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## Abstract
See also ADM002082., The original document contains color images.

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- Report: unclassified
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
Simplified OSI Network Model

Source
- APPLICATION
- TRANSPORT
- NETWORK
- LINK
- PHYSICAL

Relay
- NETWORK
- LINK
- PHYSICAL

Destination
- APPLICATION
- TRANSPORT
- NETWORK
- LINK
- PHYSICAL

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Traditional View

Source

APPLICATION

TRANSPORT

NETWORK

LINK

PHYSICAL

Relay

NETWORK

LINK

PHYSICAL

Destination

APPLICATION

TRANSPORT

NETWORK

LINK

PHYSICAL

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The Bit Pipe

Sender

PHYSICAL

Receiver

PHYSICAL

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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

bits
Encoder → Mod → Amp → AGC → Demod → Decoder → bits

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Some Interactions with the Sender’s Physical Layer

Multimedia QoS Compression

Routing Forwarding

Channel Access (MAC) Acknowledgment Retransmission

APPLICATION & TRANSPORT

Encoder Modulator Amplifier

NETWORK

LINK
Some Interactions with the Receiver’s Physical Layer

- Multimedia
- QoS
- Compression

APPLICATION & TRANSPORT

- AGC

NETWORK

- Routing
- Forwarding

LINK

- Channel Access (MAC)
- Acknowledgment
- Retransmission

Decoder

Demodulator

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Some of the Protocol Interactions

Source Coding, Modulation, & Channel Coding

Amplifier

Demod

Soft Decision Decoder

Side Information Generation

Adaptive Transmission

Forwarding & Routing

Channel Access

Application & Transport

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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, $e$
  
  $\begin{align*}
  (32,24) & \quad (32,12) \\
  r = 3/4 & \quad r = 3/8 \\
  \tau_c & \quad \text{# dwell interval erasures}
  \end{align*}$

- Power selection based on $e$, $t$, and $r$
  
  $\begin{align*}
  -\Delta \text{ dB} & \quad \text{no change} & \quad +\Delta \text{ dB} \\
  \tau_1 & \quad \tau_2 & \quad p = \hat{p}(e,t,r)
  \end{align*}$

No power measurements needed!
Physical-Layer Statistics for Adaptive Transmission in Direct-Sequence Spread Spectrum

BPF → AGC → Matched Filter → $nT$ → Soft-Decision Decoder → Encoder → Symbol Comparator

AGC Device → nT → kT₀

Adaptive Transmission

AGC Statistic → PDSQ Statistic

Symbol Error Count
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 \((\rho, \lambda)\)

\(\rho = \) fraction of the band with interference
\(\lambda = \) 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 \(\rho\) and \(\lambda\) for the previous transmission provided to the communication system
Channel with Intermittent Interference and Time-Varying Path Loss

Channel Model

3 power levels, $\Delta = 1.5$ dB

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Routing with Adaptive Transmission

Example: A Dynamic Four-Node Network

Channel State: $(\rho, \lambda)$

Path loss, $\lambda$ (dB):

$1-p$ \hspace{1cm} $\lambda=0$

$p$ \hspace{1cm} $\lambda=10$

$1-q$

Partial-band interference at terminal B:

$1-\alpha$ \hspace{1cm} $0$

$\alpha$ \hspace{1cm} $\rho$

$\beta$ \hspace{1cm} $1-\beta$

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

$\rho = \text{fraction of band for interference at terminal B}$

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Route Selection, Two Transmission Protocols

Fixed Transmissions

Adaptive Transmissions

Power level $P - 10$ dB

0 dB excess path loss

10 dB excess path loss

Power level $P$ (full power)

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:

**Fixed Transmissions**

- **Power level P (full power)**

**Adaptive Transmissions**

- **Power level P −10 dB**

0 dB excess path loss
10 dB excess path loss

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)**
  - $I(A,B) = \frac{(2t + e)}{20}$ [max redundancy is 20 for code set]
  - # of errors ($t$) and erasures ($e$) in previous transmission

• **Energy metric (energy consumption)**
  - $U(A,B) = \frac{P(A,B)}{P_{\max}} \frac{r_{\min}}{r(A,B)}$
  - $r_{\min} = \text{min code rate}; \ P_{\max} = \text{max transmitter power}$
  - $r(A,B) = \text{code rate for next transmission } A \rightarrow B$
  - $P(A,B) = \text{power for next transmission } A \rightarrow B$

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

Source
S

Traffic from C causes backlog at A

C

Destination
D

Interference causes bit errors at B

B

I

0 dB excess path loss

10 dB excess path loss
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→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:
  \[ W(B) = N_v + \omega N_d \]
  \[ N_i = \# \text{ packets of type } i \text{ (voice or data) in B’s buffer} \]
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
• 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

Throughput Efficiency (Data)

End-to-End Delay (Voice)

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)

- Energy
- Hybrid
- Quality
- Min-hop

End-to-End Delay (Data)

- Energy
- Min-hop, hybrid, quality

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

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

- 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 $\lambda_d$

Throughput Efficiency (Data) vs. Data Packet Generation Rate, $\lambda_d$

End-to-End Delay (Voice) vs. Data Packet Generation Rate, $\lambda_d$
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