where
\[ P_{\text{occ}} = \frac{G^{N-1}}{\sum_{i=0}^{N-1} G^{i}}. \]

and \( G = gT \). Since the control channel is not used for data transmissions, only \( N-1 \) channels are available for data transmissions. Figure 3 shows that the theoretical and simulated results match up well for different number of channels with respect to delay.

### B. Multi-channel MAC (MMAC)

Next, we study split phase approaches by using MMAC [9] as an example. Operation of MMAC is divided into two parts which form a cycle. MMAC is designed for IEEE 802.11 networks and it exploits Ad hoc Traffic Indication Message (ATIM) windows of IEEE 802.11 Power Saving Mechanism (PSM) which are originally used only for power management. In MMAC ATIM windows are extended and channel reservations conducted during ATIM windows on the CCC. Data transmissions take place on all available channels afterwards. We denote the length of the ATIM window by \( T_{\text{atim}} \) and the length of the data interval by \( T \), both in time slots. Thus, the total length of one cycle is \( T_c = T_{\text{atim}} + T \). Lengths of these intervals are predetermined and fixed and hence, the intervals determine the average access delay as well. We set \( T_{\text{atim}} = 0.2 \cdot T_c \) and \( T = 0.8 \cdot T_c \) since these values were used in the initial simulation model in [9]. Furthermore, it is assumed that packets fit perfectly to the chosen cycle structure. Figure 4 depicts the operation of MMAC during ATIM windows.

In case of MMAC, a node has to wait until the end of an ATIM window even though the initial transmission would be successful before transmitting data. Consequently, on average the initial transmission delay is
\[ E[D_0] = \frac{T_{\text{atim}}}{2} \cdot \frac{T_{\text{atim}}}{T_c} + \left( \frac{T_D}{2} + T_{\text{atim}} \right) \cdot \frac{T_D}{T_c}. \]

Moreover, if a node has not been able to reserve resources before the end of an ATIM window, it has to wait for the next data interval and an additional delay of \( T_c \) is added. Hence, the overall delay is
\[ D = D_0 + M \cdot T_c, \]

where \( M \) denotes the number of additional cycles. If the delay due to CSMA operations during an ATIM window is larger than the length of the ATIM window or all of the channels are occupied before a node can reserve resources, a packet will be delayed. By denoting the latency of a packet during an ATIM window with \( L \), this blocking probability can be represented as
\[ P_{\text{block}} = P\{L > T_{\text{atim}}\} + P\{L \leq T_{\text{atim}}\} \cdot P\{\text{Occupied}\}. \]

Since all resource reservations will be made during ATIM windows, the packet arrival rate has to be scaled such that all packets are generated during an ATIM window in one cycle for theoretical analysis. Hence, in theory we have the following packet arrival rate for the contention phase
\[ g_a = g \cdot \frac{T_c}{T_{\text{atim}}}. \]

First, we find out the probability that a node cannot reserve resources during an ATIM window due to the shortage of data channels. We approximate this by comparing the number of channel reservations to the number of channels. This is done by scaling the difference between the amount of successful negotiations and the number of channels with the amount of successful negotiations. All of the used probabilities are derived in Appendix B. The amount of successful data negotiations during an ATIM window is on average
\[ E[\text{packets}] = P_s g_a T_{\text{atim}}. \]

In the beginning of each ATIM window all the channels are free and hence, the previously used Markov model can not be exploited. In consequence, we approximate the probability that a packet is blocked because of channel shortage as follows
\[ P_{\text{block}}^c \approx \max \left\{ 0, \frac{P_s g_a T_{\text{atim}} - N}{P_s g_a T_{\text{atim}}} \right\}. \]

Secondly, in case of small ATIM windows, the performance will be bounded by the fact that only a certain amount of data channels can be reserved in time before the end of an ATIM window. Now, if a node senses that the control channel is busy during contention, it will backoff according to BEB. Same happens in case of collisions as well. During an ATIM window the latency of a successful RTS/CTS message exchange is \( 3\tau \). Since \( \omega = 32 \), the performance is dominated by \( P[R = 0] \) and \( P[R = 1] \) while the total delay is \( L \leq 35 \). Furthermore, \( 35 < T_{\text{atim}} \leq 2\omega, P[R \leq 2] \) dominates. Finally, if \( T_{\text{atim}} > 2\omega \) the effect of \( P_{\text{block}}^d \) becomes negligible since multiple retransmissions may take place and it is very unlikely that a packet is delayed due to the end of an ATIM window. We set the probability of a retransmission as \( P_r = P_c + P_b \) and approximate the probability of block due to the end of a contention window as follows
\[ P_{\text{block}}^d = \begin{cases} 1 - (P_s + P_r \cdot P_a \cdot \frac{T_{\text{atim}}}{\omega}), & T_{\text{atim}} \leq 35, \\ 1 - (P_s + (P_r^2 + P_r) \cdot P_b), & 35 < T_{\text{atim}} \leq 2\omega, \\ 0, & \text{otherwise}. \end{cases} \]

Figure 5 depicts theoretical and simulated results for different packet sizes. When the packet size is 100, the blocking