Goodput Analysis and Link Adaptive for IEEE 802.11a Wireless LANs

IEEE Trans. on Mobile Computing 2002

Author: D. Qiao, S. Choi, and K. G. Shin
Suggested Readings

- “A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless Lan Standards”, IEEE Communications Magazine, 2002

- IEEE Std 802.11a-1999 (only 39 pages)
Motivations

Many impediments make communications over wireless channels very difficult

- Limited available bandwidth
- Channel fading varies with time and locations
- Thermal noise and interference
- User mobility

Link adaptation
- Use different modulation and coding scheme in different channel conditions
- Mitigate the impediments
- Maximize system performance (goodput)
- Included in 3G, wireless LANs, wireless MANs systems

![Graph showing SNR over time for different modes](Image)
Outline

- Brief Review of IEEE 802.11a
- Related Work
- Goodput Analysis of an IEEE 802.11a DCF System
- Proposed MPDU-based Link Adaptation Scheme
- Performance Evaluation
- Conclusion & Limitation
IEEE 802.11a

- 5 GHz (5.15-5.25, 5.25-5.35, 5.725-5.825 GHz)
- OFDM (Orthogonal Freq. Div. Multiplexing)
- 52 Subcarriers in OFDM
- BPSK/QPSK/QAM
- FEC & ARQ
- Rates: 6, 9, 12, 18, 24, 36, 48, 54 Mbps
Channel Allocation of IEEE 802.11a Standard

IEEE 802.11a: PHY based on OFDM (Orthogonal Frequency Division Multiplexing) technology

Symbols are parallel transmitted on different sub carriers.
# Modulation and Coding Schemes in IEEE 802.11a

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modulation</th>
<th>Code Rate</th>
<th>Data Rate</th>
<th>BpS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>6Mbps</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>BPSK</td>
<td>3/4</td>
<td>9Mbps</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>1/2</td>
<td>12Mbps</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>3/4</td>
<td>18Mbps</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>1/2</td>
<td>24Mbps</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>16-QAM</td>
<td>3/4</td>
<td>36Mbps</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>2/3</td>
<td>48Mbps</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>64-QAM</td>
<td>3/4</td>
<td>54Mbps</td>
<td>27</td>
</tr>
</tbody>
</table>
## Modulation and Coding Schemes in IEEE 802.11a

<table>
<thead>
<tr>
<th>Data rate (Mbits/s)</th>
<th>Modulation</th>
<th>Coding rate (R)</th>
<th>Coded bits per subcarrier ($N_{BPSC}$)</th>
<th>Coded bits per OFDM symbol ($N_{CBPS}$)</th>
<th>Data bits per OFDM symbol ($N_{DBPS}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
Successful Frame Transmissions in IEEE 802.11

SIFS: Short Inter-Frame Space
DIFS: Distributed Inter-Frame Space
EIFS: Extended Inter-Frame Space
Frame Re-Transmission in IEEE 802.11 *

- Frame re-transmission due to Ack failure

- Frame re-transmission due to an erroneous data frame reception
Overheads of IEEE 802.11

- MAC/PHY overheads
- Backoff delay
- Inter-frame intervals
- Acknowledgment (Ack) transmission time
- Potential re-transmission times
Frame Format in IEEE 802.11

Format of Data Frame MPDU
(MAC Protocol Data Unit)

Format of Ack Frame
Frame Format in IEEE 802.11a

PPDU (PLCP Protocol Data Unit) Frame Format

(46 bits overheads)

16 µs
Parameters in IEEE 802.11a

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>tSlotTime</td>
<td>9µs</td>
<td>Slot time</td>
</tr>
<tr>
<td>tSIFSTime</td>
<td>16µs</td>
<td>SIFS time</td>
</tr>
<tr>
<td>tDIFSTime</td>
<td>34µs</td>
<td>DIFS = SIFS + 2 x Slot</td>
</tr>
<tr>
<td>aCWmin</td>
<td>15</td>
<td>min contention window size</td>
</tr>
<tr>
<td>aCWmax</td>
<td>1023</td>
<td>max contention window size</td>
</tr>
<tr>
<td>tPLCP_Preamble</td>
<td>16µs</td>
<td>PLCP preamble duration</td>
</tr>
<tr>
<td>tPLCP_SIG</td>
<td>4µs</td>
<td>PLCP SIGNAL field duration</td>
</tr>
<tr>
<td>tSymbol</td>
<td>4µs</td>
<td>OFDM symbol interval</td>
</tr>
</tbody>
</table>

ESIFS = SIFS + DIFS + Ack Transmission time (in 6Mbps rate)
Related Works

- AutoRate Fallback protocol (ARF)
- RBAR (Receiver-Based Auto-Rate) protocol
- MSDU-Based Adaptive PHY Selection Algorithm
Auto-Rate Fallback Protocol (ARF)

- ARF is currently adopted and implemented in IEEE 802.11 commercial products

- Basic Mechanism in ARF
  - Rate is reduced when two consecutive ACKs are lost and a timer is started after rate reduction
  - Rate is increased when ten consecutive ACKs are received and the timer is cancelled
  - After the timer expires the rate is increased for the first packet (a probe)
  - If ACK is lost then rate is immediately reduced and the timer restarted

- Disadvantage
  - Cannot effectively adapt the fluctuations in the channel.
**Receiver Based Auto Rate (RBAR)**

- **Key feature**
  - Receiver will choose the modulation rate and embed into CTS packet

- **Disadvantages**
  - Change IEEE 802.11 Standard
  - Requires separate processing for MAC header and data payload

---

MSDU-Based Adaptive PHY Selection Algorithm

- Key feature
  - One selected PHY mode is used throughout a frame delivery period even retransmissions may occur

- Limitations:
  - Unrealistic to assume a constant channel condition over the frame delivery period
  - Can not adapt quickly to the fast-changing wireless channel

Notations

- \( l \) : payload length
- \( m \) : PHY mode
- \( s \) : wireless channel condition
- \( n_{\text{max}} \) : maximum number of retransmission

Channel condition vector:

\[
\hat{s} = \{s_1, \ldots, s_{n_{\text{max}}}\}
\]

Transmission Strategy vector:

\[
\hat{m} = \{m_1, \ldots, m_{n_{\text{max}}}\}
\]

Note: an Ack frame is transmitted at the highest rate in the basic rate set that is less than or equal to the rate of data frame it is acknowledging.

Basic rate set = \{ 6 Mbps, 12 Mbps, 24 Mbps \}
Goodput analysis of an IEEE 802.11a DCF system

Transmission duration of a data frame

\[ T_{\text{data}}(\ell, m) = t_{\text{PLCPPreamble}} + t_{\text{PLCP\_SIG}} + \left[ \frac{28 + (16 + 6)/8 + \ell}{BpS(m)} \right] \cdot t_{\text{Symbol}} \]

\[ = 20\mu s + \left[ \frac{30.75 + \ell}{BpS(m)} \right] \cdot 4\mu s. \]  

Transmission duration of an Ack frame

\[ T_{\text{ack}}(m') = t_{\text{PLCPPreamble}} + t_{\text{PLCP\_SIG}} + \left[ \frac{14 + (16 + 6)/8}{BpS(m')} \right] \cdot t_{\text{Symbol}} \]

\[ = 20\mu s + \left[ \frac{16.75}{BpS(m')} \right] \cdot 4\mu s. \]

Backoff Delay

\[ T_{\text{backoff}}(i) = \min\left[ 2^{i-1} \cdot (aCW_{\text{min}} + 1) - 1, aCW_{\text{max}} \right] \cdot t_{\text{SlotTime}}. \]
Goodput analysis of an IEEE 802.11a DCF system

- Probability of a successful frame transmission

\[ P_{s,xmit}(\ell, s, m) = \left[ 1 - P_{e,\text{data}}(\ell, s, m) \right] \cdot \left[ 1 - P_{e,\text{ack}}(s, m') \right], \]  

(4)

- Probability of a successful frame delivery within retry limit \( n_{\text{max}} \)

\[ P_{\text{succ}}(\ell, \hat{s}, \hat{m}) = 1 - \prod_{i=1}^{n_{\text{max}}} \left[ 1 - P_{s,xmit}(\ell, s_i, m_i) \right]. \]  

(5)
Goodput analysis of an IEEE 802.11a DCF system

Average transmission duration of a data frame, if delivered successfully with \( m \)

\[
D_{\text{succ} | \ell, \hat{s}, \hat{m}} = \sum_{n=1}^{n_{\text{max}}} P[n|\text{succ}](\ell, \hat{s}, \hat{m})
\]

\[
\cdot \left\{ \sum_{i=2}^{n} \left[ D_{\text{wait}}(i) + \overline{T}_{bckoff}(i) + T_{data}(\ell, m_i) \right] \right\}
\]

\[
+ \overline{T}_{bckoff}(1) + T_{data}(\ell, m_1) + tSIFS\text{Time}
\]

\[
+ T_{ack}(m'_n) + tDIFS\text{Time} \right\},
\]
Goodput analysis of an IEEE 802.11a DCF system

Probability of data frame successfully delivered at the nth transmission

\[
P[n|\text{succ}](\ell, \hat{s}, \hat{m}) = \frac{P_{s,xmit}(\ell, s_n, m_n) \cdot \prod_{i=1}^{n-1} [1 - P_{s,xmit}(\ell, s_i, m_i)]}{P_{\text{succ}}(\ell, \hat{s}, \hat{m})}
\] (7)

Average waiting time before i\text{th} transmission attempt

\[
\overline{D}_{\text{wait}}(i) = \frac{P_{e,\text{data}}(\ell, s_{i-1}, m_{i-1})}{1 - P_{s,xmit}(\ell, s_{i-1}, m_{i-1})} \cdot [t\text{SIFSTime} + T_{\text{ack}}(m'_{i-1}) + t\text{SlotTime}] + \left[1 - P_{e,\text{data}}(\ell, s_{i-1}, m_{i-1})\right] \cdot P_{e,\text{ack}}(s_{i-1}, m'_{i-1}) \cdot [t\text{SIFSTime} + T_{\text{ack}}(m'_{i-1}) + t\text{SIFSTime} + T_{\text{ack}}(1) + t\text{DIFSTime}].
\] (8)

\(\text{Ack timeout}\)

\(\text{EFIS}\)
Goodput analysis of an IEEE 802.11a DCF system

Average time waited to attempt transmission of a data frame $n_{\text{max}}$ times in error

$$D_{\text{fail}|\ell, \hat{s}, \hat{m}} = \sum_{i=1}^{n_{\text{max}}} \left[ T_{\text{backoff}}(i) + T_{\text{data}}(\ell, m_i) + \bar{D}_{\text{wait}}(i + 1) \right].$$

(9)
Goodput analysis of an IEEE 802.11a DCF system

Expected Effective Goodput (EEG):

EEG is the ratio of the expected delivered data payload to the expected transmission time.

\[
G(\ell, \hat{s}, \hat{m}) = \frac{\ell}{\sum_{k=0}^{\infty} \left[ (1-P_{\text{suc}}(\ell,\hat{s},\hat{m}))^k \cdot P_{\text{suc}}(\ell,\hat{s},\hat{m}) \cdot (k \cdot D_{\text{fail}}|\ell,\hat{s},\hat{m} + D_{\text{suc}}|\ell,\hat{s},\hat{m}) \right]}
\]

\[
= \frac{1-P_{\text{suc}}(\ell,\hat{s},\hat{m})}{P_{\text{suc}}(\ell,\hat{s},\hat{m})} \cdot D_{\text{fail}}|\ell,\hat{s},\hat{m} + D_{\text{suc}}|\ell,\hat{s},\hat{m}
\]

\[
= \frac{P_{\text{suc}}(\ell,\hat{s},\hat{m}) \cdot \ell}{(1-P_{\text{suc}}(\ell,\hat{s},\hat{m})) \cdot D_{\text{fail}}|\ell,\hat{s},\hat{m} + P_{\text{suc}}(\ell,\hat{s},\hat{m}) \cdot D_{\text{suc}}|\ell,\hat{s},\hat{m}}
\]

\[
= \frac{E[\text{data}](\ell, \hat{s}, \hat{m})}{E[D_{\text{data}}](\ell, \hat{s}, \hat{m})},
\]

(10)
MPDU-Based Adaptive PHY Selection Algorithm

Basic idea

- PHY mode and frame retry limit are finite
- Optimal transmission strategy must exist
- Offline optimal PHY mode table (maximizing the expected effective goodput) indexed by \((l, s, n)\)
  - Compute by using dynamic programming technique
- At run-time, based on the predictions of the channel conditions during each transmission attempt, the best transmission strategy can be determined by a table lookup.
Formula for Optimal PHY Mode Table when \( n = n_{\text{max}} \)

\[
G(\ell, s, m, n_{\text{max}}) = \frac{E[\text{data}](\ell, s, m, n_{\text{max}})}{E[\mathcal{D}_{\text{data}}](\ell, s, m, n_{\text{max}})}, \quad \text{(11)}
\]

\[
E[\text{data}](\ell, s, m, n_{\text{max}}) = P_{s,xmit}(\ell, s, m) \cdot \ell, \quad \text{(12)}
\]

\[
E[\mathcal{D}_{\text{data}}](\ell, s, m, n_{\text{max}}) = \overline{T}_{b\text{off}}(n_{\text{max}}) + T_{\text{data}}(\ell, m) + tSIFSTime + T_{\text{ack}}(m') + P_{s,xmit}(\ell, s, m) \cdot tDIFSTime + [1 - P_{s,xmit}(\ell, s, m)] \cdot \overline{D}_{\text{wait}}(n_{\text{max}} + 1). \quad \text{(13)}
\]

\[
m^*(\ell, s, n_{\text{max}}) = \arg \max_{1 \leq m \leq 8} G(\ell, s, m, n_{\text{max}}), \quad \text{(14)}
\]
Formula for Optimal PHY Mode Table when $0 < n < n_{\text{max}}$

$$G(\ell, s, m, n) = \frac{E[\text{data}](\ell, s, m, n)}{E[\mathcal{D}_{\text{data}}](\ell, s, m, n)},$$

(16)

$$E[\text{data}](\ell, s, m, n) = P_{s,\text{xmit}}(\ell, s, m) \cdot \ell + \left[1 - P_{s,\text{xmit}}(\ell, s, m)\right] \int_{-\infty}^{\infty} f_{R|S}(r|s) \cdot E[\text{data}](\ell, r, m^{*}(\ell, r, n + 1), n + 1)dr,$$

(17)

$$E[\mathcal{D}_{\text{data}}](\ell, s, m, n) =$$

$$\overline{T}_{\text{bcast}}(n) + T_{\text{data}}(\ell, m) + tSIFSTime + T_{\text{ack}}(m')$$

$$+ P_{s,\text{xmit}}(\ell, s, m) \cdot tDIFSTime$$

$$+ \left[1 - P_{s,\text{xmit}}(\ell, s, m)\right] \cdot \left\{ \overline{T}_{\text{wait}}(n + 1) + \int_{-\infty}^{\infty} f_{R|S}(r|s) \right\} \cdot E[\mathcal{D}_{\text{data}}](\ell, r, m^{*}(\ell, r, n + 1), n + 1)dr,$$

(18)

$$m^{*}(\ell, s, n) = \arg \max_{1 \leq m \leq 8} G(\ell, s, m, n),$$

(19)
MPDU-Based Adaptive PHY Selection Algorithm

Fig. 10. System architecture for link adaptation
Example

Fig. 11. A two-state discrete time Markov chain to model the wireless channel variation.

- $l = 2000$ bytes
- $n_{\text{max}} = 7$
- $t_{b,g} = 0.8$
- good $\sim 15\text{dB} - 30\text{ dB SNR}$
- bad $\sim 0 - 15\text{ dB SNR}$
Bit Error Probability

Symbol Error Probability of M-ary QAM

\[ P_M(s) = 1 - \left[ 1 - P_{\sqrt{M}}(s) \right]^2, \]

where

\[ P_{\sqrt{M}}(s) = 2 \cdot \left( 1 - \frac{1}{\sqrt{M}} \right) \cdot Q \left( \sqrt{\frac{3}{M-1}} \cdot s \right) \]

Bit Error Probability of M-ary QAM after Gray Coding

\[ P_b^{(M)}(s) \approx \frac{1}{\log_2 M} \cdot P_M(s). \]

Bit Error Probability of BPSK

\[ P_b^{(2)}(s) = P_2(s) = Q \left( \sqrt{2s} \right). \]
Packet Error Probability

Data frame error probability

\[
P_{e,\text{data}}(\ell, s, m) = 1 - [1 - P_{e}^{1}(24/8, s)] \cdot [1 - P_{e}^{m}(28 + (16 + 6)/8 + \ell, s)]
\]

\[
= 1 - [1 - P_{e}^{1}(3, s)] \cdot [1 - P_{e}^{m}(30.75 + \ell, s)],
\]

(29)

Ack frame error Probability

\[
P_{e,\text{ack}}(s, m') = 1 - [1 - P_{e}^{1}(24/8, s)] \cdot [1 - P_{e}^{m'}(14 + (16 + 6)/8, s)]
\]

\[
= 1 - [1 - P_{e}^{1}(3, s)] \cdot [1 - P_{e}^{m'}(16.75, s)],
\]

(30)
Simulation Parameters

Simulation Parameters setting

- AWGN wireless channel model
- Two-state discrete time Markov chain channel variation model
- Fragmentation threshold and dot11RTSShreshold is 2332 octets
- dot11ShortRetryLimit is 7
- BSS basic rate set is 6Mbps, 12Mbps, 24Mbps
- 10000 MSDUs are sent by transmitter
- Size of each MSDU is 2000 bytes
Simulation Schemes

Schemes testing

- PHY mode 1 (SM-1)
- PHY mode 5 (SM-5)
- PHY mode 8 (SM-8)
- ARF scheme
- scheme(LA-1)
  - MSDU-based adaptive PHY mode selection
- scheme(LA-2)
  - MPDU-based adaptive PHY mode selection

Performances evaluated

- Average goodput
- Frame drop rate
- Average number of transmission attempts per MSDU delivery
Average Goodput

Fig. 14. Goodput comparison of the testing schemes
## Frame Drop Rate

<table>
<thead>
<tr>
<th>$t_{b_{eq}}$</th>
<th>average number of dropped frames</th>
<th>SM-1</th>
<th>SM-5</th>
<th>SM-8</th>
<th>ARF</th>
<th>LA-1</th>
<th>LA-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
<td>2170</td>
<td>10000</td>
<td>1</td>
<td>93</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>1050</td>
<td>6634</td>
<td>0</td>
<td>118</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>535</td>
<td>4461</td>
<td>0</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>223</td>
<td>2811</td>
<td>0</td>
<td>81</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>63</td>
<td>1766</td>
<td>0</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>21</td>
<td>1002</td>
<td>0</td>
<td>41</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>605</td>
<td>0</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>330</td>
<td>0</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>170</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>72</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>39</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
## Average Number of Transmission Attempts

<table>
<thead>
<tr>
<th>$t_{b_i,g}$</th>
<th>average number of attempts ($\text{avg_att}$)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SM-1</td>
<td>SM-5</td>
<td>SM-8</td>
<td>ARF</td>
<td>LA-1</td>
<td>LA-2</td>
</tr>
<tr>
<td>0.0</td>
<td>1.214</td>
<td>4.001</td>
<td>7.000</td>
<td>1.349</td>
<td>1.430</td>
<td>1.279</td>
</tr>
<tr>
<td>0.1</td>
<td>1.183</td>
<td>3.275</td>
<td>5.909</td>
<td>1.333</td>
<td>1.387</td>
<td>1.253</td>
</tr>
<tr>
<td>0.2</td>
<td>1.166</td>
<td>2.756</td>
<td>5.075</td>
<td>1.327</td>
<td>1.381</td>
<td>1.239</td>
</tr>
<tr>
<td>0.3</td>
<td>1.137</td>
<td>2.307</td>
<td>4.326</td>
<td>1.320</td>
<td>1.339</td>
<td>1.210</td>
</tr>
<tr>
<td>0.4</td>
<td>1.113</td>
<td>1.987</td>
<td>3.741</td>
<td>1.312</td>
<td>1.300</td>
<td>1.192</td>
</tr>
<tr>
<td>0.5</td>
<td>1.090</td>
<td>1.699</td>
<td>3.228</td>
<td>1.307</td>
<td>1.274</td>
<td>1.169</td>
</tr>
<tr>
<td>0.6</td>
<td>1.078</td>
<td>1.530</td>
<td>2.835</td>
<td>1.314</td>
<td>1.247</td>
<td>1.154</td>
</tr>
<tr>
<td>0.7</td>
<td>1.059</td>
<td>1.383</td>
<td>2.523</td>
<td>1.315</td>
<td>1.213</td>
<td>1.138</td>
</tr>
<tr>
<td>0.8</td>
<td>1.037</td>
<td>1.233</td>
<td>2.196</td>
<td>1.316</td>
<td>1.178</td>
<td>1.116</td>
</tr>
<tr>
<td>0.9</td>
<td>1.020</td>
<td>1.134</td>
<td>1.984</td>
<td>1.294</td>
<td>1.163</td>
<td>1.101</td>
</tr>
<tr>
<td>1.0</td>
<td>1.000</td>
<td>1.040</td>
<td>1.818</td>
<td>1.275</td>
<td>1.134</td>
<td>1.087</td>
</tr>
</tbody>
</table>
Behavior of the three testing link adaptation schemes

(a) wireless channel variation

(b) AutoRate Fallback (ARF)

(c) MSDU-based adaptive PHY mode selection

(d) MPDU-based link adaptation

Fig. 15. Adaptability comparison of three link adaptation schemes
Conclusion & Limitations

Contribution

- A generic method for performance analysis of IEEE 802.11a
- A link adaptation scheme for IEEE 802.11a

Limitation

- Only suit for the AWGN channel
- Need to consider the error performance under multi-path fading, interference condition.
Homework 2

- Draw curves to describe the relationship between the transmission duration and data frame size in IEEE 802.11 b (1, 2, 5.5, 11 Mbps)