Cross-Layer Design and Analysis of Wireless Networks

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University of Michigan

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Report Documentation Page

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

• Introduction
• Network and Physical Layer Design
• MAC and Physical Layer Design
Layered Approach

Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer
Why cross-layer design?

• Significant performance advantages (e.g. 10 dB in certain situations).
• Forces designers to consider other layers.
• Layers are coupled.
What causes coupling?

- Energy constraints.
- Delay constraints.
- ...
Why not cross-layer design?

• Difficulty.
• Lack of insight into design.
• Generally requires near brute-force simulation/optimization if several layers are considered simultaneously.
Amplifier Characteristics

![Graphs showing amplifier characteristics](image)

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Propagation Characteristics

\[ P_r = P_t \left( \frac{\lambda_c}{4\pi d} \right)^2 4G_tG_r \sin^2 \left( \frac{2\pi h_t h_r}{\lambda_c d} \right) \approx \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \]
Two cross layer problems

• **Problem 1:** Network routing algorithm: For fixed total energy maximize the normalized throughput between source and destination while accounting for amplifier characteristics, physical layer performance and processing energy at receiver.

• **Problem 2:** Determine the tradeoff between energy and delay in wireless networks taking into account the MAC and physical layers.
Routing Protocol
Routing Protocol
Routing Protocol

[Diagram of a network with labeled nodes S and D, and multiple intermediate nodes connected by lines, representing a routing protocol.]
Simplified Network Model
Amplifier Model

\[ P_{DC} \]

\[ P_t \]

\[ P_h \]

\[ P_{in} \]
Packet Error Rate (Packet Length=224)
Assumptions/Notation

- Total energy available for all the nodes in the linear network = $B$ (joules).
- Independent errors at different nodes.
- Energy $E_r$ for processing each packet at a receiver.
- Number of hops = $k$.
- Packet duration = $T_p$.
- Code rate = $R$ (bits/channel use).
- $P_{DC} = f(P_{in})$. 

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Performance Measure

- Expected number of successfully received bits per unit bandwidth and time.

\[
\frac{E_p}{N_0} = \frac{G_t G_r h_T^2 h_r^2}{N_0 (d/k)^4} T_p (P_{DC} - P_h)
\]

\[
S = \left( \frac{BR}{k(T_p P_{DC} + E_r)} \right)^k P_s \left( \frac{E_p}{N_0}, R \right)
\]

- Number of packets that can be transmitted end-to-end
- Number of Hops
- Packet Success Probability
- Energy used per hop (transmission and reception)
Optimization

\[ S^* = \max_{P_{in}, R, k} S(P_{in}, R, k) \]
Main Result (large $d$)

$$S^* = \frac{\delta}{d}$$

- Functional form of throughput independent of
  - Error Control Coding Scheme
  - Modulation
  - Channel (Fading, Propagation Characteristics)
  - Amplifier Characteristics

- Specific constant $\delta$ depends on all of the above.
Throughput vs. Distance (Uncoded)
Throughput vs. Distance (Uncoded)
Throughput vs. Distance
(Convolutional Code, Rate 1/2)
Throughput vs. Distance (Capacity at Optimum Rate)
Optimum Rate vs. Distance
Throughput vs. Distance (Comparison)
Conclusion: First Problem

• Optimum rate in AWGN close to 1.
• Uncoded better than rate 1/2 coded at optimum distance but requires higher density of nodes.
• Amplifier operating point is not an extreme point of amplifier characteristics.
• For other channels (e.g. faded channels) optimum rate will likely decrease.
• This problem encompasses physical layer and network layer issues.
Second Problem

• Determine the tradeoff between energy and delay in wireless networks taking into account the MAC and physical layers.
ARQ Protocol

Data: $K$  Parity: $N-K$

$R = \frac{K}{N}$

noisy channel

ACK/NACK

error-free channel
Average Energy and Average Delay

\[
\bar{E}_b \frac{E_c}{N_0 R} = 1 - P_e \left( \frac{E_c}{N_0}, R \right)
\]

\[
\bar{D} = \frac{N}{1 - P_e \left( \frac{E_c}{N_0}, R \right)}
\]
Goal

• For a fixed number of information bits, $K$, determine the optimal number of coded bits, $N$, to minimize the delay.

• Note: The $N$ that minimizes the delay also minimizes the energy.

$$\min_{N} \bar{D} = \min_{N} \left[ \frac{N}{1 - P_e \left( \frac{E_c}{N_0}, \frac{K}{N} \right)} \right]$$
Packet Error Probability Bounds

\[ P_e\left(\frac{E_c}{N_0}, R\right) \leq 2^{-N(R_0-R)} = 2^K 2^{-NR_0} \]

For an additive white Gaussian noise channel

\[ R_0 = 1 - \log_2(1 + e^{-\frac{E_c}{N_0}}) \]
Notes

• Turbo codes and LDPC codes can achieve better than the cutoff rate.
• Convolutional codes are far from cutoff rate for large block length.
• Reed-Solomon codes have near exponential dependence on $N$
Delay vs. Blocklength

![Graph showing the relationship between delay and blocklength with two labels: Large $E_c/N_0$ and Small $E_c/N_0$.]
Main Result

For large $K$ (compared to 1) at the optimum packet length ($N^*$) the resulting error probability is a constant.

$$P_e\left(\frac{E_c}{N_0}, \frac{K}{N^*}\right) = \frac{1}{1 + K \ln(2)}$$
Delay-Energy Tradeoff

\[
R^* = \frac{R_0}{1 + \frac{1}{K} \log_2(1 + K \ln(2))}
\]

\[
D^* \approx \frac{K}{R_0} \left[ 1 + \frac{\log 2(K \ln(2))}{K} \right]
\]

\[
\frac{E_b}{N_0} \approx \frac{E_c}{N_0 R_0} \left[ 1 + \frac{\log 2(K \ln(2))}{K} \right]
\]
Comments on Result

• This result is independent of the channel model and modulation technique (e.g. coherent, noncoherent, faded) except that the channel is memoryless.
• The resulting minimum average energy and delay depend on the above characteristics.
• Result implies that larger payloads ($K$) should try to achieve a smaller error probability.
Example: K=100

Approximation
Delay-Energy

![Graph showing the relationship between delay and energy efficiency](image-url)
Extension to Include MAC Layer

Node A wants to transmit a message to Node B. Node C wants to transmit a message to Node D. Without coordination Node C’s signal will interfere with A’s transmission to Node B. Node C might start its transmission after A has already begun transmitting because C cannot hear Node A’s signal. This is the hidden node problem.
RTS/CTS Mechanism

- A transmits to B an RTS (request-to-send) packet.
- If B successfully decodes the RTS packet then B transmits a CTS (clear-to-send) packet indicating the upcoming transmission of data from A to B.
- Both A and C hear the CTS and now A knows that it is clear to send a packet to B.
RTS/CTS Mechanism

DATA  ACK

A  B  C  D
Problem

• Determine the delay vs. energy for different number of users.
• For fixed data length, RTS, CTS, ACK lengths determine optimal packet sizes $N_{DATA}, N_{RTS}, N_{CTS}, N_{ACK}$.
• Similar approximations for large $K$ can be obtained for optimum $P_{e,RTS}, P_{e,CTS}, P_{e,ACK}$.
Result

- We have developed an analytical framework to evaluate the joint distribution of energy and delay of the RTS/CTS protocol in a noisy channel.
- Similar approximations to single user case.
- Assumptions
  - All $n$ users have packets ready (heavy-load assumption).
  - All users can hear all other users.
  - Memoryless channel.
  - No multiuser reception/detection capability.
  - Only transmit energy is considered.
Numerical Results (10 users)
Interpretation

For short packets the fractional overhead to access the channel becomes larger.
Numerical Results ($K_{DT}=6400$)
“Basic Protocol”

- Eliminate RTS/CTS
- Listen before send.
- If collision of data packet then wait a random (exponential) backoff time before retransmission.
Comparison with “Basic Protocol”

\[ \frac{E_c}{N_0} \ (dB) \]

- Basic
- Better
- RTS/CTS
- Better

Threshold \( K_{DT} \)

- \( n=10 \)
- \( n=20 \)
Interpretation of Results

- For a larger number of users there is a lower threshold for switching between the basic protocol and RTS/CTS protocol.
- For larger energy per coded bit, the transmission rate becomes larger. The larger rate implies a shorter time to transmit a given number of bits. A shorter duration for transmission of the data packet increases the relative burden needed to transmit the RTS/CTS packets. So the threshold of packet length where RTS/CTS is better becomes larger.
Conclusion

• Have shown certain invariants (optimum distance, optimum error probability).
• By considering a couple layers joint design/optimization and analysis is possible.
• Insight into performance analysis can be obtained.
• Still need to consider many other factors (power control, data rate control, multiple-access capability of modulation and coding).
• There are many open and interesting problems in cross-layer design.