MIMO-based Enhancement to the IEEE 802.11 Distributed Coordination Function

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Abstract—**In this paper, we propose an enhancement to the distributed coordination function (DCF) of the IEEE 802.11 MAC protocol, called the MIMO-based DCF (MBD). The MBD scheme exploits the multiple spatial channels (MSC) created by multiple inputs multiple outputs (MIMO) systems to enhance the IEEE 802.11 DCF collision-avoidance mechanism. The key idea is the sharing of the spatial channels during the contention period, i.e., instead of accessing the channel using the total spatial channels, the contending nodes only use a set of the available spatial channels. As the total concurrent used spatial channels are fewer than or equal to the degree of freedom (DOF), receivers can receive multiple contention attempts and hence they can coordinate their responses to avoid collisions. The spatial channel sharing produces other properties such as medium contention termination and medium contention selection. The former refers to the accessing node's capability to terminate its contention upon detecting other ongoing medium access attempts to avoid potential collisions. Contention selection happens when receivers detect multiple medium access requests initiated by different transmitters. Consequently, receivers either respond to some requests or keep silent to avoid further collisions. Simulation results obtained using OPNET Modeler show that the MBD scheme substantially reduces the medium access collisions. Actuating the medium contention termination and medium contention selection mode further reduces the medium contention collisions. The results of the MBD based on an adaptive MSC sharing scheme demonstrate that with different network loads using the adaptive MSC sharing scheme further reduces medium access collisions.**

I. INTRODUCTION

Recently, multiple inputs multiple outputs (MIMO) transmission techniques have been increasingly emerged in wireless communication systems including wireless local area networks (WLANs). The IEEE 802.11n comprises two medium access mechanisms, distributed coordination function (DCF) and point coordination function (PCF). In this work we concentrate our study on DCF access mechanism. The DCF implements random backoff prior to each frame transmission attempt. The random backoff can reduce the collision probability, albeit it cannot completely eliminate the collisions since two or more stations may finish their backoff procedures simultaneously. As the number of contending nodes increases, the number of collisions is also likely to increase. The DCF adopts a binary exponential backoff by increasing the contention window size exponentially upon each transmission failure in order to reduce consecutive collisions. However, in certain situations, this exponential backoff results in inefficient channel utilization. There have been remarkable studies to improve the performance of DCF. The analytical model proposed in [1] demonstrates that the performance of DCF strongly depends on the minimum contention window and the number of stations. The authors of [2] propose a dynamic and distributed algorithm which allows each node to estimate the number of competing nodes and to tune its contention window to the optimal value during runtime. Reference [3] proposes an algorithm (based on the current network status) that estimates the scheduling delay before a transmission attempts. The work in [4] proposes fast collision resolution (FCR), which actively redistributes the backoff timer for all competing nodes. The work in [5] proposes a distributed reservation-based MAC protocol called early backoff announcement (EBA) where nodes include their backoff values in the MAC header of each transmission. Nevertheless, there has been no proposal that utilizes MIMO techniques as a collision mitigation scheme in WLANs.

In this work, we introduce a novel MIMO-based DCF (MBD), that exploits the MIMO properties [6] to enhance the IEEE 802.11 DCF collision-avoidance mechanism. The basic idea is the sharing of the multiple spatial streams (MSC) created by MIMO systems, during medium contention period, to avoid medium access collisions. MSC sharing means that instead of accessing the medium using all spatial channels, a node uses only a subset. As the concurrent spatial streams used are fewer than or equal the degree of freedom (DOF), receivers can detect multiple medium contentions. MSC sharing produces other properties such as medium contention termination and medium contention selection. The former refers to the possibility of terminating the ongoing medium access attempt if the accessing node detects multiple concurrent medium accesses. However, contention selection refers to the possibility of detecting multiple concurrent medium access attempts initiated by different transmitters and hence they can coordinate their responses to avoid collisions.

Simulation results obtained using OPNET Modeler show that incorporating the MBD scheme considerably reduces the medium access collisions and boosts the channel utilization. An adaptive MSC sharing mechanism based on the network load variations is also proposed. The results obtained demonstrate that with different network loads, using the adaptive MSC sharing, consistently outperform the fixed MSC sharing.

The reminder is organized as follows: Section II briefly

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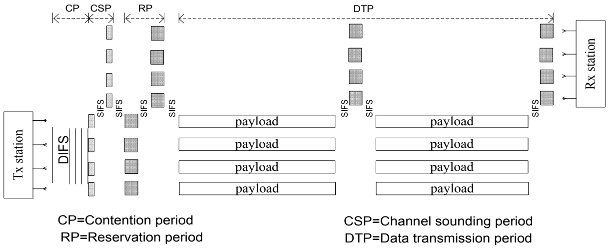


Fig. 1. IEEE 802.11n frame exchange sequence

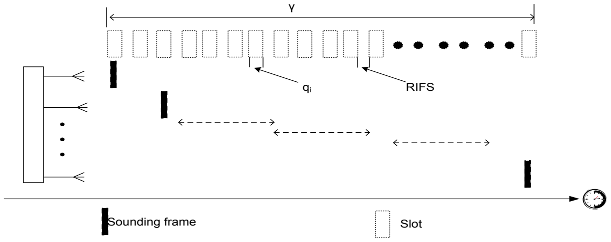


Fig. 2. γ length

reviews the IEEE 802.11n draft. In Section III we explain the proposed enhancements to the IEEE 802.11 DCF collision-avoidance mechanism. In Section IV, using OPNET Modeler, we evaluate the MBD scheme under different scenarios. Section V introduces the adaptive MSC sharing mechanism. Concluding remarks are given in the Section VI.

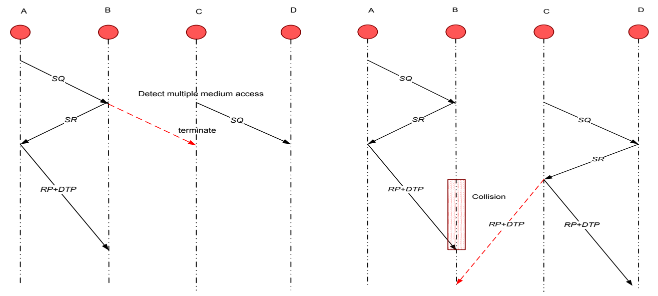
II. IEEE 802.11N

MIMO systems create multiple spatial channels, MSC, that can be used to concurrently send different data streams. To estimate the spatial channels, the IEEE 802.11n introduces transmitting a known communication setup frame, called sounding frame (SF), through all transmit antenna to help the receivers know the channel and therefore to recover the transmitted signals. SF frames can be either attached to the MAC protocol data unit (MPDU) frames if no channels feedback information is required at the transmitter node or can be exchanged. In the later case, the transmitter sends a sounding request (SQ) and the receiver responds with a sounding response (SR). The SQ and SR exchange is performed if the channels feedback information is required at both sides. Figure 1 depicts the frames exchange order between two nodes. IEEE 802.11n DCF contention phase (CP) starts right after a node gets data ready for transmission, the process then starts by monitoring the channel activity until an idle period, equal to distributed interframe space (DIFS), has been observed. In case the medium is sensed busy, a random backoff (BF) interval is selected. The backoff time counter is decremented as long as the channel is sensed idle, stopped when transmission is detected on the channel, and reactivated when the channel is sensed idle again for period of a DIFS. The backoff time is uniformly chosen from the $(0, CW-1)$ interval. The node starts the channel sounding period (CSP) when the backoff time counter reaches zero, during which a node exchange the sounding frames. After CSP phase nodes start exchanging communication frames which include the reservation period (RP) and data transmission period (DTP) respectively.

III. ENHANCEMENTS TO THE IEEE 802.11 DCF COLLISION-AVOIDANCE MECHANISM

We consider a distributed network model that consists of n stationary nodes. Each node is equipped with n_t transmit and n_r receive antennas. Receivers can decode DOF spatial streams, i.e., $\varphi = min(n_t, n_r)$, φ denotes the DOF. Each node independently apply the proposed collision-avoidance scheme. The required information is collected basing on observing the channel activity the node-of-question sees. Let z represent the total number of antennas in the node-of-question vicinity including the latter, i.e., $z = (n_e + 1) \times n_t$, n_e is the number of neighbors that have a transmission range overlap with the node-of-question. Let $f_i, i = \{1, 2, \ldots, z\}$ denotes the i^{th} antenna in the node-of-question transmission range. Each $f_{i^{th}}$ antenna when the backoff countdown of its holding node reaches zero transmits one sounding frame in a slot $q_i, i = \{1, 2, \ldots, \gamma\}$ that is uniformly selected from $(0, \gamma)$ range. γ is the number of considered slots during which the sounding frame is transmitted with probability $\frac{1}{\gamma}$. Figure 2 shows γ length which composed of multiple slots q_i separated by RIFS (reduced interframe space). We consider that each $f_{i^{th}}$ antenna uses the collected information at its holding node and independently determines its γ length. Antennas of the same node may sending their sounding frames concurrently, i.e., each contending antenna considers $\gamma = 1$. On the hand, they may use longer γ lengths, i.e., $\gamma > 1$, during which each antenna sends at any slot with probability of $\frac{1}{\gamma}$. Hence the core of our proposed scheme for enhancing the IEEE 802.11 DCF collision-avoidance mechanism is based on varying γ. In this work, we propose that when a node backoff time counter reaches zero, the accessing antennas (antennas mounted on this node) independently select their γ lengths based on the channel activity observations. If the accessing antennas consider longer γ lengths such that their holding nodes can switch to the listening mode during idle slots, nodes can observe the channel activity while they are contending for the medium. This new property can trigger the medium contention termination (T_c) mechanism, which refers to the possibility of stoping the sending of the SQ or SR sequential frames if the accessing node detects other ongoing transmissions. Node C in Figure 3(a) performed early termination because it detects another medium access attempt by node B. This is compared to Figure 3(b) where $\gamma = 1$. Node C did not detect the other medium access attempt and hence it cause a collision to the data received at node B. Algorithm 1 lists the transmitter access procedure.

Additionally, assuming longer γ lengths can help receivers detect multiple medium access contentions which triggers the medium contention selection (S_c) property. The latter can help the receivers coordinate their responses to avoid collisions. Figure 4(a) shows the scheme when the accessing antennas consider longer γ lengths. Node C receives SQ from D and



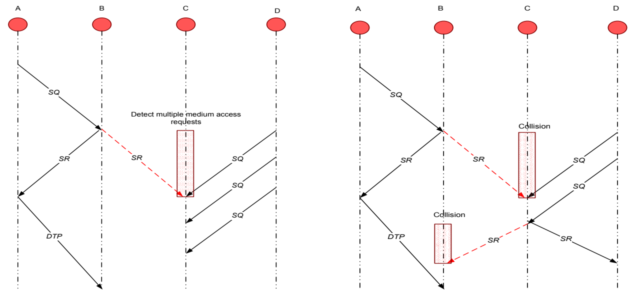
(a) MDB scheme, $\gamma > 1$ (b) IEEE 802.11 DCF, $\gamma = 1$

Fig. 3. Medium contention termination

Algorithm 1 MBD transmitter medium access procedure

```
if $BF \leftarrow 0$ then
    $determine(\gamma_{an_i}), \forall i, i = 1, 2, \dots, n_t$
    for $an_i, \forall_i, i = 1, 2, \dots, n_t$ do
        $A\{\dots\} \leftarrow q_j \leftarrow uniform(0, \gamma_{an_i})$
    end for
    if $T_c \leftarrow TRUE$ then
        $sort(A)$
        if $IDL > \Delta$ then
            Switch to listening mode and observe the channel
            if Detects other medium access attempts then
                Terminate.
            end if
        end if
    else
        Send the sounding frames without switching to listening mode
    end if
end if
```

IDL: the idle time interval between sending multiple sounding frames,
Δ: time interval sufficient for switching and listening to the media.



(a) The MBD scheme, $\gamma > 1$ (b) IEEE 802.11 DCF, $\gamma = 1$

Fig. 4. Medium contention selection

SR from B, C did not respond to node D, as its response can cause collision to B. Figure 4(b) show the same scenario but with using $\gamma = 1$. In the latter scenario the spatial streams from B and D exceeds the φ and therefore C can not decode the received signal. Node C responds to the next SQ request from D which causes a collision to the data received at B. Algorithm 2 lists the procedure followed the receiver during the contention period.

IV. PERFORMANCE OF MIMO-BASED DCF

To examine the performance of the MBD scheme we build a simulation model, using OPNET Modeler, that models all the details of the IEEE 802.11 DCF and the MIMO-based DCF. The values of the physical layer characteristics follows those defined for the IEEE 802.11n, the parameters are summarized in the Table I.

Algorithm 2 : MBD receiver medium access procedure

```
if Single SQ request is received then
    Respond
else if Multiple SQs requests destined to this node then
    Select the first SQ request.
else if Multiple SQs and SRs requests are received then
    Do not respond.
end if
```

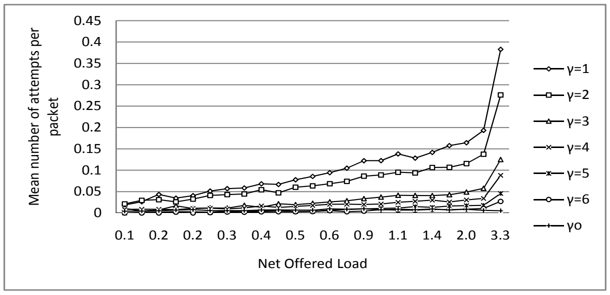


Fig. 5. Transmission attempts per packet for different γ lengths.

TABLE I
IEEE 802.11N CONFIGURATIONS

parameter	value	parameter	value	parameter	value
CW_{min}	15	CW_{max}	1023	SIFS	16 μs
PMDU	0-65535	RIFS	2 μs	Q	40 μs

The network model consists of 16 stationary nodes that uniformly distributed with distance ranges between (250-400) meters in such a way that hidden nodes are formed. Nodes generate traffic that follow a Poisson distribution with mean (inter-arrival) time (λ), The latter is a simulation parameter that models the network loads. For each generated data packet, nodes select a random neighbor as final destination. For each traffic load a set of fixed γ values are considered. The slots, $q_i = 1, 2, \dots, \gamma$ at which the i^{th} antenna transmits its sounding frame is determined by taking the uniform distribution function, i.e., $q_i = uniform(0, \gamma)$. Figure 5 shows the mean number of attempts needed to transmit a packet for different γ values and network loads. As expected, the number of collisions for smaller γ values tend to have rapid increase as the network traffic load increases. We next examine the affect of enhancing the IEEEE 802.11 DCF collision-avoidance mechanism on the average medium access delay which consists of the backoff and CSP delay. The MBD MAC delay for a light network load is dominated by the CSP delay. Therefore considering smaller γ results in lower MAC delay. As the network load increases, the number of collisions increases and therefore MBD MAC delay is dominated by the backoff delay as collided packets have to wait for longer backoff time and sometime the same packet experiences multiple collisions before being successfully transmitted which means longer and longer MAC delay. To study the affect of implementing the MBD scheme on the channel utilization

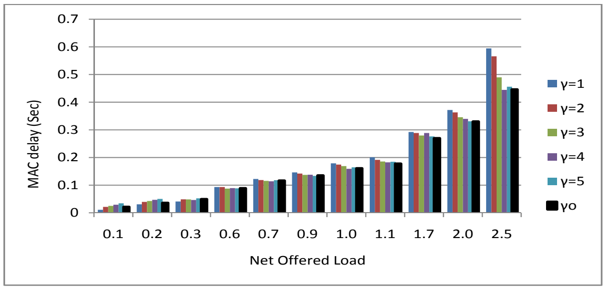


Fig. 6. MBD MAC delay for different γ lengths.

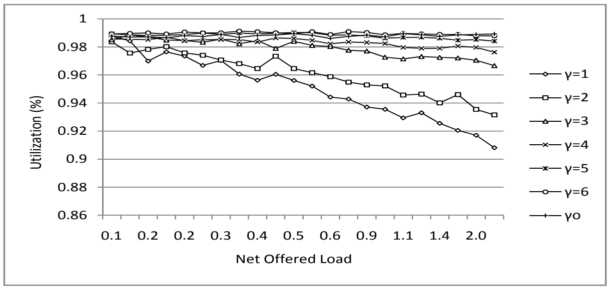


Fig. 7. System utilization under different γ lengths.

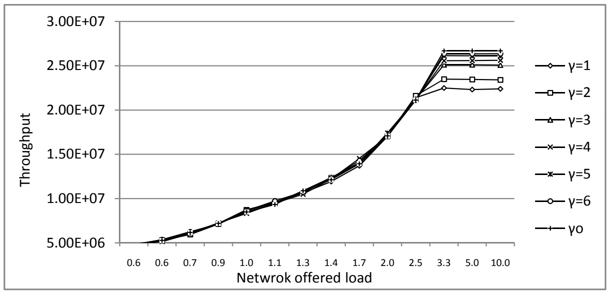
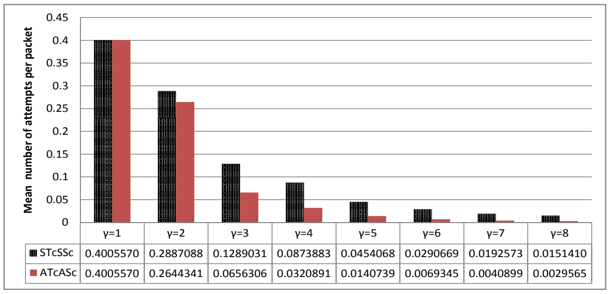


Fig. 8. Throughput for different γ lengths.



	γ=1	γ=2	γ=3	γ=4	γ=5	γ=6	γ=7	γ=8
▦ STcSSc	0.4005570	0.2887088	0.1289031	0.0873883	0.0454068	0.0290669	0.0192573	0.0151410
🟥 ATcASc	0.4005570	0.2644341	0.0656306	0.0320891	0.0140739	0.0069345	0.0040899	0.0029565

Fig. 9. Transmission attempts per packet for AT_cAS_c and ST_cSS_c modes.

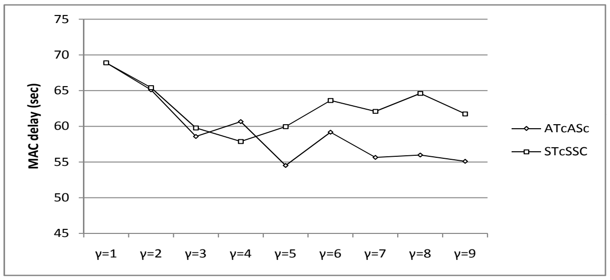


Fig. 10. MBD MAC delay difference between AT_cAS_c and ST_cSS_c modes.

which is defined as $U = \frac{T_d}{T_c+T_d}$ where T_d is the time spent in transmitting a successful data and T_c is the total control time which includes all the time spent in exchanging the coordination messages until the successful transmission. The vulnerable collision time of hidden node configuration increases the probability of collisions; hence, even with light network load, longer γ length tend to have higher channel utilization that is because collisions have higher negative affects on the channel utilization (i.e., nodes have to double the backoff size each time collision occurred) than the time wasted in CSP phase. Figure 7 and 8 show the system utilization and throughput for different network loads and γ values, respectively. As stated earlier, the MBD scheme possesses two properties: contention termination (T_c) and contention selection (S_c). Figure 9 show the number of attempts per packet difference between actuating and silencing both the T_c and S_c modes. Actuating both modes, AT_cAS_c, can further avoid collisions compared to silencing both modes, ST_cSS_c. Assuming longer γ lengths make nodes detect more medium access attempts and hence they can perform higher number of terminations which can result in fewer number of collisions compared to those schemes using smaller γ lengths. Figure 10 shows the difference in MBD MAC delay between AT_cAS_c and ST_cSS_c modes.

V. ADAPTIVE γ LENGTH

From the results above it is clear that, even with slightly loaded network, adapting longer γ lengths can avoid very considerable amount of collisions compared to those runs using smaller γ lengths. We can also observe that longer γ lengths at light network loads tend to have slightly higher MBD MAC delay. Because network loads vary over time between very high and very light traffic loads, adapting a proper γ lengths according to the traffic loads can avoid collisions and boost the channel utilization. Therefore, in this Section we propose an online scheme by which each contending antenna, during the runtime and according to the variations of the traffic load, adopts its γ to an optimal γ_o length such that it maximizes the success probability, i.e., having antennas anywhere from one to the degree of freedom transmit. The proposed scheme is based on estimating the number of active antennas v and their considered slot lengths. Hence, in this Section we differentiate between two slot lengths: γ is the slot length considered by this antenna (antenna-of-question), and $\beta_i, i = \{1, 2, \ldots, v-1\}$ is the slot lengths considered by $v - 1$ active antennas in the antennas-of-question vicinity. $v = (C_e + 1) \times n_t$ is the estimated number of active antennas including the antenna-of-question. C_e is the number of active nodes, which estimated by monitoring the channel activity, using carrier sensing, during the virtual transmission (t_v) interval. The latter, as shown in Figure 11, is the span of time between the observing of the DIFS period to the end of a transmission attempt, i.e.,

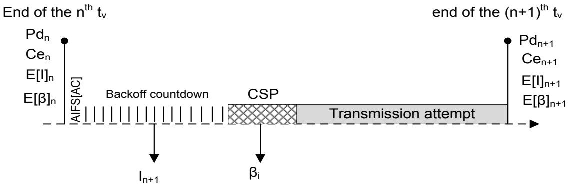


Fig. 11. Virtual transmission period.

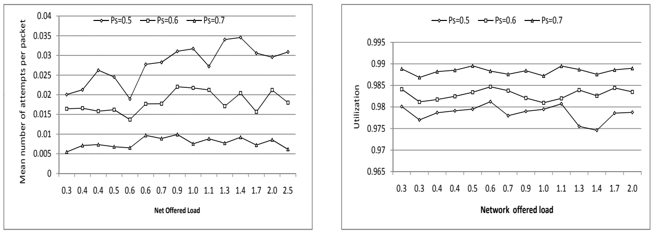
successful or collided transmission attempt. C_e estimation is based on counting the number of consecutive idle slots I during the n^{th} virtual transmission period. This number is then used to carry the average $E[I]$ computations over multiple virtual transmissions, $E[I]_{n+1} = \alpha \times E[I]_n + (1 - \alpha) \times I_{n+1}$. As discussed in [2], the average idle slots, $E[I]_{n+1}$, and the current transmission probability, Pd_{n+1}, can be used to estimate the number of active nodes,

$$C_{comp} = \frac{\ln(\frac{E[I]_{n+1}}{E[I]_{n+1}+T_{slot}})}{\ln(1 - Pd_{n+1})}. \tag{1}$$

The computed active nodes, C_{comp}, then is substituted in the exponential moving average function to smooth the variations that is resulted from the network traffic load fluctuations, $C_{e_{n+1}} = \alpha \times C_{e_n} + (1-\alpha) \times C_{comp}$, where Pd_{n+1} in Equation (1) expresses the probability that a node (not antenna in this case) transmits in a randomly chosen slot ξ time. ξ is the slot at which the node finishes the IEEE 802.11 backoff countdown and starts the channel sounding phase. Given $E[I]_{n+1}$ the Pd_{n+1} is estimated as follows, $Pd_{n+1} = \frac{1}{2 \times E[I]_{n+1}}$. Let $E[\beta]_{n+1}$ represent the average number of slots that is used by antennas during the previous virtual transmissions. The $E[\beta]_{n+1}$ computation is performed by observing the channel activity during each t_v period and record the number of slot, β_i, length considered by the $f_{i^{th}}$ antenna element to transmit its sounding frame. During each virtual transmission and at each transmitted sounding frame the antenna-of-question computes the average $E[\beta]_{n+1}$ by using the exponential moving average, $E[\beta]_{n+1} = \alpha \times E[\beta]_n + (1 - \alpha) \times \beta_{i_{n+1}}$. Let $m = 1, 2, \ldots, v$ represent the number of antennas that are going to transmit. Let $p_s(m)$ be the probability that m antennas are going to transmit. Allowing higher than the degree of freedom antennas to transmit causes collision and hence must be avoided. Accordingly we define $p_s(0 < m \leq \varphi)$ as the probability of success, i.e., receiving decodable signals. This probability is a function of the number of contending antennas v, their transmission probabilities $\frac{1}{E[\beta]_{n+1}}$, and the degree of freedom φ. Equation (2) relates the defined success probability to the aforementioned parameters.

$$\begin{aligned} p_s(0 < m \leq \varphi) = \\ (\frac{1}{\gamma})\sum_{r=0}^{\varphi-1}\binom{v-1}{r}(\frac{1}{E[\beta]_{n+1}})^r(1-\frac{1}{E[\beta]_{n+1}})^{v-r-1}+ \\ (1-\frac{1}{\gamma})\sum_{r=1}^{\varphi}\binom{v-1}{r}(\frac{1}{E[\beta]_{n+1}})^r(1-\frac{1}{E[\beta]_{n+1}})^{v-r-1} \end{aligned} \tag{2}$$

Where r is an index represent the number of spatial streams. The Probability of succuss, $p_s(0 < m \leq \varphi)$, can be set to any desirable value to satisfy any system performance metric such as maximizing channel utilization or minimizing medium access collisions. Based on the preferred success probability the accessing antennas select their transmission probabilities such that the desired success probability is approximately achieved. Figure 12 shows the affects of changing the success probability. Figure 12(a) considering higher probability of success values can produce less collisions which results in achieving higher channel utilization as shown in Figure 12(b). We compare the performance of the MBD scheme with using adaptive and fixed γ lengths. Refer to Figures 5-8. By observing the results, controlling the γ length according to the network load changes was found to have fewer mean number of attempts per packet (Figure 5), fewer MBD MAC delay (Figure 6), higher channel utilization and throughput as shown in Figure 7 and 8, respectively.



(a) Attempts per packet (b) Channel utilization

Fig. 12. The affect of changing the success probability value

VI. CONCLUSION

In this paper we have proposed an MBD scheme which exploits the MIMO properties to enhance the IEEE 802.11 DCF collision-avoidance mechanism. The basic idea of the MBD scheme is the sharing of the multiple spatial channels during the medium access period to avoid collisions. Under light network loads, the MBD scheme results in lower medium access collisions and higher channel utilization than the IEEE 802.11 DCF. To further improve the performance of the MBD scheme, an adaptive spatial channels sharing during the medium access period is also proposed.

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