Multi-Packet Reception Technology in Random Access Wireless Networks: A Survey

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***Abstract*— Medium Access Control (MAC) Layer plays an important role in Wireless Local Area Network (WLAN). However, as it has to deal with many packets received by the users, it faces lot of challenges in terms of packet collisions and reception. Multi-Packet Reception (MPR) technology will address the above problems and provides the capability for a wireless receiver to parallely decode multiple packets from concurrent transmissions. New research advances are leading to increase in the reception capability of a single centrally receiving node called as Access Point (AP) in WLAN. In this paper, a detailed discussion about the usage of MPR technology in wireless networks is carried out in the form of survey. The benefits of MPR technology in terms of throughput gain and reduction in packet collision and its various technologies that enable MPR at the physical layer of a wireless network stack are highlighted.**

***Keywords*— Multi-packet reception, medium access control, wireless local area network, IEEE 802.11.**

I. INTRODUCTION

In a Multi-Packet Reception (MPR) technology, one node receives multiple packets concurrently from multiple transmitters and ensures high capacity and throughput. MPR finds its application in an uplink scenario of a random access wireless network, in which multiple nodes transmit packets simultaneously to the AP. A network node capable of correctly receiving signals from multiple transmitters is called as an MPR Node.

A. Need for MPR

The conventional collision channel model allows only a single user to transmit a packet to the receiver successfully and all other active users are kept idle to avoid collisions. This approach under-utilizes the capacity of a wireless network. However, MPR technology helps in improving throughput especially in high traffic conditions. MPR is realized using sophisticated spread spectrum, space-time coding, signal processing techniques and antenna arrays for channel access and enabling the receiver to be able to decode multiple concurrent signals from different transmitters. The lack of synchronization among physically separated nodes in distributed networks introduces significant challenges towards adopting MPR technology in the physical layer of the 802.11 Wireless LAN protocol stack and in the data link layer specifically MAC layer for systems using MPR.

B. MPR Channel Model

The two widely used MPR Channel Models are,

1. **Generalized MPR Channel**: With generalized MPR channel model [1], a node will be able to receive j out of i transmissions with some non-zero probability. When there are simultaneous transmissions, the conditional probabilities described the reception instead of deterministic failure. Also, the probability of successful reception depends only on i and j as per equation (1),

   For, $i \geq 1, 0 \leq j \leq i$

   $$P_{i,j} = P_r \{ j \text{ packets are received} \mid i \text{ packets are transmitted} \} \quad \text{... (1)}$$

   A generalized MPR channel is characterized by the probabilities for all values of i and j. These values can be summarized in a new multi-packet reception model and is defined by the **MPR reception matrix** of the channel as per equation (2),

   $$P_{i,j} = \begin{bmatrix} P_{1,0} & P_{1,1} & & \\ P_{2,0} & P_{2,1} & P_{2,2} & \\ P_{3,0} & P_{3,1} & P_{3,2} & P_{3,3} \\ \cdots\cdots & & & \\ P_{n,0} & P_{n,1} & P_{n,2} \cdots\cdots\cdots & \cdots P_{n,n} \end{bmatrix} \quad \text{… (2)}$$

   where, $P_{i,j}$ is the conditional probability that, given i users transmit, and j out of i transmissions are successful.

2. **k - MPR**: In a k - MPR channel, a node will be able to receive all the packets successfully without any loss if the number of transmitted packets is not greater than k. Equation (3) shows that with the number of transmissions going above k, it will lead to packet collisions and the nodes will not be able to receive any of the packets which will lead to complete packet loss. Let's assume that if k denotes the number of concurrent transmissions in a collision domain,

   $$P_r = \begin{cases} 1 & if \quad k \leq n \\ 0 & if \quad k > n \end{cases} \quad \text{… (3)}$$

II. MPR IMPLEMENTATION TECHNIQUES

Various MPR techniques are summarized in the Figure 1. Many of these MPR techniques are used only for mobile communication systems like cellular networks but only a few of the techniques are used for distributed wireless random access networks due to its random channel access behaviour. Based on the currently available research work on MPR technologies, MPR implementation techniques can be grouped under three main categories.

A. MPR enabled Transmitter

It enables MPR techniques at the wireless transmitting node. CDMA, SC-FDMA and OFDMA techniques come under this category.

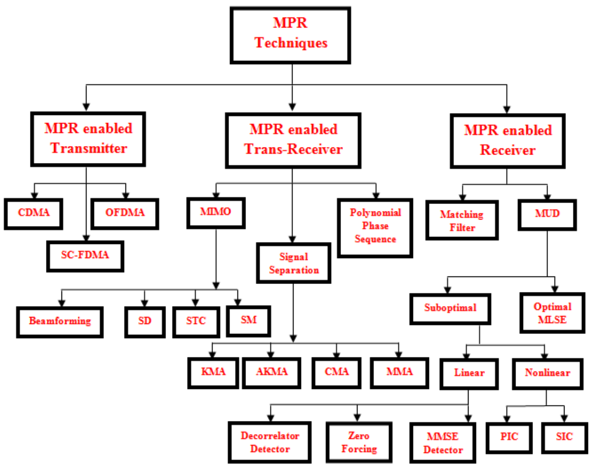

Fig. 1 MPR Techniques

B. MPR enabled Trans-Receiver

It enables MPR by enabling both the wireless transmitting and receiving nodes. Multiple-Input Multiple-Output (MIMO), Signal Separation and Polynomial Phase Sequence techniques come under this category. Beamforming, Spatial Diversity (SD), Space-Time Coding (STC) and Spatial Multiplexing (SM) are some of the well known MIMO techniques. Known Modulus Algorithm (KMA), Algebraic KMA (AKMA), Constant Modulus Algorithm (CMA) and Multiple Modulus Algorithm (MMA) are signal separation techniques.

C. MPR enabled Receiver

It enables MPR at the wireless receiving node. It makes the receiver responsible for implementing MPR technology and has a more realistic approach. The Match Filter (MF) and Multiuser Detection (MUD) techniques come under this category.

III. MPR LITERATURE SURVEY

An attempt has been made to do a detailed survey of MPR techniques, channel model adopted and performance parameters analyzed for WLAN.

The Generalized Channel Model for MPR [1] was first introduced for Slotted ALOHA with no CSMA and analyzed one-hop throughput and stability [1], [4] properties. The model states that when there are simultaneous transmissions, the conditional probabilities described the reception at MPR node instead of deterministic failure. This channel model has been widely accepted and used in many of the research works [1], [4-9], [11-13], [15-16], [19], [24] and [27-28]. k-MPR Model has been cited in few of the research works [14] and [25-26].

A lot of work has been carried out in analyzing various MPR techniques and its associated performance parameters. The probability of error parameter for a multiple-access channel shared by multiple users transmitting asynchronously has been analyzed using Optimal Maximum Likelihood Sequence Estimation (MLSE) MUD technique [3]. This MPR technique demonstrates excellent performance but it is too complex. The bit-error-rate performance of a suboptimal linear de-correlated detector [5] has been analyzed for demodulation of asynchronous CDMA signals. It shows that the bit-error-rate is independent of the energy of the interfering users and shows similar near-far resistance as the optimal MUD. The de-correlated detector is less complex than the optimal MLSE detector, does not require information about the received energies and shows similar performance.

The signal processing techniques implemented at the physical layer of a MPR receiver impact the MAC layer since it needs to schedule and handle simultaneous packet reception and avoid collisions. MPR is not supported by the conventional DCF MAC protocol. Several research works involved re-designing the MAC layer to support MPR and maximize network throughput and capacity. Cross-Layer interactions between physical and MAC layers have been proposed to support multi-access channel at the MAC layer using temporal, spatial and spectral diversities of the signal at the physical layer. Local and End-to-End throughput parameters for MIMO, CMA and CDMA based systems along with MAC protocols are discussed in [6]. It summarizes that the MPR matrix depends on the channel conditions, capture models and signal separation algorithms. Signal separation algorithms like KMA and AKMA [8] are analyzed for SINR and bit-error-rate parameters in an asynchronous multiuser ad hoc network. AKMA has a better performance than KMA. The throughput using AKMA was also analyzed in [21]. The throughput parameter has been evaluated using polynomial phase-modulating sequences algorithm [10] for asynchronous random access wireless mobile ad hoc networks (MANETs). A cross-layer design for PHY-MAC layers [11] was proposed for the first time for Slotted ALOHA and analyzed throughput, capacity and stability parameters of the MAC layer using beamforming, matched filter, MMSE and orthogonal CDMA techniques at the PHY layer for WLAN. The spatial, local and end-to-end throughput of a multi-hop network with Slotted ALOHA MAC protocol is analyzed and compared for matched filter and linear MUD MMSE techniques [14] at the receiver. MMSE detector shows better performance. In [15], similar work has been carried out with zero forcing, matched filter and MMSE techniques for a two-user case and proves that the cross-layer design (PHY-MAC) approach improves the network performance to a great extent.

A new MPR system with modified version of DCF MAC protocol and multiple antennas at the PHY layer of AP for 802.11 WLAN [16] greatly improves the throughput. It shows that the throughput increases roughly linearly with increase in the number of antennas and ensures scalability of MPR system. It assumes synchronous packet transmission scenario and modifies the control frames format of CTS and ACK frames by copying client stations addresses. It achieves throughput of 25 and 50 Mbps for 50 nodes with MPR Capability of 2 and 4 respectively. [20] extends the earlier work of [16] and proposed that the multi-antenna MIMO systems can achieve MPR by making use of spatial diversity of the transmissions technique by placing multiple antennas as far as possible. The transmitted signals experience independent fading leading to a maximum diversity gain. It uses RTS/CTS based MAC protocol to achieve simultaneous packet reception and avoid collisions. Many of the PHY layer parameters like channel state information, space time coded beamforming, multiuser detection, subcarrier frequency and power allocation have been considered.

Cross-layer contention resolution algorithm using optimal retransmission probability for MPR in a slotted ALOHA WLAN was analyzed in [27]. The algorithm uses centralized information and chooses the optimal retransmission probability to maximize the expectation of the system. A joint MAC-PHY layer protocol for random access WLAN [28] is proposed to implement MPR with exponential backoff mechanism. Zero forcing MUD technique at the AP is the best option to estimate CSI using orthogonal training sequences in the preamble of data packets.

Another MPR system using SIC technique [17], [22] provides a better capacity improvement for random wireless ad hoc networks than network coding. Under the SINR model, the MPR technology using SIC [18] increases the capacity of random wireless ad hoc networks for multi-pair unicast applications by a factor of . [23] improves the work of [17] by analyzing energy efficiency being an important factor for increasing the capacity of the network using SIC technique. [29] introduces blind channel equalization algorithms (CMA and MMA) and proposes an adaptive multi-modulus equalization method. [30] proposes a super-linear scaling for throughput in non-saturated WLAN and uses queuing model for analysis. [31] proposes multi-round contention protocol to enhance channel utilization.

Using k-MPR model, the capacity of wireless ad hoc networks [26] is analyzed.

IV. MAC PROTOCOLS FOR MPR TECHNOLOGY

A MAC protocol for multi-packet reception technology is designed and implemented based on the underlying physical layer technology which is known as a Cross Layer (PHY-MAC) protocol. The de facto standard for WLAN medium access is the IEEE 802.11 DCF MAC. DCF MAC protocol is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In 802.11 DCF, only one station is allowed to transmit at a particular point of time. An attempt has been made to do a detailed survey of MPR adapted MAC protocols.

In the early 2000s, a random access MAC protocol Receiver Controlled Transmission (RCT) [7] was proposed for multi-hop ad hoc networks with MPR nodes. The hybrid scheduling determines receiver nodes & then transmitters for each receiving node. The throughput performance of RCT was 2.5 packets / slot (SPR) and 4.7 packets / slot (MPR). Multiqueue Service Room (MQSR) [9] was the first MAC protocol designed specifically for networks with MPR capability. But, the disadvantage of this protocol is that it requires a central controller which selects an optimal number of users who can access the channel in each slot. It proposes a new MAC protocol for heterogeneous networks with finite population. MQSR controls the size of the access set dynamically based on the channel MPR capability and the traffic load so that the expected number of successfully transmitted packets is maximized under a set of delay constraints. With transmission probability, P = 1 and 0.5, it achieves maximum SPR and 2-MPR throughput of 1.05 and 1.95 respectively. Later, a dynamic queue protocol [12] with a much lesser computational complexity compared to MQSR protocol was proposed. It divides time axis into transmission periods and adaptively controls the number of users gaining access to the channel in the same slot. It has a comparable performance with MQSR. The normalized throughput is 1.75 at transmission probability of 0.8 for 2-MPR system.

A new cross-layer XL-CSMA Protocol [13] was proposed which used channel sensing technique for the first time. Its disadvantages were that it neither modeled ACKs nor timer-based backoff mechanism. It shows moderate throughput improvement across the MPR channels. It achieves normalized throughput of 5.1 (XL-CSMA) and 4.5 (CSMA) with channel capacity of 7 for 10 nodes scenario with packet length of 100. In the late 2000s, a new cross-layer Channel State Information (CSI) based random access MAC Protocol [19] was proposed which adjusts each node's transmission probability dynamically based on the estimated channel condition, network population and MPR. It modifies IEEE 802.11 RTS/CTS handshaking procedure but has overheads due to RTS/CTS. The throughput is improved as number of nodes increases. The MPR capability value increases as the network size increases. It achieves throughput of 5.25 and 7.75 Mbps for 10 and 100 nodes respectively with average transmission probability of 0.5, MPR capability of 4 and average SNR value of 25 dB at receiver.

A Generic Distributed Probabilistic Protocol (GDP) [34] which addresses near-far problem in a wireless network was proposed. It modifies contention window. The node decreases its transmission probability following success and increases it following failure. It improves throughput and fairness. A Cooperative Multi-Group Priority Queuing (CMGPQ) MAC Protocol [35] was proposed which exploits cooperative diversity design for MPR MAC protocol for improving system throughput. It uses Client-Server model with one part in the base station and the other in wireless nodes. In a new approach, a slotted non-persistent CSMA Protocol [24] was proposed which used Poisson random traffic model. When a packet arrives at a node within a mini-slot, the node does not perform carrier sense until the beginning of the next mini-slot. Its disadvantages were that it neither modeled ACKs nor timer-based backoff mechanism. It recommends MPR Capability of {2,3} for hardware implementation. It achieves normalized throughput of 0.98 at traffic rate of 10 with MPR capability being 2.

Earlier work on MPR MAC protocols involved only synchronous transmission by WLAN nodes. For the first time, a cross-layer asynchronous MPR MAC Protocol [32] was proposed which uses an asynchronous MPR method for the

PHY and a random access MAC for WLANs. This protocol relies on space-time coding techniques. This MPR method detects multiple asynchronous packets while providing diversity and low bit error rates at the PHY layer. By resolving collisions at the PHY layer for simultaneous transmissions, it can simplify the design of MAC layer because the PHY layer can detect a number of simultaneous packet receptions but the MAC layer is still required to handle higher layer collisions. The disadvantage of this protocol is that it didn't model ACK packets.

In the latest state of the art research work, an asynchronous MPR MAC Protocol with reduced acknowledgement delays [33] was proposed which assumes asynchronous packet transmission by WLAN nodes. It modifies the backoff timer mechanism and handles acknowledgement packets as well. It also considers the nodes estimating incorrectly about the number of ongoing transmissions in the channel. It analyzes saturation throughput, packet delay, packet dropping probability and packet collision probability performance parameters. It achieves normalized saturation throughput of 1.6 and 2.4 for MPR capability of 2 and 3 respectively with number of WLAN nodes being 10.

V. Conclusions

In today's context, MPR technology has become increasingly popular in Wireless Local Area Networks to meet the growing demands of higher data rates, lesser probability of collision, lesser packet delay, higher capacity and maximum stability. MPR techniques were originally proposed for mobile communication systems like 3G, 4G etc but later introduced for WLANs as well. In general, MPR enabled WLANs use uplink network model of a WLAN with an Access Point receiving multiple packets concurrently from multiple surrounding WLAN nodes transmitting packets. Conventional IEEE 802.11 WLANs could support synchronous transmissions and single reception with only one node having access to the channel for packet transmission at a particular point in time based on DCF MAC protocol. Due to this limitation, the throughput and capacity of WLANs is constrained. This paper lists out consistent progressive research work done in the past in relation to MPR and its impact on the PHY and MAC layer of the WLAN protocol stack. With MPR, a receiver node can receive multiple packets simultaneously and thus improves the capacity and throughput of the network. It is important to note that MPR techniques are implemented at the PHY layer but better performance improvements are observed only by cross-layer design approach (PHY-MAC) which involves changes to the conventional MAC layer algorithm to avoid packet collisions at the higher layers. This survey paper classifies MPR techniques based on different approaches. This paper also lists wireless network performance parameters like throughput, capacity and stability which are impacted by MPR.

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