size is increased, which makes MMAC unsuitable for delay-sensitive applications.

We conclude that G-McMAC achieves highest throughputs in case of small or moderate packet arrival rates while packets are small. On the other hand, SYN-MAC outperforms other approaches in case of small packets and high packet arrival rates. Finally, MMAC provides the best performance with respect to throughput when the packets are large. However, MMAC causes very high latencies in general. Our delay analysis undoubtedly shows that G-McMAC outperforms other protocols clearly in terms of delay.

C. System Stability

When embarking on any wireless communication design, it is essential to understand the operation region of the used MAC protocol to ensure system stability. Figure 16 illustrates delay-throughput curves of MMAC, SYN-MAC and G-McMAC. Evidently, MMAC performs the worst since it induces high latencies and becomes unstable when the throughput is low. After this point, the throughput of MMAC starts to decrease while delay continues to grow. On the other hand, we can see that G-McMAC clearly outperforms SYN-MAC by offering lower delays in general. However, G-McMAC becomes unstable before SYN-MAC and in fact after the stability point of G-McMAC the throughput of SYN-MAC still continues to improve. Based on this observation we conclude that in order to minimize access delay, G-McMAC should be used. Whereas, if it is important to maximize throughput at the expense of access delays, SYN-MAC should be exploited.

VI. CONCLUSIONS

In this paper, the performance of multi-channel Media Access Control (MAC) protocols in ad hoc networks was studied with respect to two important Quality of Service (QoS) parameters, delay and throughput. We deduced average access delays and throughputs for different multi-channel MAC approaches in closed-form by considering Poisson arrivals. Theoretical results were verified by simulations for each of the considered protocols. Throughput and delay analyses were given in terms of critical system parameters such as number of available channels, arrival rate and packet sizes. We conclude that Generic Multi-channel MAC (G-McMAC) consistently outperforms other protocols with respect to delay. G-McMAC also achieves higher throughputs in some cases compared to other approaches, whereas, in some cases other approaches will achieve better throughput. Moreover, the low stability point of G-McMAC may be a problem for some applications and in those cases other approaches should be used. Presented results can be exploited to study the performance and suitability of different multi-channel MAC approaches for different wireless applications and to guide system design.

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APPENDIX A: PROBABILITIES FOR G-McMAC

Performance evaluation of random access schemes has been traditionally carried out by exploiting busy period analysis in which the average busy time $\bar{B}$ and average idle time $\bar{I}$ are used for determining the characteristics of various schemes. In this appendix we consider G-McMAC and derive the following probabilities using the busy period analysis [19]: $P_s$ is the probability of successful transmission, $P_c$ is the probability of collision and $P_b$ is the probability that the control channel is sensed as busy. We model multi-channel communications with a Markov chain. States represent the number of occupied data channels such that we have $N - 1$ data channels in total. Hence, the probability that all channels are occupied can be found using the Erlang B formula [21] and is given by

$$P_{\text{ooc}} = \frac{G^{N-1}}{N!} \sum_{i=0}^{N-1} \frac{G^i}{i!}.$$  \hspace{1cm} (A-1)

where $G = \frac{\lambda}{\mu}$. To find out the probabilities we need to derive the average idle and busy periods. For a start, the average idle period consists of $k - 1$ times no arrivals and at least one arrival in the last slot. Hence, the average idle time $\bar{I}$ is

$$\bar{I} = \frac{\tau}{1 - e^{-\frac{\tau}{\mu}}}.$$  \hspace{1cm} (A-2)

Next, we derive the average busy period which is defined as follows. The length of the busy period consists of $k$ transmission periods if there is at least one arrival in the last $k - 1$ slots and no arrival in the last slot. Moreover, in case of G-McMAC each busy period lasts $3\tau + \tau$. Consequently, we find out the average busy period of G-McMAC as follows

$$\bar{B} = \frac{4\tau}{e^{-\frac{\lambda}{\mu}}}.$$  \hspace{1cm} (A-3)

In one cycle, the number of possible time slots for successful transmission is $\bar{I}/\tau$ given that there is a packet arrival.