Goodput Analysis and Link Adaptive for IEEE 802.11a Wireless LANs

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

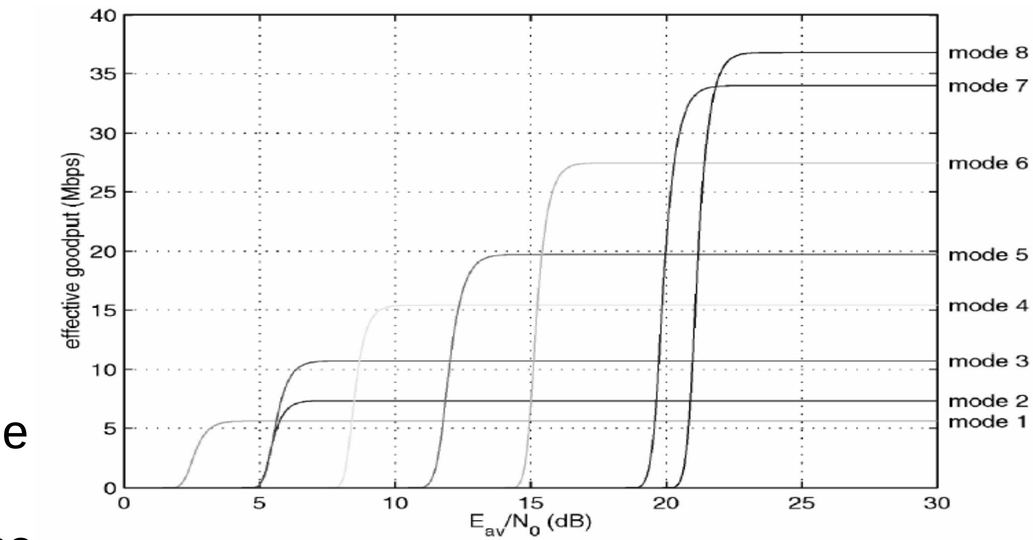
Suggested Readings

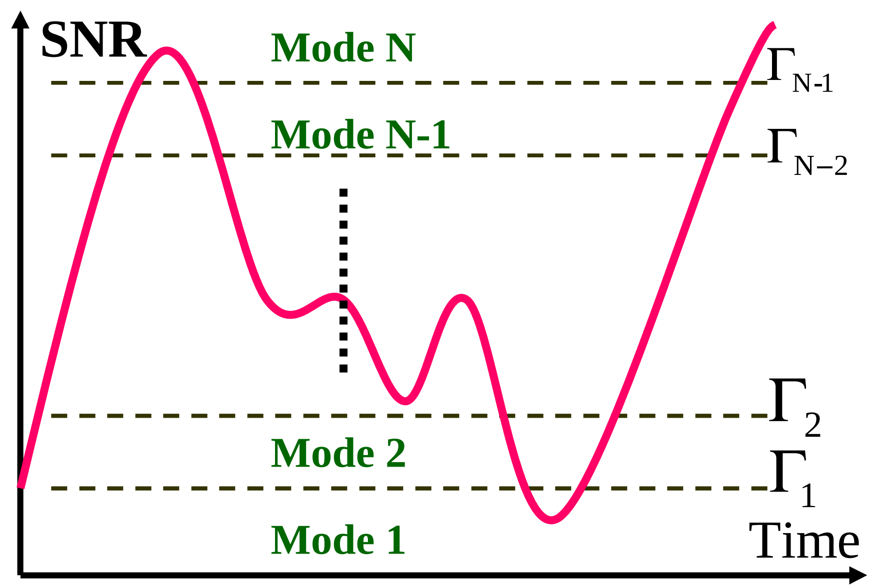
- “A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless Lan Standards”, IEEE Communications Magazine, 2002

- 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





Outline

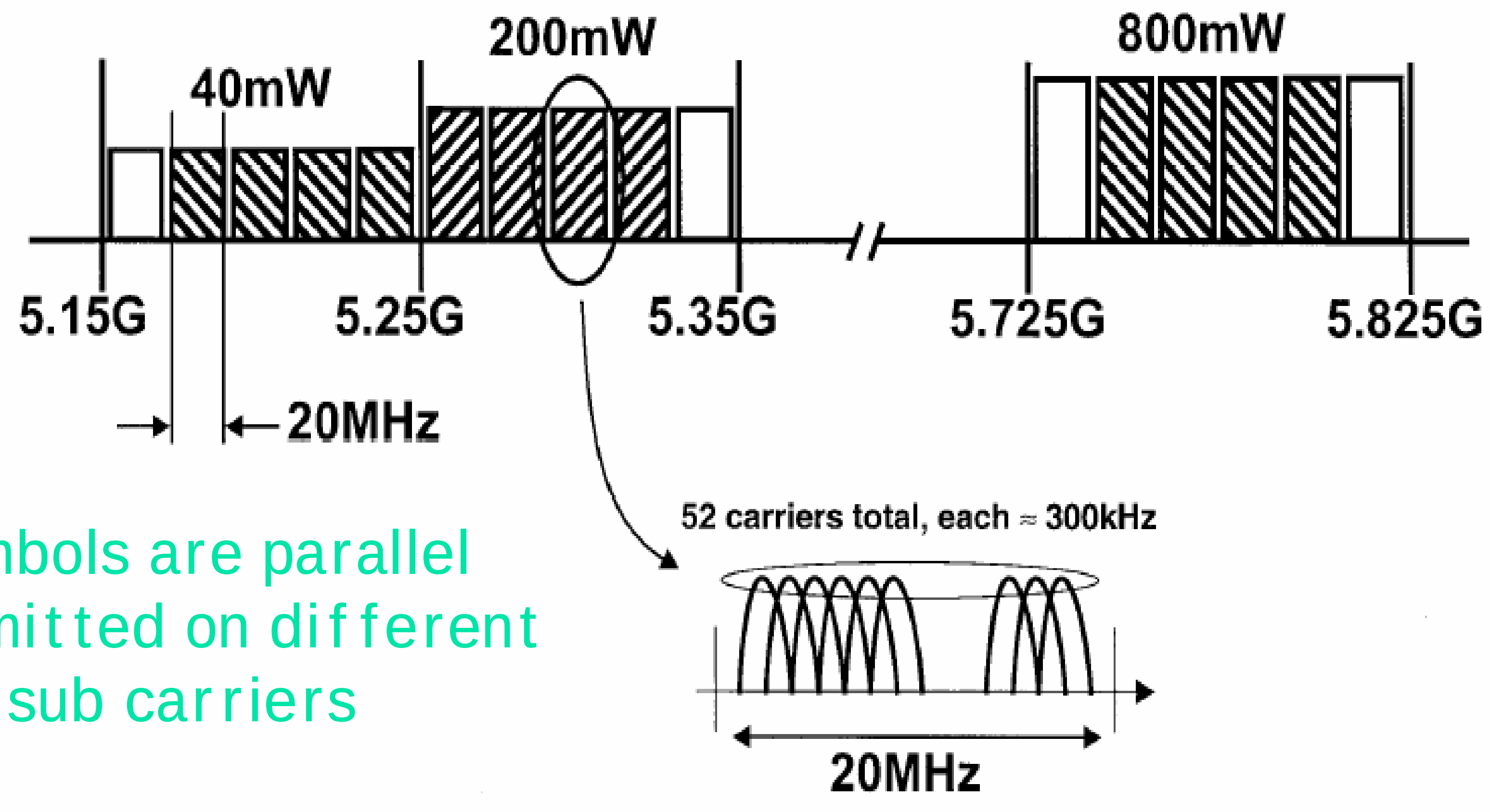
- Brief Review of IEEE 802.11 a
- Related Work
- Goodput Analysis of an IEEE 802.11a DCF System
- Proposed MPDU-based Link Adaptation Scheme
- Performance Evaluation
- Conclusion & Limitation

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

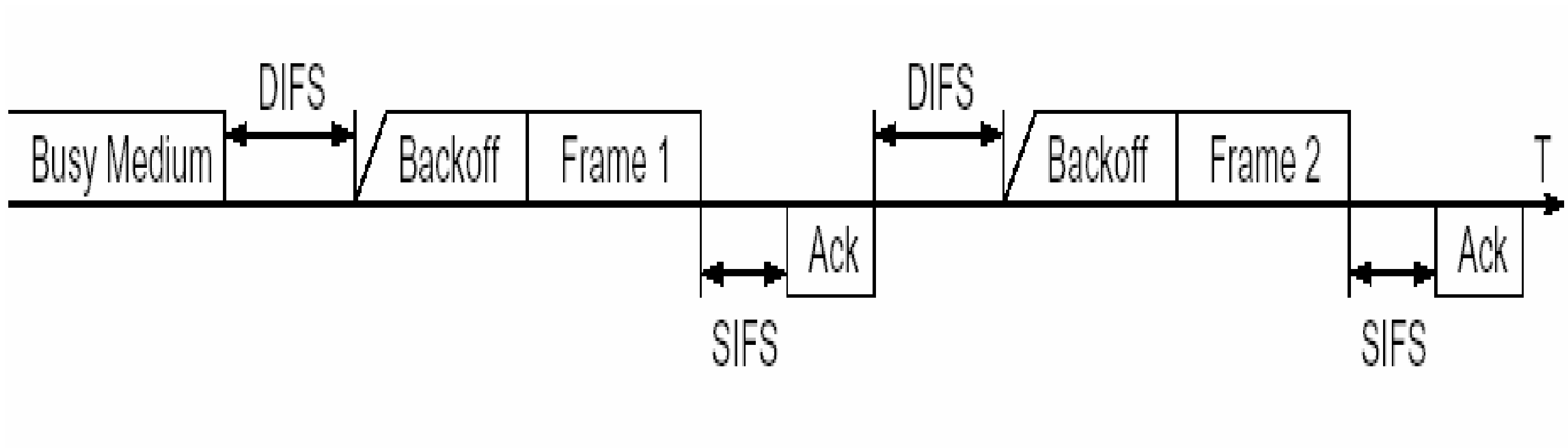
Modulation and Coding Schemes in IEEE 802.11a

Mode	Modulation	Code Rate	Data Rate	BpS
1	BPSK	1/2	6Mbps	3
2	BPSK	3/4	9Mbps	4.5
3	QPSK	1/2	12Mbps	6
4	QPSK	3/4	18Mbps	9
5	16-QAM	1/2	24Mbps	12
6	16-QAM	3/4	36Mbps	18
7	64-QAM	2/3	48Mbps	24
8	64-QAM	3/4	54Mbps	27

Modulation and Coding Schemes in IEEE 802.11a

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

Successful Frame Transmissions in IEEE 802.11



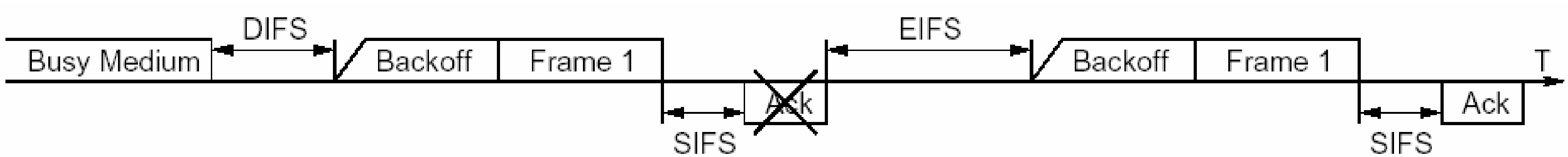
SIF: Short Inter-Frame Space

DIFS: Distributed Inter-Frame Space

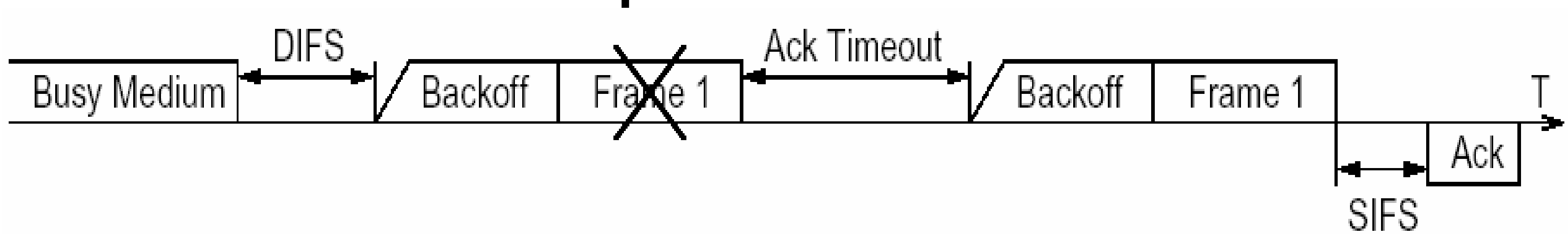
EIFS: Extended Inter-Frame Space

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)

octets: 2	2	6	6	6	2	0-2304	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Frame Body	FCS

MAC Header

(28 bytes overhead)

- Format of Ack Frame

octets: 2	2	6	4
Frame Control	Duration	Receiver Address	FCS

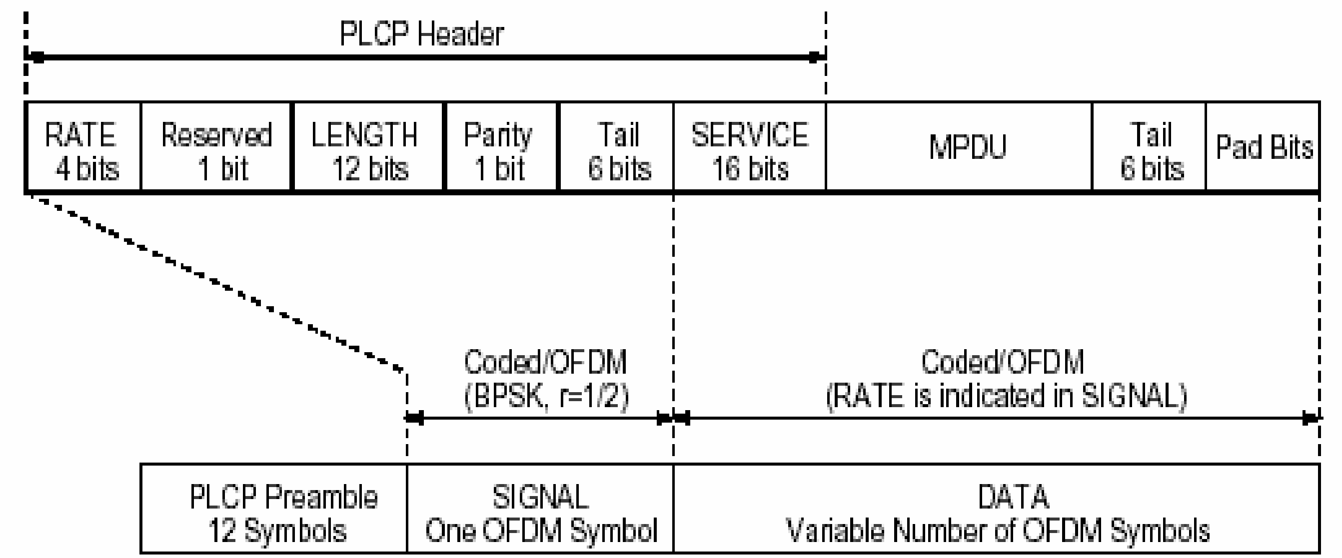
MAC Header

(14 bytes overhead)

Frame Format in IEEE 802.11a *

§PPDU (PLCP Protocol Data Unit) Frame Format

(46 bits overheads)



16 ms

Parameters in IEEE 802.11a

Characteristics	Value	Comments
tSlotTime	9μs	Slot time
tSIFSTime	16μs	SIFS time
tDIFSTime	34μs	DIFS = SIFS + 2 $\times$ Slot
aCWmin	15	min contention window size
aCWmax	1023	max contention window size
tPLCPPreamble	16μs	PLCP preamble duration
tPLCP_SIG	4μs	PLCP SIGNAL field duration
tSymbol	4μs	OFDM symbol interval

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

Related Works

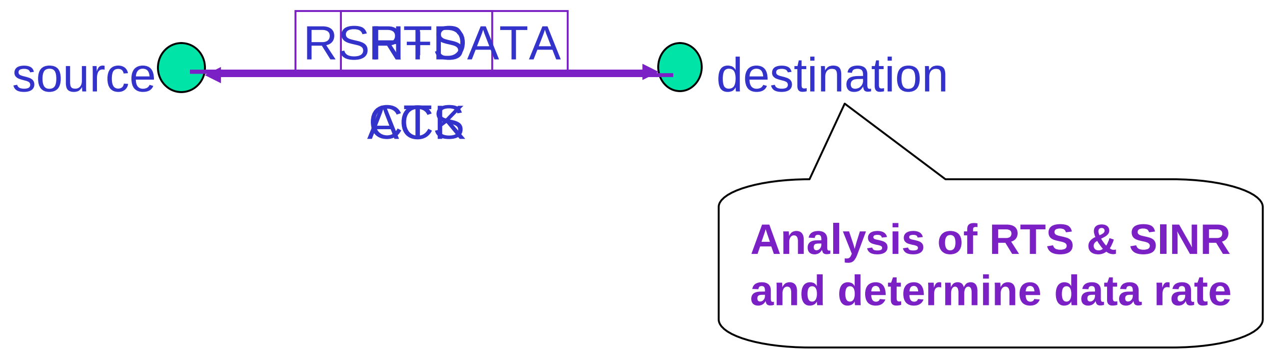
- AutoRate Fallback protocol (ARF)
- RBAR(Receiver-Based Auto-Rate) protocol
- MSDU-Based Adaptive PHY Selection Algorithm

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



G. Holland, N. Vaidya, and P. Bahl. “A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks”. In *Proceeding ACM MOBICOM*, July 2001.

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 fame delivery period
  - Can not adapt quickly to the fast-changing wireless channel

D. Qiao and S. Choi, "Goodput Enhancement of IEEE 802.11a Wireless Lan via Link Adaptation", Proceedings of IEEE ICC'01

Notations

- l : payload length
- m : PHY mode
- s : wireless channel condition
- n_{max} : maximum number of retransmission
- Channel condition vector:

$$\hat{s} = \{s_1, \cdots\cdots, s_{n_{\max}}\}$$

- Transmission Strategy vector:

$$\hat{m} = \{m_1, \cdots\cdots, m_{n_{\max}}\}$$

Note: an Ack frame is transmitted at the highest rate in 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

$$T_{data}(\ell, m) = tPLCPPreamble + tPLCP\_SIG + \left\lceil \frac{28 + (16+6)/8 + \ell}{BpS(m)} \right\rceil \cdot tSymbol = 20\mu s + \left\lceil \frac{30.75 + \ell}{BpS(m)} \right\rceil \cdot 4\mu s. \quad (1)$$

- Transmission duration of an Ack frame

$$T_{ack}(m') = tPLCPPreamble + tPLCP\_SIG + \left\lceil \frac{14 + (16+6)/8}{BpS(m')} \right\rceil \cdot tSymbol = 20\mu s + \left\lceil \frac{16.75}{BpS(m')} \right\rceil \cdot 4\mu s. \quad (2)$$

- Backoff Delay

$$\overline{T}_{bkoff}(i) = \frac{\min[2^{i-1} \cdot (aCWmin + 1) - 1, aCWmax]}{2} \cdot tSlotTime. \quad (3)$$

Goodput analysis of an IEEE 802.11a DCF system

- Probability of a successful frame transmission

$$P_{s,xmit}(\ell, s, m) = \left[1 - P_{e,data}(\ell, s, m)\right] \cdot \left[1 - P_{e,ack}(s, m')\right], \tag{4}$$

- Probability of a successful frame delivery within retry limit n_{max}

$$P_{succ}(\ell, \hat{s}, \hat{m}) = 1 - \prod_{i=1}^{n_{max}} [1 - P_{s,xmit}(\ell, s_i, m_i)]. \tag{5}$$

Goodput analysis of an IEEE 802.11a DCF system

- Average transmission duration of a data frame, if delivered successfully with $\hat{m}$

$$\mathcal{D}_{succ|\ell,\hat{s},\hat{m}} = \sum_{n=1}^{n_{max}} P[n|succ](\ell,\hat{s},\hat{m}) \cdot \Bigg\{ \sum_{i=2}^{n} \left[\overline{\mathcal{D}}_{wait}(i) + \overline{T}_{bkoff}(i) + T_{data}(\ell, m_i)\right] + \overline{T}_{bkoff}(1) + T_{data}(\ell, m_1) + tSIFSTime + T_{ack}(m'_n) + tDIFSTime \Bigg\}, \quad (6)$$

Goodput analysis of an IEEE 802.11a DCF system *

§ Probability of data frame successfully delivered at the nth transmission

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

- Average waiting time before i_{th} transmission attempt

$$\begin{aligned}\overline{\mathcal{D}}_{wait}(i) = &\frac{P_{e,data}(\ell, s_{i-1}, m_{i-1})}{1 - P_{s,xmit}(\ell, s_{i-1}, m_{i-1})} \\ &\cdot [tSIFSTime + T_{ack}(m'_{i-1}) + tSlotTime] \\ &+ \frac{[1 - P_{e,data}(\ell, s_{i-1}, m_{i-1})] \cdot P_{e,ack}(s_{i-1}, m'_{i-1})}{1 - P_{s,xmit}(\ell, s_{i-1}, m_{i-1})} \\ &\cdot [tSIFSTime + T_{ack}(m'_{i-1}) + tSIFSTime \\ &+ T_{ack}(1) + tDIFSTime].\end{aligned} \quad (8)$$

Ack timeout

EFIS

Goodput analysis of an IEEE 802.11a DCF system

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

$$\mathcal{D}_{fail|\ell,\hat{s},\hat{m}} = \sum_{i=1}^{n_{max}} \left[\overline{T}_{bkoff}(i) + T_{data}(\ell, m_i) + \overline{\mathcal{D}}_{wait}(i+1) \right]. \tag{9}$$

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.

$$\begin{aligned}\mathcal{G}(\ell,\hat{s},\hat{m}) &= \frac{\ell}{\sum_{k=0}^{\infty}\left[(1-P_{succ}(\ell,\hat{s},\hat{m}))^k\cdot P_{succ}(\ell,\hat{s},\hat{m})\cdot(k\cdot\mathcal{D}_{fail|\ell,\hat{s},\hat{m}}+\mathcal{D}_{succ|\ell,\hat{s},\hat{m}})\right]} \\ &= \frac{\ell}{\frac{1-P_{succ}(\ell,\hat{s},\hat{m})}{P_{succ}(\ell,\hat{s},\hat{m})}\cdot\mathcal{D}_{fail|\ell,\hat{s},\hat{m}}+\mathcal{D}_{succ|\ell,\hat{s},\hat{m}}} \\ &= \frac{P_{succ}(\ell,\hat{s},\hat{m})\cdot\ell}{(1-P_{succ}(\ell,\hat{s},\hat{m}))\cdot\mathcal{D}_{fail|\ell,\hat{s},\hat{m}}+P_{succ}(\ell,\hat{s},\hat{m})\cdot\mathcal{D}_{succ|\ell,\hat{s},\hat{m}}} \\ &= \frac{E[data](\ell,\hat{s},\hat{m})}{E[\mathcal{D}_{data}](\ell,\hat{s},\hat{m})},\end{aligned} \tag{10}$$

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 $n = n_{max}$

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

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

$$\begin{aligned} E[\mathcal{D}_{data}](\ell, s, m, n_{max}) = \\ \overline{T}_{bkoff}(n_{max}) + T_{data}(\ell, m) + tSIFSTime + T_{ack}(m') \\ + P_{s,xmit}(\ell, s, m) \cdot tDIFSTime \\ + [1 - P_{s,xmit}(\ell, s, m)] \cdot \overline{\mathcal{D}}_{wait}(n_{max} + 1). \end{aligned} \qquad (13)$$

$$m^*(\ell, s, n_{max}) = \arg \max_{1 \le m \le 8} \mathcal{G}(\ell, s, m, n_{max}), \qquad (14)$$

Formula for Optimal PHY Mode Table when $0<n<n_{max}$

$$\mathcal{G}(\ell, s, m, n) = \frac{E[data](\ell, s, m, n)}{E[\mathcal{D}_{data}](\ell, s, m, n)}, \tag{16}$$

$$\begin{aligned} &E[data](\ell, s, m, n) \\ &= P_{s,xmit}(\ell, s, m) \cdot \ell + \left[1 - P_{s,xmit}(\ell, s, m)\right] \\ &\cdot \int_{-\infty}^{\infty} f_{R|S}(r|s) \cdot E[data](\ell, r, m^*(\ell, r, n+1), n+1) dr, \end{aligned} \tag{17}$$

$$\begin{aligned} &E[\mathcal{D}_{data}](\ell, s, m, n) = \\ &\overline{T}_{bkoff}(n) + T_{data}(\ell, m) + tSIFSTime + T_{ack}(m') \\ &+ P_{s,xmit}(\ell, s, m) \cdot tDIFSTime \\ &+ [1 - P_{s,xmit}(\ell, s, m)] \cdot \Bigg\{ \overline{\mathcal{D}}_{wait}(n+1) + \int_{-\infty}^{\infty} f_{R|S}(r|s) \\ &\cdot E[\mathcal{D}_{data}](\ell, r, m^*(\ell, r, n+1), n+1) dr \Bigg\}, \end{aligned} \tag{18}$$

$$m^*(\ell, s, n) = \arg \max_{1 \le m \le 8} \mathcal{G}(\ell, s, m, n), \tag{19}$$

MPDU-Based Adaptive PHY Selection Algorithm

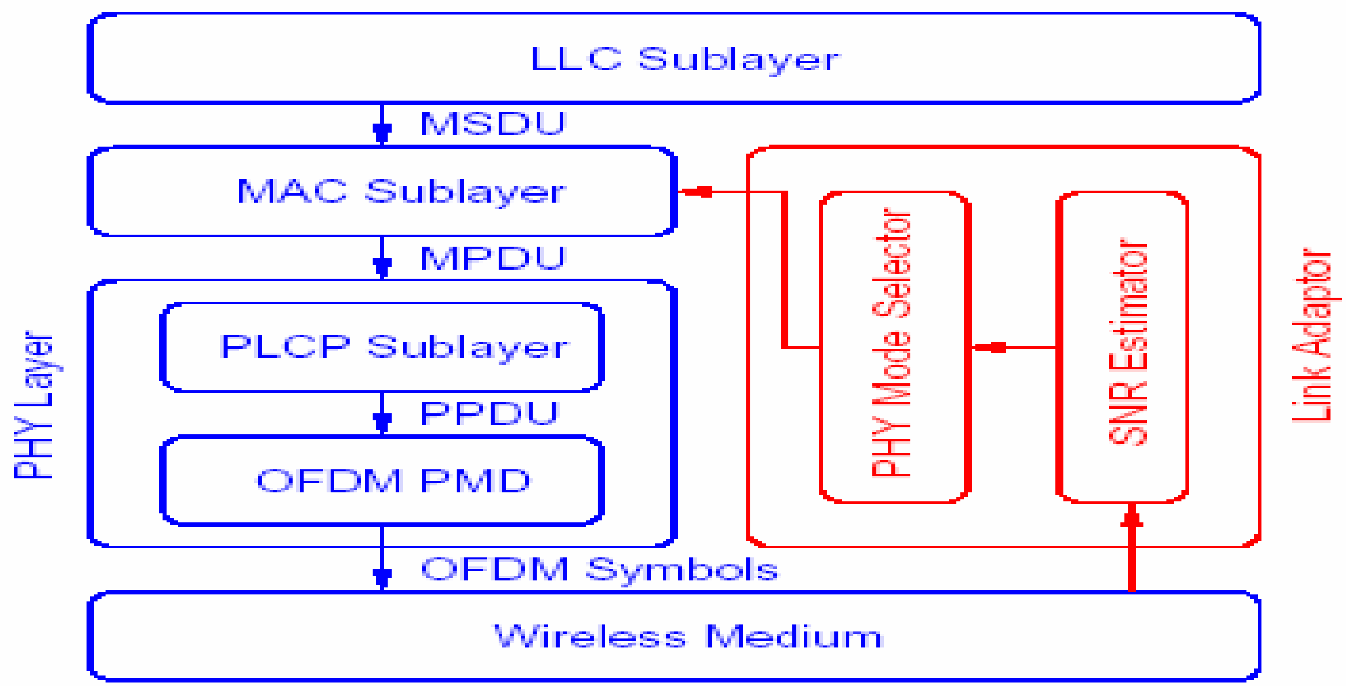


Fig. 10. System architecture for link adaptation

Example

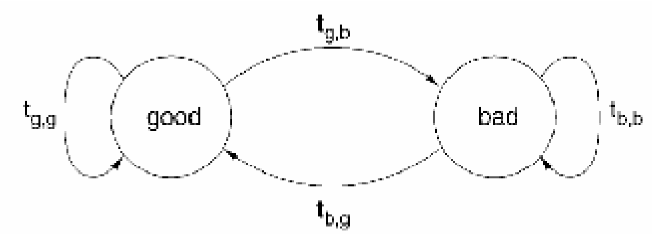
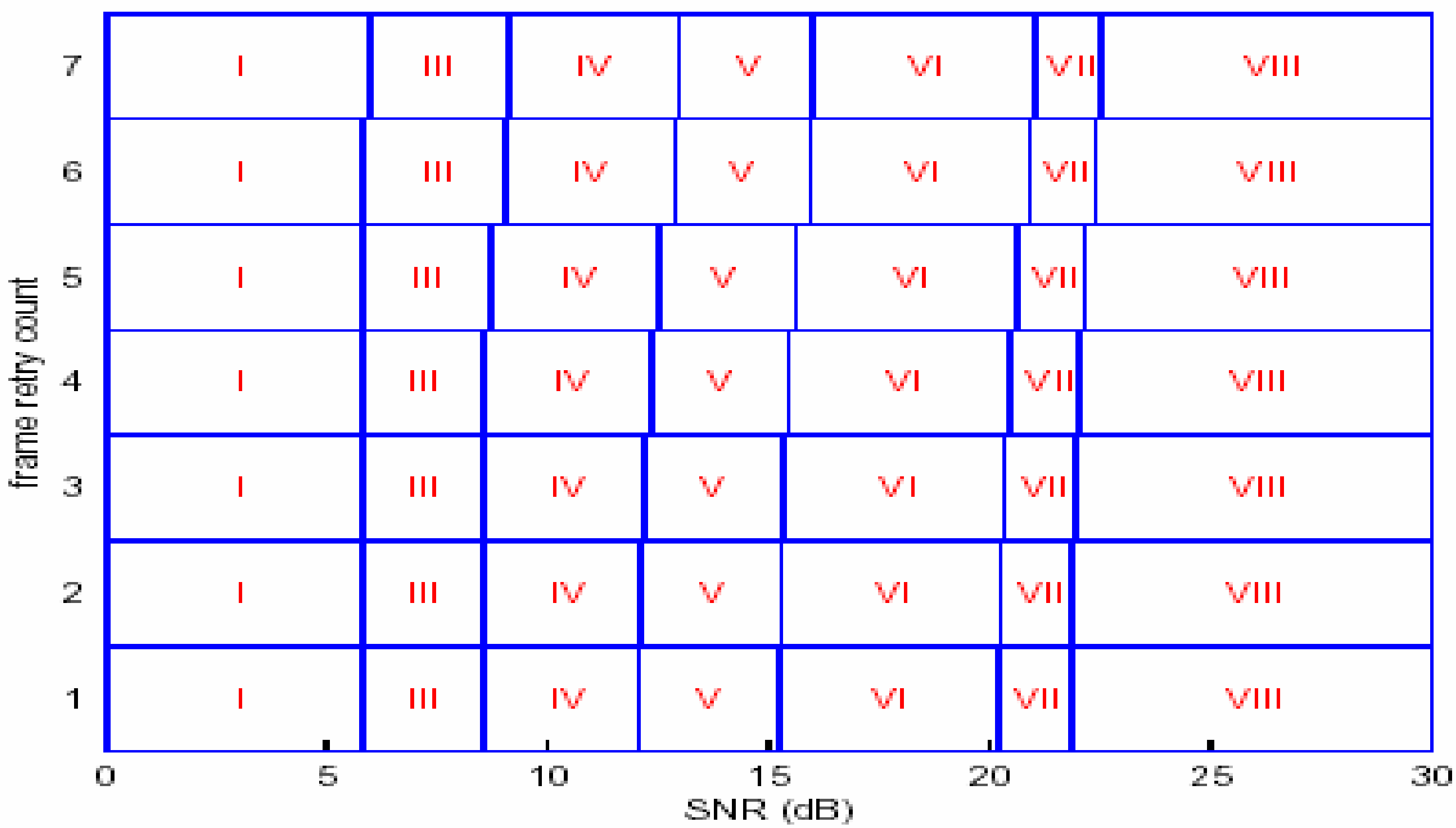


Fig. 11. A two-state discrete time Markov chain to model the wireless channel variation.

l = 2000 bytes
n_{max} = 7
$t_{b,g}$ = 0.8
good ~ 15dB - 30 dB SNR
bad ~ 0 - 15 dB SNR



Bit Error Probability

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy.$$

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

$$
\begin{aligned}
&P_{e,data}(\ell, s, m) \\
&= 1 - \left[1 - P_e^1(24/8, s)\right] \cdot \left[1 - P_e^m(28 + (16+6)/8 + \ell, s)\right] \\
&= 1 - \left[1 - P_e^1(3, s)\right] \cdot \left[1 - P_e^m(30.75 + \ell, s)\right],
\end{aligned}
\tag{29}
$$

- Ack frame error Probability

$$
\begin{aligned}
&P_{e,ack}(s, m') \\
&= 1 - \left[1 - P_e^1(24/8, s)\right] \cdot \left[1 - P_e^{m'}(14 + (16+6)/8, s)\right] \\
&= 1 - \left[1 - P_e^1(3, s)\right] \cdot \left[1 - P_e^{m'}(16.75, s)\right],
\end{aligned}
\tag{30}
$$

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

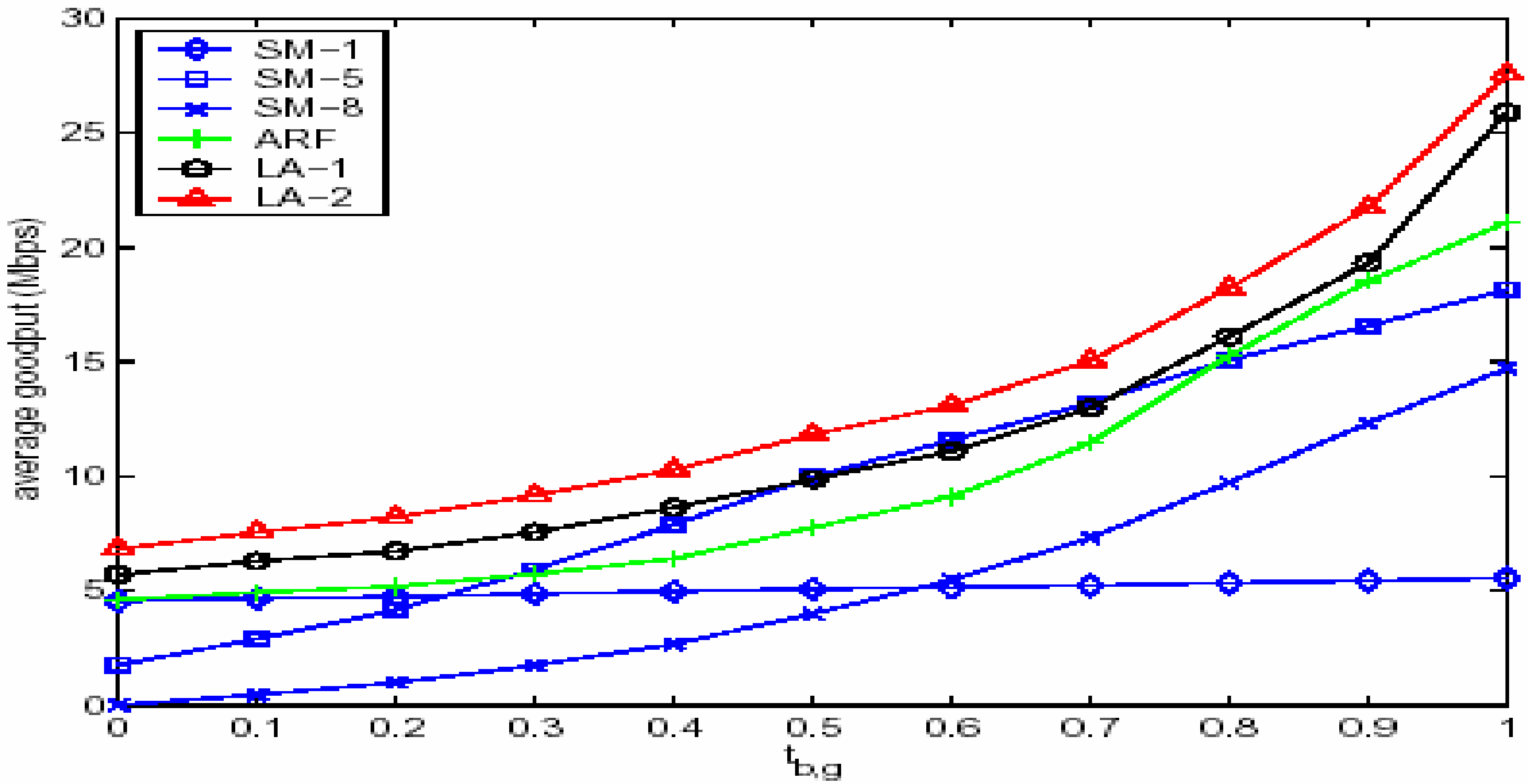


Fig. 14. Goodput comparison of the testing schemes

Frame Drop Rate

$t_{b,g}$	average number of dropped frames					
	SM-1	SM-5	SM-8	ARF	LA-1	LA-2
0.0	0	2170	10000	1	93	0
0.1	0	1050	6634	0	118	0
0.2	0	535	4461	0	99	0
0.3	0	223	2811	0	81	0
0.4	0	63	1766	0	60	0
0.5	0	21	1002	0	41	0
0.6	0	5	605	0	28	0
0.7	0	0	330	0	17	0
0.8	0	0	170	0	8	0
0.9	0	0	72	0	6	0
1.0	0	0	39	0	2	0

Average Number of Transmission Attempts

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

Behavior of the three testing link adaptation schemes

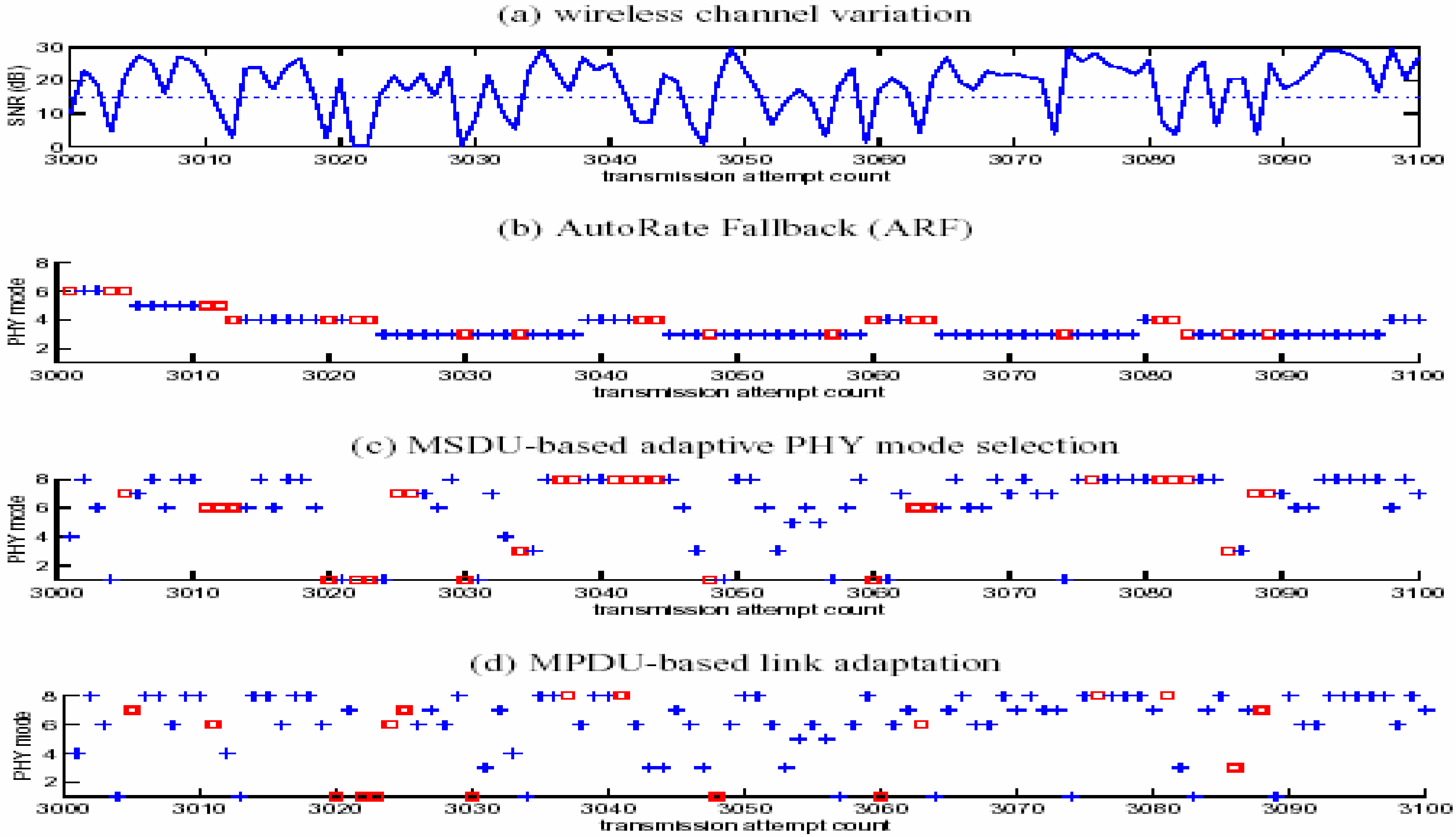


Fig. 15. Adaptability comparison of three link adaptation schemes

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)