Designing MAC Protocols for Spread Spectrum Ad Hoc Networks: Thinning versus Spatial State-Dependent Packing

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Abstract — **Achieving high spatial reuse in ad hoc networks exploiting a spread spectrum physical layer can be quite challenging. Designing a MAC protocol for such systems must take into account the physical layer characteristics. Most existing MAC designs for spread spectrum ad hoc networks perform contention resolution to *thin* the intended transmissions. This is fundamentally similar to the designs for a narrow-band system. In this paper, we show that fundamentally a thinning approach is not efficient toward achieving a high level of spatial reuse and significantly compromises system capacity. We then propose a novel design concept: state dependent spatial *packing* of transmissions. We design a multistage contention protocol to realize this spatial packing concept and show it is very efficient in terms of spatial reuse and handling power control, robust to network load and imperfect configuration, and easily implemented in a distributed fashion with small overhead. The performance of this scheme is impressive, with only two stages capable of offering 100%-500% gain over simple thinning protocols such as ALOHA-like random channel access.**

I. Introduction

MAC protocol design for ad hoc networks has been extensively researched. Although many protocols have been proposed, so far the design of MAC protocols for ad hoc networks, still lacks insight on several fundamental issues:

1. What is the maximum capacity a system can support?
2. How close to the maximum capacity can a practical MAC protocol get?
3. Under what regimes will a MAC protocol achieve good performance and is its performance robust to network load etc.?

In this paper, we focus on spread spectrum ad hoc networks. As shown in Fig.1, in spread spectrum ad hoc network, thanks to the interference averaging capability provided by CDMA, a certain amount of overlapping is allowed among concurrent transmissions, which is fundamentally different from a narrow-band system in which concurrent transmissions are not possible within a carrier sensing range. Thus, a spread spectrum PHY layer allows concurrent transmissions to happen with transmission ranges exceeding the nearest neighbor distances. This fundamental difference relative to narrow-band systems has multiple benefits in terms of: meeting end-to-end delay QoS requirements by using a smaller number of relay hops; enabling energy savings by allowing more nodes to stay in the low-power sleep mode and making more routes available for load balancing to avoid capacity and energy bottlenecks. However, these benefits come at the cost of higher interference and thus possibly compromise capacity. Thus in order to realize these benefits and efficiently utilize limited capacity, one must design MAC protocols to leverage the capability of a CDMA PHY layer and achieve a high degree of spatial reuse.

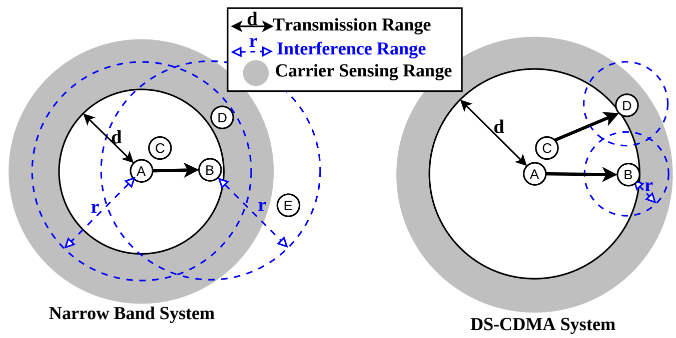

Figure 1: The transmission range, interference range and carrier sensing ranges for an idealized narrow-band and spread spectrum system. Since $A \rightarrow B$ requires no concurrent transmission in the critical interference range r around a B, $C \rightarrow D$ is not allowed in a narrow-band system, but may be allowed in a CDMA system.

II. Previous work and our main contributions.

MAC protocol designs for narrow-band ad hoc networks mostly focus on the concept of 'thinning', i.e., given a set of contenders, use MAC layer contention resolution to reduce the number of contenders until (almost) all survivors can realize successful transmissions. For spread spectrum ad hoc networks, most existing approaches are rooted in design concepts for narrow-band systems which do not fully leverage a CDMA PHY layer's capabilities. We begin by briefly reviewing a few representative MAC designs for spread spectrum ad hoc networks and identify some popular ideas considered in previous literature, some of which are specific to spread spectrum ad hoc networks. Comprehensive reviews of ad hoc network MAC protocols can be found in [1][2].

- ALOHA-like random channel access [3][4][5]. In this approach, potential contenders transmit data randomly, e.g., by alternating transmit/receive modes based on a pseudo-random sequence, without first performing handshaking with receivers or signaling neighbor contenders. Random channel access is simple and analytically tractable, but as discussed in the sequel performs poorly (in terms of capacity and energy) under moderate or heavy loads [6]. In addition, many more complicated MAC protocols have similar performance in terms of spatial reuse.

- Random contention and handshaking, e.g., IEEE802.11. In this approach, transmitters and receivers perform signaling and handshaking before data transmission, and overhearing nodes back off during the transmission time period. This reduces the energy wasted from data transmission failures, at the cost of small overheads for signaling. Yet in terms of spatial reuse, it does not provide much improvement over ALOHA-like random channel access, particularly in a heavy load regime[1][2].
- Multistage elimination and handshaking [7][8][9]. The concept embodied in the work of [7][8][9] is to use multistage signaling to gradually reduce/refine the subset of surviving contenders, assuming signaling messages are *always* successful. Note the *simple* random contention approach is basically the simplest version of this with only a single stage. However, [7] requires centralized control, [8] requires a random number of signaling iterations, and [8][9] both assume signaling is always successful even when a large number of nodes contend concurrently. As we shall discuss in the sequel, multistage handshaking can potentially enhance spatial reuse over previous approaches if it can be implemented efficiently and the cost of such overheads is warranted.
- Multi-channel approach [10][11]. In particular, for a CDMA based ad hoc network, this approach uses different channels for signaling and data transmission. In [10], both signaling and data are transmitted with spreading, which is basically an adaptation of random contention/handshaking to spread spectrum ad hoc networks. By contrast, [11] uses a (narrow-band) common code channel for signaling and spreading only for data transmissions. All nodes need to be active and update state information for all neighboring transmissions in order to determine whether initiating a new transmission will interfere with other transmissions.

In this paper, instead of focusing on a particular protocol design, we offer insights on: how spread spectrum affects MAC design; what is the optimal performance one could possibly achieve using idealized or centralized scheduling schemes; and, how to roughly attain the same performance with practical and distributed designs. We show that for a spread spectrum ad hoc network, the 'thinning' approach may not be suitable because it can not achieve efficient spatial reuse, robustness in handling heavy loads, or properly support nodes using heterogeneous transmission powers.

We propose a novel approach, state-dependent spatial *packing*, to address these issues. We advocate such a packing approach for MAC design of spread spectrum ad hoc networks and show it has significant advantages over the thinning approach. We also show that such spatial packing can be realized in a distributed fashion with small overheads.

The rest of this paper is organized as follows. In Section III we introduce the idea of spatial 'packing'. In Section IV we summarize some previous analytical results on spatial reuse achieved by different schemes. In Section V we propose a practical and efficient multistage contention scheme for realizing the idea of spatial packing. In Section VI we compare the spatial reuse performance of various schemes. We conclude this paper in Section VII.

III. MAC BASED ON *thinning* VERSUS *packing*

We first explain the concepts of 'thinning' and 'packing' and provide intuition on why packing may be more desirable than thinning with the following simple example. We consider 'thinning' first. A common 'thinning' approach, e.g., IEEE 802.11b ad hoc mode, uses request-to-send (RTS) and clear-to-send (CTS) signaling messages. A transmitter intending to transmit sends an RTS to its receiver; the receiver, upon successfully receiving the RTS message, sends back a CTS message to confirm a successful handshake. As shown on the top of Fig.2, suppose three intended transmissions contend simultaneously but will interfere with each other, in particular, C interferes B and A interferes F. After contention, only the transmission from C→D can succeed in handshaking and proceed with data transmission, while B and F are not able to successfully receive RTS messages due to the interference from C and A respectively.

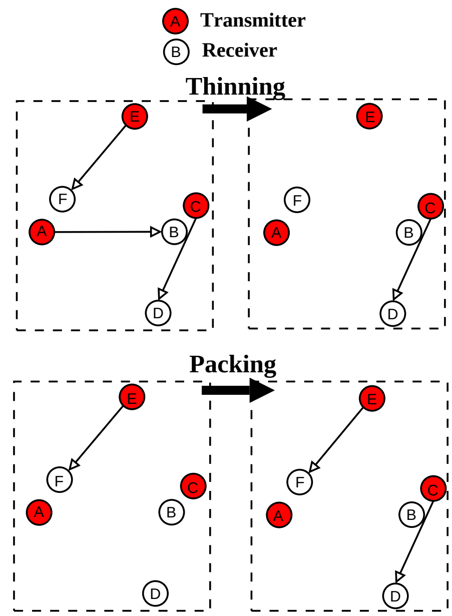

Figure 2: On the top, an example of thinning contenders with only one surviving transmission. On the bottom, an example of a packing of contenders with two surviving transmissions.

Instead, consider the 'packing' approach as shown at the bottom of Fig.2. Conceptually, we start by scheduling only a subset of the transmissions and then check whether it is possible to schedule (pack) more transmissions incrementally given the previously scheduled transmissions. In this example, if we start with the transmission E→F, then A→B should not be scheduled since A will interfere with receiver F. However it is possible to schedule the transmission C→D successfully without (severely) interfering with the transmission E→F.

From this simple example, it is straightforward to observe the advantage of packing over thinning: with packing we might schedule two concurrent transmissions while with thinning we can at most schedule one transmission.

In a thinning based MAC, elimination phases might involve random contention and RTS/CTS handshaking etc. In contrast to 'thinning', 'packing' is a mechanism where incremental scheduling of contention stages attempt to pack additional transmissions that do not (severely) interfere with previously scheduled/successful contenders. We can conceptually view 'thinning' and 'packing', as shown in Fig. 3, as a series of functions defined on the set of all contenders S.

- Thinning can be represented by functions $f_2, f_3, \ldots$ such that $S_{i+1} = f_{i+1}(S_i)$, where S_i is the set of surviving contenders at the beginning of Stage i and Stage1 includes all the contenders, i.e., $S = S_1$. If thinning ends at Stage n, the set of scheduled contenders is S_{n+1}. A MAC based on thinning will be designed such that the transmissions in S_{n+1} will be successful with high probability.

- Packing can be represented by functions $f'_2, f'_3, \ldots$ such that $S_{i+1} = f'_{i+1}(S^*_1, \ldots, S^*_i)$, where S_i is the set of contenders for Stage i and $S^*_i \subset S_i$ is the set of surviving contenders of Stage i. If packing ends at Stage n, the set of scheduled contenders is $S^*_1 \cup S^*_2 \ldots \cup S^*_n$, which again should correspond to a set of concurrent transmissions with high probability to be successful.

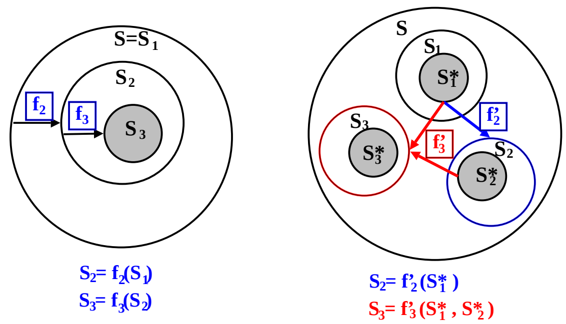

Figure 3: On the left, an abstract representation for thinning and on the right for packing.

In the sequel, we will show that a packing approach indeed achieves efficient spatial reuse and solves the above problems with designs based on thinning.

IV. Analytical Network Model and Spatial Reuse Analysis

Spatial geometric network model. To formally study the performance improvement of spatial packing over thinning, we begin by introducing, and then elaborating on, a simple stochastic geometric model for transmitters and receivers in an ad hoc network. The simplicity is key to allowing tractable analysis, yet the salient characteristics are still captured. We assume that a set of transmit nodes (including nodes relaying packets) are spatially distributed according to a homogenous Poisson point process $\Pi = \{X_i, i \in \mathbb{N}\}$ with intensity λ [12]. Nodes are interchangeably referred to/by their locations. Each transmitter is assumed to be sending to a receiver, which is modeled as being at a random location a distance d away. For simplicity, we will assume receive nodes, are always available at these randomly selected locations. The model captures a homogenous offered load where packets are typically relayed along hops with a transmission range d, leading to a homogenous distribution of transmitters. We shall further assume there is no mobility in the time scale of transmissions, and that transmissions are synchronous, or at least approximately so. As discussed in [13] even an approximate synchronization provides significant advantages. See [3][5] for representative protocols based on synchronized contention.

We capture the spatial attenuation of signal power using a basic path loss model where if a transmitter uses a power level ρ the receive power at a distance d is given by $\rho_r(d) = \rho \times d^{-\alpha}$. The path loss exponent α is typically assumed to be between 3 and 5. A receiver, in our model, sees the degraded powers from other concurrent transmitters, as interference, albeit reduced by spread spectrum processing gain. Outage happens when the SINR at the receiver does not exceed a certain threshold, resulting in an unsuccessful transmission.

To evaluate the outage probability we condition on a typical transmitter at the origin O giving what is known as the Palm distribution for receivers on the plane [12]. An outage event occurs when, after de-spreading with processing gain m, the SINR is below some threshold, β. Thus mathematically, for conventional DS-CDMA, the outage probability for a typical receiver $p_o(\lambda, d)$, depending on the intensity of transmitters and transmission range, is given by

$$p_o(\lambda, d) \approx \mathbb{P}\left(\frac{\rho_r(d)}{\sum_{X_i \in \Pi} \rho |X_i|^{-\alpha}} \leq \frac{\beta}{m}\right), \qquad (1)$$

where $|X_i|$ denotes the Euclidean distance from interferer i to the receiver located at the origin.[1] Note we have neglected the role of ambient noise since the capacity of a dense network is mostly interference constrained.

Efficient spatial reuse - analysis. Consider the naive thinning approach similar to that in Section III, where contenders perform handshaking synchronously and only those transmitters/receivers that successfully negotiate handshaking proceed with their transmissions. If the density of contenders is high, most of contenders will not be able to finish handshaking successfully. If the contention is sparse, there are not enough candidates to fully achieve the potential spatial reuse. Therefore there is an optimal contention density that achieves the maximal spatial reuse. Note that in terms of spatial reuse, it is roughly equivalent to ALOHA-like random channel access[2]. Thus the following result from our previous work [6] provides a rough capacity analysis for both of these schemes.

Fact IV.1. *A simple thinning approach, e.g., ALOHA-like random channel access or 802.11 like random contention, achieves its maximal density of concurrent successful transmissions on the order of* $\frac{1}{4\pi d^2}\left(\frac{m}{\beta}\right)^{\frac{2}{\alpha}}$ *when the density of contending transmitters is* $\frac{1}{2\pi d^2}\left(\frac{m}{\beta}\right)^{\frac{2}{\alpha}}$.

In order to show thinning is not particularly efficient in spread spectrum systems, we consider what is the maximum spatial reuse that could be possibly achieved if we could arbitrarily place transmissions. The pioneering work of [14] showed that the optimal spatial reuse could be achieved by placing transmitters/receivers on a regular grid. We shall extend their result to a spread spectrum ad hoc network, where optimal spatial reuse is achieved by clustering transmitters/receivers on a regular grid, in order to show that packing achieves a spatial reuse close to this optimal deterministic scenario and thus is efficient.

Fact IV.2. *The maximum spatial reuse in terms of the density of successful transmissions achieved by clustered placement of transmitters and receivers respectively on a regular grid, is given by* $\frac{1}{2d^2}\left\lfloor\frac{m/\beta+1}{k(\alpha)}\right\rfloor$, *where* $k(\alpha) \approx 4$ *is a constant depending on* α.

Note that the spatial reuse under the simple thinning approach increases slower than m, in particular when $\alpha > 2$, yet the maximum spatial reuse allowed by the system increases linearly in m. This implies a reduced efficiency in spread spectrum systems if we use thinning. When m is large, such degradation can be significant and lead to very inefficient spatial reuse.

Therefore, to be efficient, a MAC protocol should achieve a spatial reuse that scales approximately linearly in m. As we shall see later in Section VI, when $\alpha > 2$ and $m \gg 1$, 'packing' indeed achieves a spatial reuse that scales roughly as $\Theta(m)$, which is much higher than a simple thinning approach.

[1] Such attenuation law has a simple form but is unrealistic when $|X_i| < 1$. However it will not change the analytical results since there will be an outage anyway. One can use more realistic attenuation functions like $|X_i + 1|^{-\alpha}$ and the analysis will basically remain the same.

[2] This is true when we assume all CTS will be successfully received, which is likely the case.

V. A PRACTICAL 'PACKING' SCHEME - MULTISTAGE CONTENTION

Description of the multistage protocol. We present a general concept of multistage packing strategy, geared at achieving high spatial reuse. As an example, we show the timing diagram of a two-stage contention scheme in Fig. 4.

Stage 1 handshaking: In Stage 1 a subset of transmitters perform the three-way handshaking with their intended receivers, i.e., RTS, CTS, followed by an additional 'confirmation' RTS message. Only transmitter-receiver pairs who successfully exchange the three messages survive the first stage. These survivor pairs serve as 'seeds' for clusters in the subsequent handshaking stage(s).

Stage 1 monitoring: During Stage 1 contention, potential transmitters and receivers[3] not participating in the first stage handshaking process synchronously monitor interference levels, for which they can indeed distinguish RTS and CTS time slots. Doing so permits them to evaluate their proximity to surviving Stage 1 transmitters and receivers.

Stage 2 handshaking: In Stage 2, transmitters that sensed a 'strong' (see below) CTS signal in Stage 1 do not participate in Stage 2, i.e., are suppressed since they would likely interfere with the a successful Stage 1 receiver. Similarly a Stage 2 receiver which successfully receives an RTS from a transmitter, will only send back a CTS, if during Stage 1 it did not sense a 'strong' confirmation RTS signal. Thus the role of the Stage 1 'confirmation' RTS is to signal receivers in the Stage 2 that they will be interfered with and thus to suppress subsequent CTSs.

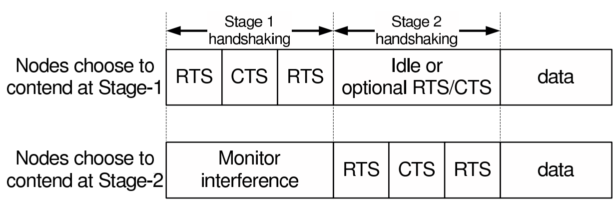

Figure 4: Timing diagrams of a two-stage contention MAC with the top for Stage 1 transmitter/receiver and the bottom for Stage 2 transmitter/receiver.

This process can be carried out through multiple stages for a higher level of spatial reuse and might be performed in different ways, e.g., survivors of Stage 1, might also concurrently participate in Stage 2, to permit estimation of aggregate interference, rather than simply local interactions. Fig.5 illustrates the two stage packing of transmissions. In Fig. 5 the area around each transmitter or receiver is of radius $\frac{r}{2}$, where r is the interference range shown in Fig. 1. Thus if a receiver and a transmitter are too close with overlapping areas, i.e., an interfering transmitter is within distance r to a receiver, transmissions will not be successful. However, overlapping among only transmitters or only receivers will likely be allowed for successful transmission. Following this rule, overlapping transmissions can still be successful thanks to the processing gain from the CDMA physical layer, as long as transmitters are not too close to receivers[15].

Supporting power control via multi-class/multistage packing. A realistic network may support transmissions with different relay distances, in which nodes should use power control to choose transmit power levels possibly depending on the relay distances. Multistage packing naturally supports such scenarios by adopting a multi-

[3]Those who will not be active at this cycle do not need to monitor, which is more efficient than [11] in which all nodes have to do consistent monitoring.

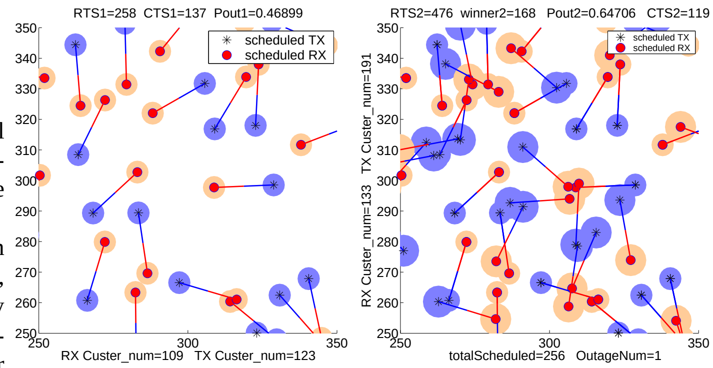

Figure 5: On the left, contention result of successful transmitter-receiver pairs of Stage 1. On the right the contention result after Stage 2.

class and multistage packing approach. The idea is to allow transmissions with higher transmission power to perform handshaking first so as to enable transmitters and receivers in subsequent stages to detect their RTS/CTS and correctly estimate interference regions. Specifically, consider a network where nodes use one of k possible relay distances $d_i, i = 1, \ldots k$ satisfying $d_1 > d_2 \ldots > d_k$ each with an associated transmit power level $\rho_i^t, i = 1 \ldots k$. Suppose these power levels are roughly a known priori. We assume that only class i nodes perform handshaking at Stage i based on monitoring interference levels for stages $1, \ldots i-1$ and thus estimating whether they will interfere with or be interfered by contenders in previous stages, by taking into account predefined power levels used at each stage. This approach, achieves a multi-scale packing of successful transmissions and high spatial reuse, as shown in Fig. 6.

Overheads. With the multistage contention MAC, the overhead for each successful transmission, is fairly close to the simple RTS/CTS mechanism only with additional overhead to monitor local interference levels. In the sequel, we will show the performance gain attained by multiple stage warrant this overheads. Moreover, interference measurement is simpler and more feasible than signaling with neighbors proposed, e.g., [11].

VI. PERFORMANCE EVALUATION

We define the following two schemes as the baselines for performance comparison:

Centralized$_{greedy}$: centralized greedy contention resolution. Given a set of contenders, this scheme iteratively examines the subset of remaining transmissions and removes one transmission pair at a time based on which is currently seeing the worst SINR on either its transmitter or receiver side. Contention resolution finishes when all surviving transmissions have sufficient SINR at both receivers and transmitters such that signaling and data transmissions are guaranteed to be successful. Clearly though impractical, such a scheme is close to optimal.

Centralized$_{rand}$: centralized random contention resolution. Given a set of contenders, this scheme iteratively examines the subset of remaining transmission pairs and *randomly* removes one transmission pair with an insufficient SINR on either its transmitter or receiver side. Contention resolution finishes when all surviving transmissions have sufficient SINR at both receivers and transmitters such that signaling and data transmissions are guaranteed to be successful.

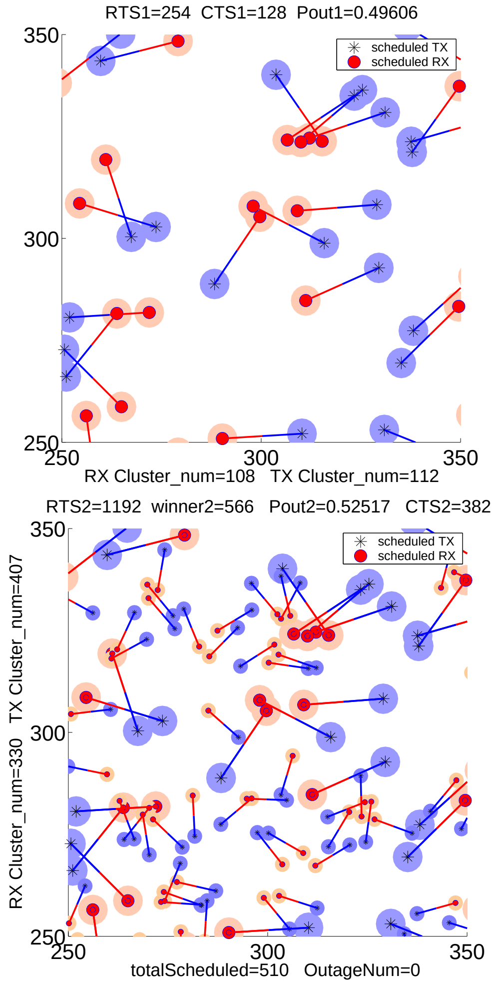

Figure 6: On the top, the resulting transmitter-receiver pairs of a multistage multi-class contention protocol's Stage 1 contention among nodes using longer relay distances and high transmission powers. At the bottom, the resulting transmitter-receiver pairs for Stage 1 and 2 for a multi-class multistage contention protocol.

We shall compare the performance of multistage contention (later referred as Packing) and random channel access or contention (later referred as Thinning) with these two centralized schemes. In particular the Packing scheme has three stages, with the first two stages being identical to the two-stage version discussed in Section V and the last stage consists of retries by those who fail in the previous two stages.

We fix the path loss exponent to be 4 and assume all transmissions are of the same distance. If not specifically mentioned, the spreading factor is 512 and the SINR threshold required for successful transmission after de-spreading is 10dB. We fix the number of nodes in a rectangle area and randomize their locations for each round, for which different MAC schemes are applied to the same realization of nodes. Each performance point is an average of ten rounds. We also only consider nodes falling inside some margin to eliminate edge effects.

Our first simulation examines the spatial reuse achieved by different schemes given the same set of intended transmissions. We also vary the density of contending transmissions and show how spatial reuse scales with the contention intensity. As shown in Fig. 7, we plot the number of successful transmissions achieved by Centralized$_{greedy}$, Centralized$_{rand}$ and Thinning. For Packing, we plot the *overall* successful transmissions achieved at the end of each stage. As expected, Centralized$_{greedy}$ has the best performance and Thinning has the worst performance. The performance of Packing is slightly lower than Centralized$_{greedy}$ but remains better than Centralized$_{rand}$, which is very impressive for Packing since Centralized$_{rand}$ is centralized. In this simulation, Packing is properly configured by choosing the right contention intensities at each stage, in particular, we let the Stage2 contention intensity be approximately twice of that in Stage1. The performance of Packing almost remains increasing in the range of contention intensities tested. However, as discussed before, Thinning's performance is sensitive the contention intensity and there is some optimal contention intensity for Thinning to achieve the best performance, e.g., in Fig. 7 this happens when the normalized contention intensity is roughly 4. Finally, Stage2 achieves most of the performance gain, which indicates that our multistage protocol can be implemented with only two or three stages without compromising potential performance.

Our second simulation tests the robustness of Packing by intentionally assigning suboptimal contention intensities at each stage. In particular, we let the contention intensity at Stage1 be twice that of Stage2, i.e., we have too high contention intensity initially and insufficient contention intensity at Stage2. As shown in Fig. 8, the performance of Packing is only slightly worse than the previous simulation when parameters are optimally chosen and remains increasing or flat throughout the range of intensities tested. It is only when the overall intensity is extremely high, that its performance starts decreasing as Thinning. We can also observe that Stage3 contributes more significantly to the overall spatial reuse when the Packing is not optimally configured. Therefore, Packing is quite robust in performance thanks to a multistage implementation.

Finally we examine the scaling of spatial reuse in spreading factor m for different schemes. Recall that in Section IV we show that optimal scheme can achieve a spatial reuse linear in m while thinning can only achieve one which is sub-linear ($m^{\frac{2}{\alpha}}$) in m. As shown in Fig. 9, Centralized$_{greedy}$ and Packing are both efficient because not only their spatial reuse scales roughly linearly in m but also much faster than Centralized$_{rand}$ and Thinning, whose spatial reuse scales only sub-linearly. Therefore, Packing is well suited as the choice for spread spectrum ad hoc networks.

VII. Conclusion

The packing concept is particularly efficient to realize a high degree of spatial reuse in spread spectrum ad hoc networks. By using a multistage contention protocol, such packing can be realized in a distributed way with small overheads and achieve a close-to optimal performance. Note that such benefit, however, becomes marginal in a narrow-band system or if the path loss is not severe, say one with path-loss exponent $\alpha = 2$ in vacuum.

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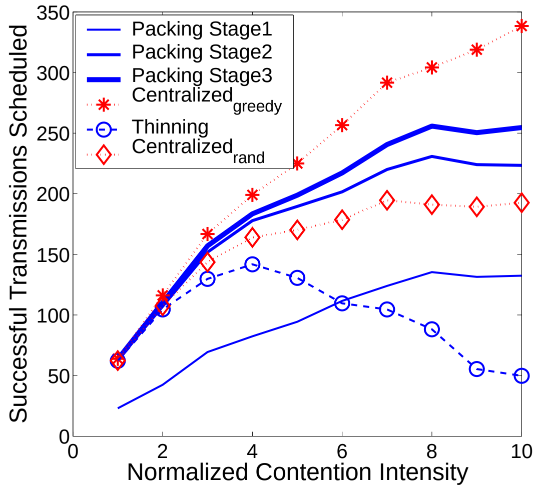

Figure 7: Performance of the Packing approach surpasses Centralized$_{rand}$ when contention intensity at each stage is optimally chosen.

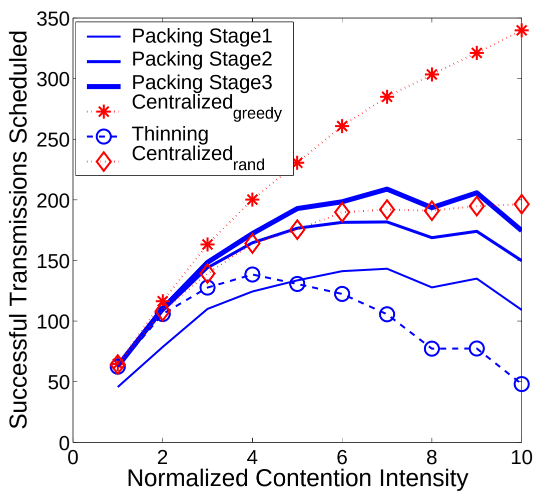

Figure 8: Performance of Packing is robust when contention intensity at each stage is not optimally chosen.

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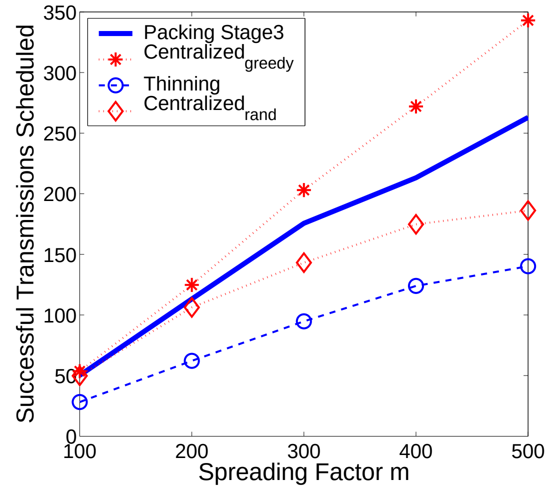

Figure 9: The scaling of performance of different approaches in spreading factor *m*.

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