Integrated Cross-Layer Protocols for Adaptive Transmission and Routing of Multimedia Traffic in Tactical Spread-Spectrum Networks

Michael B. Pursley, Harlan B. Russell, and Jeffrey S. Wysocarski

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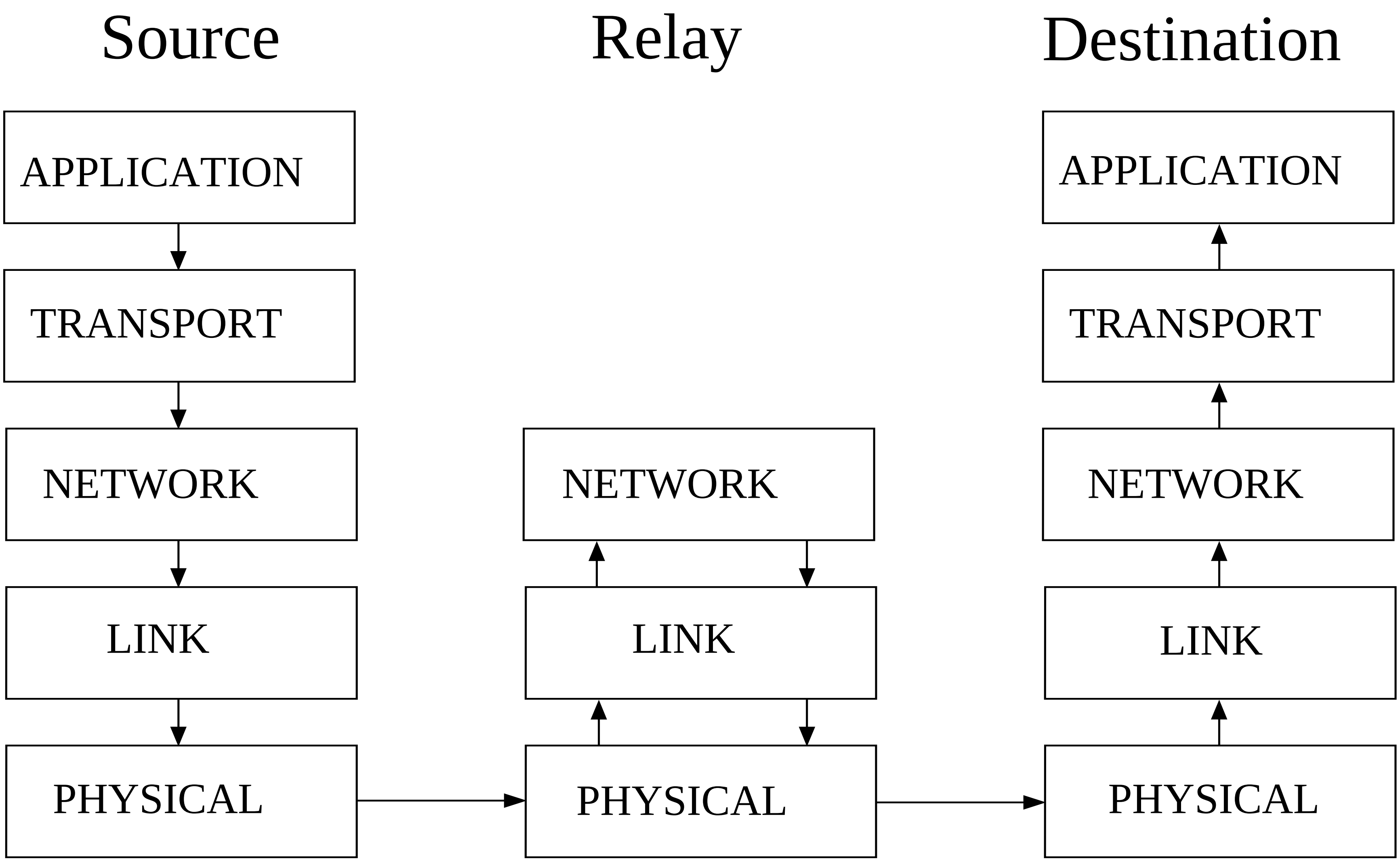
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

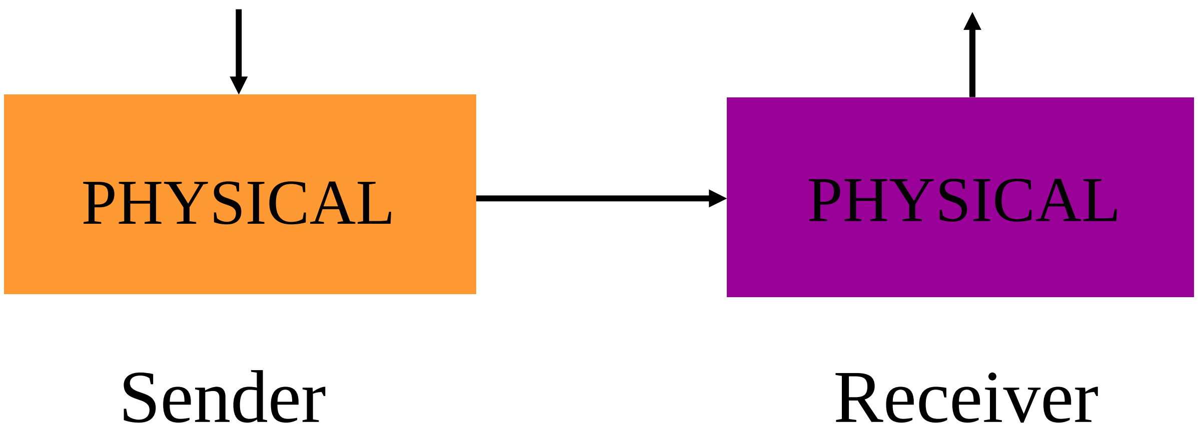
Simplified OSI Network Model

Source	Relay	Destination
APPLICATION		APPLICATION
TRANSPORT		TRANSPORT
NETWORK	NETWORK	NETWORK
LINK	LINK	LINK
PHYSICAL	PHYSICAL	PHYSICAL

Traditional View



The Bit Pipe



The Need for Cross-Layer Protocols: A Voice Message Example

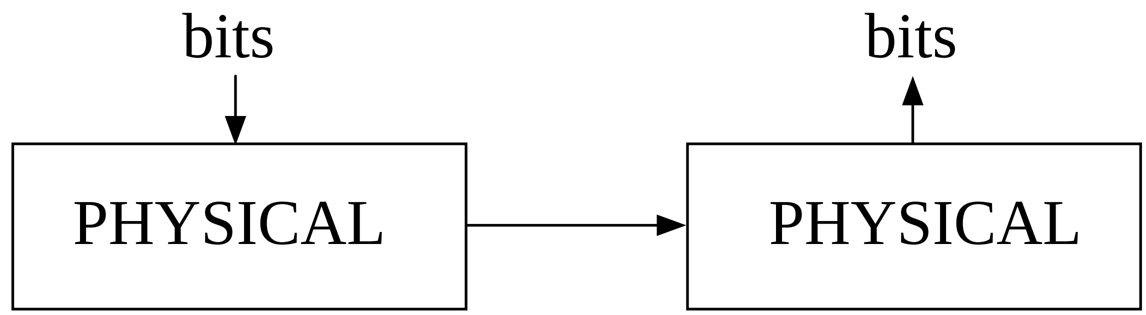
- Require low delay, some frame erasures acceptable
- Application layer: Speech compression must match available routes and links and satisfy QoS needs (intelligible speech vs. speaker recognition, etc.)
- Network layer: Routing should emphasize delay, high-quality (low bit error rate) routes not needed
- Link layer: Reserve multiple time slots on each link via the channel access (MAC) protocol. Detected errors may not result in a retransmission.
- Physical layer: Low-rate codes on poor links (avoid retransmissions), high-rate codes on good links (reduce delay), energy conservation secondary

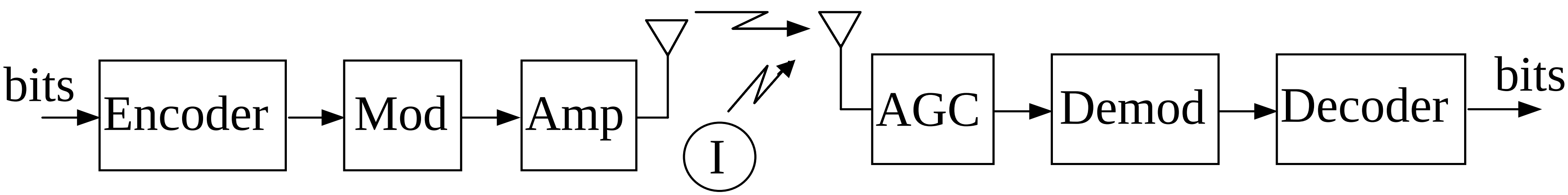
Cross-Layer Protocols: The Previous Millennium

Terminology (early 1980s to late 1990s):

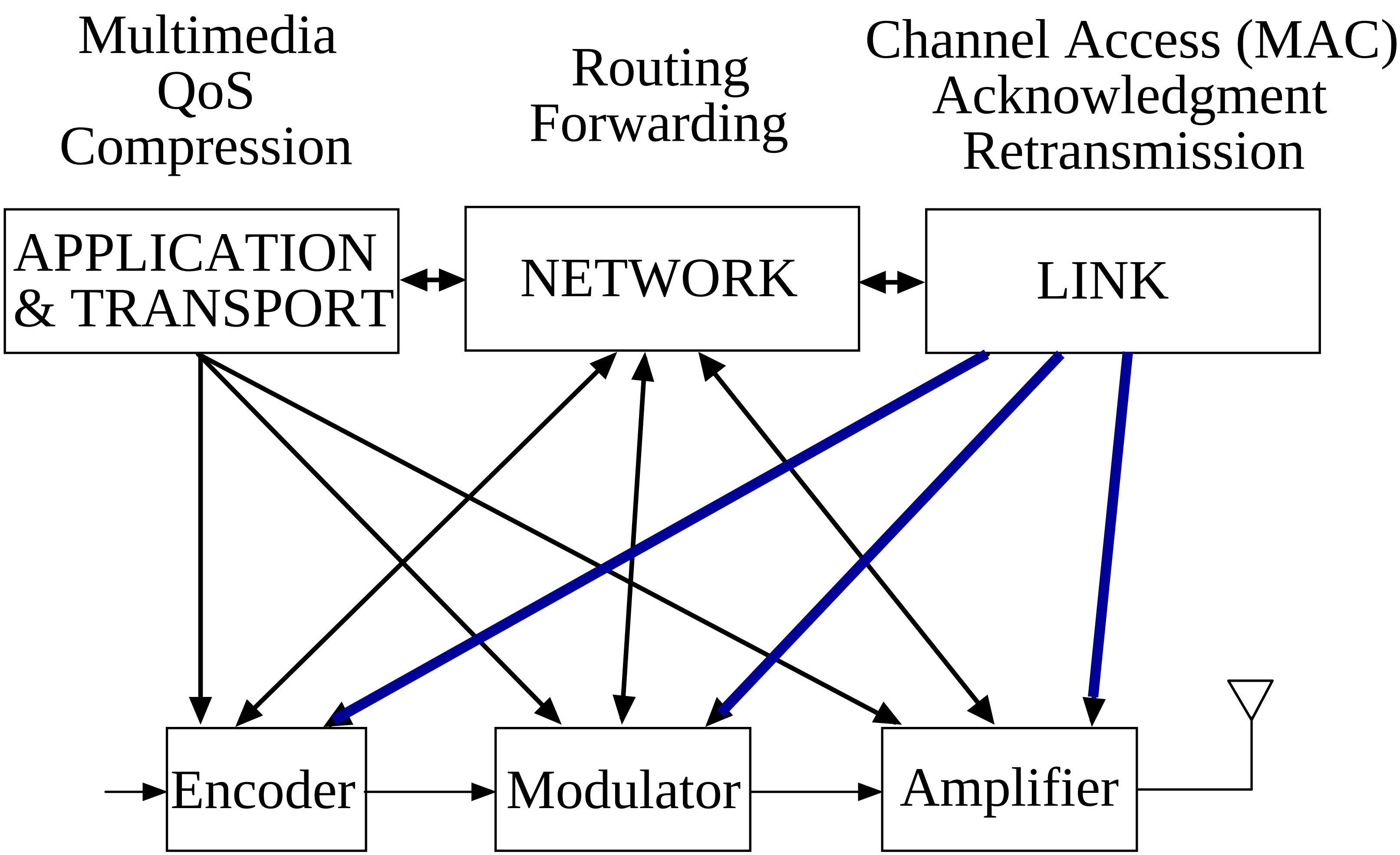
- Interaction between network operation and the communication subsystem
- Interaction between layers in the network model
- Interplay between spread spectrum and network protocols
- Network layer issues merging with link layer issues
- Interactions between the network layer and the link and physical layers in a spread-spectrum radio network
- Integration of physical-layer information into routing protocols; use of receiver side information in routing
- Tightly coupled protocols; interactive protocols; integrated protocols
- No particular name or phrase; layers simply ignored

A Look Inside the Bit Pipe for Wireless Communications

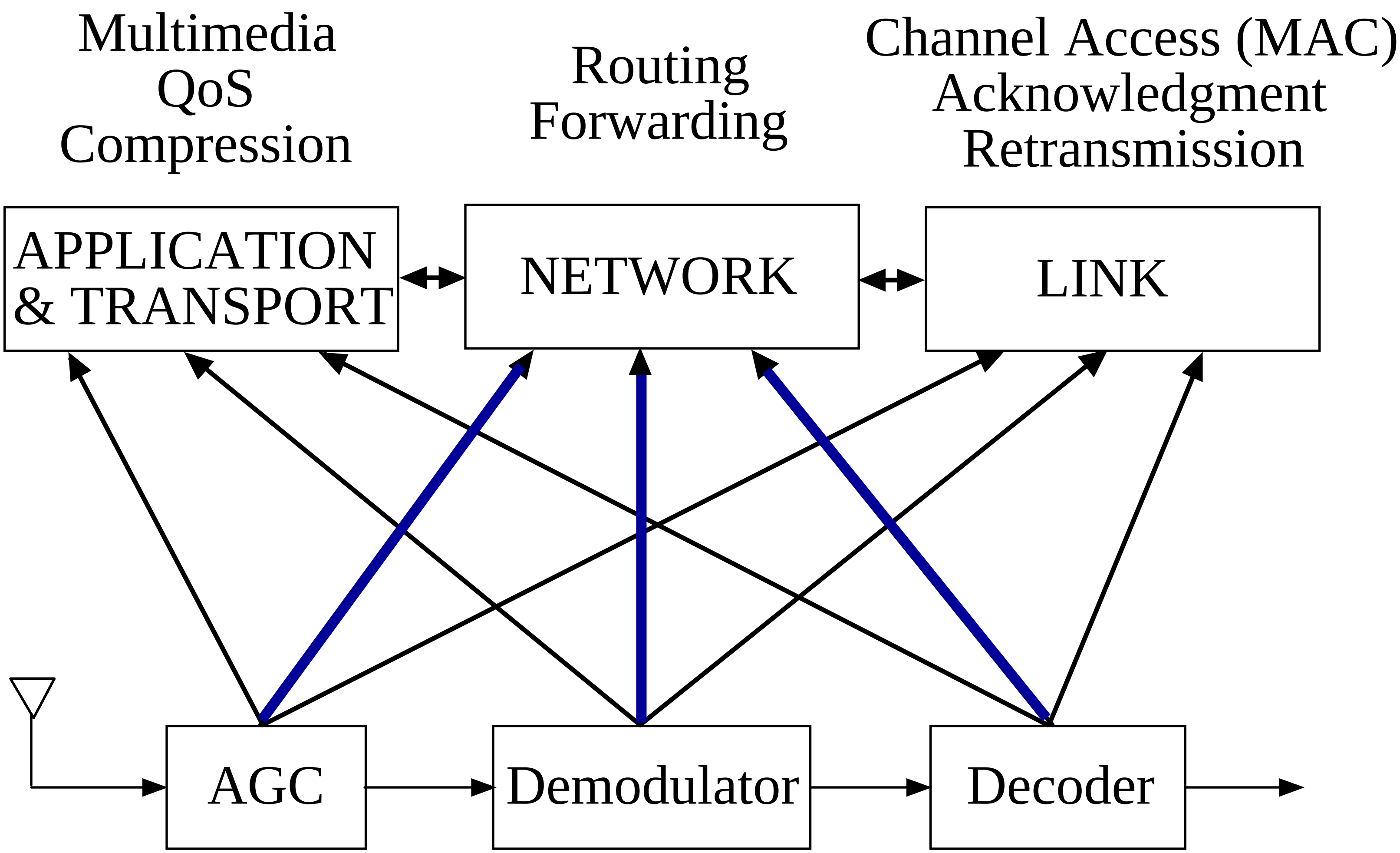


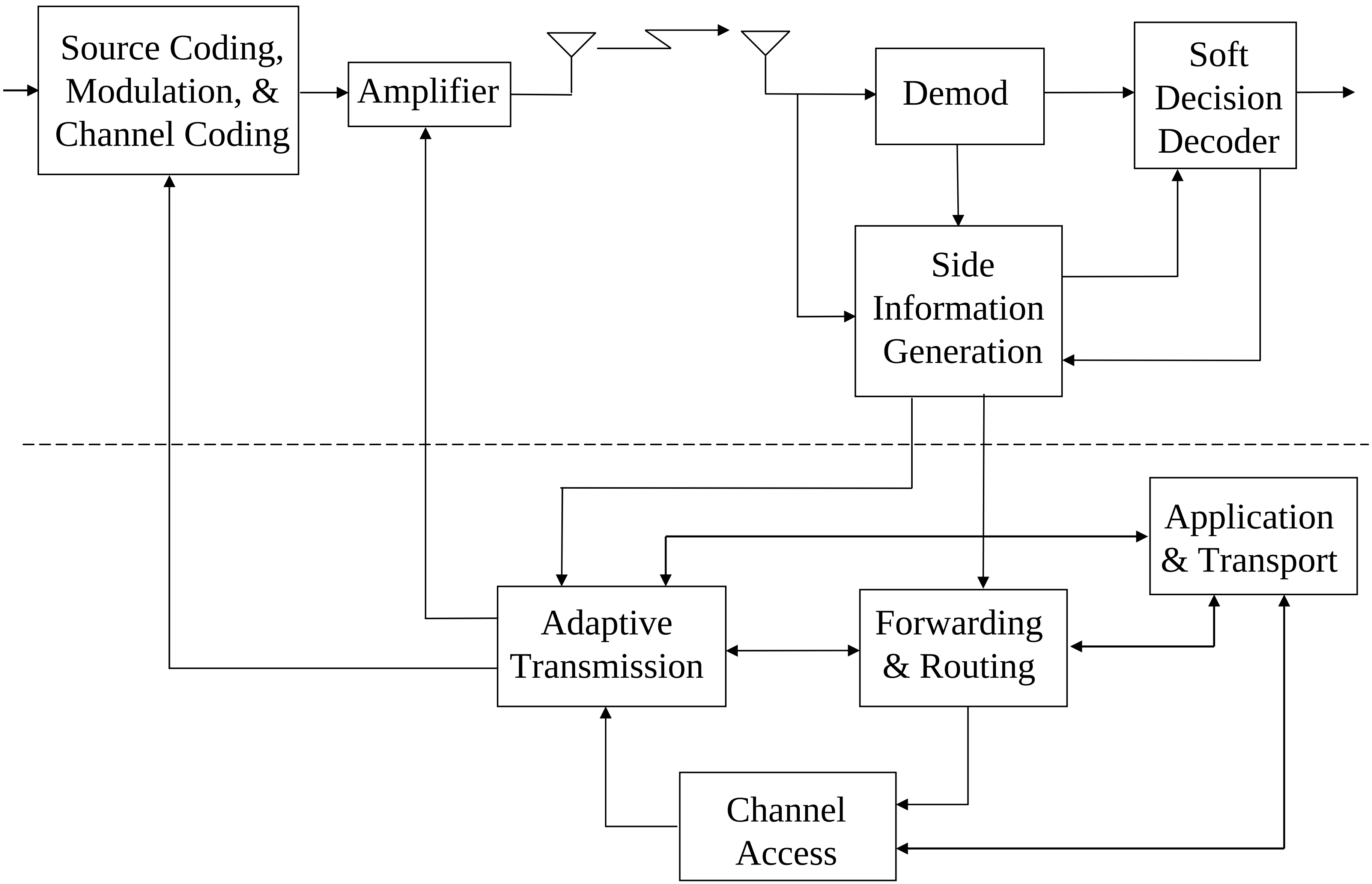


Some Interactions with the Sender's Physical Layer



Some Interactions with the Receiver's Physical Layer





Some of the Protocol Interactions

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Network and Traffic Characteristics

- Multiple-hop wireless spread-spectrum network
  - Store-and-forward relaying of packets required
  - Network must conserve energy (e.g., number of batteries)
- Frequency-hop or direct-sequence spread spectrum
- Dynamic environment
  - Variable propagation
  - Time-varying interference
- Multimedia traffic of three types
  - Delay-sensitive traffic, perhaps error-tolerant (e.g., voice)
  - Delay-tolerant, error-intolerant traffic (e.g., data)
  - Delay-tolerant, error-tolerant traffic (e.g., imagery)

The Need for Adaptivity

Time-Varying Transmission Requirements

network mobility
fluctuating traffic rate
multiple traffic types (multimedia)
variable propagation conditions
dynamic interference environment

source coding
error-control coding
symbol rate
modulation
spreading factor
transmit power

adaptive transmission
adaptive routing

Efficient Handling of Multimedia Traffic

- Adaptive transmission protocol
  - reduce energy and on-air time for delay-tolerant messages (e.g., decrease power, increase code rate)
  - increase reliability for delay-sensitive messages
- Adaptive routing protocol
  - conserve energy for delay-tolerant messages
  - sacrifice energy conservation for delay-sensitive messages

Cross-layer protocols for adaptive transmission and energy-efficient routing of multimedia traffic

Goals of Adaptive Transmission and Routing

- Make each communication link as energy and time efficient as possible
- Minimize detectability and interference for unintended recipients
- Supply routing protocol with energy-efficient paths
- Select routes that exploit differences in QoS requirements to conserve energy

Adaptive Transmission in Tactical Networks

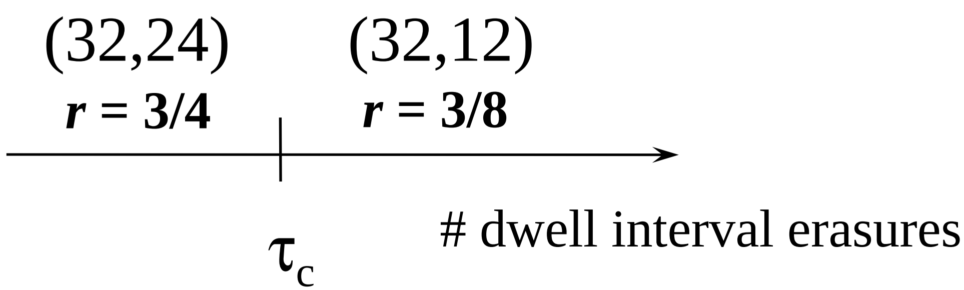
- Half-duplex radios: Feedback opportunities limited to ACK packets, reservation replies, control packets, etc.
- Channel adaptation: Primarily for such phenomena as changes in range, shadowing, and interference (not fast fading)
- QoS adaptation: Primarily for changes in QoS requirements from message to message when handling multimedia traffic
- Adapt to improve reliability when channel conditions deteriorate or when required for QoS
- Adapt to reduce power and on-air time when channel conditions improve and QoS requirements permit (e.g., to save energy, reduce interference, provide LPI)

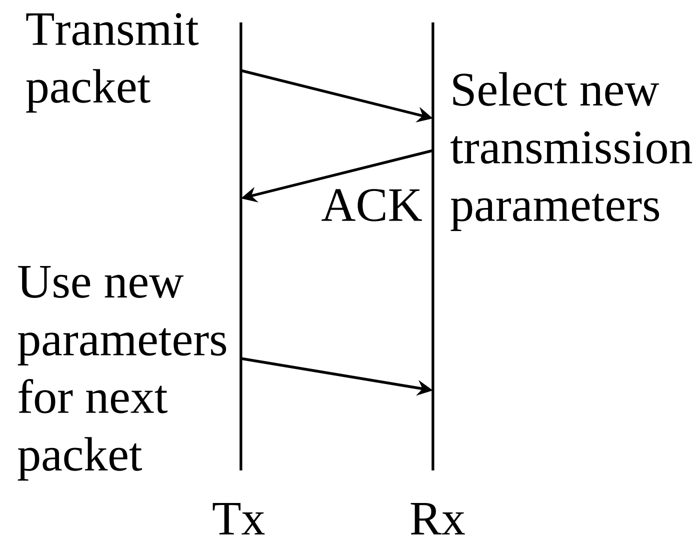
Protocol Suite for Frequency-Hop Spread Spectrum

- Channel Access Protocol: RTS/CTS/ACK
- Receiver-directed FH patterns
- Adaptive Transmission Protocol:
  - Use error count (*t*) and erasure count (*e*) to adapt code rate and transmit power
  - No power measurements needed
- Adaptive Routing Protocol:
  - Least-resistance routing (LRR) -- a distributed distance-vector routing protocol based on link resistance measures
  - Link resistance derived from metrics that account for link quality, energy consumption, and backlog
  - For multimedia traffic, link resistance depends on message type

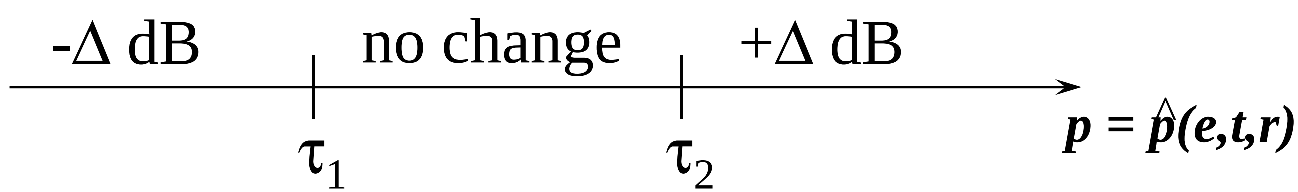
Adaptive Transmission Protocol for FH

- Code selection (RS codes) based on erasure count, *e*



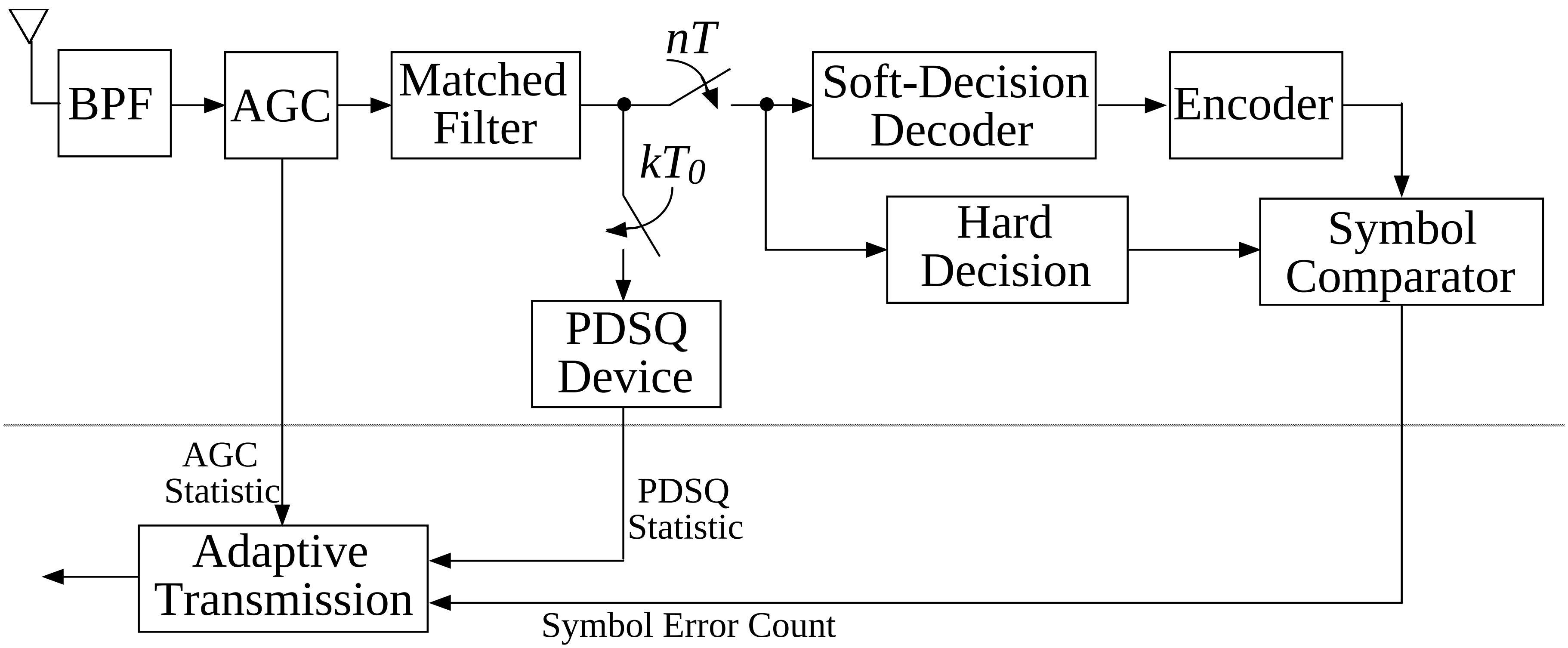


- Power selection based on *e*, *t*, and *r*



No power measurements needed!

Physical-Layer Statistics for Adaptive Transmission in Direct-Sequence Spread Spectrum



Performance Measures

- **Correct packet:** packet that is correct at intended receiver's decoder output

- **Unit of energy:** amount of energy required to transmit a packet at the lowest code rate and highest power (max energy/packet)

- **Throughput Efficiency (link):** Average number of correct packets at decoder output per unit of energy

Channel State Information for FH

Channel State (ρ,λ)

ρ = fraction of the band with interference

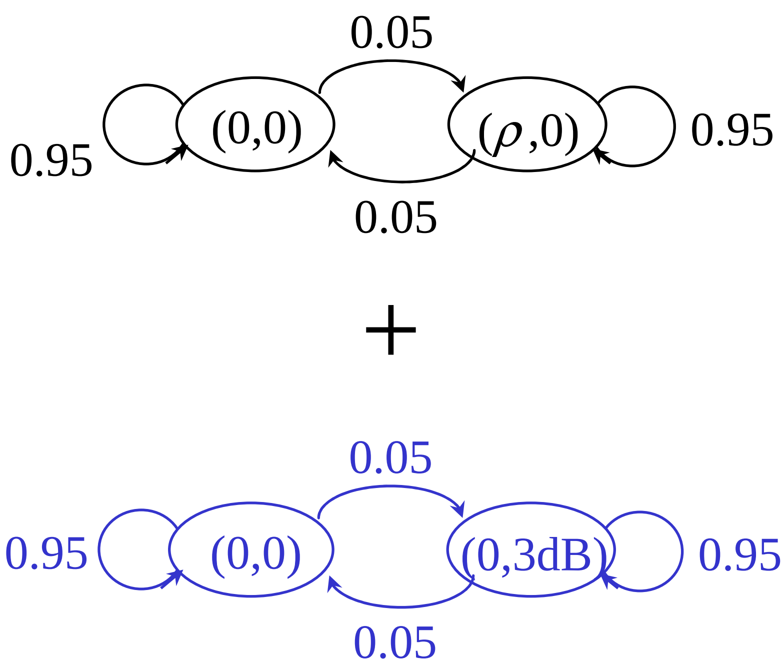
λ = propagation loss

Side Information - information about the channel state that is derived within the communication receiver

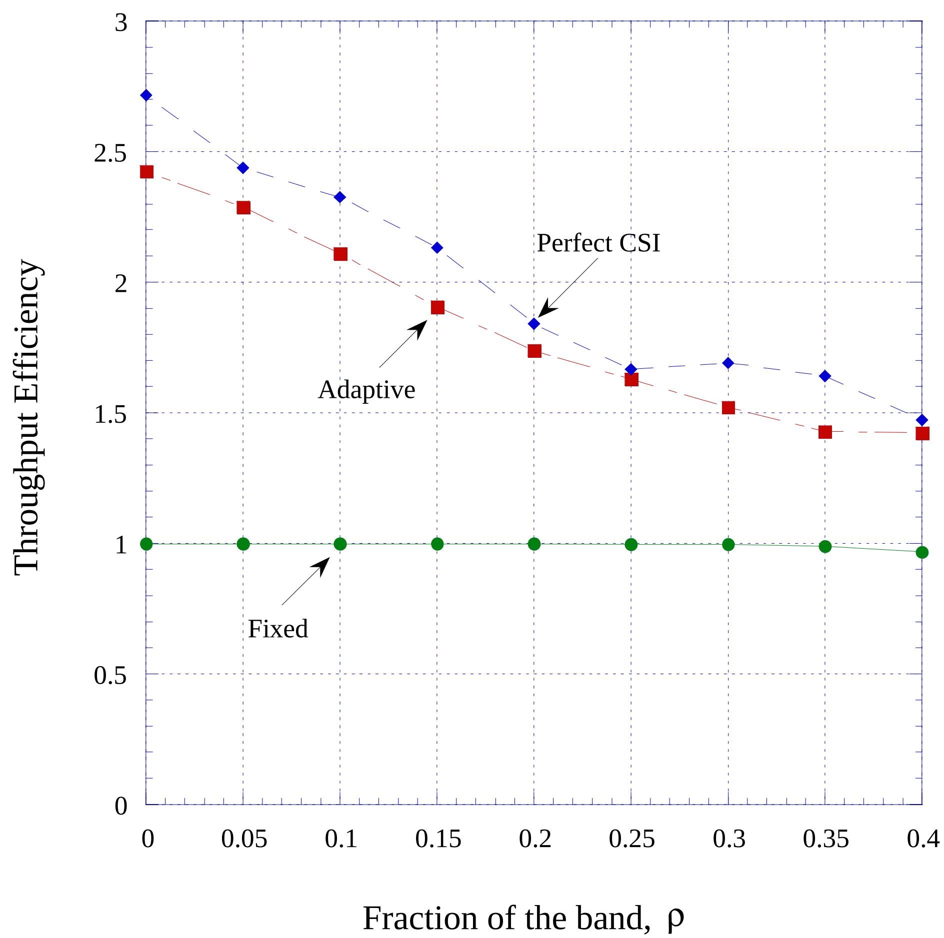
Channel State Information (CSI) - information about the channel state that is supplied from external sources (e.g., special measurement system)

Perfect CSI - exact values of ρ and λ for the previous transmission provided to the communication system

Channel with Intermittent Interference and Time-Varying Path Loss

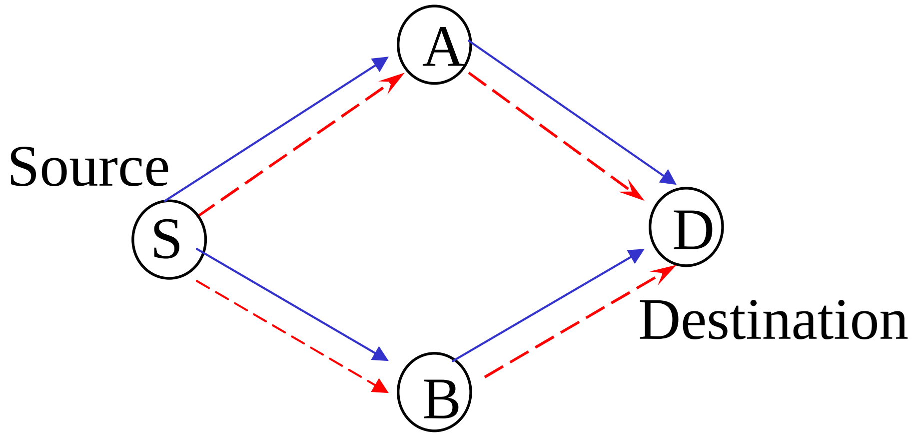


Channel Model



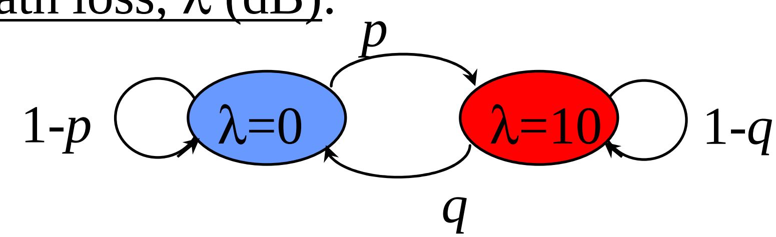
3 power levels, Δ = 1.5 dB

Routing with Adaptive Transmission Example: A Dynamic Four-Node Network



Channel State: (ρ, λ)

Path loss, λ (dB):



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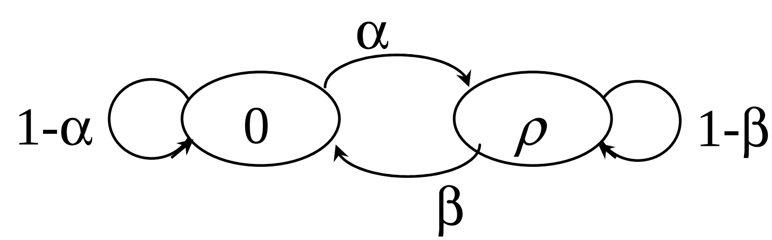
0 dB excess path loss

10 dB excess path loss

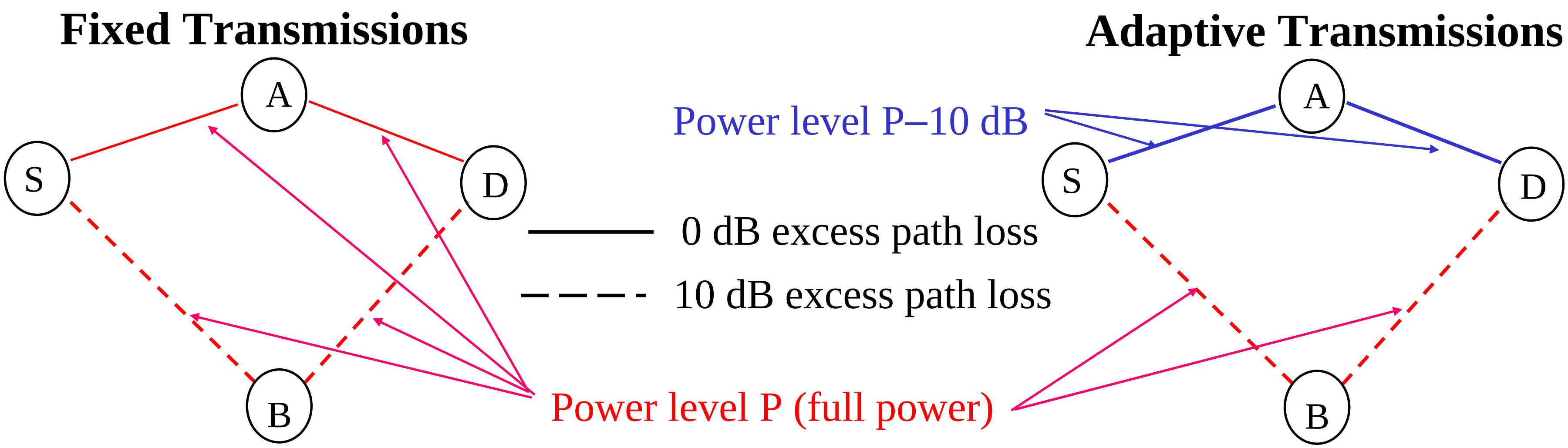
Full power adequate for 10 dB excess loss
Without adaptation, each link uses full power

Partial-band interference at terminal B:



ρ = fraction of band for interference at terminal B

Route Selection, Two Transmission Protocols

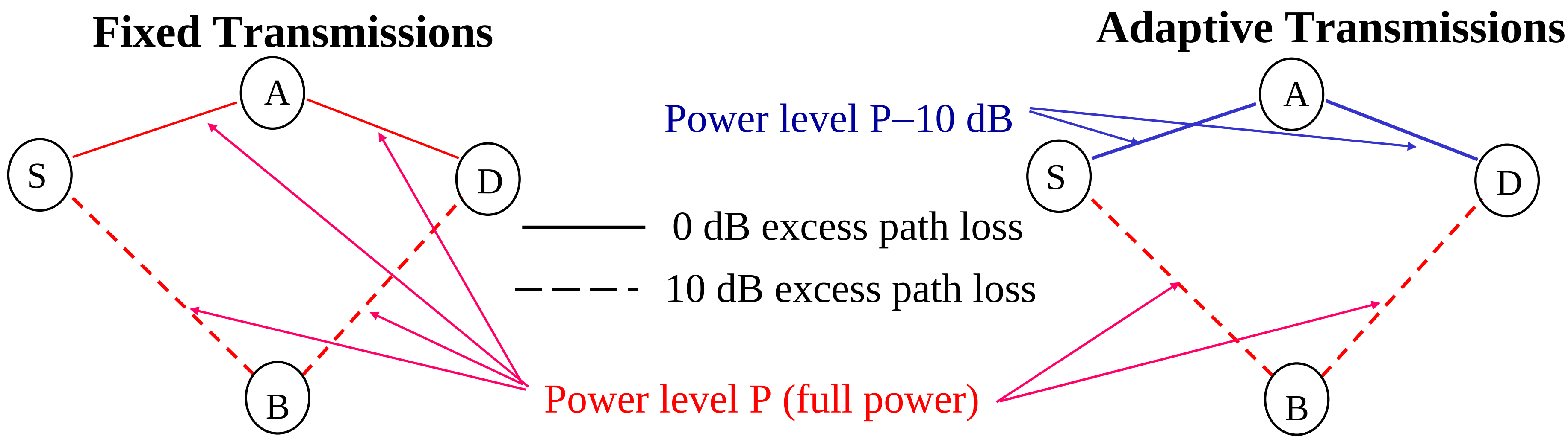


All packets routed from S to D

With fixed or adaptive transmissions:

- min-hop routing has no preference for upper vs. lower route
- error probability, throughput, delay same for both routes
- QoS routing has no preference for upper vs. lower route

Adaptive Transmission Creates an Opportunity



Adaptive Transmission: enables upper route to use only 1/10 the energy required by lower route; creates opportunity for routing protocol to save energy

Least-Resistance Routing with appropriate resistance metric takes advantage of opportunity created by adaptive transmission

Physical-layer information required for routing metrics and adaptive transmission

Resistance Metrics for Generic Traffic

- Quality metric (reception quality)
  - I(A,B) = (2t + e)/20   [max redundancy is 20 for code set]
  - # of errors (t) and erasures (e) in previous transmission
- Energy metric (energy consumption)
  - U(A,B) = P(A,B) $r_{\min}$ / $P_{\max}$ r(A,B)
  - $r_{\min}$ = min code rate; $P_{\max}$ = max transmitter power
  - r(A,B) = code rate for next transmission A$\rightarrow$ B
  - P(A,B) = power for next transmission A$\rightarrow$ B

$$LR(A,B) = \alpha_1 I(A,B) + \alpha_2 U(A,B) + c$$

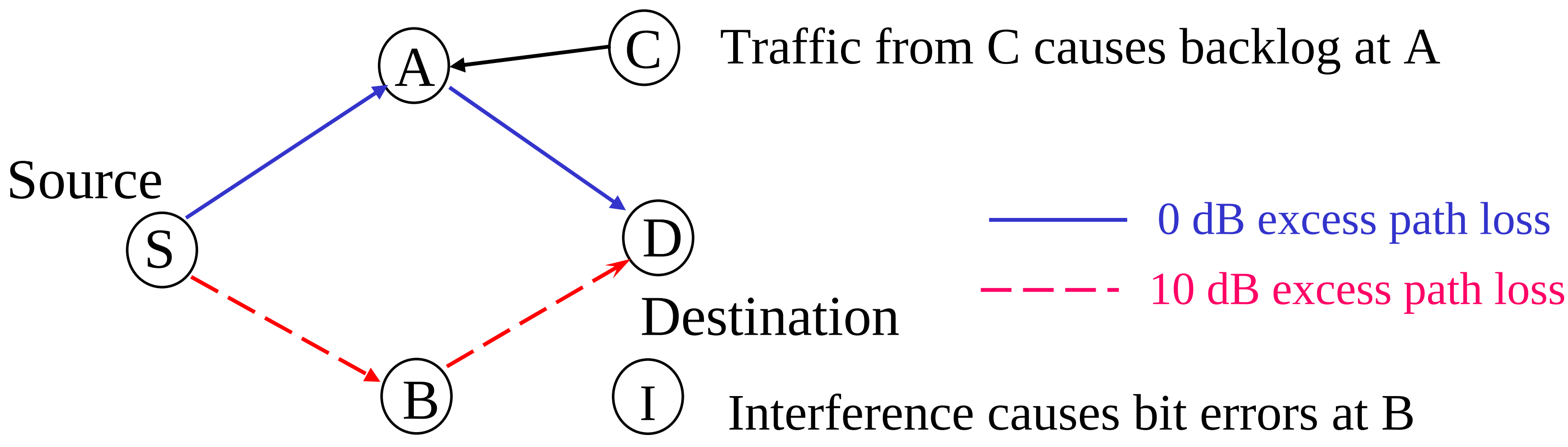
Four Resistance Measures

$$LR(A,B) = \alpha_1 I(A,B) + \alpha_2 U(A,B) + c$$

Resistance coefficients:

- quality: $\alpha_1 = 4$, $\alpha_2 = 0$, $c = 1$
  $$LR(A,B) = 4\ I(A,B) + 1$$
- energy: $\alpha_1 = 0$, $\alpha_2 = 10$, $c = 0$
  $$LR(A,B) = 10\ U(A,B)$$
- hybrid: $\alpha_1 = 2$, $\alpha_2 = 2.5$, $c = 1$
  $$LR(A,B) = 2\ I(A,B) + 2.5\ U(A,B) + 1$$
- min-hop: $\alpha_1 = 0$, $\alpha_2 = 0$, $c = 1$; $LR(A,B) = 1$

Multimedia Considerations in LRR



Voice traffic (previous example) and data traffic from S to D:

- Backlog at A causes delay for route S-A-D, but S-A-D suitable for data traffic; energy conserved if data packets use S-A-D
- Interference causes frame erasures in voice traffic sent over S-B-D, but meets QoS requirements for voice; S-B-D requires more energy
- Approach: Conserve energy for data packets, sacrifice energy conservation for voice packets to meet delay constraint
- Requires interaction among Application/Transport, Network, Link, and Physical Layers

Resistance Measures for Multimedia Traffic

- Each type of traffic routed independently
- Resistance measure tailored to service requirements
  - Emphasize energy consumption for delay-tolerant traffic
  - Emphasize backlog at nodes for delay-sensitive traffic
- MM resistance measures (link $A \rightarrow B$):

$$LR_d(A,B) = 2\, I(A,B) + 8\, U(A,B) + c_d$$

$$LR_v(A,B) = 4\, I(A,B) + W(B) + 2.5\, U(A,B) + c_v$$

- Backlog metric for terminal B:

$$W(B) = N_v + \omega N_d$$

N_i = # packets of type i (voice or data) in B's buffer

Performance Measures

Correct packet: packet that is correct at destination receiver's decoder output

Unit of energy: amount of energy required to transmit a packet at the lowest code rate and highest power (max energy/packet)

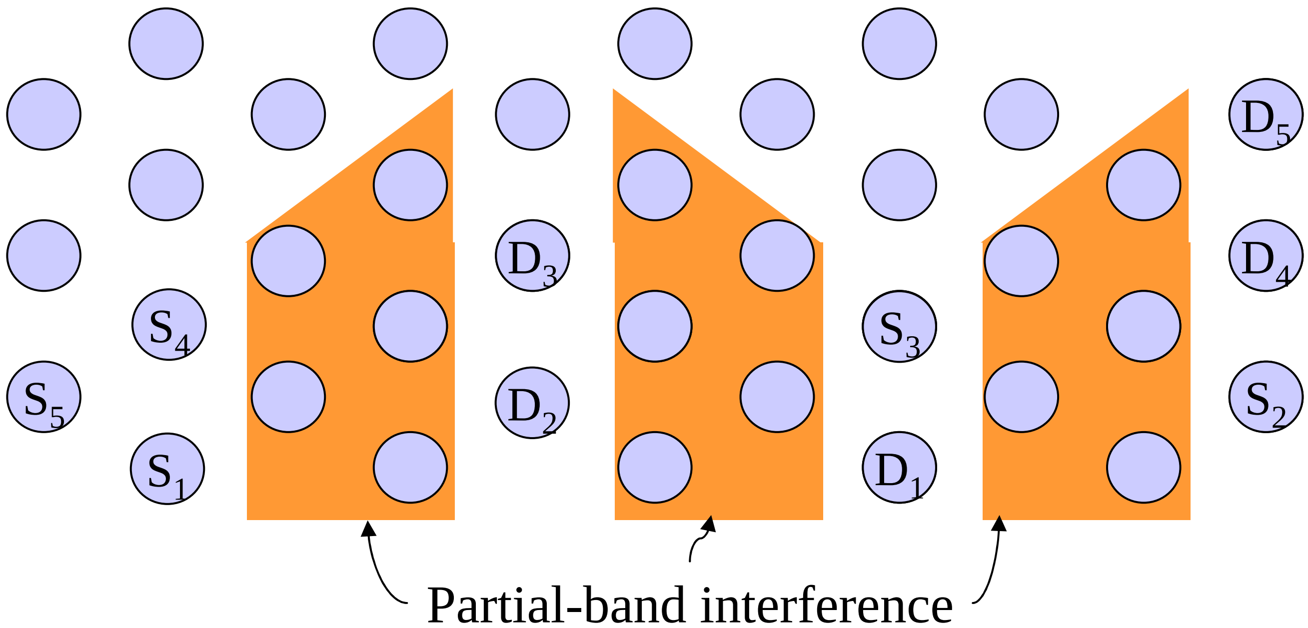
- **Throughput Efficiency (network):** Average number of correct packets at decoder output of destination terminal per unit of energy transmitted by all terminals in network

Generic vs. Multimedia Traffic

- Simply minimizing energy gives poor performance
- Routing based on link quality and min-hop routing give poor throughput efficiency
- Hybrid quality-energy routing is best compromise for generic traffic

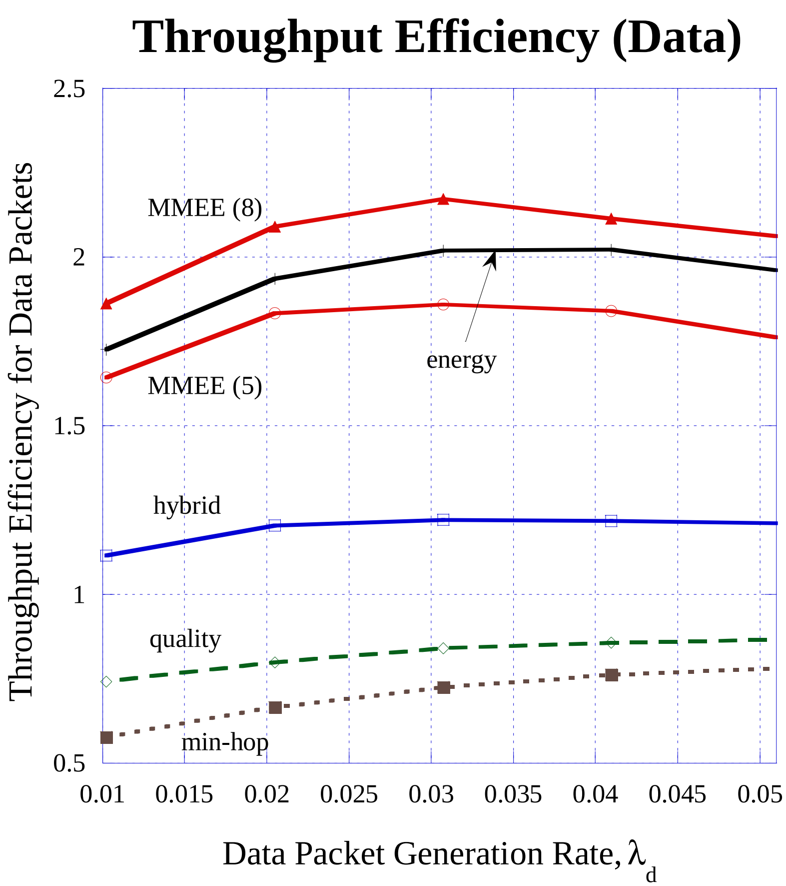
- Emphasize conserving energy for delay-tolerant messages
- Can sacrifice energy conservation for delay-sensitive messages
- Multimedia energy-efficient (MMEE) routing

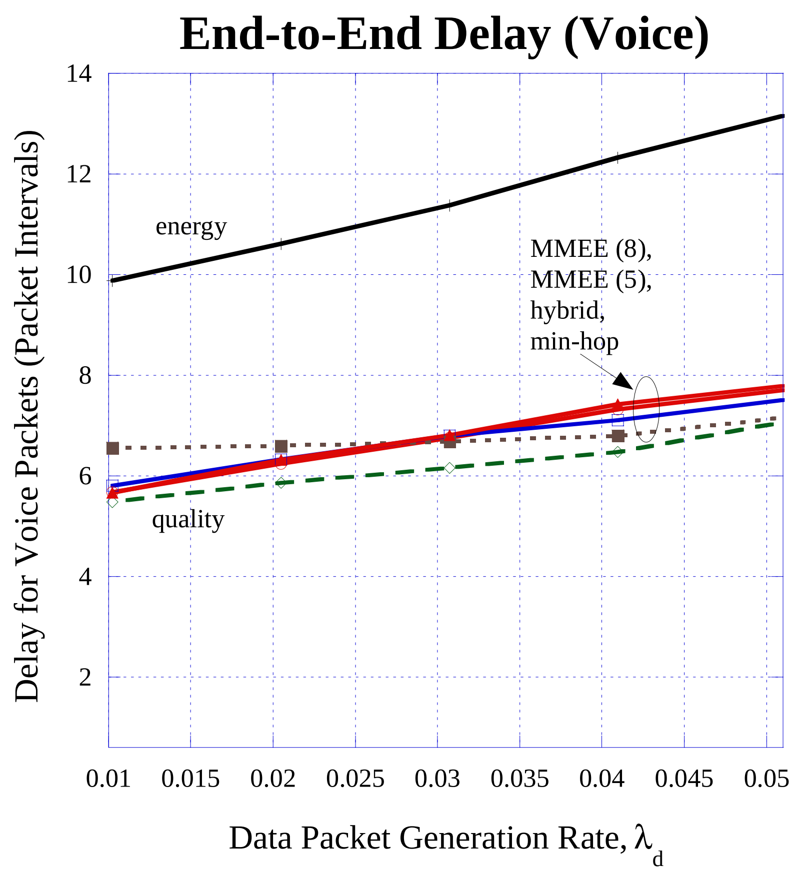
38-Node Network



- Node S_i generates voice packets for destination D_i
- Unlabeled nodes generate data packets with random destinations
- Interference occupies 20% of band, affects 15 nodes
- Network uses adaptive transmission (2 code rates, 8 power levels)

Performance of MMEE Routing for 38-Node Network with Multimedia Traffic

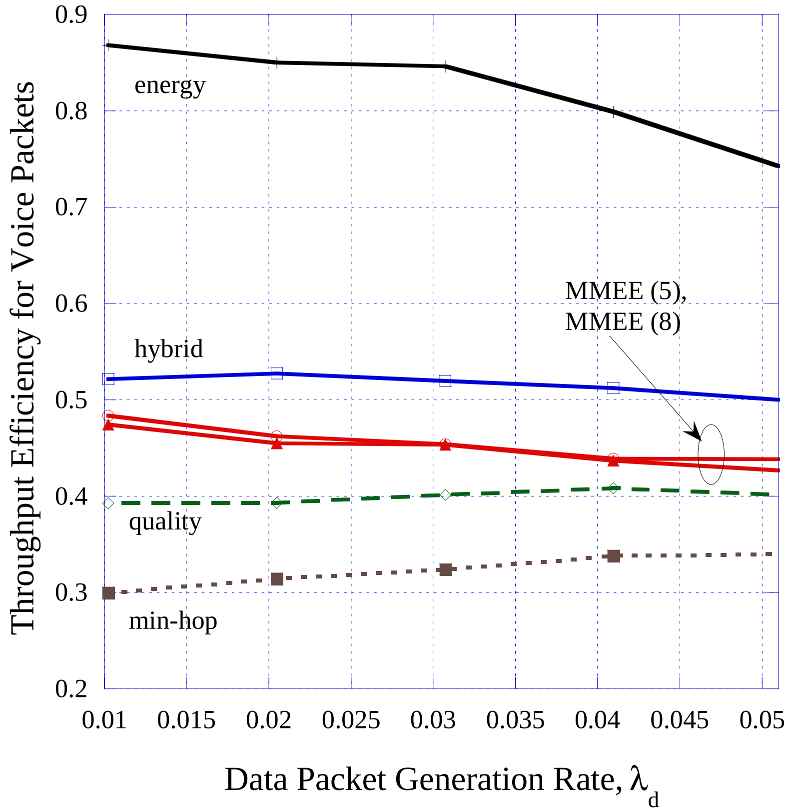




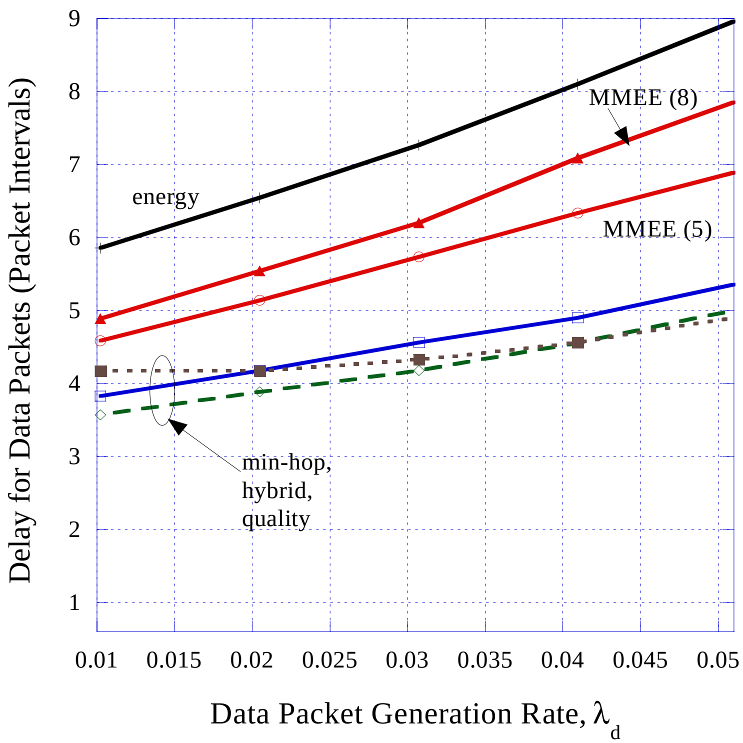
Voice traffic generated at fixed rate of 0.01 packets/packet interval

Performance of MMEE Routing for 38-Node Network with Multimedia Traffic

Throughput Efficiency (Voice)



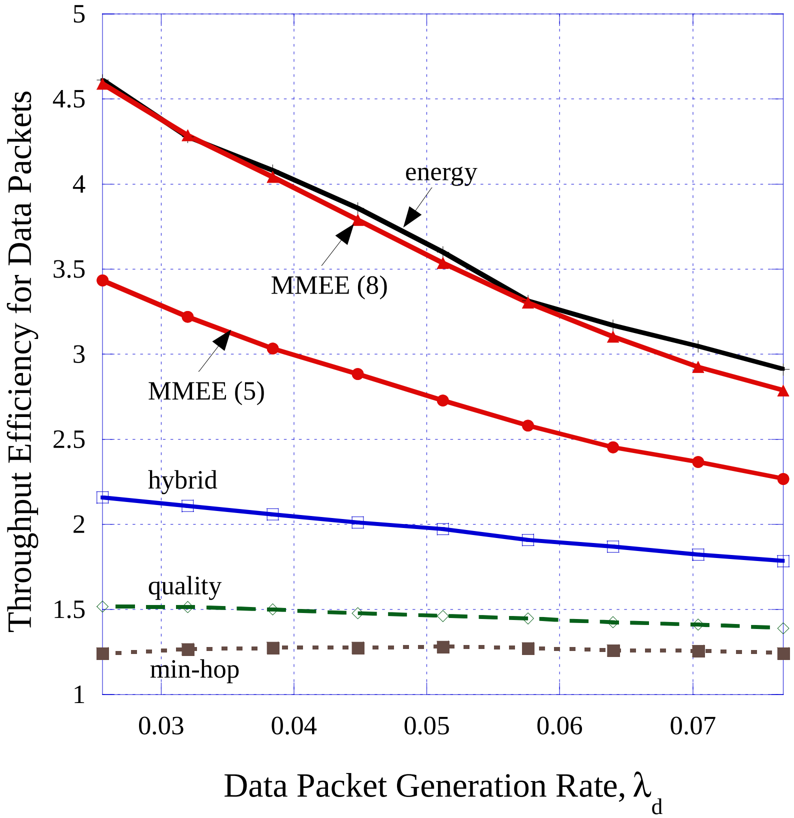
End-to-End Delay (Data)



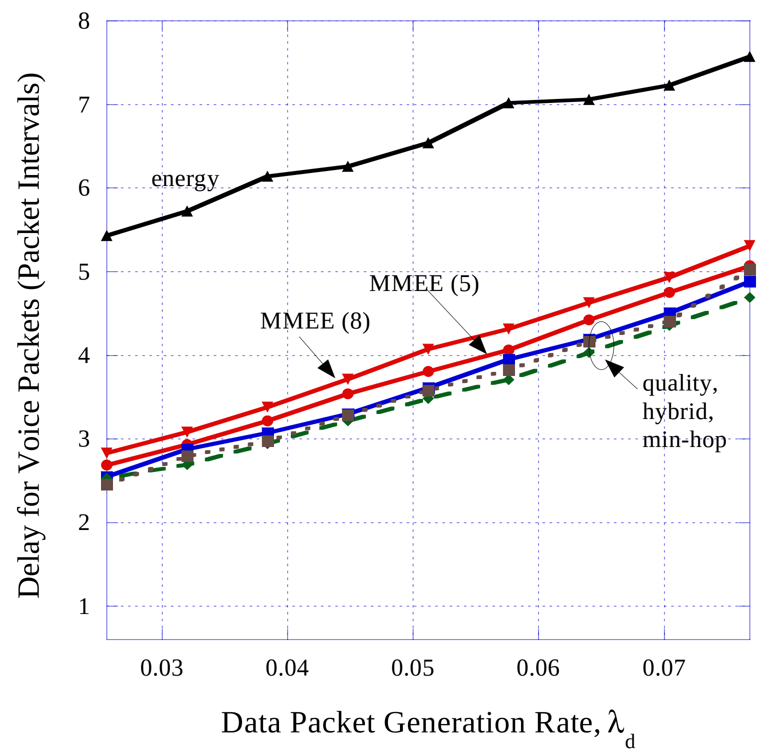
Voice traffic generated at fixed rate of 0.01 packets/packet interval

Performance of MMEE Routing for 65-Node Network with Multimedia Traffic

Throughput Efficiency (Data)



End-to-End Delay (Voice)



- 45 nodes generate data traffic with uniformly random destinations; 10 voice connection pairs
- packet generation rates are in packets per packet interval; voice generation rate is twice λ_d

General Conclusions

- Hybrid quality-energy measure is the best compromise for generic traffic
- MM resistance measures lead to high throughput efficiency for delay-tolerant traffic and low delay for delay-sensitive traffic
- Best resistance measures for multimedia traffic are the MM resistance measures
- Interaction among layers is essential for energy-efficient routing of generic or multimedia traffic