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Performance study of block ACK and reverse direction in IEEE 802.11n using a Markov chain model

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Introduction

The 802.11n standard (2009) introduced several key features:

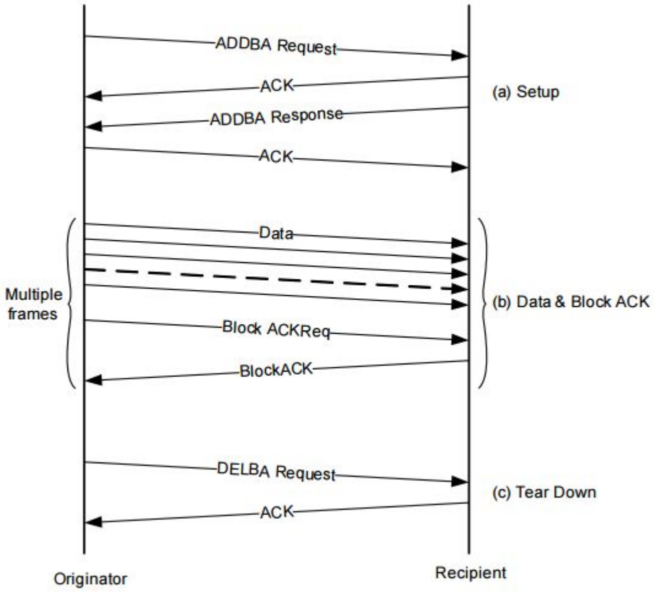
- Block acknowledgement (BA)
- Reverse direction protocol. (RD)

In this paper, researchers studied:

- Interdependencies of BA and RD mechanisms using a Markov chain model under non-saturated traffic loads.
- A mathematical model to derive throughput, delay, and packet loss probability.
- Analytical model to track and trace the performance fluctuation issues of 802.11n networks.

Preliminaries - Block Acknowledgement

- A new ACK mechanism in the 802.11e standard (2005).
- Unlike the traditional ACK mechanism, an ACK is transmitted tc reply to multiple data frames rather than per frame.
- The basic idea is aggregate several ACK frames into a single frame to enhance wifi throughput and channel utilization.
- Originator and the recipient exchange Add Block Acknowledgement Request/Response frames.
- When the frame consists of only one data frame it suffers from severe throughput degradation.
    - Due to additional frames (BA request and BA).



Preliminaries - Block Acknowledgement

Two BA subclasses:

- Protected Block ACK; before transmitting an entire data burst the originator will transmit a single data frame.
- Unprotected Block ACK; burst entire data.
    - Wastes transmission opportunity (TXOP) especially in collisions.

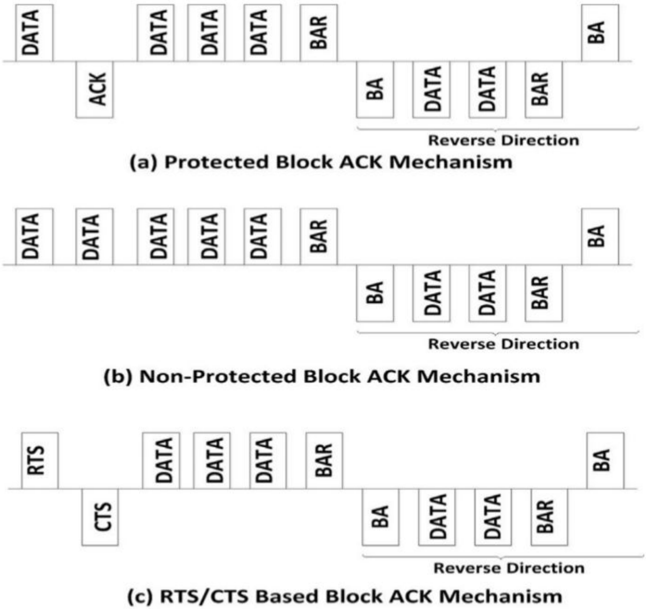


Fig. 1. Various block ACK mechanisms with reverse direction.

Preliminaries - Reverse direction

- Until now, when the sender STA is allocated with a TXOP, it informs surrounding STAs about how long the wireless medium will be engaged.
- In 802.11n RD, receiver may request a reverse data transmission.
- This allows the transportation of data frames and also aggregates frames;
  - in both directions.
  - in one Transmission Opportunity (TXOP) period.
- RD achieves better results by supporting “on-demand” bi-directional data flows.

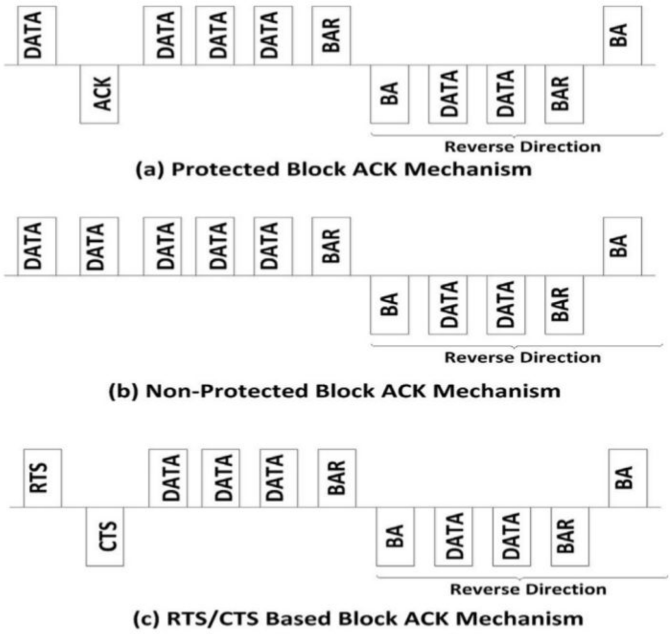


Fig. 1. Various block ACK mechanisms with reverse direction.

Markov model

- An analytical model is proposed to evaluate the performance of 802.11n under non-saturated load conditions by taking into account protected Block ACKs and Reverse Direction.
- A two dimensional Markov model is developed to derive;
  - Channel throughput.
  - End-to-end delay of successful data transmissions.
- Assumptions;
  - Finite number of stations.
  - Unsaturated load i.e. there is a certain probability that the transmission queue is empty.
  - Channel is prone to errors.
  - No hidden terminals.
  - Packets are destroyed only through collisions exceeding the retry limit.
  - Packets are of equal length.

Backoff mechanism

- For a STA to transmit, it senses the medium to determine if another STA is in transmission.
- Transmitting STA must ensure that the medium is idle for a period before attempting to transmit.
- STA selects a random backoff interval and decrements the backoff interval counter while the medium is idle.
- The timer value must be within the Contention Window values.
- A transmission is successful if an acknowledgement (ACK) frame is received.
- STA will increase its contention window size after each failed transmission until it reaches the maximum backoff stage.

Backoff mechanism - Abbreviations

- **n** is the number of stations (STAs) in a WLAN.
- $\mathbf{CW_i}$ stands for the contention window size.
- **τ** is the transmission probability of a station in a randomly chosen slot time.
- $\mathbf{p_f}$ denote the frame failure transition probability from one stage to another. (row i−1 to row i)
- **k = b(t)** backoff counter at time t.
  - Decremented at the start of every idle slot and a contending station wins the channel when it reaches to zero.
  - Chosen to be uniformly distributed over k ∈ [0, CWi]
  - After successful transmissions, if the STA has more data to send new value would be set
- **i = s(t)** backoff stages at time t.
  - Starts at 0 and is increased by 1 everytime transmissions collide.
  - Once the CW reaches CWm, it will remain at this value until it is reset.
- **m′** is a maximum number by which the contention window can be doubled.

Backoff mechanism - Collision

- Collision; there is a chance that two STAs end up with the same b(t) values and transmit data simultaneously.
- In order to avoid further collisions, the collided STAs will generate new b(t) values determined by:

$$CW_i = \begin{cases} 2^i CW_{min};\ i \leq m', \\ 2^{m'} CW_{min} = CW_m;\ i > m' \end{cases}$$

- Once the CW reaches CW_m, it will remain at this value until it is reset. That means STA will keep transmitting the packet till it reaches the retry limit.
- If the transmission is still unsuccessful the packet will be dropped.

Markov Chain

- **(s(t), b(t))** will denote the state of this Markov chain.
  - **i = s(t)** backoff stages at time t.
  - **k = b(t)** backoff counter at time t.
- The probability of the station to be in state (i, 0) can be expressed as a n stage transition probability as follows:

$$b_{i,0} = p_f^i b_{0,0} \quad 0 \le i \le m$$

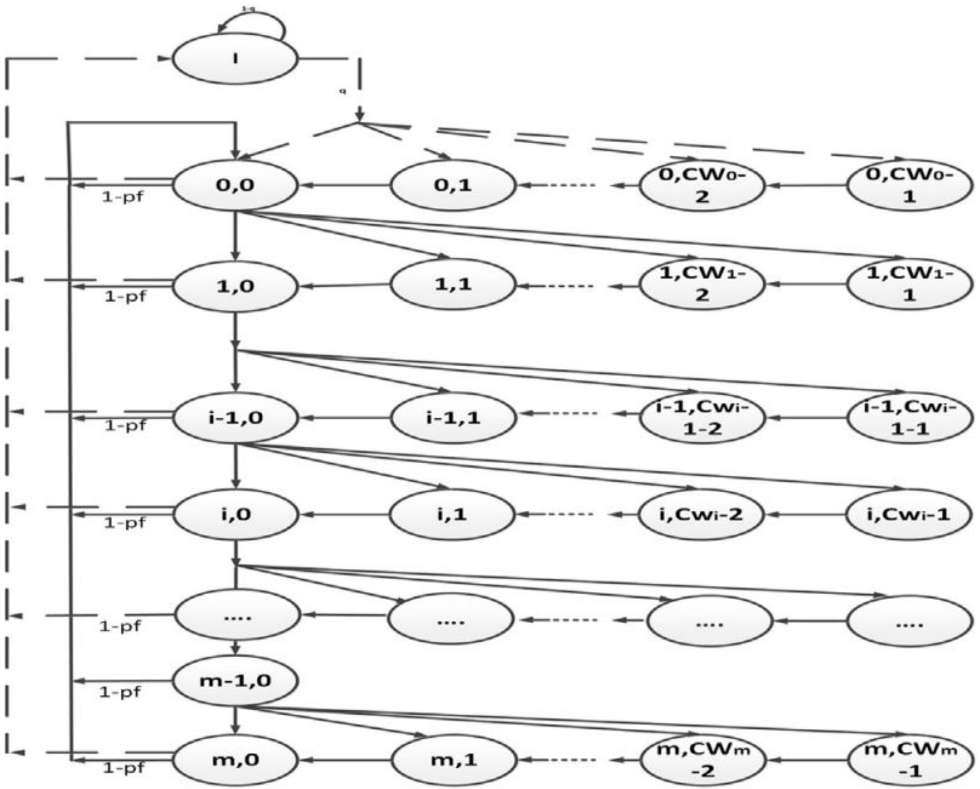


Fig. 2. Two dimensional Markov chain model for 802.11n backoff.

Transmission Fail Probability

- Unsuccessful transmission attempt can happen due to the collision of a station with at least one of the n−1 remaining stations, occurring with probability:

$$p_{coll} = 1 - (1 - \tau)^{n-1}$$

- And by having a frame with errors (fading, noise). FER (frame error probability)

$$p_{err} = 1 - (1 - FER_{data})(1 - FER_{ack}) = FER_{data} + FER_{ack} - FER_{data} \cdot FER_{ack}$$

- Since both events are independent, the probability of unsuccessful transmission:

$$p_f = 1 - (1 - p_{coll})(1 - p_{err}) = p_{coll} + p_{err} - p_{coll} p_{err}$$

$$p_f = 1 - (1 - \tau)^{n-1}(1 - FER_{data})(1 - FER_{ack})$$

Transmission Queue

- The unsaturated traffic behavior is characterized by defining a MAC queue.
- Packet arrival rate at each STA buffer from upper layer is λ pkt/s.
- μ represent the packet processing rate assuming that the queue has a length of K.
- By using a M/M/1/K queueing model, the probability that there is at least one packet to be transmitted in the STA queue;

$$q = 1 - \frac{1 - \frac{\lambda}{\mu}}{1 - \left(\frac{\lambda}{\mu}\right)^{K+1}}$$

Throughput analysis

- Ts is the average time that the channel is captured with successful transmission.
- Tc is the average time that the channel is captured by stations which collide.
- Te is the average wasted time due to a channel access failure caused by channel error.
- Transmission times (measured in microseconds) of an MPDU, an ACK frame, a RTS frame, a CTS frame, a BlockAckReq frame, a BlockAck, a Head of Brust and a Head of ACK frame.

$$T_s = \begin{cases} T_{ack} + T_{sifs} + (T_{data} + T_{sifs})\cdot B + T_{bar} + T_{sifs} + T_{ba} + T_{RD}; \\ \text{Protected Block ACK Scheme} \\ T_{data} + T_{T_{sifs}})\cdot B + T_{bar} + T_{sifs} + T_{ba} + T_{RD} + T_{difs}; \\ \text{Unprotected Block ACK Scheme} \\ T_{rts} + T_{cts} + 2T_{sifs} + (T_{data} + T_{sifs})\cdot B + T_{bar} + T_{sifs} + T_{ba} + T_{RD} + T_{difs}; \\ \text{RTS/CTS scheme} \end{cases} \tag{13}$$

$$T_e = \begin{cases} T_{hob} + T_{eifs} + (T_{sifs} + T_{hack}) \times \dfrac{1 - FER_{hob}}{FER_{hob} + FER_{hack} - FER_{hob}FER_{hack}} \\ \text{Protected Block ACK Scheme} \\ (T_{data} + T_{T_{sifs}})\cdot B + T_{bar} + T_{sifs} + T_{ba} + T_{RD} ++ T_{difs} \\ \text{Unprotected Block ACK Scheme} \\ T_{rts} + T_{eifs} + (T_{sifs} + T_{cts}) \times \dfrac{1 - FER_{rts}}{FER_{rts} + FER_{cts} - FER_{rts}FER_{cts}} \\ \text{RTS/CTS scheme} \end{cases} \tag{14}$$

$$T_c = \begin{cases} T_{hob} + T_{eifs} \\ \text{Protected Block ACK Scheme} \\ (T_{data} + T_{T_{sifs}})\cdot B + T_{bar} + T_{sifs} + T_{ba} + T_{RD} ++ T_{difs} \\ \text{Unprotected Block ACK Scheme} \\ T_{rts} + T_{eifs} \\ \text{RTS/CTS scheme} \end{cases} \tag{15}$$

Packet drop probability

- A packet can be dropped;
  - a packet is dropped when the retry limit is reached,
  - a packet may be dropped when the sending queue is full.
- Total packet drop probability is the sum of both of these events.

Packet drop due to retry limit

- A packet is found in the last backoff stage m if it encounters m collisions in the previous stages and it is eventually discarded.
- Packet drop probability due to reaching the retry limit;

$$P_{drop} = \frac{b_{m,0}}{b_{0,0}} p_f = p_f^m \cdot p_f = p_f^{m+1} = [1 - (1 - p_f)(1 - \tau)^{n-1}]^{m+1}$$

Packet drop due to queue

- Consider the M/M/1/K queue system, where there are K frames in the system;

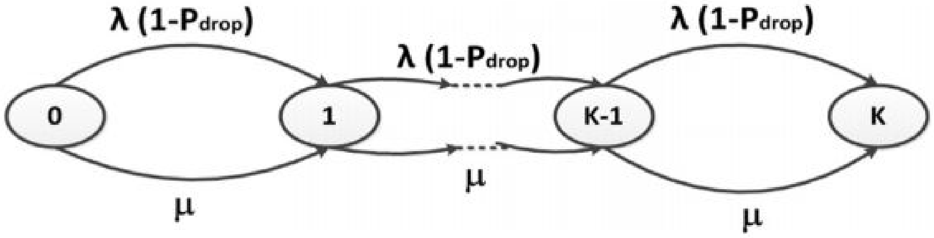


Fig. 3. M/M/1/K queue model.

- The frames are dropped with probability;

$$P_k = \rho^k p_0 = \left(\frac{\lambda(1-p_{drop})}{\mu}\right)^K \cdot \frac{1-\dfrac{\lambda(1-p_{drop})}{\mu}}{1-\left(\dfrac{\lambda(1-p_{drop})}{\mu}\right)^{K+1}}$$

Packet drop probability final

- The total probability of packet loss is;

$$P_{loss} = P_{drop} + P_K = [1 - (1 - p_f)(1 - \tau)^{n-1}]^{m+1} + \left(\frac{\lambda(1 - P_{drop})}{\mu}\right)^K \cdot \frac{1 - \frac{\lambda(1 - P_{drop})}{\mu}}{1 - \left(\frac{\lambda(1 - P_{drop})}{\mu}\right)^{K+1}}$$

Mean delay

- Delay D can be defined as the time elapsing;
  - from the frame is inserted in the MAC buffer,
  - to is successfully transmitted.
- Delay is associated with two factors:
  - medium access delay due to the number of contending stations,
  - queueing delay.
- So, average delay is;

$$D_{avg} = D_{MAC} + D_Q$$

$$D = \sum_{n=0}^{m} \left[\frac{(p_f^i - p_f^{m+1})((CW_i + 1)/2)}{1 - p_f^{m+1}} \right] \cdot ((1 - p_{tr})\sigma + P_{tr} P_s (1 - P_{err}) T_s$$

$$+ P_{tr}(1 - P_s) T_c + P_{tr} P_s P_{err} T_e) + \left(\frac{\rho(1 - (K+1)\rho^K + K\rho^{K+1})}{(1-\rho)(1-\rho^{K+1})} \right) \times$$

$$\frac{1}{\lambda(1 - P_{drop})}$$

Numerical studies

- Paper studied the characteristics of various IEEE 802.11n Block ACK methods.
- Analytical model is validated MATLAB based numerical study.
- Parameters used in the numerical study;

Table 1
Summary of IEEE 802.11n parameters.

Payload	1500 bytes	r	2 Mbps
T-PHY	192	r*	1 Mbps
T-DATA	192+(224+Payload)/r	Data rate	11 Mbps
T-ACK	192+112/r*	Block size	5
T-RTS	192+160/r*	Block size RD	3
T-CTS	192+112/r*	Fading margin	0.05
T-BAR	192+192/r	Velocity	5 m/s
T-BA	192+1216/r	Queue length	50

Numerical studies

- Packet arrival rate of 8 pkts/s.
- Increments of network size significantly reduce the throughput due to collisions.
- Protected Block ACK RD provides 32.54% higher throughput than Block ACK with RD.

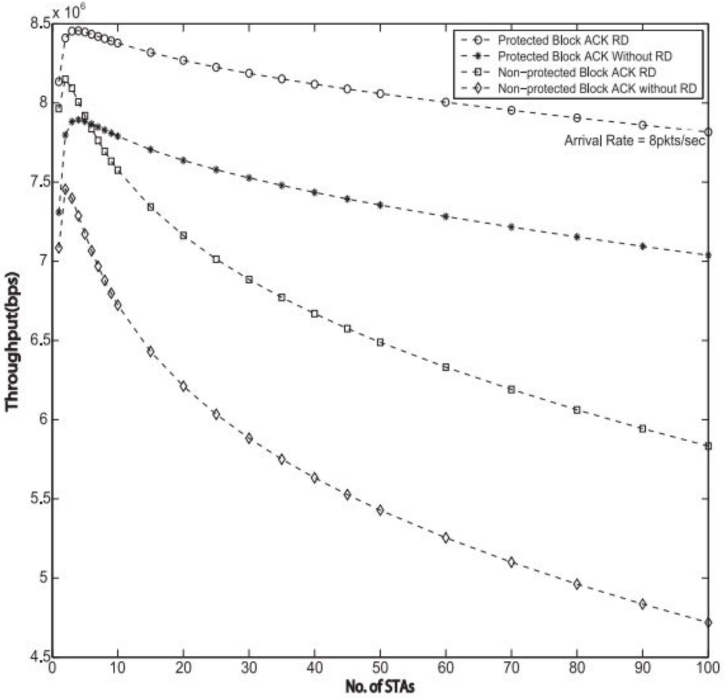


Fig. 4. Channel throughput of protected Block ACK with and without RD and non-protected block with and without RD.

Numerical studies

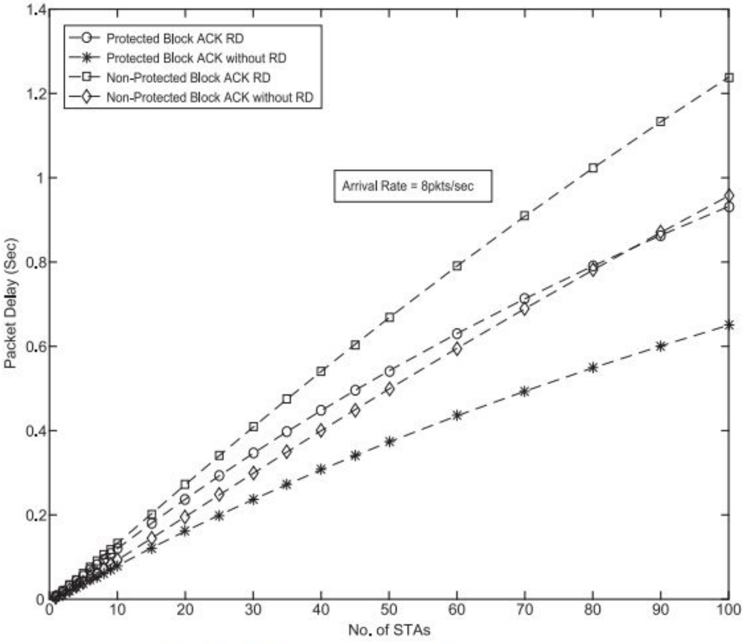


Fig. 5. Packet delay versus number of stations.

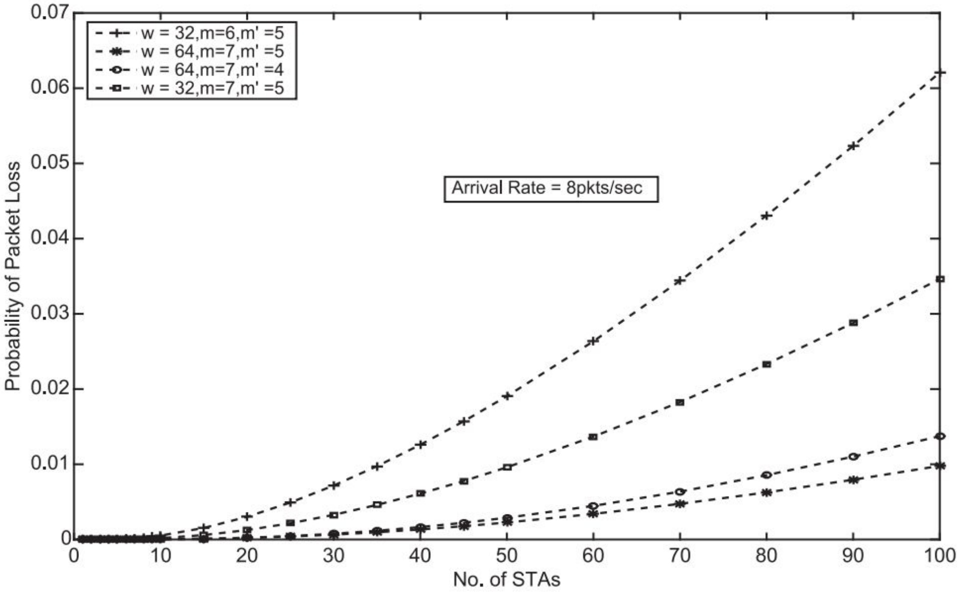


Fig. 7. Probability of packet loss against the number of stations.

Conclusion

- Paper investigated the interdependencies of Block ACK and RD mechanisms for 802.11n using a discrete bi-directional Markov chain model under non-saturated traffic loads.
- Results obtained have shown that the better system performance (i.e. up to 33% higher throughput and 48% less packet dropping) can be achieved using protected Block ACK in conjunction with RD data transmission.
- ‘unprotected Block ACK’ wastes TXOP especially during collisions and degrades system performance significantly.
- To fully utilize the system performance, 802.11n stations should employ protected Block ACK mechanism with RD flows.

Thank you for listening!

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