CSMA k-SIC - A Class of Distributed MAC Protocols and their Performance Evaluation

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***Abstract*—The CSMA/CA protocol is based on the "Interference as Noise" (IAN) paradigm i.e. it always gets rid of strong interference near a receiver to ensure quality of reception. However, it is well known from Multi-user Information Theory that treating Interference as Noise is not optimal. This paper proposes a class of protocols that employ the Successive Interference Cancellation (SIC) technique in a systematic fashion to move beyond always treating interference as noise. Such protocols allow one to pack more links than the classical CSMA. We describe the protocols along with their signaling mechanism to implement them in a distributed fashion. We then perform Monte Carlo simulations to evaluate the performance and show significant gains over the IAN based CSMA/CA protocol in large random networks.**

I. Introduction

Wireless medium is a broadcast medium and is hence interference limited i.e. only a limited number of wireless transmissions can happen concurrently in any region of space. Thus, a natural spatial scheduling question arises which is taken care of by "Medium Access Control" (MAC) algorithms. There is a vast literature on the design of MAC algorithms for decentralized networks (ex: ad-hoc) starting from the simplistic protocol of ALOHA, which has now culminated in CSMA (Carrier Sense Multiple Access) type protocols.

The CSMA (more specifically CSMA/CA) protocol is the most popular Medium Access protocol for wireless ad-hoc networks in practice today. Its popularity stems from three important reasons (1) Ease of distributed implementation through the RTS/CTS based handshakes [1]. (2) Reasonable guarantees provided to a scheduled receiver in the form of an interference free *guard zone*. (3) Very low receiver decoding complexity which is based on treating all interference as noise.

The CSMA/CA protocol can be parametrized by a quantity γ which defines the *guard zone*. Once a receiver is granted medium access, the protocol ensures that the maximum interference due to any single interfering transmitter is below γ at this receiver. In other words, a scheduled receiver under the CSMA/CA protocol *kills* all strongly interfering transmitters, namely those contributing an interference power larger than γ at this tagged receiver and treats the other weakly interfering transmitters (namely those that individually contribute an interference power of less than γ at the tagged active receiver) as noise. We call this conventional CSMA/CA protocol CSMA IAN which is described in Section V.

However, this guard zone based scheduling only makes sense for the *Interference As Noise* (IAN) paradigm and it is known from results in Network Information Theory that treating all interference as noise is not always optimal [2]. In this paper, we show how one can do much better without having to compromise on any of the above desirable properties present in the CSMA IAN protocol. We define a class of protocols based on Multi-user Information Theory called CSMA k-SIC. The rationale for this terminology is explained in Section VI. We outline a simple distributed signaling scheme. We then perform extensive simulations to quantify the performance gains obtained by employing these protocols as compared to CSMA IAN.

II. Related Work

The distributed algorithm to implement CSMA IAN (i.e. classical CSMA/CA) was first proposed in [1]. Much effort has been devoted from then for optimizing the parameters of this original CSMA protocol (for ex. [3], [4], [5]). Recent developments in Stochastic Geometry have also enabled a tuning of the parameters to optimize for spatial averages or Palm averages of large random CSMA networks (for ex: [6], [7]).

In this paper, we focus on redefining the CSMA protocol by incorporating results from Multi-user Information Theory. Our work is motivated by the discussions in [2], which has succinctly outlined the improvements in spatial throughput by adopting Information Theoretic tools. We propose a distributed protocol similar in spirit to [1] as a first attempt in realizing these benefits.

The survey by Ephremides and Hajek [8] highlights the difference in Information Theory and networking

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practices. Following this, [9] address the problem by developing enhanced Aloha protocols that exploit results in Information Theory. [10] proposed SIC aware Aloha like random access MAC algorithms using ideas from Game Theory. The benefits of employing SIC in combination with Aloha was studied experimentally in [11] using Universal Software Radio Peripheral. Analytical performance gains obtained by employing SIC in an Aloha based wireless networks were also studied by [12] and [13] using Stochastic Geometry. However, we find that such Aloha based random access protocols do not perform well in large random networks. This is linked to the fact that Aloha based protocols are scheduling algorithms that are interference oblivious. In our work, we aim to propose distributed algorithms that *intelligently* chose which links to be scheduled and which interferers must a receiver cancel. To aid us in proposing the algorithms, we use insights and results from Multi-user Information Theory.

III. Network Model

The network is assumed to consist of a collection of links or transmitter-receiver pairs. Each transmitter wants to communicate to its receiver at a common fixed rate R. All transmitters transmit at a fixed known power and do not employ any power control. The signal from a transmitter to any receiver in the network is attenuated through a random fading whose statistics are known and a distance dependent propagation loss. The propagation loss suffered by a signal on traveling a distance u in space is given by $l(u) = u^{\beta}$ with $\beta > 2$ [14].

We assume a time slotted system i.e. the clocks of all devices are synchronized similar to the beacon enabled IEEE 802.15.4 standard. Each slot is further divided into a small initial signaling phase (the length of which is assumed to be 1 time unit) followed by a larger transmission phase. During the signaling phase, all links contend for medium access by signaling algorithms. At the end of the signaling phase, only the links that gained access, transmit during the transmission phase. We do not consider back off mechanisms as the timers are assumed to be in the continuum and hence prevent collisions. All devices contend for the channel at the beginning of a slot in the signaling phase irrespective of the channel access histories.

IV. Successive Interference Cancellation

SIC is a receiver decoding algorithm used in the Multiple Access Channel. A Gaussian Multiple Access Channel consists of k transmitters trying to communicate simultaneously an independent message to one receiver. The rate-region or the capacity of this system is the set of rate tuples $(R_1, ...R_k)$ such that all k sources can be decoded by the receiver when they transmit at these rates. The special case of $k = 1$ is called the point-to-point (ptp) communication channel.

Classical result in Information Theory [15] states that the rate region of this channel $\mathcal{R} = (R_1, ...R_k)$ satisfying

$$0 \leq \sum_{j \in \mathcal{S}} R_j < C\left(\sum_{j \in \mathcal{S}} x_j\right) \; \forall \mathcal{S} \subset \{1, 2, ...k\}, \quad (1)$$

where x_j is the SNR of transmitter j and $C(x) = \frac{B}{2}\log_2(1+x)$ with B as bandwidth in Hz.

The capacity result also gives the k-SIC algorithm, (described in Algorithm 1) which along with time-sharing is an achievability scheme for this rate region. Under this algorithm, the receiver first decodes the signal having the highest rate, cancels it and then goes on to decode the signal with the next highest rate recursively.

Algorithm 1 k-SIC Algorithm

```
Y - The sum of the k received signals plus noise
for 1 ≤ i ≤ k do
    X̂_i is the decoded version of the signal with i^th lowest rate from Y.
    Y = Y − X̂_i
end for
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For Algorithm 1, a necessary and sufficient condition is for all the k steps to be successful

$$C\left(\frac{P_i}{N_0 + \sum_{j=i+1}^{k} P_j}\right) \geq R_i \;,\; 1 \leq i \leq k, \quad (2)$$

where P_i is the received power from the i^{th} lowest rate transmitter and $\sum_{k+1}^{k} = 0$.

A very useful feature of the SIC algorithm is that each of the transmitters can use a codebook pertaining to ptp communication. This follows from the fact that the receiver decodes only one signal at a time without having to do any joint decoding. This is an important requirement as this enables each link to have a pre-defined set of codebooks encoded into the hardware and is still optimal in the Information Theoretic sense.

In a setting where all transmitters use the same rate ($R_i = R$), the order of decoding in SIC is in the decreasing order of received power and the necessary and sufficient conditions for SIC is then

$$\frac{P_i}{N_0 + \sum_{j=i+1}^{k} P_j} \geq Q \;,\; 1 \leq i \leq k, \quad (3)$$

where P_i is the i^{th} strongest signal and $Q = C^{-1}(R)$. The quantity $\frac{P_i}{N_0+\sum_{j=i+1}^{k} P_j}$ is called as the *effective*

SINR for the i^{th} stage of decoding. One can see from algebra that for maximizing the chance of success, the powers must be well separated i.e. $P_i > P_{i+1}$ with the minimum difference needed depending on Q and N_0.

As a simple example to illustrate this, consider a Multiple Access Channel with 3 transmitters (T_1, T_2 and T_3) and 1 receiver. Denote by P_i the power from transmitter i at the receiver. Let $P_1 \geq P_2 \geq P_3$, i.e. the receiver first decodes the signal from T_1 followed by T_2 and then T_3. This Multiple Access Channel is embedded in a large network with other transmitters being far away but still contributing a cumulative Gaussian interference. Let the SINR threshold be 1 and noise plus ambient interference power be N_0 . Under this setting, the necessary and sufficient conditions for SIC is $\frac{P_1}{P_2+P_3+N_0} > 1$ and $\frac{P_2}{P_3+N_0} > 1$ i.e. $P_1 > P_2 + P_3 + N_0$ and $P_2 > P_3 + N_0$. If N_0 is large (this is the case in a large network where the ambient interference is significant), then P_1 must be significantly larger than P_2 which in turn must be significantly larger than P_3. More generally for a k transmitter Multiple Access Channel, one needs P_i to be significantly larger than P_{i+1} $\forall i < k$ [12].

Note that if the threshold is arbitrarily close to 0, then the separation of powers is not crucial for the success of SIC. However, in most practical systems, Q is not very small [16] (is around 1) and thus this separation in interference power is essential in practice.

A. SIC in Ad-Hoc Networks - Main Idea

The main idea is that a scheduled receiver forms a Multiple Access Channel with its own transmitter and a few other strongly interfering transmitters. The way to exploit SIC in designing MAC algorithms is based on Equation (3) which shows that, if an interferer is strong enough, then it can be decoded and canceled off without affecting the weaker signals.

The CSMA IAN protocol, kills all interferers in the guard zone around a receiver and forms a ptp channel with its own transmitter. In contrast, the proposed protocols *selectively* retain certain strong interferers around a receiver. Here strong interferers of a receiver are those whose interference power at this receiver is larger than that of its own signal. This receiver can then form a Multiple Access Channel with these retained strong interferers and its own transmitter while treating all other weakly interfering transmitters (i.e. those weaker than its own transmitter) as noise. During the decoding step, the receiver can first decode and cancel the interference from the strong interferers before decoding its own signal.

However, such protocols must be selective in retaining the strong interferers, in the sense that they must ensure that the powers from these strong interferers at any other scheduled receiver are "well separated" for effective cancellation. The CSMA k-SIC protocols we describe below are randomized protocols such that the interference powers at *any* scheduled receiver are well separated for interference cancellation.

V. CSMA IAN Protocol

This protocol is parameterized by a positive real number γ which denotes the Energy Threshold for conflict between a receiver and transmitter. A receiver and an interfering transmitter are said to *conflict* if the power from the transmitter at this receiver exceeds γ. This energy threshold γ is also referred to as the Carrier Sense range in the WLAN literature. The CSMA IAN protocol provides a guarantee to any scheduled receiver R that there will be no interfering transmitter conflicting with R. Note that this is a pair-wise guarantee that only bounds the maximum interference at a receiver due to any one single transmitter.

A. Protocol

The abstract version of the slotted time protocol can be described by the following dynamics.

- Every link picks a timer uniformly distributed in $[0, 1]$. (Recall the Signaling Phase duration is 1 time unit)
- A link with timer value t *arrives* at time t.
- Upon arrival, a link is either scheduled or yields. A link yields if either its transmitter or receiver yield. An arriving transmitter yields if it conflicts with any previously arrived and scheduled receiver. An arriving receiver yields if it conflicts with any previously arrived and scheduled transmitter.

In the absence of fading, the energy threshold γ is equivalent to a guard radius $r = (\gamma)^{\frac{-1}{\beta}}$ around a receiver.

VI. CSMA k-SIC

This is a class of protocols, one for each positive integer k. We call them CSMA since they involve transmitters and receivers sensing the channel before deciding to transmit. The k-SIC term indicates that the receivers perform *up to* k stages of SIC. We first specify the CSMA 1-SIC protocol before specifying CSMA k-SIC and the signaling mechanisms.

The CSMA 1-SIC protocol is one where a scheduled receiver can cancel up to 1 strong interfering signal. From the discussion in the previous section, for getting reasonable chances of success of cancellation, this interfering signal power must be significantly higher than both the useful signal power and the interference from the rest of the network (for $Q > 1$). From these observations, we define the CSMA 1-SIC algorithm with two parameters γ_1 and γ_2 ($\gamma_1 \leq \gamma_2$) denoting energy sensing thresholds. Denote by $\alpha = \frac{\gamma_2}{\gamma_1}$.

The protocol provides guarantees to any scheduled receiver R that the other transmitters scheduled in the network will be such that:

- There is at most one strong interfering transmitter (called the co-transmitter of R) with energy exceeding γ_2 at R.
- There is no interfering transmitter with energy in the range $[\gamma_1, \gamma_2]$ at R.

If the channel gains are deterministic, then the above guarantees translate to the exclusion region as depicted in Figure 1.

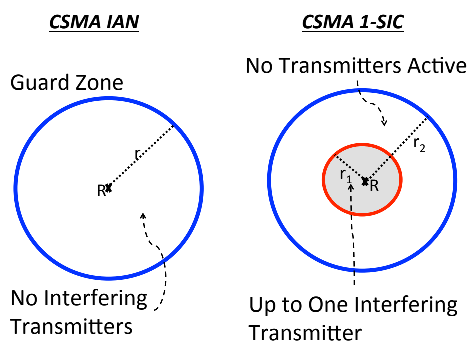

Fig. 1: The figure on the left illustrates the CSMA IAN guard zone around a receiver while the figure on the right illustrates the relaxed guard zone in the case of CSMA 1-SIC. These guard zones are in the absence of fading.

A. *CSMA k-SIC Protocol*

By extension, the k-SIC protocol is one where a receiver is capable of canceling up to k strongly interfering signals. The decoding will be successful with a good chance if the signal powers from the interferers are well separated (Equation (3)).

The CSMA k-SIC ($k \geq 1$) protocol is parametrized by $2k$ parameters or k *blocks* of energy. The parameters $0 < \gamma_1 < \gamma_2 ... < \gamma_{2k} < \infty$ denote energy sensing thresholds. For notational purposes, let $\gamma_0 = 0$ and $\gamma_{2k+1} = \infty$.

The protocol is described by the guarantees it provides to any scheduled receiver R which are as follows.

For each $i = \{1, 2, ..., k\}$:

1) There is at most one interfering transmitter with energy at R in the range $(\gamma_{2i}, \gamma_{2i+1})$.
2) There are no interfering transmitters with energy at R in the range $[\gamma_{2i-1}, \gamma_{2i}]$.

In the case with no fading, the parameters translate into $r_1 > r_2 > ... > r_{2k}$ with $r_i = \frac{1}{(\gamma_i)^{\frac{1}{\beta}}}$ (cf. Figure 2).

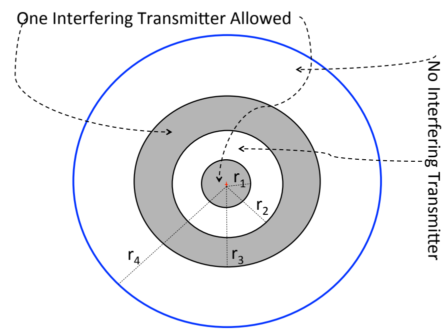

Fig. 2: Illustration of the guarantees for CSMA 2-SIC in the absence of fading. The receiver is in the center which allows up to one interferer in each of the shaded portion and no interferer in the un-shaded portion.

This range of allowed powers $(\gamma_{2i}, \gamma_{2i+1})$ is called *block* i. All these interferers are called the *strong interferers* of R. This block based relaxation of the guard zone of CSMA IAN is to ensure separation in the powers of the different strong interferers.

If any of the above guarantees fails to hold for a given receiver R, then we say that the guarantees for R is *violated* by the set of scheduled transmitters. The protocol providing the above guarantees can be described by the following dynamics:

- Every link picks a timer uniformly distributed in $[0, 1]$.
- A link with timer value t *arrives* at time t.
- Upon arrival, a link either yields or gets scheduled in that slot. An arriving link yields if either its transmitter or receiver yield.
  - An arriving receiver R yields if the set of scheduled transmitters that arrived before t violates R's guarantees.
  - An arriving transmitter T yields if its inclusion to the set of scheduled transmitters that have arrived before t violates the guarantees of any scheduled receiver that has arrived before t.

This model for a SIC protocol is the most natural as it provides reasonable guarantees on interference level at every scheduled receiver and ensures a separation of powers at every scheduled receiver for effective cancellation. The CSMA k SIC protocols provide more guarantees than the Aloha based SIC protocol of [13].

B. *Implementation*

For implementation, we introduce new signals in addition to the *RTS* and *CTS* signals called *ESTABLISHED* which will be broadcast by the transmitter and k other signals *BLOCKED(i)* for $i = \{1, 2, ...k\}$ which will be broadcast by the receiver.

The transmitters transmit an *ESTABLISHED* signal on receiving a *CTS* signal from their intended receivers. The receivers transmit a *BLOCKED(i)* signal to prevent more than one interfering transmitter to be scheduled in a block. This is broadcast as soon as an interfering transmitter arrives in block i of a receiver. The exact algorithm is outlined in Algorithms 2 and 3.

Algorithm 2 CSMA k-SIC[$\gamma_1 : \gamma_{2k}$] Transmitter side

Pick t from $U[0,1]$.
counter $\leftarrow 0$.
while counter $< t$ **do**
    Y - Listen for *CTS* from the network
    if Power(Y) $\in [\gamma_{2i-1}, \gamma_{2i}]$ for any $i = \{1, 2, ..., k\}$ **then**
        Switch off in the current slot
    end if
    Y(i) - Listen for *BLOCKED(i)* from the network
    if Power(Y(i)) $\in (\gamma_{2i}, \gamma_{2i+1})$ **then**
        Switch off and retry in the next slot
    end if
    Decrement counter
end while
if Not Switched off **then**
    Transmit *RTS* signal and wait for *CTS*
end if
if *CTS* Received **then**
    Transmit *ESTABLISHED*
end if

A receiver will first decode the interferer in block k before attempting to decode the interferer in block $k-1$ and so forth. A receiver need not know which interferer it is decoding in practice. It has to perform SIC $k^{'} \leq k$ times before decoding its intended signal. Here $k^{'} = \sum_{i=1}^{k} InCount(i)$ which will be known at the end of the signaling phase. If any of the decoding stages fails, then the communication in that link fails. This is only schematic and we do not consider collisions in signals as we assumed that the timer values are from a continuum.

C. Remarks

Although, the protocol was described for the case of Q being 1 or more, this protocol easily extends to the case of low Q as well, where the separation of powers is not crucial. In that case, one can implement the algorithm with contiguous blocks (i.e. $\alpha = 1$ in the case of CSMA 1-SIC as an example). Hence, the CSMA k-SIC are general protocols that can be tuned for any Q.

The CSMA IAN and the CSMA k-SIC protocols are defined by pair-wise energy based conflicts and are not

Algorithm 3 CSMA k-SIC[$\gamma_1 : \gamma_{2k}$] Receiver Side

InCount(i) $\leftarrow 0$ for all $i = \{1, 2, ..., k\}$
while *RTS* from my transmitter not received **do**
    Y - Listen for *ESTABLISHED* from the network
    if Power(Y) $\in [\gamma_{2i}, \gamma_{2i+1}]$ **AND** InCount(i) > 0 **then**
        Switch Off in the current slot
    end if
    if Power(Y) $\in (\gamma_{2i}, \gamma_{2i+1})$ **AND** InCount(i) < 1 **then**
        InCount $= 1$
    end if
    if Power(Y) $\in [\gamma_{2i-1}, \gamma_{2i}]$ for any $i = \{1, 2, ...k\}$ **then**
        Switch off and retry in next slot
    end if
    if Signaling Phase Ends **then**
        Switch off and retry in next slot
    end if
end while
Transmit *CTS*
if InCount $== 1$ **then**
    Transmit *BLOCKED(i)*
    Get ready for Transmission Phase
end if
while Signaling Phase not over **AND** InCount(i) < 1 for any $i = \{1, 2, ..., k\}$ **do**
    Y - Listen for *ESTABLISHED* in the network
    if Power(Y) $\in (\gamma_{2i}, \gamma_{2i+1})$ **then**
        InCount(i) $= 1$
        Transmit *BLOCKED(i)* signal
    end if
end while

SNR based. In particular, the yielding decisions of both transmitter and receivers of a link only depend on the energy from other interfering links, regardless of its own channel quality. As a consequence, if the channel quality of a link is exceptionally good, then it can so happen that some of its strong interferers may in-fact be weaker in strength compared to its own received signal. This needs to be taken into account when optimizing the protocols while operating in fading environments.

VII. Performance Evaluation

In this section, we quantify the gains that can be realized in moving from CSMA IAN to CSMA k-SIC. Most of our focus is on the performance evaluation of CSMA 1-SIC and its comparison with CSMA IAN. As can be seen from Figures 10 and 11, in a large random network, CSMA 1-SIC schedules much more links concurrently in a slot as compared to CSMA IAN. This gain in packing need not be valid for every network configuration (see Figure 3). Hence, we need a systematic model for the wireless network, over which to compare the performance of CSMA 1-SIC and CSMA IAN in some averaged way.

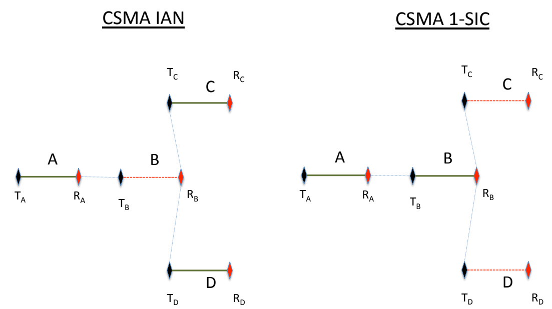

Fig. 3: An example network where CSMA 1-SIC schedules less links than CSMA IAN. The timer of link A is the smallest followed by B,C and then D. The green links are the scheduled links in each case.

A. Stochastic Model

The network is modeled as a collection of Transmitter-Receiver pairs or links. Further, for simplicity, we assume that all links are of a constant fixed length r. More formally, we assume that the receivers of the links come form a homogeneous Poisson Point Process [6] of intensity λ and their corresponding transmitters are located at distance r away at an independent and uniform random angle.

All transmitters transmit data and signal at unit power. The signal from any transmitter to a receiver is subject to the effects of fading and path loss. The CDF of fading is denoted by $F(.)$ which is independent and identically distributed between any transmitter and receiver. The path loss function considered is $l(u) = u^4$. The received power from a transmitter at location x is $\frac{F_{xy}}{l(||x-y||)}$ at location y, where $F_{xy} \sim F()$. For successful reception, the effective SINR in all stages of SIC must exceed a fixed threshold Q (Equation (3)).

B. Simulation Setup

We take a large square of the Euclidean plane of size 50×50 with each link being of unit length. A Poisson number of links uniformly over this square with intensity λ which forms a parameter in our simulations.

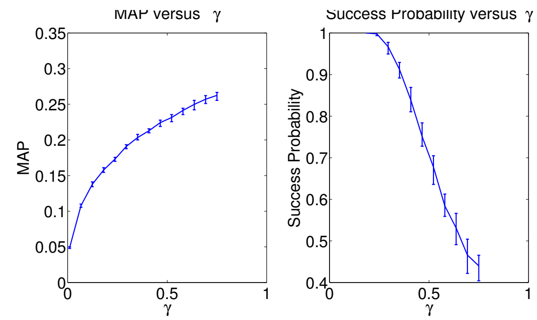

Fig. 4: An errorbar plot of the MAP and SP of CSMA IAN. $\lambda = 1$ and $Q = 1.5$

The ends of the square are wrapped around to form a torus to mitigate edge effects. The simulations are done in MATLAB [17]. We are interested in spatial averages i.e. performance metrics that are averaged over different realizations of the Poisson Point Process. Such spatial averages aid in optimizing the protocol parameters as a function of various network characteristics (λ and Q in particular). All plots in this section give the spatially averaged performance metric on the Y-axis.

From the theory of stationary and ergodic point process, spatial averages are the same as the mean performance of a 'typical' link. Since, we are dealing with finite windows in our simulations, we generate 20 different realizations of the finite window and compute the performance metric for each realization separately by averaging over all the links of a given window. We then take a further average of these spatial averages with 95% confidence. Figure 4 shows that these numbers give reasonable approximations to the true spatial averages.

We consider both the Rayleigh fading and the deterministic channel (no fading) scenarios. Rayleigh fading refers to $F(x) = 1 - e^{-x}$ i.e. exponential of mean 1. This is a popular fading model for wireless communication [14]. The deterministic case or the no fading case corresponds to $F(x) = \mathbf{1}(x \geq 1)$.

The transmit power and the link length r are normalized to 1. This implies, that the received signal power at any receiver from its own receiver is 1 in the absence of fading. The SINR threshold Q in this section must then be interpreted as the ratio of the actual threshold to the received signal power in the absence of fading.

C. Performance Comparisons

The performance metric of importance for single hop networks is the *throughput* of the network. In this paper, throughput translates to *Success Density*, i.e. the mean number of links that get both scheduled and communicate successfully in a slot.

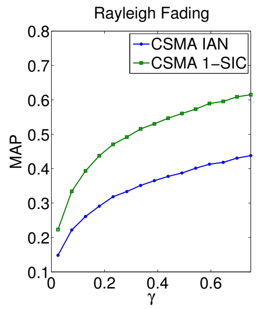

Fig. 5: Comparison of the MAP . $\alpha = 2$ and $\gamma_1 = \gamma$ (X axis) for CSMA 1-SIC. $\lambda = 0.5$.

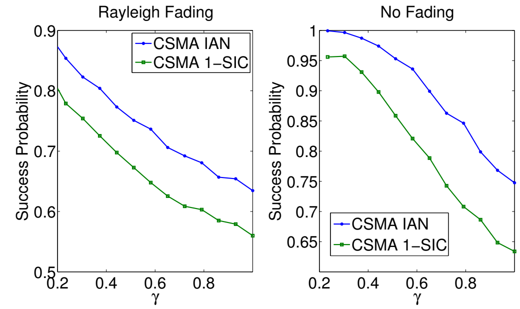

Fig. 6: Comparison of SP. $Q = 0.75$, $\lambda = 0.5$. $\alpha = 2$ and $\gamma_1 = \gamma$ (X-Axis) for CSMA 1-SIC.

To compute Success Density, one needs to compute two related quantities - 1) Medium Access Probability (MAP) which denotes the probability that a typical link gets scheduled. 2) Success Probability (SP) which denotes the probability that a typical link communicates successfully *given* that it is scheduled.

The MAP is computed with respect to the Palm probability of the underlying PPP while SP is computed with respect to the Palm probability of the process representing the scheduled links. Note that, the performance of a 'typical link' or the spatial average is the same as the Palm Probability [6]. Since all the protocols we consider here are translation invariant, the Success Density is λ times SP times MAP [6]. If either the MAP is too low or if the SP is too low, the Success Density becomes low. Hence, the optimal value of Success Density denotes the optimal trade off between spatial reuse or packing density and link quality.

In simulations, the ratio of links that get channel access to the total number of links provides the estimate of the MAP and the ratio of successful links, to the total number of links that get channel access that of the SP. These estimates converge to the true spatial averages as the size of the window considered grows large [6]. Figure 4 shows the 95% confidence in the finite window size chosen in our simulations.

*1) **MAP**:* Figure 5 plots the variation of the MAP with respect to γ (CSMA 1-SIC is restricted to one parameter i.e. α is fixed). Although there exists degenerate network configurations like in Figure 3, this result says that on average in large random networks, CSMA 1-SIC schedules more links than CSMA IAN. This also in turn implies that the interference levels seen at a receiver is higher on average in CSMA 1-SIC.

*2) **SP**:* Figure 6 plots the success probability of a typical scheduled link under CSMA 1-SIC and CSMA IAN. One can see that the link quality in CSMA 1-SIC is poorer on average compared to CSMA IAN. This observation can be attributed to the increased interference in the network under CSMA 1-SIC. Although there is interference cancellation happening at the receivers, each receiver cancel at most one strong interfering signal thereby making the overall interference power large and hence the typical link's performance poorer. Nonetheless, this is compensated by the larger MAP under CSMA 1-SIC which yields higher throughput on average as compared to CSMA IAN.

*3) **Throughput and Optimization**:* The main result of our paper is that the throughput achievable through CSMA 1-SIC is much larger than the optimal throughput through either CSMA IAN or even 1-SIC Aloha protocol of [13]. In 1-SIC Aloha, each link transmits independently in a slot with probability p. During decoding, the receivers employ the same 1-SIC decoding algorithm used in CSMA 1-SIC i.e. the receiver first tries decoding its own signal. If this is unsuccessful, it decodes the strongest interferer, cancels it and then decodes its own signal. If this also fails, then the communication in that link fails for that slot. We compare the optimal throughput obtainable by the various protocols for a given network configuration (w.r.t λ and Q). Optimal Throughput refers to the supremum of the achievable throughput for a given λ and Q, where the supremum is taken over all $\gamma > 0$ for CSMA IAN, over all $0 < \gamma_1 \leq \gamma_2$ for CSMA 1-SIC and over $p \in [0, 1]$ for 1-SIC Aloha. Figure 7 clearly demonstrates that CSMA 1-SIC is better in performance than CSMA IAN and 1-SIC Aloha. The reason for the poor performance of Aloha is the lack of any reasonable guarantees provided to a receiver. One can observe a saturation of the optimal throughput with increasing λ. This corresponds to the "jamming regime" of the various Random Sequential Models in Statistical Physics [18].

Figure 8 plots the optimal success density for different SINR thresholds and the corresponding optimal param-

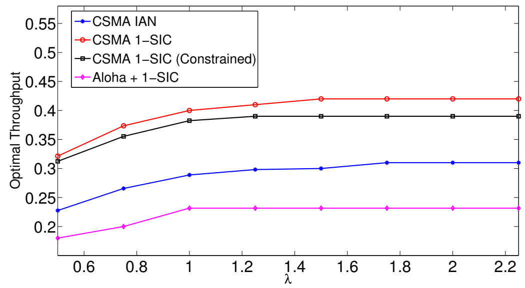

Fig. 7: Optimal Throughput as a function of λ. The threshold $Q = 0.5$ and there is no fading

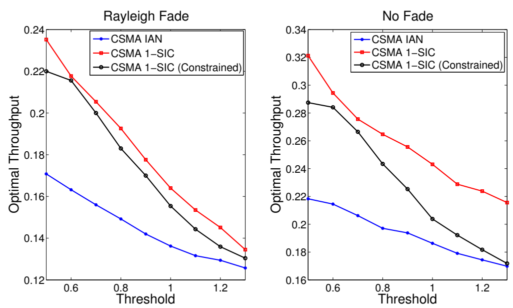

Fig. 8: Comparing the optimal Throughput for various threshold. $\lambda = 0.5$.

TABLE I: Optimal CSMA 1-SIC parameters for $\lambda = 0.5$

Q	γ_1^*	α^*	γ_1^*	α^*
	No Fading		Rayleigh Fade	
0.5	0.8812	3.62	0.5129	2.18
0.6	0.8147	3.6	0.4842	2.10
0.7	0.6438	2.87	0.5079	1.94
0.8	0.5646	2.62	0.3553	1.64
0.9	0.5371	2.65	0.3445	1.62
1	0.525	2.5	0.3316	1.61
1.1	0.5042	2.42	0.3223	1.63
1.2	0.4854	2.37	0.3553	1.58
1.3	0.4.62	2.22	0.2566	1.48

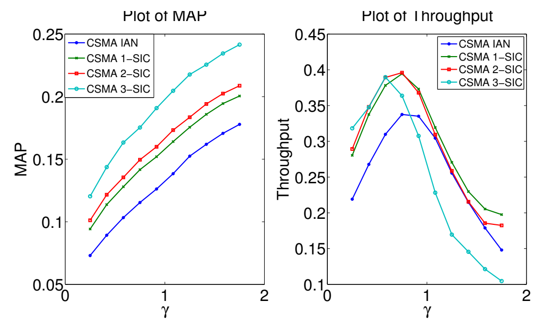

Fig. 9: This is an illustrative plot showing that although MAP increases with increasing k as expected, it does not necessarily translate into gains in throughput. $\lambda = 4$

eters are tabulated in Table I. This also validates the necessity to have separation in received signal powers for effective cancellation since the optimal value of α is larger than 1 in all cases. Hence, to extract good performance from the protocol, one must define it in terms of separate energy blocks that a receiver can cancel the interference from. To further illustrate the necessity of having to separate the interference powers, in Figures 7 and 8, we compare the unconstrained optimal throughput obtainable from CSMA 1 SIC and the optimal throughput that can be obtained under the constraint $\gamma_1 = \gamma_2$ i.e. $\alpha = 1$. The plots show that having a separation of energy blocks yields a better throughput.

Table I also shows that the optimal value of γ_1 is lower in the presence of fading. A smaller value of γ_1 implies that the optimal protocol is more "conservative" in the presence of fading than in the case of a deterministic channel. The optimal throughput is also lower in the presence of fading than in the absence of fading. This is linked to the fact that the links make yielding decisions regardless of their own fading gain.

D. Higher Order k

We briefly comment on the higher order CSMA k-SIC protocols. In Figure (9), we parametrized all four protocols by a single parameter. The parameter $\gamma_i = \gamma i^{0.5}$ with γ being varied on the X-axis. The parameters for CSMA IAN was just γ_1, for 1-SIC the parameters were γ_1 and γ_2, for 2-SIC they are γ_1,γ_2,γ_3 and γ_4 while for 3-SIC, the parameters was all of γ_1 through γ_6. In this setting, one can see that the packing density or MAP increases with increasing k as expected. However, this also increases the overall interference level at a receiver, thereby indicating that for a given λ and Q, there must exists an optimal k. The detailed characterization of this behavior of diminishing return with increasing k is left for future work.

E. Random Sequential Packing

This class of algorithms which schedule links sequentially falls under a broader class of mathematical problems called Random Sequential Packing [19]. We call our algorithms sequential in the sense that set of links that contend for channel access are sequential sorted by increasing order of timer values.

The CSMA IAN can be seen as a packing of hard spheres or more specifically corresponds to the Random Sequential Adsorption model [19]. In the CSMA IAN protocol, links arrive randomly in space, and are scheduled if they can be packed i.e. the arriving link is *far* away from other scheduled links. In CSMA 1-

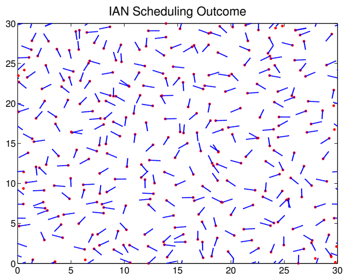

Fig. 10: A snapshot of the packing under CSMA IAN

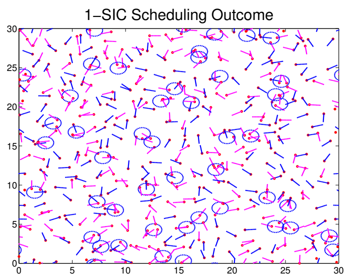

Fig. 11: A snapshot of the packing under CSMA 1-SIC. The rings are around transmitters which are part of more than 1 Multiple Access Channel.

SIC, however, the spheres are not hard, i.e. each receiver allows up to one strong interfering transmitter if it is close enough. One can see from simulations (Figure 11), that making a small relaxation from the hard spheres significantly increases the packing. Such packing of non-convex and soft bodies has not been studied and can be an interesting direction for mathematical research

VIII. Conclusion

This paper presents protocols that incorporate in a systematic fashion, results from Multi-user Information Theory into MAC design along with the required distributed signaling implementation. We showed through simulations that the throughput can be improved by at-least 20% in the presence of fading (Figure 8) and upto 40% in absence of fading (Figure 7) if one is willing to move away from the IAN paradigm. We could also conclude from simulations that of CSMA k-SIC protocols are superior in terms of performance compared to Aloha based SIC protocols.

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