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A MAC PROTOCOL WITH MULTI-USER MIMO SUPPORT FOR AD-HOC WLANS

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ABSTRACT

Multiple Input-Multiple Output (MIMO) is a wide set of multiple antenna technologies, which significantly increase the capacity of wireless networks, without additional bandwidth or increased transmission power. They are widely recognized as methods that can meet the ever growing network capacity requirements. With a MIMO physical layer (PHY), the transmission channel gains a layered structure, which gives another degree of freedom in scheduling transmissions. Additionally, support from higher layers with a cross-layer approach that provides efficient management of the channel's spatial layers, can significantly increase the networks' performance on both link and system level.

Single-User-DCF (SU-DCF), a Multiple Access Control (MAC) protocol with the support for Single-User (SU)-MIMO transmissions in Ad-Hoc WLANs, has been previously presented. In this paper we extend that protocol to support Multi-User (MU) transmissions. In the new protocol - Multi-User-DCF (MU-DCF), destination stations for the frames in a MIMO frame can be different stations. We have studied and compared different transmission strategies and schedulers including the IEEE 802.11n system, to explore the benefits of transmitting in MU mode.

I. INTRODUCTION

MIMO technology, a promising means of boosting the performance of wireless networks [1–3], has already been included in both cellular and ad-hoc network standards [4–6]. However, most of the research done in this area covers the Physical Layer (PHY) aspects of the system at hand. In this paper we present a MAC layer design adapted to the MIMO channel layered structure. The most important feature of the new system is the capability to support MU-MIMO transmissions. We study how the potential benefits of this approach depend on traffic characteristics in a given scenario.

The paper has the following structure: in Section II, the new protocol is described. An overview of the SU-MIMO support from SU-DCF is given, followed by the necessary MAC layer extensions for MU transmissions. This Section also covers the overhead estimation. In Section III, Quality of Service (QoS) support adapted to the new transmission scheme using a Dynamic Priority Scheduler (DPS) is presented, and in Section IV comparison with the IEEE 802.11n [4] standard is provided. In Section V we present and analyze simulation results for all the described systems, and the conclusions are compiled in Section VI.

II. MU-DCF PROTOCOL DESCRIPTION

A. *SU-MIMO support in the IEEE 802.11 Distributed Coordination Function (DCF) - SU-DCF*

SU-DCF [7] enhances the IEEE 802.11 DCF [8] with SU-MIMO capability. Prior to data transmissions, in the association procedure, stations share among each other the information about their hardware capabilities. Similarly as in the IEEE 802.11 DCF, medium access in SU-DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), with a random backoff procedure. A station with pending data frames draws a random number between 0 and Contention Window Size (CW), which determines the duration of the backoff timer in timeslots. CW has a minimum starting value of 15, doubles after a collision, can rise up to 1023, and is set back to its minimum value after a successful transfer. After detecting the medium free for a time interval equal to DCF Inter-Frame Space (DIFS), the station counts down the backoff timer until it reaches zero and initiates a transmission. If during the countdown another station occupies the medium, all the stations in backoff interrupt their count down and defer until they detect the medium free for at least DIFS.

The IEEE 802.11 standard [8] includes an optional Request-to-Send (RTS)/Clear-to-Send (CTS) handshake prior to the transmission to alleviate the hidden node problem and reserve the medium for the data transmission. A station with a pending data frame, after finishing the backoff procedure, first transmits an RTS frame. Stations which receive the RTS frame and are not its intended receivers defer from the medium in order not to interfere with the transmission. If the intended receiver of the RTS is idle and thus able to receive data, it responds with a CTS frame. After receiving the CTS frame, the initiator of the transfer transmits the data frame. If successfully received by the intended receiver, the data frame is acknowledged with an Acknowledgment (ACK) frame.

SU-DCF uses extended forms of RTS and CTS - MIMO-RTS (M-RTS) and MIMO-CTS (M-CTS) to exchange the information about multiple antennas. The frames are presented in Figures 1 and 2. In order to support multiple antennas, both frames have a new field: in M-RTS this field is called Proposed Antenna Bitmap (PAB) and encodes the chosen subset of available antennas proposed for the following transmission. M-RTS also includes in the preamble the training sequence for the channel estimation (in PHY). The receiver of the frame confirms which antennas should be active in the Confirmed Antenna Bitmap (CAB) of M-CTS. The transmitter makes the final decision about which MIMO scheme should be used, based on the receiver's instructions about the antennas to be used. Afterwards, multiple frames may be transmitted at a time, and they are acknowledged by a MIMO-ACK (M-ACK) frame.

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The M-ACK contains a new field for per-stream acknowledgments, and it is presented in Figure 3. When the transmitter receives the M-ACK frame, it removes the frames from the queue. If the M-ACK frame is not received, after a timeout the transmitter will retransmit the data. Setting the Network Allocation Vector (NAV) timer is same as in the IEEE 802.11 standard [8], as well as the usage of inter-frame spaces.

2 bytes	2 bytes	6 bytes	6 bytes	1 byte	4 bytes
Frame Control	Duration	Receiver Address	Transmitter Address	**Proposed Antenna Bitmap (PAB)**	Frame Check Sequence

Figure 1: M-RTS Frame

2 bytes	2 bytes	6 bytes	1 byte	4 bytes
Frame Control	Duration	Receiver Address	**Confirmed Antenna Bitmap (CAB)**	Frame Check Sequence

Figure 2: M-CTS Frame

2 bytes	2 bytes	6 bytes	1 byte	4 bytes
Frame Control	Duration	Receiver Address	**Acknowledged Packet Bitmap (APB)**	Frame Check Sequence

Figure 3: M-ACK Frame

All the control frames are transmitted using a scheme which is supported by all the stations, independently of their hardware capabilities, including the stations with only one antenna. The choice of the scheme used for data transmission is a system design issue: random or adaptive antenna selection, transmit or receive diversity or both, etc. Using diversity schemes, for example, will increase the probability of correct reception, whereas spatial multiplexing increases the throughput. The MIMO scheme used for the transmission of data frames is selected based on the stations' hardware capabilities, Quality of Service (QoS) demands of the connection, radio propagation conditions, and current status of the network. How the receiver and the transmitter choose the antennas is their internal procedure. This procedure of choosing the applied MIMO scheme on per frame basis provides fast link adaptation. More details on SU-DCF can be found in [7].

2 bytes	2 bytes	n * 6 bytes	6 bytes	1 byte	4 bytes
Frame Control	Duration	n * Receiver Address	Transmitter Address	Proposed Antenna Bitmap (PAB)	Frame Check Sequence

Figure 4: MU-RTS Frame

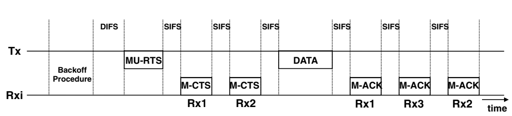

Figure 5: MU-MIMO Transmission

B. *MU-MIMO support in the IEEE 802.11 DCF - MU-DCF*

SU-DCF protocol performs very well in a network under heavy load, because of the increased system capacity provided by MIMO technology. However, when the load is not high, the frame delay grows due to the fact that the protocol does not allow a station to start a transmission before the number of frames in the queue is equal to the number of spatial streams.

In ubiquitous networking, a station might be communicating with more stations at a time, e.g. Access Point (AP) in a Wireless Local Area Network (WLAN). By relaxing the rule that a MIMO frame has to be constructed from the frames with a common destination, the transmission could be started earlier. Particularly applications with light load would benefit from this.

In MIMO systems, achieving a high network throughput becomes less critical than ensuring a timely delivery for a specific flow. With respect to the latter characteristic, MU-DCF provides two important advantages compared to M-DCF. First, under light load, the delay characteristic is improved. Second, under heavy load, the delay jitter is reduced. Improving the delay characteristic is especially important for applications such as Voice-over-IP (VoIP), Video Conferencing, interactive gaming, etc.

MU-DCF is extended from SU-DCF, supporting MU-MIMO transmissions. It facilitates channel access with a four-way handshake procedure involving multiple users prior to the data transmission, as illustrated in Figure 5. In order to support MU transmissions, M-RTS is extended. The new frame is called MU-RTS, and is presented in Figure 4. The difference compared to M-RTS frame is that new receiver address fields are added, to address multiple stations at a time.

In the following we describe the additional MAC protocol functionality during a transmission cycle in MU-MIMO scenarios, compared to SU-DCF protocol. The procedure is illustrated in Figure 5:

- A transmission is initiated by a MU-RTS frame transmission (see Figure 4), which polls multiple receivers.
- Upon receiving the MU-RTS frame, the stations which are present in the receiver list reply with M-CTS frames, built as in SU-DCF. The order of replies is implicitly determined by the receivers' order in the MU-RTS frame.
- Upon receiving the M-CTS frame(s), the transmitter compiles the collected information, and creates and transmits a MIMO frame.
- The stations receiving the MIMO frame, generate M-ACK if they receive correctly at least one frame. The order of M-ACK frames is implicitly determined by the order of data frames of the MIMO frame.
- When the transmitter receives the M-ACK frames, it removes the acknowledged frames from the queue and initiates another transmission. Unacknowledged frames are retransmitted.

It is worth noting that the polled stations do not necessarily have to be transmitted a data frame within a MIMO frame, as illustrated in the Figure 5. This decision is made by the transmitter which does the final scheduling after receiving the M-CTS replies.

The essential features of MU-DCF are:

- Simultaneous transmission of multiple frames which do not necessarily have a common destination - MU-MIMO.
- Alleviating hidden station problem in the MU case using MU-RTS and M-CTS frames as replies to MU-RTS.
- M-ACK for acknowledging correctly received data frames.
- Same as SU-DCF, MU-DCF supports fast link adaptation. It is scalable, and interoperable with stations with different number of antennas (including single-antenna stations), and backward compatible with the IEEE 802.11.

C. Protocol Overhead Estimation

The overhead is illustrated by means of an example with a single transmitter with 4 frames for 4 receivers. All the stations have 4 antennas, and 4 x 4 multiplexing scheme is applied. We calculate the time needed to transmit the frames.

- SU approach:

$T_{SU} = 4*$(M-RTS + M-CTS + MIMO frame + M-ACK)

- MU approach (each MIMO frame consists of one frame from each receiver; in a real system, not all the frames need to have different destinations):

$T_{MU} = 4*$(MU-RTS + 4M-CTS + MIMO frame + 4M-ACK)

The transmission clearly lasts longer in the MU case, but the average delay per station in the SU case differs much if the station was the first one or the last one to receive its frames. In the MU case all the stations experience the same average delay. For some stations such long delays might not be acceptable.

Up to now, it was assumed that at the beginning, all four frames destined to four stations were already generated. But there are many applications with low offered load requiring very low delay, so station can not wait too long for more frames to build a full MIMO frame. Otherwise, sending immediately what is present in the queue in the SU mode might often mean transmission of a single spatial stream, which effectively means multiplication of the overhead. Last but not least, in case of light load, MU approach will reduce jitter.

Most of the overhead introduced by the MU signaling comes from Short Inter-Frame Space (SIFS) durations between each two consecutive frames and from preambles. Therefore we propose using another multiple access scheme to transmit M-CTS and M-ACK frames instead of using Time Division Multiple Access (TDMA). In MIMO systems it is possible to spatially multiplex them, but we do not assume the channel knowledge at the transmitter. In an Orthogonal Frequency Division Multiplexing (OFDM) system (which is assumed in this work), an Orthogonal Frequency Division Multiple Access (OFDMA) extension would bring smallest hardware complexity (compared to other multiple access schemes such as Code Division Multiple Access (CDMA) or Multi-Carrier Code Division Multiple Access (MC-CDMA) that would have similar effect on the protocol performance).

By using a quarter of subcarriers, short frames such as M-CTS and M-ACK, are not four times longer compared to the case of using all the available subcarriers - since the major part of the frame is the preamble. Depending on the PHY, M-CTS and M-ACK are only a small number of symbols longer. For the parameters that we use in the simulations, the average transmission window has the following durations: SU - 338 μs; MU (TDMA) - 578 μs; MU (OFDMA) - 362 μs.

III. Cross-layer Optimization and QoS Support in MU-DCF

The QoS support in the IEEE 802.11n [4] assigns a frame to a Traffic Class (TC) with an appropriate priority. Prioritization is carried out using different Arbitration Inter-Frame Space (AIFS) prior to starting backoff countdown, and different CW. However, this method does not fully exploit the additional degree of freedom (spatial dimension) when building a MIMO frame in MU-DCF. In the MU case, most critical frames are to be identified, independently of their destination. For this purpose, each frame is assigned a priority level, which determines its position in the transmitter's queue.

The simplest policy is to transmit frames in the order of arrival (First In - First Out (FIFO) order). For more efficient QoS support when more TCs are present, we assign each frame a Dynamic Priority (DP). The DPS schedules a number of frames equal to the number of spatial streams with the highest priority. We use the Largest Weighted Delay First (LWDF) scheduler [9]. QoS requirements for the application of the receiver i are defined by:

$$P(W_i > T_i) \leq \delta_i \quad (1)$$

where $T_i(t)$ is the maximum tolerable delay for the specific application, $W_i(t)$ is the time the first frame from connection i has already spent in the queue, and δ_i is the allowed violation probability. The priority assigned to the frame of the receiver i is calculated using the following function:

$$priority_i = \frac{-\log \delta_i}{T_i} \cdot W_i \quad (2)$$

In order to improve the delay characteristic under low load, we allow stations to transmit even before they have enough frames in the queue. This fully exploits the channel capacity. The station will try to postpone the transmission so that possibly more frames can be transmitted, but not too much to avoid that the frames with a limited lifetime get discarded. The detailed description of this algorithm is out of the scope of this paper.

IV. Comparison of MU-DCF with the IEEE 802.11n

The IEEE 802.11n standard is intended to provide MAC and PHY enhancements to support throughput of 100 Mb/s and greater, as measured at the MAC layer. A station operating in an IEEE 802.11n network is called a High Throughput (HT) station. One of the most important MAC features that is added is frame aggregation. Additionally, Reduced Inter-Frame Space (RIFS) for separating consecutive frames from one station significantly increases the MAC efficiency. The standard defines extensibility to up to four streams, and operating in 20 MHz or 40 MHz channels. These features are capable of supporting data rates of up to 600 Mb/s on the PHY. Low-density parity-check codes are added. Other features at both transmit and receive side are 400 ns short guard interval, transmit beamforming, HT greenfield format, and space-time block codes. The maximum frame length is extended to 65535 byte [4].

Table 1: System Parameters.

Max. TxPower/Noise Level	$17dBm/-93dBm$
Path loss Factor	3.5
Channel Bandwidth	$20MHz@5.25GHz$
Number of Subcarriers	48 Data + 4 Pilot
Symbol Interval/Guard Time	$4\mu s/0.8\mu s$
aSlotTime/SIFS/DIFS	$9\mu s/16\mu s/34\mu s$
AIFS: IEEE 802.11n RT/NRT	DIFS/DIFS+SIFS
CWmax	1023 slots
CWmin: DCF, SU-DCF & MU-DCF	15 slots
CWmin: IEEE 802.11n RT/NRT	15 slots/31 slot
Data Frames PHY Mode	64QAM3/4$(54Mb/s)$
Control Frames PHY Mode	16QAM3/4$(36Mb/s)$
Load Type	Poisson, 1024 byte frames

The main difference of MU-DCF compared to the IEEE 802.11n is the capability of MU-MIMO transmissions. For this reason, we have also adapted the QoS support, by using DPS. As will be shown in the next Section, in many realistic scenarios MU-DCF performs better, despite higher overhead. It should be noted that in order to provide fair comparison, not all the options of the IEEE 802.11n are activated (such as Block Acknowledgment (BA), link adaptation, 40 MHz channel bandwidth etc.). The same options would improve the performance of MU-DCF as well.

V. Simulation Results

In this Section we present the simulation results on a hot-spot scenario with downlink connections from the AP to 14 randomly located stations. All the stations are assigned an equal fraction of the total offered load. Other relevant parameters are given in Table 1.

In the first case study, all the connections have the same traffic type - without any delay requirement, to study the maximum achievable throughput. We present the performance of SU-DCF, and MU-DCF with the control frames separated in time and using OFDMA. As the reference cases, the DCF performance is given (single antenna system), and the performance of the IEEE 802.11n on the same scenario.

The maximum theoretically achievable throughput using one spatial stream is 20.2 Mb/s. The maximum throughput

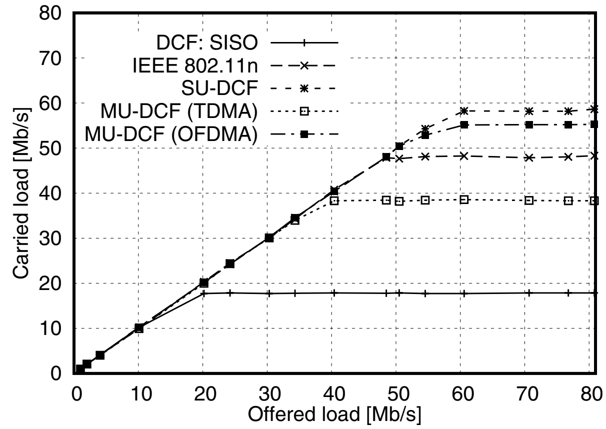

Figure 6: Case study 1: Total carried load vs. offered load

achieved in DCF according to the results presented in Figure 6 is about 18 Mb/s, slightly smaller than the maximum due to erroneously received frames. In MIMO systems we assume four transmit and four receive antennas and use all the four spatial subchannels. In this case, the maximum theoretically achievable throughput is 80.8 Mb/s, whereas the achievable throughput of any simulated scheme does not exceed 60 Mb/s, which indicates higher error rate than in DCF. The reason is that the transmit power per stream is four times lower than in Single Input-Single Output (SISO) case.

The highest throughput is achieved when SU-DCF is used. This is because SU transmissions produce the smallest overhead. The IEEE 802.11n has somewhat lower throughput due to the longer channel access time (the traffic is classified as best effort, and has therefore longer AIFS and higher Minimum Contention Window Size (CWmin): AIFS = DIFS + SIFS, CWmin = 32). The performance of MU-DCF in case of consecutive replies from the receiver (TDMA) is significantly lower than that of the IEEE 802.11n, but using OFDMA recovers the performance close to SU case, as expected.

In the second simulation setup we study the ability of different policies to provide QoS. We randomly divide the connections into two subsets: the traffic class in the first one remains the same as in the previous simulations, and for the second one we define the maximum frame lifetime to be 100 ms. M-CTS and M-ACK replies in MU-DCF are done with OFDMA. As for the QoS support in the IEEE 802.11n, the frames of the real-time applications are assigned the following parameters: AIFS = DIFS, CWmin = 15, and the parameters for the non-real-time applications remain the same. The results are presented in the Figure 7 (total carried load) and in Figure 8 (Packet Loss Rate (PLR) for real-time applications). Four main conclusions can be made:

1. SU-DCF achieves the highest network throughput. However, QoS of real-time applications can not be supported when the offered load is higher than 60 Mb/s, since some frames get discarded at the transmitter due to long waiting times. MU-DCF (with both FIFO and DP schedulers)

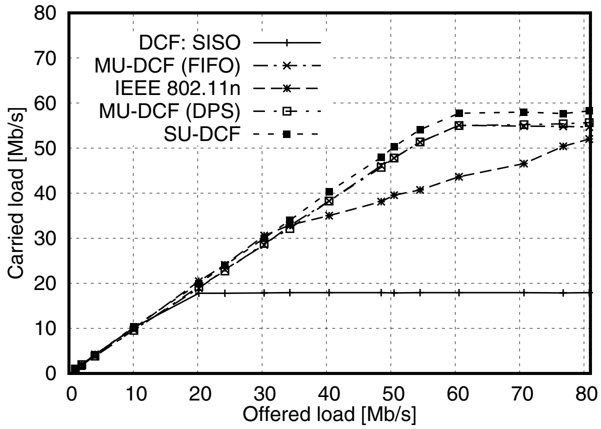

Figure 7: Case study 2: Total carried load vs. offered load

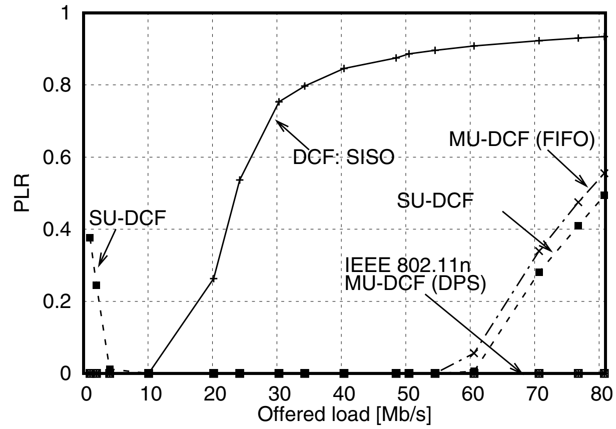

Figure 8: Case study 2: PLR vs. offered load for real-time applications

has similar performance, with smaller network throughput due to the higher overhead.

2. PLR under low load in SU-DCF is very high, since there is no prioritization of real-time traffic. While waiting for the non-real-time traffic to be delivered according to the FIFO order, their frames' maximum lifetime is reached and they get discarded. This is not the case for MU-DCF with FIFO scheduler (and with DPS), since frames with different destinations can be combined and transmitted simultaneously.

3. When introducing DPS to MU-DCF total carried load remains the same, but the QoS performance of real-time applications is significantly improved. By assigning higher priority to frames of real-time application, they are transmitted earlier and do not get discarded at the transmitter, even when the total offered load exceeding 80 Mb/s (in FIFO case frames get discarded already at 55 Mb/s offered load). However, at the same time the non-real-time frame queue size is growing.

4. The IEEE 802.11n can also provide QoS to real-time applications as MU-DCF with DPS, but with lower total throughput due to the higher overhead for non-real-time applications (longer channel access time).

VI. Conclusion

In this paper, a MAC protocol with MU-MIMO support, called MU-DCF, has been presented. To efficiently deal with significantly higher signaling overhead that MU-MIMO systems have compared to SU ones, we proposed applying OFDMA for simultaneous signaling to and from multiple users. On the system level, MU-MIMO transmissions were proved beneficial compared to SU systems (SU-DCF and the IEEE 802.11n) when QoS is needed.

The future work will focus on the link adaptation: finding the (sub)optimal MIMO scheme with the corresponding Modulation and Coding Scheme (MCS), as well as exploring the gains of channel aware scheduling with respect to the overhead introduced by channel estimation and Channel Quality Information (CQI) feedback.

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References

[1] M. Haardt and A. Alexiou, "Smart Antennas and Related Technologies," *WWRF - WG4 White Paper*, May 2005.

[2] A. J. Paulray, D. A. Gore, R. U. Nabar, and H. Bölcskei, "An overview of MIMO communications - A Key to Gigabit Wireless," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198–218, February 2004.

[3] E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–596, November/December 1999.

[4] *IEEE P802.11n/D2.02 Draft STANDARD for Information Technology-Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Higher Throughput*, IEEE 802.11 WG, May 2007.

[5] *IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE 802.16 WG, October 2004.

[6] *Physical Layer Standard for CDMA2000 Spread Spectrum Systems, C.S0002-D, Revision D, v2.0, available at: http://www.3gpp2.org/Public_html/specs/C.S0002-D_v2.0_051006.pdf*, 3GPP2, September 2005.

[7] J. Mirkovic, G. Orfanos, H.-J. Reumerman, and D. Denteneer, "A MAC Protocol for MIMO Based IEEE 802.11 Wireless Local Area Networks," *IEEE Wireless Communications and Networking Conference, WCNC*, pp. 1–6, March 2007.

[8] *Supplement to IEEE Standard for Information technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- High-Speed Physical Layer in the 5 GHz Band*, IEEE 802.11 WG, September 1999.

[9] A.L. Stolyar and K. Ramanan, "Largest Weighted Delay First Scheduling: Large Deviations and Optimality," *Annals of Applied Probability*, Vol.11, No.1, pp. 1-48, 2001.