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OMAC: An Opportunistic Medium Access Control Protocol for IEEE 802.11 Wireless Networks

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Abstract—The ambitious goal of the upcoming IEEE 802.11ax (HEW) standard for wireless LANs (WLANs) to enhance throughput by four times (and beyond), compared with IEEE 802.11ac, demands a radical improvement of present medium access control (MAC) functionality. To this end, a promising paradigm would be a graceful migration towards new MAC protocols which incorporate higher certainty in their decisions. However, this requires adequate information to be available to the devices, which in turn incurs excessive costs due to information exchange between devices. Also, scalability becomes an issue for emerging dense networks. In this paper, we take a step forward by proposing an opportunistic MAC (OMAC), which restrains these costs, while increasing throughput of the new generation HEW. OMAC eliminates overhead costs by solely relying on the local capability of devices in measuring signal activities in the channel. A particular OMAC node continually collects and records the received signal strengths (RSS) overheard from the channel, and regards each individual RSS level as being transmitted by a unique node without the need to know the actual identity of the node. The OMAC node uses this knowledge to select a recorded RSS as its reference, and triggers a desired transmission policy whenever a transmission with an RSS sufficiently close to this reference RSS is detected. Our results, obtained using simulations, indicate that OMAC improves the throughput performance significantly, and that the performance gain increases with an increase in network density.

I. INTRODUCTION

There is an increasing demand for high throughput wireless access, driven by the proliferation of mobile devices, the increasing demand for bandwidth-hungry services, and the growing trend of dense network scenarios. This has led to an unprecedented growth of the market for wireless local area networks (WLANs), as evidenced by their ubiquitous penetration in homes and enterprises, as well as public hot spots. Moreover, wireless operators are embracing WLANs as an enabling technology for offloading cellular traffic and to expand network capacity and coverage by means of device to device (D2D) communications and small-cell deployments within future generation 5G technology [1]. The result is that the demand for WLANs will continue to grow and, according to recent forecasts [2], a significant proportion of traffic will originate from devices capable of using this access technology.

This trend has spurred a new wave of standardization activities, leading to the recently-developed, multi-gigabit IEEE 802.11ac (WiGig) standard, and moving towards a new standard, called High Efficiency Wireless (HEW), with an ambitious target of achieving at least a four times increase of medium access control (MAC) throughput per station

compared to WiGig [3]. While the previous standardization efforts were highly focused on increasing link throughput through physical layer developments such as high-density modulation and multi-user MIMO technology, the new efforts are mobilized towards enhancing MAC performance in terms of spectrum utilization and the achieved user experience (e.g. latency) in the face of applications with stringent quality of service requirements. However, the inefficiency of the conventional CSMA/CA-based random access mechanism of 802.11 potentially compromises the mentioned targets. It yields a satisfactory performance when the network is in light traffic conditions, while imposing decreased channel utilization in dense networks and bursty traffic situations due to the increase of idle backoff slots and collisions [4], [5]. The performance of the random access mechanism deteriorates further when the population of small frames is substantially high [6]. The Point Coordination Function (PCF), developed within the 802.11 standard, was aimed at enhancing quality of service support, however it also introduces excessive overhead due to null frames sent by a central coordinator to devices without any packet to transmit [7]. At the other extreme, there are deterministic control access mechanisms (e.g. TDMA) which perform well under saturated traffic conditions, at the cost of excessive overhead that is imposed when traffic is non-saturated. Moreover, TDMA-based methods do not scale well with network size, and the implementation of these mechanisms requires tight synchronization and the presence of a central entity responsible for resource allocation. An alternative scheme would be the use of hybrid CSMA/CA and TDMA techniques, as in IEEE 802.15.4. However, these inherit the weaknesses of the two schemes, plus the challenges arising from the need for adaptive duty-cycle configuration and balancing between the contention-free (CFP) and contention access periods (CAP) of the underlying duty cycles [8].

In this paper, we propose a novel, opportunistic medium access control mechanism for IEEE 802.11 networks, called OMAC. OMAC takes advantage of the physical-layer capabilities of 802.11 devices and the fact that such capabilities are increasingly enhanced with the recent advancement of signal processing techniques, leading to the proliferation of high sensitivity wireless devices. Our main idea is to augment CSMA/CA with a higher level of certainty in transmission control policy without requiring explicit information exchange and coordination between participating nodes. To this end, each node relies on its physical carrier-sensing capability in order to

overhear the channel, and collects information about received signal strength (RSS) levels from (active) peer nodes. Knowing that each RSS level uniquely maps to an active node, an OMAC node can use this fact to choose a reference RSS, and trigger an appropriate policy when a transmission from a node with RSS close to its reference RSS is detected. Such a policy can take on many different forms and in this work it is limited to a simple reconfiguration of backoff parameters. The RSS collection and reference selection process is continual; therefore, the proposed mechanism adapts to changes in network topology by selecting new reference nodes. OMAC can be thought of as a point on a spectrum with its extreme points corresponding to the conventional random and deterministic channel access control mechanisms. However, OMAC is different from the existing hybrid CSMA/CA and TDMA protocols as it does not involve collocated CAP and CFP periods, synchronization, and explicit exchange of control information between nodes and a central coordinator (e.g. an access point).

The remainder of this paper is organized as follows. Section II presents an overview of related work. In Section III, we detail the proposed medium access control mechanism. Section IV describes our simulation results, followed by Section V which concludes the paper and puts forward the future extensions of the present work.

II. RELATED WORK

Our work in this paper has properties in common with (semi-) deterministic medium access control mechanisms. In the following, we present the features of this approach and contrast with our approach.

Hybrid medium access control has been the focus of a significant body of previous work. Examples of such studies are [9], [10], where the authors proposed hybrid mechanisms by combining random access and TDMA. These slotted-based mechanisms — either hybrid or pure TDMA — require synchronization between nodes, which is usually performed by explicit beaconing. By contrast, OMAC is fully asynchronous, without the need for centralized coordination.

The idea of a hybrid deterministic and random access mechanism was later introduced in IEEE 802.11-based networks to support the quality of service requirements of high priority, real-time applications. The Point Coordination Function (PCF) in the basic 802.11 and HCF Controlled Channel Access (HCCA) designed for 802.11e are examples of this kind. Both schemes rely on a polling service performed by a centralized coordinator. The centralized architecture and the waste of bandwidth due to null polling packets are found as the main drawbacks of the basic PCF and HCCA schemes [11]. Distributed polling [11] and multi-polling [12] were proposed to combat the weaknesses of the basic polling services. These methods led to substantial improvements compared to the primary polling methods, however relying on a point coordinator was not fully eliminated. Also, the enhancements with regard to standard 802.11 were solely targeted to the contention-free period in favour of high priority traffic. Thus, the case of the contention-based operation mode and its significant performance degradation in congestion

scenarios were not addressed. By contrast, OMAC does not rely on a single coordinator (as in polling mechanisms); it is not limited to a single operation mode; and it treats sparse and dense traffic regimes in a unified manner. Moreover, OMAC is generally neutral to traffic priority, but can be tailored with a high granularity to various traffic prioritization schemes and the resultant traffic classes.

More recent works on hybrid CSMA/TDMA can be found in [8], [13]. In [8], a Markov decision process (MDP) was proposed to use the local information in a node to dynamically determine the length of CAP and CFP in 802.15.4 wireless networks. While this work achieves a substantial improvement in throughput, it suffers from excessive computation complexity. Furthermore, similar to other hybrid schemes, it relies on the coordination and the broadcast of superframes by a central node, thus, it is not applicable to WLANs as the main target of OMAC. In [13], a protocol termed Z-MAC [13] was introduced to leverage the strengths of CSMA and TDMA methods in different situations. Z-MAC uses CSMA as the baseline operation and TDMA as a supporting mechanism to enhance contention resolution. The overall goal of Z-MAC is to achieve collision-free operation by assigning an owner(s) to each slot, but other nodes can also contend for an owned slot, albeit with longer window size. Z-MAC is a slot-based method, thus its operation requires synchronization. Additionally, it requires explicit exchange of owned slots between neighbouring nodes, whereas OMAC only relies on information measured locally by each node. OMAC also does not require synchronization and does not mandate any slotted scheme.

Distributed scheduling is regarded as an alternative approach to migrating from random to deterministic medium access control. Distributed scheduling schemes are classified as link-level [14], [15], [16] and packet-level [17] methods. In the former approach, the on/off states of links are scheduled with regard to some objectives of interest such as interference mitigation, while in the latter method scheduling is performed on a per-packet basis. Most distributed scheduling techniques suffer from multiple drawbacks including the need for explicit information exchange, tight synchronization, incompatibility with the legacy 802.11 standard, and, above all, scalability. Our proposed protocol is not a scheduling method, but it resembles the packet-level scheme in that it enforces a (batch) packet-level strategy when a certain triggering event occurs, that is, when a transmission from a reference node is detected. Furthermore, OMAC does not involve signaling and resource reservation.

In another direction, the migration from random to (semi) deterministic MAC has been the focus of a body of research works with a primary objective of reducing collisions by means of applying a higher level of determinism to the backoff procedure and/or contention window adjustment. Reservation-based backoff methods are the prevalent schemes of this kind. In these methods, the participating nodes inform (implicitly or explicitly) each other of their future backoff strategies (e.g. the backoff slot). When a node is informed of the backoff strategy of its peers, it adjusts its strategy accordingly and informs others. EBA [18] and BCR-CS [19] are examples

of backoff reservation methods using explicit announcement of future backoff strategies. These reservation-based methods impose excessive overhead due to the exchange of backoff strategies. Tuysuz et. al. [20] proposed UCFA, a zero-overhead deterministic backoff. It keeps track of empty slots and the last backoff slot resulting in successful transmission to determine the next backoff slot. Misra et. al. [21] proposed a semi-deterministic backoff procedure by enforcing a receiver-side backoff stage when the sender encounters a collision. In [22], the authors present a mechanism to achieve a perfect collision-free operation by changing reserved slots upon detecting transmission failures. Unlike the above methods, OMAC does not rely on backoff reservation, rather it activates a predetermined backoff policy when it detects its awaited opportunity, i.e. when a transmission from a reference node is detected.

III. OPPORTUNISTIC MEDIUM ACCESS CONTROL

The main objective of OMAC is to improve throughput performance by reining in the negative impacts of random medium access. To this end, a higher level of determinism is incorporated in the medium access policy. OMAC achieves this by measuring and collecting information about physical activity on the channel and using this information to create opportunities for switching to a desired medium access policy.

The operation of OMAC is depicted in Figure 1a. In this figure, the vertices correspond to the nodes and the directional edges correspond to the pair-wise relation of the nodes. The relation describes a node (u_2) selected as a reference by a node (u_1). The details of the reference selection process will be described later. Once u_1 has selected its reference node (u_2), it continues to overhear the channel in order to detect when a transmission from u_2 occurs. Then u_1 uses this opportunity to enable a desired policy. The desired strategy for OMAC nodes is defined as a channel access policy superior to the default strategy. More concretely, an OMAC node becomes more aggressive upon detecting its opportunity.

The performance of OMAC is significantly governed by the unique selection of reference nodes. In an undesirable situation, as depicted in Figure 1b, two nodes u_1 and u_2 have selected a common reference node (u_3). The consequence is that u_1 and u_2 simultaneously enable their desired (i.e. more aggressive) policies once they detect a transmission from u_3 . A solution to avoid situations of this kind is to allow the nodes to explicitly coordinate and agree on their selected reference nodes, or otherwise delegate the task to a central coordinator (e.g. an access point). However, OMAC pursues a substantially different mechanism which does not rely on explicit coordination between the nodes or enforcement by an external entity. Each OMAC node considers each unique RSSI Indicator (RSSI) detected on the channel as a unique identifier of a device, and tries to select an RSSI as its reference which is less likely to be selected by peer nodes. This approach is corroborated by the fact that, in a normal environment where WiFi is used, devices are usually stationary. Therefore, fast fading should be more limited than, for example, a cellular

scenario. Also, a typical 802.11 WLAN usually covers a limited area, so the detected RSSIs should present substantial differences. Our conjecture is also supported by our results presented in Section IV.

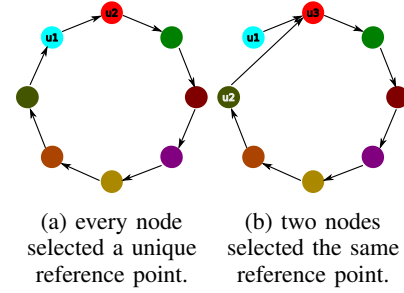


Fig. 1: Reference node selection in OMAC.

The reference selection process in OMAC is dynamic. Whenever a new frame is received from the physical layer, OMAC classifies and records the received RSSI in a set of unique RSSI elements. Denote this set, recorded until time t , by $\mathcal{P}(t)$. Also denote by \bar{p}_t the mean RSSI of the members of $\mathcal{P}(t)$. Each OMAC node selects as its reference the element of $\mathcal{P}(t)$ that is closest to \bar{p}_t , i.e.

$$p_T(t) = \{p_T \in \mathcal{P}(t) : |p_T - \bar{p}_t| \leq |p' - \bar{p}_t| \forall p' \in \mathcal{P}(t)\} \quad (1)$$

When a transmission with RSSI p_i is detected by the node, it triggers an event $\langle Trigger \rangle$ if $|p_T(t) - p_i| < \epsilon$, where ϵ is the maximum sensitivity of the device. This event, in turn, activates the desired strategy in the node.

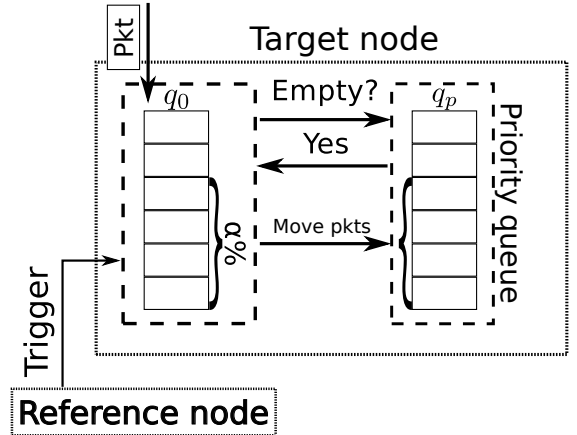


Fig. 2: OMAC operation with a single class of traffic.

OMAC implements a priority queue q_p to enact its policy. If a packet is enqueued in q_p , it will be assigned the highest priority amongst packets in all queues. This property is achieved by tuning the Arbitration Inter-frame Spaces (AIFSS) and minimum Contention Window (CW) parameters in the 802.11 MAC. In the most basic form, we assume there is only a single traffic class and a predefined queue q_0 . As shown in Figure 2, packets arriving from the upper layer are enqueued in q_0 . When an event $\langle Trigger \rangle$ occurs, OMAC checks whether the priority queue q_p is empty. If so, an $\alpha\%$ of the packets from

the front of q_0 are transferred to the priority queue, where α is a tunable parameter of OMAC, otherwise the node waits for q_p to discharge and waits for the next opportunity (see Algorithm 1). Note that OMAC does not affect the maximum queue length (q_{max}) dedicated by the MAC layer, and the total number of packets in queues q_0 and q_p does not exceed q_{max} .

OMAC behaves differently in cases where there is a single class of traffic, versus multiple classes of traffic priorities (e.g. EDCA). The former case is depicted in Figure 2.

Algorithm 1 OMAC operation with a single class of traffic.

```

1: on event  $\langle Trigger \rangle$  do
2:   if  $q_p$  is empty then
3:      $ToMove \leftarrow \alpha\%$  of sizeof  $q_0$ 
4:     move  $ToMove$  packets in the front of  $q_0$  to  $q_p$ 

```

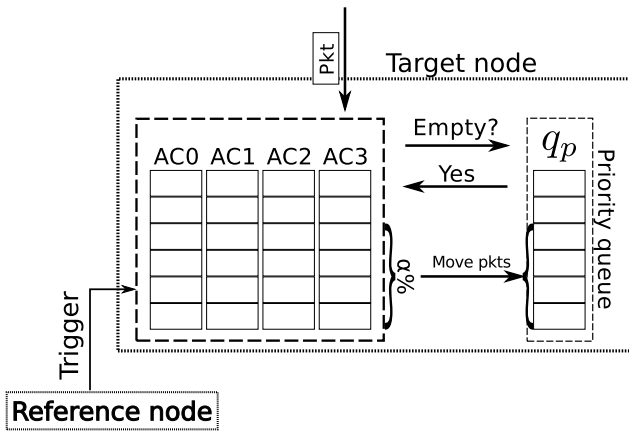


Fig. 3: OMAC extension to multiple classes of traffic priorities.

OMAC differs from the standard 802.11e EDCA in the way packets are distributed between queues. It opportunistically moves packets from the pre-existing queues to the priority queue q_p , while in 802.11e the decision is made in the upper layer with respect to a predefined packet classification scheme. However, like the EDCA scheme, it uses different Arbitration Inter-frame Spaces (AIFSs) and minimum Contention Windows (CW) parameters to differentiate between q_p and the other queues.

The extension of OMAC to support multiple-queue scenarios like 802.11e is straightforward. In such scenarios, OMAC must preserve the existing traffic priorities while enforcing its opportunistic policy. The new, modified procedure is depicted in Figure 3 and described by Algorithm 2. When an event $\langle Trigger \rangle$ occurs and q_p is empty, an $\alpha\%$ of the packets in all predefined queues are transferred to q_p , starting from the front of AC_3 , where AC_s denotes the traffic class queues in decreasing order (similar to $AC_s, s \in \{3, 2, 1, 0\}$ in 802.11e). This new mechanism also takes into account the arrival of new packets from the upper layer. When a packet pk with traffic class n (with $n > 0$) arrives from the upper layer, if q_p is not empty and there is at least one packet pk' in q_p with traffic class $n' < n$, then pk' is returned to $AC_{n'}$, and pk is enqueued

in q_p in its place. This mechanism prevents any deviation from the traffic classification mandated by the application layer.

Algorithm 2 OMAC extension to multiple classes of traffic priorities.

```

1: on event  $\langle Trigger \rangle$  do
2:   if  $q_p$  is empty then
3:      $ToMove \leftarrow \alpha\%$  of  $\sum_{n \in AC_s} \text{sizeof } AC_n$ 
4:     for  $n \in AC_s$  do
5:       if  $ToMove > 0$  then
6:         move  $\min\{\text{sizeof } AC_n, ToMove\}$  in the
           front of  $AC_n$  to  $q_p$ 
7:         Decrease  $ToMove$  by the number of moved
           packets
8:       else
9:         exit loop

```

IV. SIMULATION RESULTS

We have conducted simulation studies using OMNeT++ and the INET package to verify the performance of OMAC. The simulation studies were performed using the base use-case depicted in Figure 2. The upper layer traffic is directly enqueued in a predefined queue q_0 . This traffic is opportunistically moved to a priority queue q_p , according to the procedure described in Section III. We have compared the proposed protocol, termed OMAC-RSSI for distinction, with four other medium access mechanisms described as follows:

- OMAC-Perfect: unlike OMAC-RSSI, the selection of reference nodes is performed using MAC addresses. Also, unlike OMAC-RSSI, a centralized entity (e.g. an access point) is responsible for generating a non-conflicting sequence (like in Figure 1a) of active MAC addresses in the network, and informing each node about the MAC address assigned as its reference node. This process is performed only once, at the beginning of the simulation. The rest of the operation is similar to the OMAC-RSSI.
- Random Packet Assignment (RPA): a packet arriving at the MAC layer is enqueued in q_p and q_0 with probabilities α and $1 - \alpha$, respectively. OMAC is disabled.
- Legacy Single Queue (LSQ)-1: this scenario corresponds to the legacy 802.11 DCF. All arriving packets are enqueued in the predefined queue q_0 . OMAC is disabled in this scenario.
- Legacy Single Queue (LSQ)-2: this scenario also corresponds to the legacy 802.11 DCF with single queue. The difference of this scenario with LSQ-1 is that all arriving packets are directly buffered in the priority queue q_p . OMAC is disabled in this scenario.

Simulation parameters and configuration values are summarized in Table I. Packets are generated in the application layer with a Poisson distribution. Packet lengths are uniformly distributed between 14 bytes (the ACK size) and 2000 bytes. The AIFS and contention window size (CW) of q_0 and q_p are respectively similar to the default configuration of AC_0 and AC_3 in 802.11e. Experiments using the AC_1 configuration for q_0 are comparable

to our results. For each configuration scenario, 100 simulation runs are conducted, with a duration of 100 seconds per run. In the simulated scenarios, only uplink traffic is considered, i.e., the nodes send data to a sink (i.e. an access point).

In the following, we present a number of results corresponding to saturation scenarios since, in non-saturation scenarios, the performance of the described medium access control mechanisms is almost perfect and the gain achieved by the OMAC scheme is not significant. Nonetheless, the gain is always positive. Our selected scenarios include network densities of 10, 30 and 60 nodes. The saturation traffic is different for the considered network densities. For the 10 node scenario, this occurs at 200 packet/second and beyond, whereas for 30 and 60 nodes the saturation occurs at 100 packets/sec.

The Figures 4, 5 and 6 show the performance of OMAC-RSSI compared with other schemes for 10, 30 and 60 node densities and in saturation conditions. In these figures, the goodput is normalized. It is defined as the ratio of successfully received bits (by the sink) to sent bits (by all nodes), and measured in the application layer. The results are presented with 95% confidence interval. The delay performance is omitted due to the lack of space, however, our simulations indicate that the packet delay is always lower in OMAC compared to the other schemes.

TABLE I: Parameters and configuration values.

	Parameter	Value
Physical	Frequency	2.4 GHz
	Noise Power	-110 dBm
	SINR Threshold	4 dB
	Transmission Power	20 mW
	Reception Threshold	-85 dBm
	Data Rate	54 Mbps
	Slot Time (σ)	9 μ s
	Scenario	Scenario dimensions
Channel model		Free space
Free space exponent		2
Number of nodes		10, 30, 60
Application	λ_r	10 to 200 packets/sec
	Packet generation rate	$\sim Poisson(\lambda_r)$ packets/sec
	Packet length	$\sim Uniform(14, 2000)$ bytes
MAC	CW_0^{min}	31
	CW_p^{min}	7
	AIFS (q_0)	$7\sigma + SIFS$
	AIFS (q_p)	$2\sigma + SIFS$
	q_{max} (packets)	100
	$\alpha(\%)$	10, 20, ... 100

From the figures it can be observed that the OMAC scheme (OMAC-RSSI and OMAC-Perfect) outperforms the other schemes in terms of reduced number of collisions and goodput. However, the performance gain varies between node densities and with respect to parameter α (the proportion of packets moved to q_p). The general trend shows that, with an increase in node density, the performance gain increases, indicating the

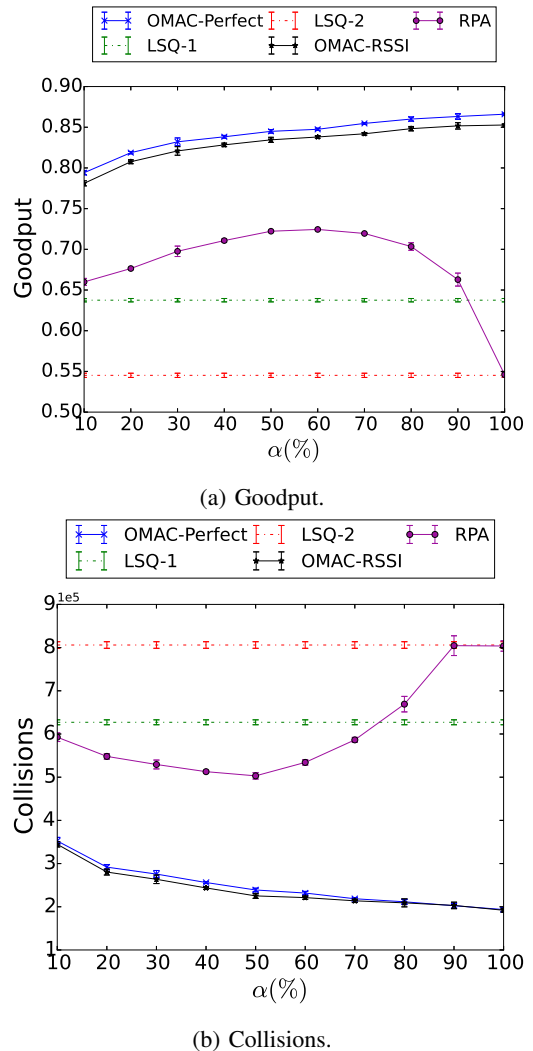
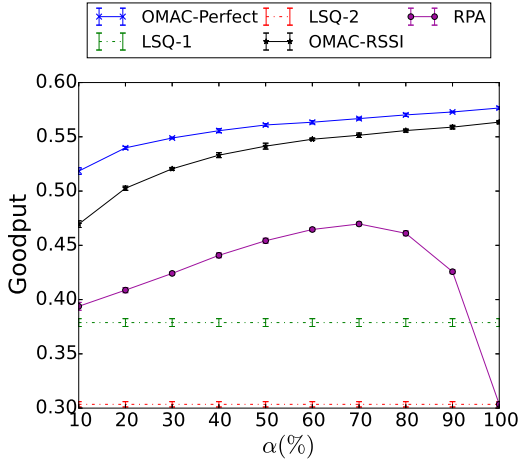
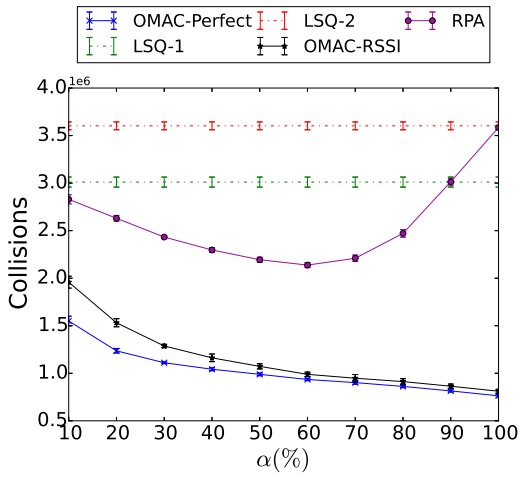


Fig. 4: 10 nodes, $\lambda_r = 200$ packets/sec.

suitability of OMAC for the emerging dense scenarios targeted by HEW standard. The goodput improvement in OMAC-RSSI compared to the basic LSQ-1 scheme and averaged over the entire range of α is approximately 30%, 41% and 50% for 10, 30 and 60 node densities, respectively. It achieves around 60% less collisions in each of the three node densities. The achieved gain compared to LSQ-2 is substantially higher, indicating the fact that the blind increase of the MAC aggressiveness leads to performance deterioration. Surprisingly, the RPA scheme outperforms both LSQ-1 and LSQ-2 for the most part of the α range. However, as shown in the figures, it loses its gain when α grows, which eventually converges to the worst performing scheme (i.e. LSQ-2). The OMAC schemes, on the other hand, show a growing performance gain with the increase of α . With the OMAC-RSSI, when $\alpha = 100\%$, the goodput gain compared to LSQ-1 is approximately 34%, 49% and 61% for 10, 30 and 60 nodes, respectively. The trend also shows that the performance of the OMAC schemes improve with an increase in node density. This observation suggests a straightforward tuning of the parameter α in the OMAC schemes. That is,



(a) Goodput.

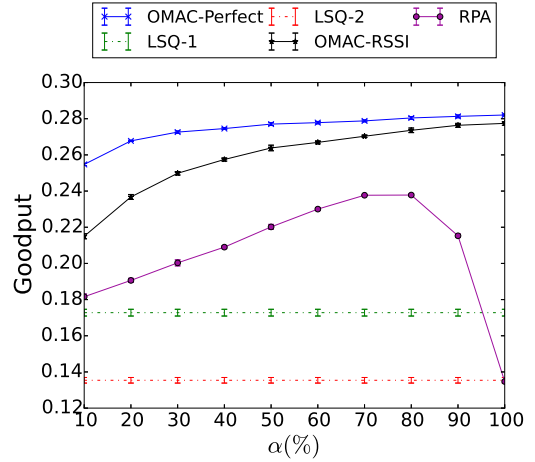


(b) Collisions.

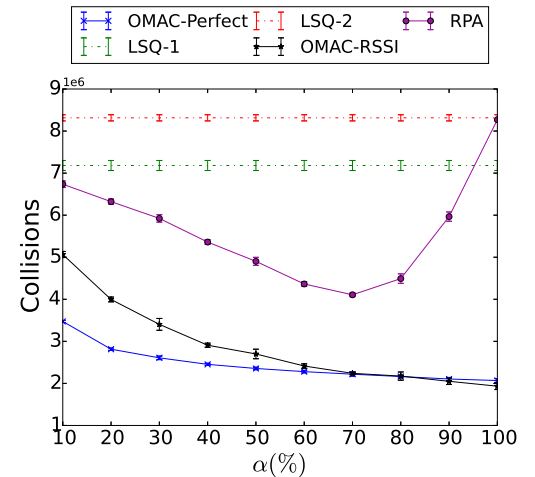
Fig. 5: 30 nodes, $\lambda_r = 100$ packets/sec.

by setting α to 100%, the maximum gain is achieved. This implies that a node will be better-off if it moves all packets from its default queue q_0 to the priority queue q_p , when its opportunity comes and the queue q_p is already discharged.

Another observation is the difference between the behaviour of the OMAC-RSSI and OMAC-Perfect schemes. As shown in the figures, OMAC-Perfect almost always outperforms OMAC-RSSI. This is not surprising, recalling the fact that in the OMAC-Perfect scheme the assignment of reference node is perfect and no pair of nodes share a single reference node. This perfect reference selection implies that the contention between opportunistic OMAC nodes decreases compared to the non-perfect RSSI based OMAC. This leads to a reduced number of collisions and an increased chance of moving more packets from q_0 to q_p . This is verified by observing Figure 7 which shows the population of packets moved from q_0 to q_p . For both node density scenarios, the percentage of packets moved to q_p is substantially higher in OMAC-Perfect compared to OMAC-RSSI. This observation implies for the enhancement of the node selection mechanism in the OMAC-RSSI, which will be addressed as part of our future work.



(a) Goodput.



(b) Collisions.

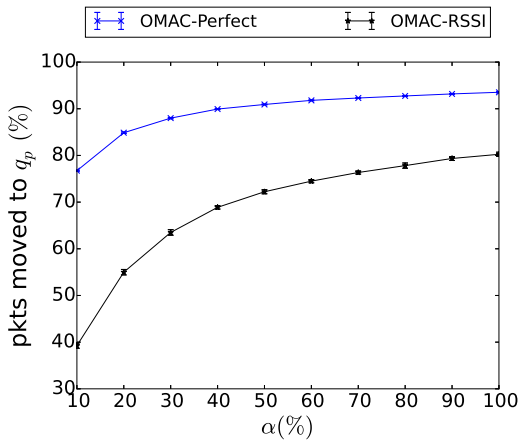
Fig. 6: 60 nodes, $\lambda_r = 100$ packets/sec.

V. CONCLUSION AND FUTURE WORK

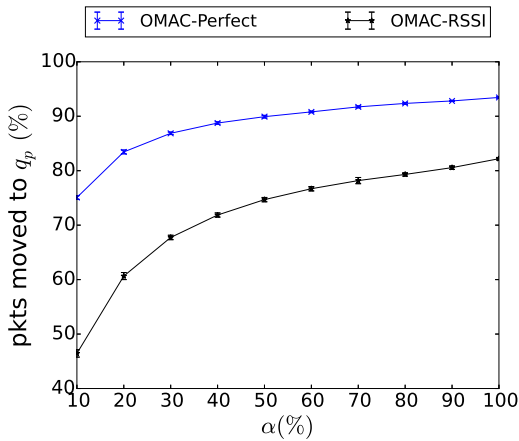
In this paper, we proposed OMAC, a novel opportunistic medium access control mechanism. OMAC eliminates the need for explicit exchange of information by relying only on the signal measurement capability of the devices. An OMAC node continuously measures the different RSS levels by overhearing the ongoing signal activities on the channel. The OMAC node uses this information to select a reference RSS which, subsequently, is regarded as an opportunity for the node to switch to a desired strategy whenever a channel activity with a similar RSS level is detected.

OMAC does not require decoding of the signal, thus it is robust to varying channel conditions. It preserves privacy because it does not require the actual identities (e.g. MAC addresses) of the signal sources. Additionally, it is adaptive to changes in channel conditions and network topology since the RSS measurement and reference selection is a continuing process. OMAC is also a lightweight protocol and easy to implement in devices.

Our simulations show that OMAC achieves a significant



(a) 60 Nodes.



(b) 30 Nodes.

Fig. 7: Proportion of packets moved to q_p . $\lambda_r = 100$ packets/sec.

throughput gain compared to the legacy 802.11 MAC. Our future work will address the theoretical bounds of OMAC performance. We also plan several extensions for OMAC, including the design of more sophisticated reference selection mechanisms to ensure an eligible node is guaranteed to have a unique reference node, where eligibility is determined by fairness, traffic priority, and the contribution of the node to the overall network performance and energy efficiency. Another equally important extension is to adapt OMAC for frame aggregation as an important feature of the upcoming HEW standard.

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