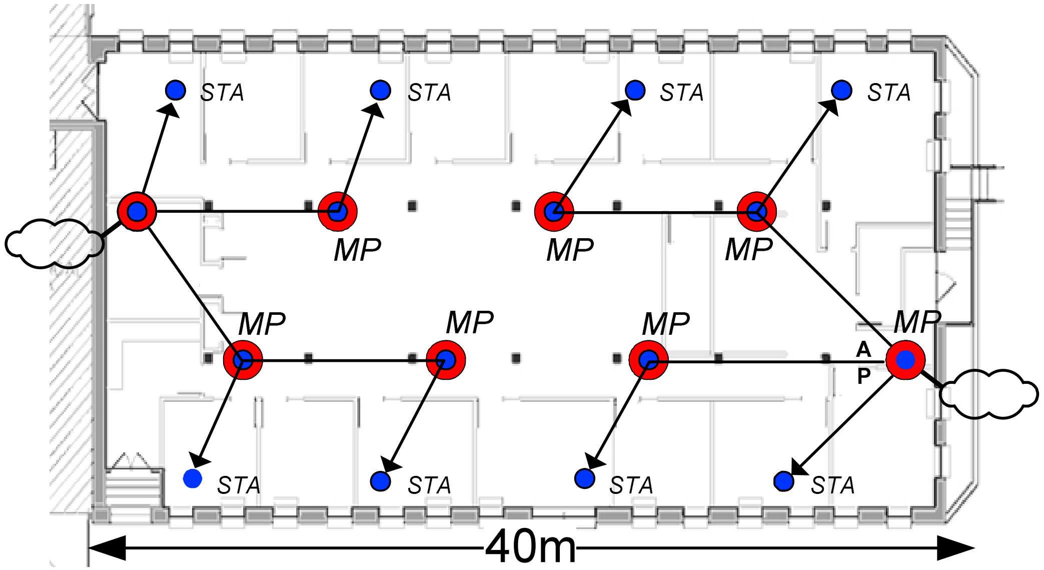
- **EDCA (prio. 0), throughput per route, packet size 1500 B**
- **MNA MAC, throughput per route, packet size 1500 B**



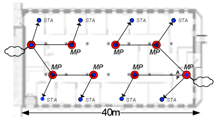


Office scenario (2)

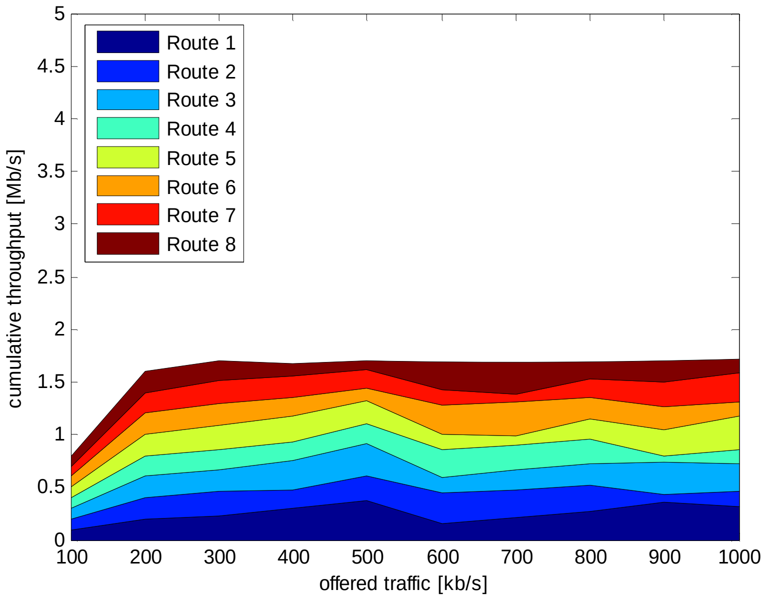
- **Offered traffic: CBR**
  - Downlink routes
- **OFDM PHY, 64QAM¾ (54Mb/s)**
- **~13ms – 18ms Superframe duration**
- **Cubicles, full line of sight**
  - No obstacles

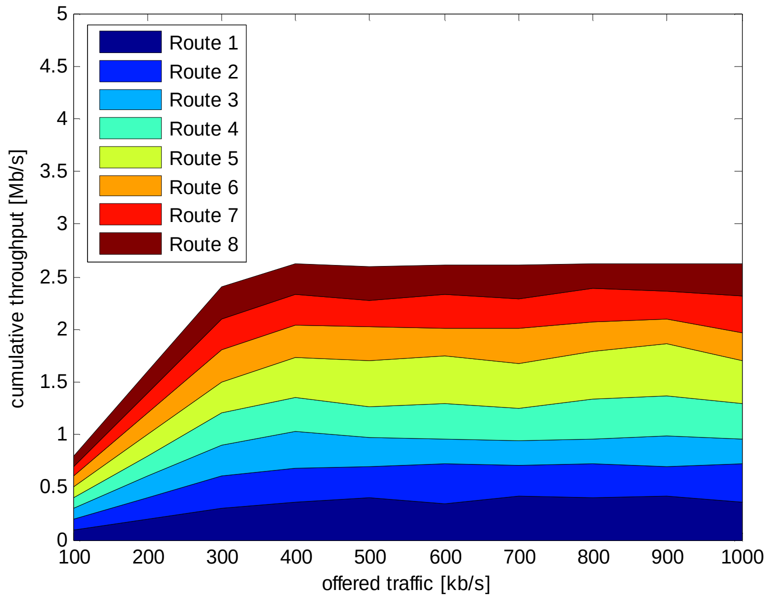


Office scenario (2) – Simulation results

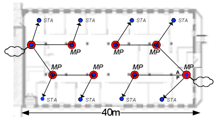


- legacy, throughput per route, packet size 80 B
- MNA MAC, throughput per route, packet size 80 B

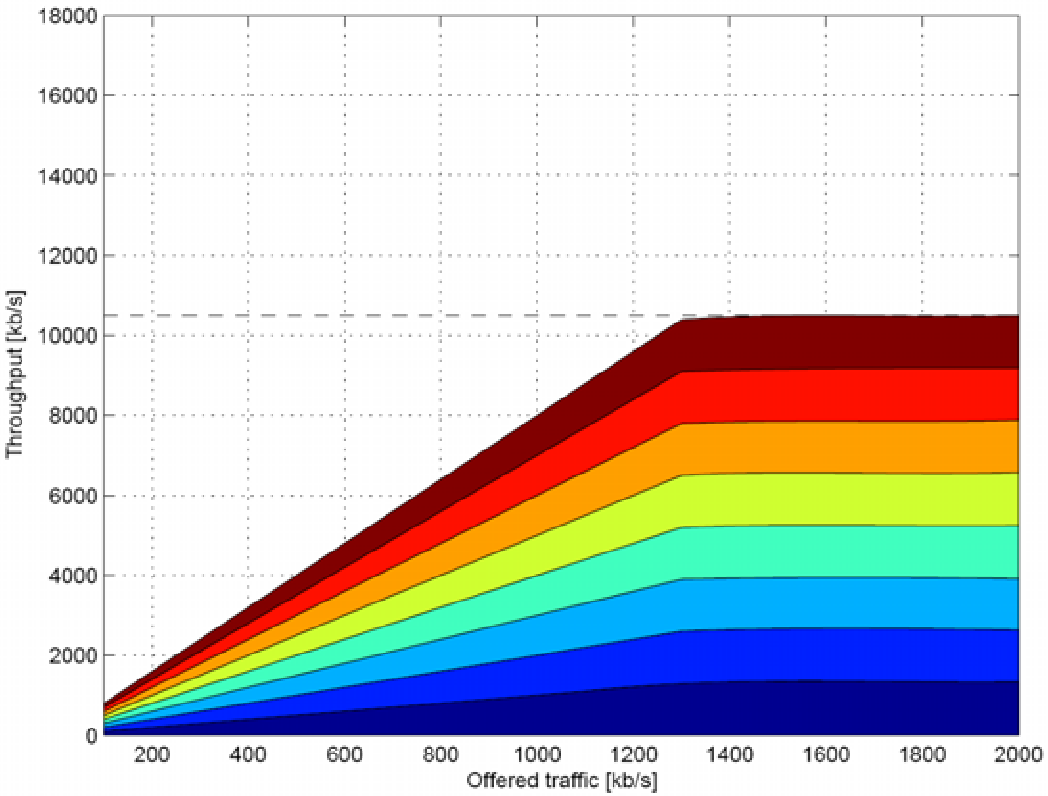




Office scenario (2) – Outlook: Single radio, multiple channels



- **4 channels available**
- **Less dependent on spatial frequency reuse**
- **Fully scaleable solution**
  - No performance degradation
  - Optimum resource usage



Comparison criteria

- **Same simulation scenario!**
  - Amount of stations
  - Hop count
  - Offered traffic
  - Propagation conditions
  - Transmission power
  - …
- **Spectral efficiency**
  - System throughput * Spectrum^{-1}
  - Example:10Mb/s * $(20\text{MHz})^{-1}$ = 0.5b/(s*Hz)
- **Scalability**
  - Minimal set of radios (1, 2, …)
  - Minimal amount of spectrum (20MHz, 40MHz …)
- **Coexistence support**
  - Exclusive Mesh WLAN channel needed? (Yes, No)
  - Robustness against legacy 802.11 devices in Mesh WLAN channel
- **Cumulative system & single route throughput**

Summary

- **Mesh Networks Alliance uses existing technology**
  - Contention Free Period, Beacon frame & Transmission Opportunity
  - Seamless integration with legacy 802.11 stations
  - Segregation of Mesh WLAN traffic
- **Simulation results**
  - Detailed channel model for all kind of Mesh WLAN
  - Full MAC implementation
  - Results show high potential of spatial frequency reuse
  - Fully scaleable solution

Thank you for your attention!

Mesh Networks Alliance
(MNA)

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