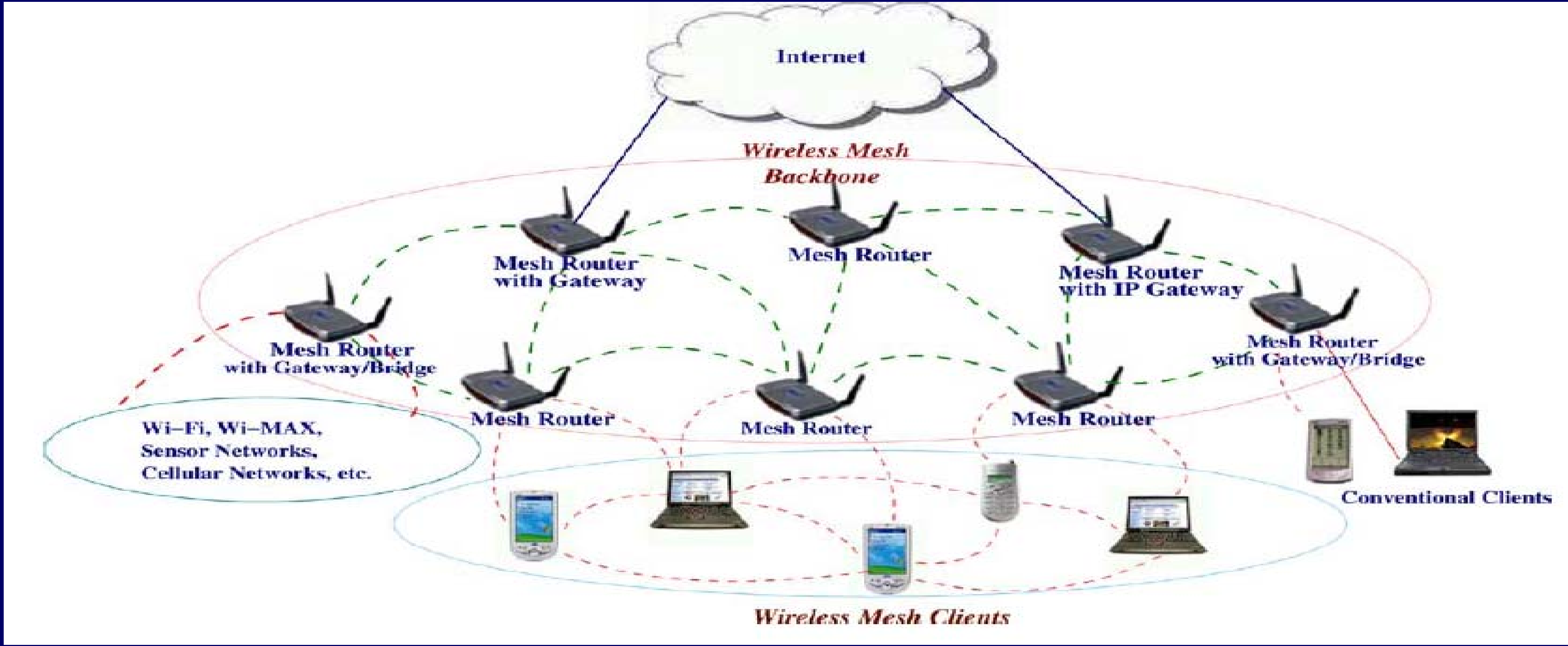
CROSS LAYER DESIGN IN WIRELESS MESH NETWORKS

I. F. AKYILDIZ

Broadband Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology
Tel: 404-894-5141; Fax: 404-894-7883
Email: ian@ece.gatech.edu
Web: http://www.ece.gatech.edu/research/labs/bwn

Wireless Mesh Networks

I.F. Akyildiz, et.al., "Wireless Mesh Networks; A Survey",
Computer Networks (Elsevier) Journal, March 2005.
Shorter version in IEEE Communications Magazine, Sept. 2005.



Critical Factors influencing Network Performance

1. Radio Techniques:

* Directional and smart antennas
* MIMO systems ← (Key Tech for IEEE 802.11n)
* Multi-radio/multi-channel systems

(More Advanced Technologies) Under Development:

* Reconfigurable radios
* Cognitive radios

These advanced radio technologies require revolutionary design in higher layer protocols, in particular, MAC and routing!!!

Critical Factors Influencing Network Performance

2. Scalability (NW performance degrades with increasing NW size)

e.g., throughput degrades with the number of hops.
max. available bandwidth degrades at the rate of 1/2,1/4,1/8 depending on the number of hops!!

4 hops away from the sender, the max BW becomes 1/16 of the total available BW.

Critical Factors Influencing Network Performance

3. **Mesh Connectivity** (for protocol design)

4. **Broadband and QoS**

   (end-to-end delay, fairness, delay, jitter, aggregate and per-node throughput, packet loss ratios)

5. **Compatibility and Inter-Operability**

   (for mesh and conventional clients)

Critical Factors Influencing Network Performance

6. Security

(new encryption algorithms, key distribution, secure MAC and routing protocols, intrusion detection, monitoring)

7. Ease of Use

(autonomic network, automatic power management, self organization, dynamic topology control, robust to link failures, fast network subscription/user authentication procedure)

MAC LAYER

Differences between MACs of WMNs and of WNs

* Concerned with more than one hop communication

* Distributed and collaborative

* Multipoint-to-multipoint communication

* Network self-organization is needed for better collaboration between neighboring nodes and nodes in multi-hop distances

MAC PROTOCOLS

Single Channel MACs

1. Improving Existing MAC Protocols
2. Cross-Layer Design with Advanced PHY Layer Techniques
    A. MACs based on Directional Antennas
    B. MACs with Power Control

Multiple Channel MACs

A. Multi-Channel Single-Radio MACs
B. Multi-Channel and Multi-Rate MACs
C. Multi-Channel Multi-Radio MACs

MAC LAYER - Open Research Issues:

1. SCALABILITY
   - Not fully resolved yet
   - Most of existing MAC protocols based on CSMA/CA solve partial problems of the overall issue, but raise other problems.

Example:

Multi-channel or multi-radio MAC can improve multihop throughput performance by adding more frequency channels but result in higher system complexity and higher cost.

Also an effective channel allocation is still an open research problem !

MAC LAYER - Open Research Issues:

2. CROSS LAYER DESIGN

- For multi-channel operation, MAC/ROUTING
- For MIMO and cognitive radios we need novel MAC protocols (PHY/MAC)
- Hybrid ARQ could improve error control capability

MAC LAYER - Open Research Issues:

3. HETEROGENEOUS ACCESS TECHNOLOGIES

- Advanced bridging functions must be developed in the MAC layer (IEEE 802.11, 802.16, 802.15, etc., seamless work operation).

- Reconfigurable/software radios and the related radio resource management schemes may be the ultimate solution to these bridging functions.

MAC LAYER - Open Research Issues:

4. QoS SUPPORT

- So far existing MAC research is focused on capacity, throughput, or fairness.

- To support broadband multimedia communication in WMNs, MAC protocols with multiple QoS metrics such as delay, packet loss ratios and delay jitter need to be developed.

MAC LAYER - Open Research Issues:

5. RECONFIGURABLE MACs

For software radios and cognitive radios.

MAJOR CHALLENGE: THROUGHPUT DEGRADATION

V. Gambiroza, B. Sadeghi, E. W. Knightly. "End-to-end performance and fairness in multihop W backhaul NWs," Proc. ACM MobiCom, Sept. 2004.

The throughput degrades with the number of hops in the network !!!

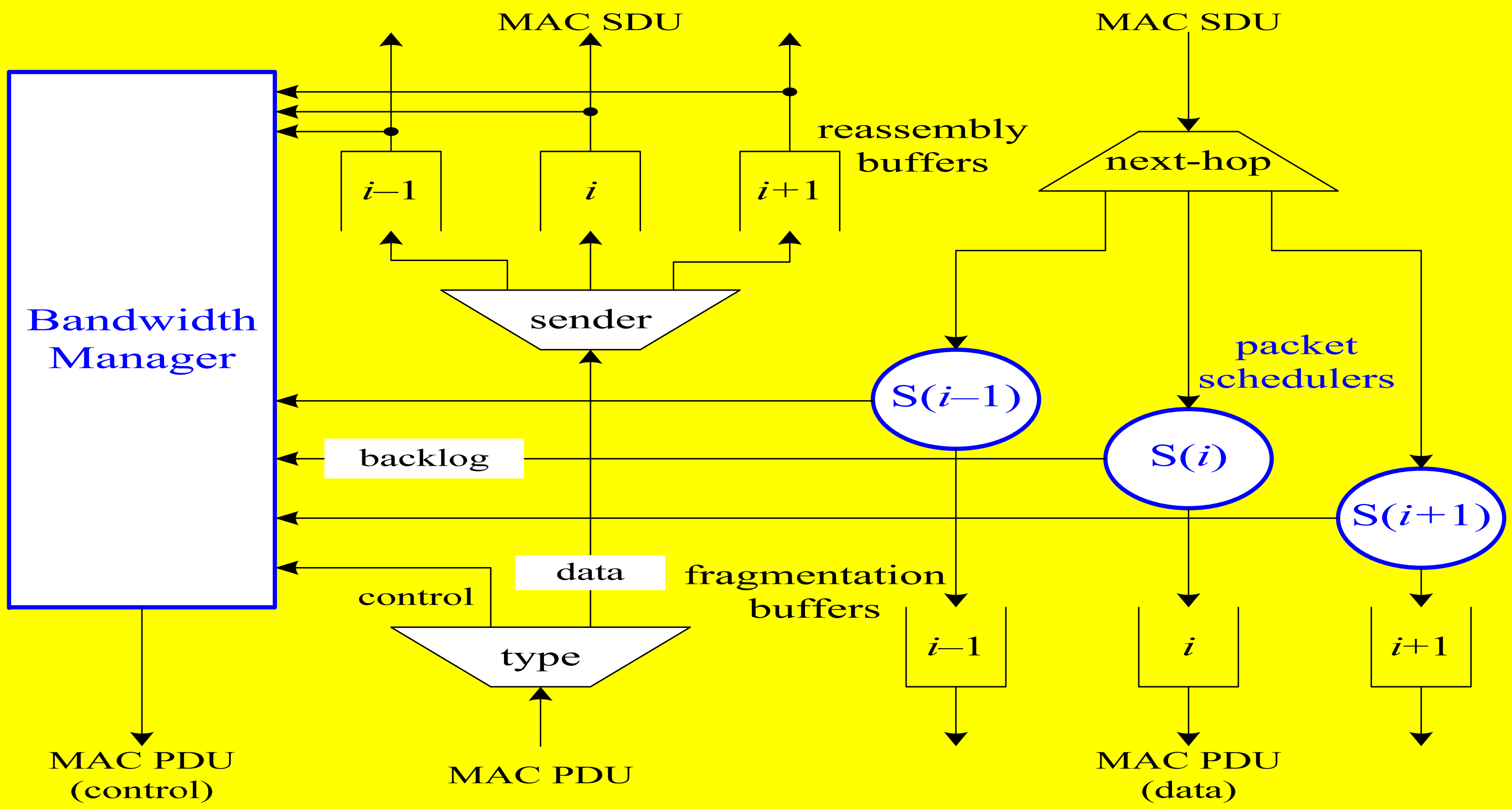
Bandwidth Balancing in Multi-channel IEEE 802.16 Wireless Mesh Networks,

C. Cicconetti, I.F. Akyildiz, L. Lenzini, IEEE Infocom'07, May 2007

Longer version: to appear in IEEE Tr. on Networking, 2009.

Design *bandwidth manager* and a *packet scheduler* algorithms → to provide fair allocation of bandwidth among traffic flows with different path lengths

MAC Architecture



FEBA - Overview

- Fair End-to-end Bandwidth Allocation (FEBA) Algorithm → a B*andwidth Manager*
- The main idea of FEBA is to assign bandwidth requests and grants at each neighbor:
  - in a round-robin fashion;
  - with an amount of service proportional to the number of end-to-end flows going to or coming from the neighbor, respectively;
  - within a time window whose size depends on the frequency with which the neighbor transmits control messages.

Routing Layer

Optimal routing protocol for WMNs must capture the foll. features:

1. Multiple Performance Metrics
2. Scalability
3. Robustness
4. Adaptive Support of both Mesh Routers and Mesh Clients

Routing Layer:
1. Multiple Performance Metrics

* Most of the existing routing protocols use minimum hop-count as a performance metric to select the routing path → ineffective!!

* e.g., when a link on the the minimum hop-count path has bad quality or experiences congestion, it becomes a bottleneck to the end-to-end throughput.

* To solve this problem, other performance metrics, e.g., link quality and round trip time (RTT), must be considered in the routing protocols.

Routing Layer:
2. Scalability

- Setting up a routing path in a very large WN may take a long time.
- Furthermore, even when the path is established, the node states on the path may change.

Routing Layer:
3. Robustness

* Robust to link failures or congestions
* Fault-tolerant
* Achieve load balancing

4. Better Performance Metrics

- New performance metrics need to be developed.
- Necessary to integrate multiple performance metrics into a routing protocol so that the optimal overall performance is achieved.

- Hop Count Routing (2005, 2006 and 2007)
- Link-Quality Routing (*2004 and 2005*)
- *Interference Based Routing (2005 and 2006)*
- *Load Balanced Routing (2006)*
- *Routing with Residual Link Capacity (2005 and 2006)*
- *End to End QoS Routing (2006)*
- *Multipath Routing (2005 and 2006)*
- *Stability Based Routing (2007 and 2008)*
- *Hierarchical Routing (2006 and 2007)*
- *Geographic Routing (2005)*
- *Distributed Multichannel Routing (2009)*

Routing: Research Challenges

- Scalable ro

Transport Layer: Research Challenges:

Effect of Multi-channel Operations

- Interference levels or multi-path channel characteristics can be very different

→ end-to-end rate adaptation and congestion control mechanisms inefficient !!

Transport Layer: Research Challenges:
Unfair Service between Short and Long Flows

- As the number of hops on a path increases, the probability of a link failure and consequential packet losses on the path increase.

- This implies that shorter flows enjoy an unfair advantage in throughput compared to longer flows.

Cross Layer Design

I.F. Akyildiz and X. Wang,
"Cross Layer Design in Wireless Mesh Networks,"
IEEE Transactions on Vehicular Technology,
Vol. 57, Issue 2, pp. 1061-1076, March 2008.

Traditional Layered Approach

Application Layer
Transport Layer
Network Layer
MAC Layer
Physical Layer

ADVANTAGES OF LAYERED PROTOCOL DESIGN

* Each protocol layer designed independently
  - Limited information is passed between layers

* Protocols in one layer can be designed, enhanced, or even replaced without any impact on other protocol layers

* Good for abstraction, debugging, design and development

DISADVANTAGES OF LAYERED PROTOCOL DESIGN

- Bad for energy efficiency, overhead, performance

- No mechanism for performance optimization between different protocol layers

- Especially for WMNs because → scalability problems but also, e.g.,
  - heterogeneous QoS constraints,
  - multihop wireless communications, and
  - variable link capacity

LAYERED vs CROSS LAYER?

Is LAYERED or CROSS LAYER DESIGN better for optimal protocol performance in WMNs?

→ Still an on-going research problem !!

OPTIMIZATION DECOMPOSITION AS CROSS LAYER SOLUTION

M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, ``Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures,'' Proceedings of IEEE, Jan. 2007.

- Each protocol in each layer works as an OPTIMAL MODULE to achieve the best network performance
- Various protocol layers are integrated into one single coherent theory
- Asynchronous distributed computation over the network is applied to solve a global optimization problem

which has the form of generalized Network Utility Maximization (NUM).

Key Idea:

Decompose the optimization problem into subproblems

Each subproblem corresponds to a protocol layer

Functions of primal or Lagrange dual variables coordinating these subproblems correspond to the interfaces between layers

Generalized Network Utility Maximization (NUM)

M. Chiang, S. H. Low, A. R. Calderbank, and J. C. Doyle, ``Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures,'' Proceedings of IEEE, Jan. 2007.

- Basic NUM is usually formulated for protocol layer performance optimization

- Generalized NUM captures the entire protocol stack.

Generalized Network Utility Maximization (NUM)

$$
\begin{aligned}
\text{maximize} \quad & \sum_s U_s(x_s, P_{e,s}) + \sum_j V_j(w_j) \\
\text{subject to} \quad & \mathbf{R}\mathbf{x} \le \mathbf{c}(\mathbf{w}, \mathbf{P}_e) \\
& \mathbf{x} \in \mathcal{C}_1(\mathbf{P}_e),\ \mathbf{x} \in \mathcal{C}_2(\mathbf{F}),\ \text{or } x \in \Pi \\
& \mathbf{R} \in \mathcal{R},\ \mathbf{F} \in \mathcal{F},\ \mathbf{w} \in \mathcal{W}.
\end{aligned}
$$

User utility function U(.) and resources V_j on network element j.

x_s and w_j denote the rate for source s and PHY resources at network element j,

R is a routing matrix, and x denotes the link capacity as a function of PHY resource w and desired error probability P_e after decoding.

NOTE:
All PHY factors such as interference, power control, etc. should be captured in function c.

Generalized NUM

- First constraint represents the routing layer

- Coding and error control mechanisms versus the rate are captured in function $C_1(.)$,

- Contention based MAC or scheduling based MAC is captured in $C_2(.)$ and Π,

where F is the contention matrix and Π is a schedulability constraint set.

Generalized NUM

- Second line of constraints stands for link layer behavior → takes into account the effect of PHY.

- From the above generalized NUM →

network performance must be optimized at the transport layer subject to the constraints in routing, MAC, and physical layers.

Stochastic NUM

- A deterministic fluid model → cannot capture the packet level details and microscopic queueing dynamics.
- Stochastic NUM is a preferred formulation !!
- Stochastic NUM has been an active research area, in which many challenging issues still remain to be resolved.

Deterministic or Stochastic Generalized NUM

Optimization decomposition is usually carried out by the following three steps:

1. Generalized NUM is formulated independent of layering
2. A modularized and distributed solution is developed to perform optimization by following a particular decomposition
3. The space of different decompositions is explored such that a choice of layered protocol stack is made

Generalized NUM

- The objective function is usually comprised of two parts: User and Operator Objective Functions

- These two parts can be integrated via a weighted sum.

Generalized NUM

Another Option:

Multi-objective optimization that characterizes the Pareto-optimal tradeoff between user and operator objectives.

Optimization Decomposition for the Generalized NUM

* Vertical Decomposition

* Horizontal Decomposition

Vertical Decomposition

- Entire network functionalities are decoupled into different modules such as congestion control, routing, scheduling, MAC, power control, error control, and so on.

- Different modules can be classified into different layers in the protocol stack.

Horizontal Decomposition

- Devise a distributed computation solution for individual module
- More specifically, this step will work out a specific distributed mechanism and algorithm for protocols such as congestion control, scheduling, MAC, and so on..

Optimization Decomposition lays a Theoretical Ground for Cross-layer Design

1. Gives a better insight to existing layered protocols.

   e.g., comparing a decomposition result with the existing protocol stack can tell us which layers need cross-layer optimizations and how to optimize the interactions between layers.

Optimization Decomposition lays a Theoretical Ground for Cross-layer Design

2. Provides a systematic approach for the design of an optimized protocol architecture

3. Implies the need for a cross-layer design

CAUTIONS FOR CROSS LAYER DESIGN

V. Kawadia and P. R. Kumar,
``A Cautionary Perspective on Cross Layer Design,"
IEEE Wireless Communications, Feb. 2005.
L.-L. Xie and P. R. Kumar,
"A Network Information Theory for Wireless Communication: Scaling Laws and Optimal Operation",
IEEE Transactions on Information Theory, May 2004.

* Cross-layer design can only improve throughput by at most a constant factor and

* An unbounded performance improvement cannot be achieved.

Problems with these Statements

V. Kawadia and P. R. Kumar, "A Cautionary Perspective on Cross Layer Design,'' IEEE Wireless Communications, Feb. 2005.

L.-L. Xie and P. R. Kumar, "A Network Information Theory for Wireless Communication: Scaling Laws and Optimal Operation", IEEE Transactions on Information Theory, May 2004.

- These statements are exaggerated in many scenarios, especially when we want to design actual protocols rather than the asymptotic analysis.
- Theoretical results are only based on simplistic network models and only meaningful asymptotically.
- These results cannot really prove that the cross-layer design is not necessary !!

Features Demanding Cross-Layer Design:

1. No Clean-Slate Protocol Architecture

- By optimization decomposition, it can result in a new protocol architecture that is quite different from TCP/IP protocol stack

- How to match layered protocol architecture derived from optimization decomposition to TCP/IP protocol stack is a challenge!

- Highly possible that no match can be achieved in several cases.

- Thus, the cross-layer design becomes indispensable !!

Features Demanding Cross-Layer Design:

2. Advanced Physical Layer Technologies in WMNs

1. Multi-rate transmission technology
2. Advanced antenna technology
3. Multichannel or multiradio technology

Features Demanding Cross-Layer Design:

3. Imperfect MAC

- MAC has always been a critical part in all wireless networks.
- Many solutions are available.
- None of them is perfect because of two major factors:

  i) the wireless medium is always imperfect in nature;

  ii) the MAC itself

  has no guaranteed performance.

Features Demanding Cross-Layer Design: 3. Imperfect MAC

- For a perfect MAC, routing must be an integral part of MAC.
- MAC and routing protocols

  * two modules in one layer or
  * even just one module in the same protocol layer.

  e.g., IEEE 802.11s for 802.11 WMNs, MAC/routing are together in the same MAC layer.

- However, optimal interactions between MAC and routing have not been exploited yet in IEEE 802.11s.

Features Demanding Cross-Layer Design:

4. Mixed Traffic Types with Heterogeneous QoS.

- Many traffic types with heterogeneous QoS requirements
- For these services in WMNs
  transport layer, routing, and MAC protocols need to cooperate smoothly !
- Otherwise, either service quality is not guaranteed or the network resources may be wasted.

Features Demanding Cross-Layer Design:

4. Mixed Traffic Types with Heterogeneous QoS.

Example:

Separate transport layer protocols for VoIP, video, and Data traffic.

For VoIP and video traffic, finding a reliable routing path is obviously not the goal, since a path does not guarantee the quality of VoIP or video, no matter how reliable the path can be.

Features Demanding Cross-Layer Design:

4. Mixed Traffic Types with Heterogeneous QoS.

This has been researched as a QoS routing topic.

But in WMNs with advanced PHY technologies, this is more than a QoS routing problem

We need to involve tight routing/MAC cross-layer design.

e.g., variation of bandwidth demand on a given
routing path or change of a routing path can trigger
reallocation of time slots, channels, antenna directions, etc.
on all links related to the given routing path or vice versa.

CROSS LAYER DESIGN

Cross-layer design can be done between multiple layers or between just two layers

* MAC/Physical
* MAC/Routing
* Physical/Transport

MAC/Physical Cross-Layer Design

- In many wireless networks, MAC/PHY are implemented on the same card or even on the same chipset.
- Real-time interactions between the two layers occur frequently.

MAC/Physical Cross-Layer Design

Several advanced technologies are being developed:

1. Multiple coding and modulation schemes
2. Advanced Antenna Techniques
3. MIMO
4. Orthogonal Frequency Division Multiplexing (OFDM) Technologies
5. Ultrawideband (UWB)

MAC/Physical Cross-Layer Design

These technologies can be combined into one device.

e.g., a WiMedia UWB device,

UWB is based on multi-band OFDM (MB-OFDM),
multirate is supported through variable coding and modulation,
and link throughput can be improved through MIMO.

Advanced PHY technologies provide a great potential for improved performance of delay, throughput, packet loss, etc.

MAC/Physical Cross-Layer Design

* However, PHY itself cannot determine how to adaptively fine-tune the parameters in these advanced technologies.

* Such fine tuning is a critical task of a MAC protocol.

* Thus, cross-layer design between MAC and PHY becomes indispensable !!!

Routing/MAC Cross-Layer Design

No matter how the routing protocol is optimized, if the underlying MAC does not provide satisfying performance, the overall performance perceived by a routing protocol can be poor.

A MAC protocol aims to provide medium access opportunities to nodes sharing the same medium, given any condition of traffic load, interference, noise, and topology of a network.

Routing/MAC Cross-Layer Design

However, traffic load, interference, etc. are closely related to a routing protocol.

Thus, the performance of a MAC protocol can be significantly impacted by a routing protocol.

In order to achieve the best network performance, routing and MAC must be jointly optimized.

Methodology of Routing/MAC Cross-Layer Design

A routing protocol collects information in the MAC layer

e.g., link quality,

interference level, or

traffic load information,

to determine the best routing path.

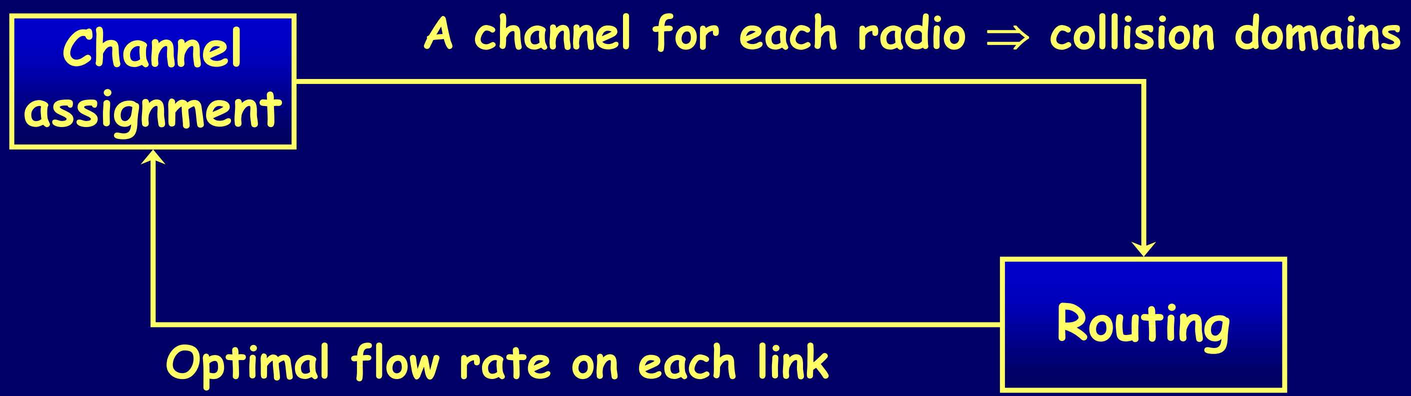
Layer-2 Routing Algorithm

S. Avallone, I.F. Akyildiz, G. Ventre, "Channel Assignment and Layer 2 Routing Algorithms for Multiradio WMNs" to appear in IEEE Transactions on Networking 2009.

- Each mesh router is configured with the set of pre-computed flow rates associated with its links
- Packets are *forwarded* using such information (rather than *routed* using routing tables)
  - Layer-2 information are used, hence the name
- Each mesh router attempts to keep the utilization of the outgoing links proportional to their pre-computed flow rates

Channel Assignment & Routing

- Channel assignment and routing are inter-dependent on each other



Cross-Layer Optimization between TCP and Physical Layers

Previous Research:

CASE 1:

Congestion control algorithm of TCP is optimized by considering the information collected from PHY.

Cross-Layer Optimization between TCP and Physical Layers

Example

Use the PHY information to differentiate packet loss due to congestion from link layer errors.

Such type of optimization can only achieve limited performance improvement, because the interaction between TCP and PHY is not considered.

Cross-Layer Optimization between TCP and Physical Layers

When a link is congested, PHY can adjust its parameters, e.g., transmit power, to avoid congestion, which will also help TCP achieve better performance.

Similarly, when a link experiences low quality, PHY parameters such as coding rate or transmit power can be adjusted to enhance the link quality.

Cross-Layer Optimization between TCP and Physical Layers

- **CASE 2:**
  - * Thus, instead of passively taking action only in TCP, TCP and PHY control schemes can be jointly optimized.
  - * Involves more complicated algorithms and also more sophisticated protocols and their implementations.

Concluding Remarks

No doubt that the cross-layer design can definitely improve the network performance.
However,

1. System Complexity

For many cross-layer design schemes, they can be easily shown to achieve great performance through simulations or even prototypes.

However, in actual implementations there will be complexities of modifying protocols in different layers.

Concluding Remarks

2. Protocol Interoperability and Compatibility

- With cross-layer design, the standard working mechanism in the protocol stack is broken.

  Interoperation between different networks is difficult to maintain.

  Networks with and without cross-layer design need to work together.

Concluding Remarks

3. Evolution Capability.
   - In a layered protocol architecture, protocols in one layer can evolve separately without disrupting the functionalities of protocols in another layer.
   - When cross-layer design is adopted, any upgrade or change in protocols must be coordinated among different protocol layers.
   - This requirement significantly limits the capability of product evolution.

Concluding Remarks

Several rules that can be followed to avoid blind use of cross-layer design:

1. Achieve enough margin of performance improvement.

- Using cross-layer design, we can easily see some performance improvement in throughput, delay, packet loss, etc.

  e.g., 5%, then it is not a wise strategy to adopt cross-layer design, since such performance improvement can easily vanish due to uncertainties in a wireless network like interference, noise, shadowing, etc.

Concluding Remarks

2. Explore any possible opportunity that can improve network performance using layered protocol design

3. Carry out cross-layer design without compromising framework specified by standards.

4. Push standardization of cross-layer design framework and methodology.