Best Node Selection Through Distributed Fast Variable Power Multiple Access

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***Abstract*—In many wireless applications, it is highly desirable to have a fast mechanism to resolve or select the packet from the user with the highest priority. Furthermore, individual priorities are often known only *locally* at the users. In this paper we introduce an extremely fast, local-information-based multiple access algorithm that selects the best node in 1.8 to 2.1 slots, which is much lower than the 2.43 slot average achieved by the best algorithm known to date. The algorithm, which we call Variable Power Multiple Access Selection (VP-MAS), uses the local channel state information from the accessing nodes to the receiver, and maps the priorities into the *receive* power. It is inherently distributed and scales well with the number of users. We show that mapping onto a discrete set of receive power levels is optimal, and provide a complete characterization for it. The power levels are chosen to exploit packet capture that inherently occurs in a wireless physical layer. The VP-MAS algorithm adjusts the expected number of users that contend in each step and their respective transmission powers, depending on whether previous transmission attempts resulted in capture, idle channel, or collision.**

I. INTRODUCTION

Many wireless multi-agent scenarios require the system to discover or select, from a set of nodes, the most suitable candidate for accessing an appropriate sink. More formally, we can assign a "suitability metric" to each user, and aim to discover the user with the best metric. For example, a system that exploits multiuser diversity allows the node with the best channel state to transmit so as to maximize the overall system throughput [1]. In a sensor network, a node can be selected to minimize total power consumption or maximize the network lifetime. In collaborative communications, a transmitting source needs to select the best relay for collaboration [2].

Often times, due to the decentralized nature of the network, the information necessary to evaluate whether a node is the most suitable candidate is initially available only locally at the node itself and not elsewhere in the network. In this case, delivering all the information to a centralized node or sink for a decision is inefficient due to its high communication overhead and possible latency increase. Thus, it is highly desirable that the process of selection be fast and decentralized. An attractive option for accomplishing this is a *multiple access selection* mechanism in which the nodes themselves compete with each other based on their local information such that the best node is the first to successfully send its packet to the sink for further processing or identification.

Multiple access has been studied extensively in the last three decades, e.g., [3]–[5]. A common assumption in the design of multiple access schemes is that in the event of a collision, none of the colliding packets can be decoded properly [4]–[6]. However, the collision model is a coarse and pessimistic model for a wireless physical layer that routinely handles and overcomes interference. In fact, so long as the received power of one signal is sufficiently stronger than the interference power, the receiver can decode (capture) the stronger signal [7].[1] The collision model ignores, to its detriment, the fact that receive powers are often asymmetric due to different path gains or different transmit powers of the users – the very fact that aides successful reception. Capture has been exploited in many systems such as Aloha networks [8], 802.11 wireless local area networks [9], and cellular radio systems [10]. A promising generalization of capture called Multi-packet reception (MPR) has also been studied extensively in the literature [11].

It has also been shown recently that the local channel knowledge can be exploited to significantly improve the efficiency of contention-based multiple access. For example, the channel-aware Aloha scheme incorporates channel knowledge to control channel access [6]; each user transmits only if its channel gain exceeds a system-determined threshold. The Opportunistic Aloha (O-Aloha) protocol [12] sets the probability of transmission as a function of the local channel knowledge.

In this work, we introduce a decentralized, fast Variable Power Multiple Access Selection (VP-MAS) algorithm that uses local channel knowledge to control the power with which each packet is received (or equivalently, the power with which it is transmitted). VP-MAS adjusts the receive power of a packet from a node as a function of the metric locally available at the node. The algorithm aims to capture as soon as possible the packet from the best node, i.e., the node with the best metric, even when multiple nodes transmit simultaneously. It adjusts the expected number of users that contend in each step and their respective transmission powers, depending on

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[1] This statement is valid even if no special measures for interference mitigation, such as multiuser detection or smart antennas, are used.

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whether previous transmission attempts resulted in capture, idle channel, or collision. We show that mapping the metrics into a discrete set of receive powers is an optimal strategy; and we derive analytical expressions for the probability of success. In a time-slotted system, VP-MAS can select the best node within 1.8 to 2.1 slots on average, regardless of the number of contending nodes in the system. This is remarkably fast given that at least one slot is always needed to receive a packet, and is considerably below the 2.43 slots required on average by the fastest known collision-model-based opportunistic splitting algorithm [13].

The remainder of the paper is organized as follows. Section II describes the system model. An explicit characterization of the optimal power-mapping function is provided in Sec. III. Section IV describes the complete multiple-access selection algorithm. This is followed by simulation results in Sec. V and conclusions in Sec. VI.

II. SYSTEM MODEL

We consider a wireless network that consists of $N \geq 2$ accessing nodes and a message sink. Each node, i, has a metric, μ_i, that describes the priority of getting its packet to the sink and is known only locally to the node. The probability distribution of the metric is known globally in the system. For ease of presentation, the metric is assumed to be independent and uniformly distributed in this paper.[2]

We consider a time-slotted system where all packets have the same size, and the transmission rate of packets is the same. The channel gain between node i and the message sink is denoted by h_i, and is assumed to be known only at the node i. This assumption is similar to the one made in channel-aware Aloha [12].

Let P_i denote the power received from node i (we shall henceforth call it 'receive power' or RP). The sink decodes the packet transmitted by node i successfully if the received signal to interference and noise ratio (SINR) exceeds a threshold:

$$\frac{P_i}{\sum_{j \neq i} P_j + \sigma^2} \geq \bar{\gamma}, \qquad (1)$$

where σ^2 is the noise power, and $\bar{\gamma} \geq 1$ is a threshold that depends on the modulation and coding used for the packet transmission. Thus, a packet might be decoded successfully even when two or more users transmit simultaneously.

The ability to control RP is crucial to the development of a fast MAS algorithm that takes advantage of (1). This requires (i) channel state information at the transmitter, and (ii) ability to regulate the transmit power. In reciprocal channels, each node can easily and locally compute its channel gain to the message sink by listening to a (predefined) pilot sequence that is periodically broadcast by the sink; in non-receiprocal channels, feedback can be used to communicate the channel states [7]. For a target receive power P and an estimated channel gain h, a node transmits at power P/h.

In this work, we assume that the RP of every node lies between $P_{\min}$ and $P_{\max}$, where $P_{\min}$ and $P_{\max}$ depend on the receiver's hardware limitations.[3] The RP dynamic range can be tens of decibels, depending on the acceptable best and worst channel gains in the system and the dynamic range of transmitters. For example, the mobile station transmit power dynamic range is about 34 dB in GSM systems [15] and 74 dB in WCDMA systems [16].

At the beginning of a time slot, each node independently decides, depending on criteria that will be specified later, whether or not to transmit its packet. If it does transmit, it sets the RP of its packet according to a *metric-to-receive power mapping* $\pi(\cdot)$. That is, it transmits at a power of $\pi(\mu_i)/h_i$, which depends on its metric and channel gain. At the end of every slot, based on the RP and checksum of the received packet(s), one of three outcomes is possible. If no node transmits in the slot ($RP < P_{\min}$), the outcome is *idle*. If the receive powers are such that the signal of one of the transmitting nodes can be captured as per (1) ($RP \geq P_{\min}$ and checksum okay), the outcome is a *success*. Otherwise, if none of the transmitted signals can be captured ($RP \geq P_{\min}$ and checksum fails), the outcome is a *collision*. The sink broadcasts *only* this outcome at the end of every slot.

III. FUNDAMENTAL INSIGHTS

Our aim is to design a fast multiple access selection algorithm such that the packet sent by the best node is the first to be successfully decoded by the message sink. Before describing the complete algorithm, we first consider the metric-to-receive-power mapping for the case in which exactly two nodes simultaneously transmit. We then generalize it to the case in which a fixed, but arbitrary, number of nodes transmit. Finally, the complete VP-MAS algorithm is developed in the following section. Proofs are deferred to [14] due to space constraints.

A. Simultaneous Transmission by Two Nodes

In this scenario, exactly two nodes, a and b, with corresponding metrics μ_a and μ_b, simultaneously transmit their packets. We assume that the metrics are uniformly distributed in the range $[\mu_{\min}, \mu_{\max})$. As mentioned, the general non-uniform case is considered in [14]. Without loss of generality, let $\mu_a < \mu_b$.

We first find the optimal function $\pi(.)$ that maximizes the probability that the receiver (sink) decodes the packet transmitted by b successfully. This is an infinite dimensional optimization problem, which can be stated mathematically as:

$$\max_{\pi} \Pr\left\{\frac{\pi(\mu_b)}{\pi(\mu_a) + \sigma^2} \geq \bar{\gamma}\right\}, \qquad (2)$$

subject to $P_{\min} \leq \pi(\mu) \leq P_{\max}$.

The following lemma states an important result that an optimal solution to (2) is to map the metrics into a set of *discrete* power levels. The number of levels depends on the dynamic power range $[P_{\min}, P_{\max}]$.

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[2] The general non-uniform distribution case is addressed in [14].

[3] Nodes for which the RP is smaller than $P_{\max}$ when they transmit at maximum power are considered out of range, and are excluded from the system.

Lemma 1: Let $\pi(\cdot)$ be a function that maps the metrics into $(L+1)$ discrete power levels in the set $\mathbf{Q} = \{q_0, q_1, q_2, \cdots, q_L\}$ such that

$$L = \left\lfloor \log_{\bar{\gamma}} \left(\frac{(\bar{\gamma}-1)P_{\max} + \sigma^2\bar{\gamma}}{(\bar{\gamma}-1)P_{\min} + \sigma^2\bar{\gamma}} \right) \right\rfloor, \qquad (3)$$

and

$$q_i = \bar{\gamma}^i P_{\min} + \sigma^2\bar{\gamma}\frac{\bar{\gamma}^i - 1}{\bar{\gamma}-1}, \quad 0 \le i \le L. \qquad (4)$$

Then $\pi(\cdot)$ optimizes the probability of success in (2). ■

The power levels shown in (4) result from setting $q_0 = P_{\min}$, and minimizing the gap between the adjacent power levels. While the above solution is optimal, it need not be unique. For example, if $P_{\max} < \bar{\gamma}(P_{\min} + \sigma^2)$, all mappings are optimal and all result in a zero probability of success. Also note that the optimal solution need not occupy the entire dynamic range, i.e., q_L can sometimes be less than $P_{\max}$.

Let users with metrics in the range $[m_i, m_{i+1})$ be mapped to the receive power q_i, for $0 \le i \le L$, with $m_0 = \mu_{\min}$ and $m_{L+1} = \mu_{\max}$. The following theorem provides a complete characterization of the optimal power mapping.

Theorem 1: Let

$$m_i = \mu_{\min} + \left(\frac{\mu_{\max} - \mu_{\min}}{L+1} \right) i, \quad 0 \le i \le L+1, \qquad (5)$$

then a power mapping that sets

$$\pi(\mu) = q_i, \quad \text{if } m_i \le \mu < m_{i+1}, \qquad (6)$$

optimizes the probability of success in (2). The corresponding highest probability of success is $P_{\text{succ}}^{\pi} = 1 - \frac{1}{L+1}$. ■

In other words, the optimal support consists of equal length intervals: $m_{i+1} - m_i = m_i - m_{i-1}$, for $1 \le i \le L$. A larger RP dynamic range allows more levels, which increases the success probability by improving the odds that the best user's signal can be resolved.

B. Simultaneous transmissions from fixed but unknown number of interferers

During multiple access, the actual number of nodes that transmit in a slot need not be 2; it lies between 0 and N. When only one node transmits, its transmission can be decoded properly so long as $P_{\min} = \sigma^2\bar{\gamma}$. (This is therefore assumed for the rest of this paper.) It can be shown that the optimal receive power levels are discrete even for the general case in which many nodes transmit. However, deriving the power level values is analytically cumbersome [14]. We therefore generalize the power levels as follows:

$$q_{a,i} = (a\bar{\gamma})^i P_{\min} + \sigma^2\bar{\gamma}\frac{(a\bar{\gamma})^i - 1}{a\bar{\gamma}-1}, \quad 0 \le i \le L_a \qquad (7)$$

where $a \ge 1$, $a \in \mathbb{R}$, is called the *adversary order*. This criterion ensures that the best node's packet can be captured even when the RP from each of $\lfloor a \rfloor$ contending nodes (adversaries) is just one level below the RP of the best node.

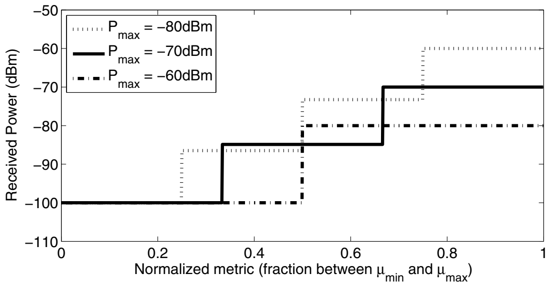

Fig. 1. The receive powers as a function of the normalized metric $\frac{\mu-\mu_{\min}}{\mu_{\max}-\mu_{\min}}$ for different values of $P_{\max}$ for 2 contending users, $\sigma^2 = -110$ dBm, and $\bar{\gamma} = 10$ dB.

The number of power levels, $L_a + 1$, depends on $P_{\max}$. For an adversary order a, we have

$$L_a = \left\lfloor \log_{a\bar{\gamma}} \left(\frac{(a\bar{\gamma}-1)P_{\max} + \sigma^2\bar{\gamma}}{(a\bar{\gamma}-1)P_{\min} + \sigma^2\bar{\gamma}} \right) \right\rfloor. \qquad (8)$$

A node with metric μ ensures that the power received from it is as per the following power mapping:

$$\pi(\mu) = q_{a,i}, \quad \text{if } m_i \le \mu < m_{i+1}, \qquad (9)$$

where the $\{m_0, \ldots, m_{L_a+1}\}$ is the support.

The following lower bound can be derived for the probability of success, S_k, when k nodes actually transmit.

$$S_k = \frac{\sum_{i=1}^{L_a} \binom{k+1}{1} (m_{i+1} - m_i)(m_i - m_0)^k}{(\mu_{\max} - \mu_{\min})^{L_a+1}}, \qquad (10)$$

for $1 \le k \le \lfloor a \rfloor + 1$. And for $k = 0$ or $k > \lfloor a \rfloor + 1$, $S_k = 0$. This is a lower bound since it pessimistically assumes that capture *never* occurs when the number of transmitting nodes exceeds $\lfloor a \rfloor + 1$.

In choosing the adversary order a, we are faced with the tradeoff between having more power levels and having a larger gap between power levels. A thorough study of a is given in [14]. Intuitively, one can argue that the number of levels should not be sacrificed. This corresponds to choosing as large a value of a as possible without reducing the number of levels:

$$a^{\star} = \max\{a : L_a = L\}. \qquad (11)$$

To conserve space, only results for this special case are presented in this paper. In Fig. 1, we illustrate the power mapping function when $a = a^{\star}$, for different values of $P_{\max}$, which depends on the dynamic range of the receiver.

IV. VARIABLE POWER MULTIPLE ACCESS SELECTION ALGORITHM

We now design the Variable Power Multiple Access Selection (VP-MAS) algorithm. It controls (i) how many nodes transmit at any time so as to improve the odds of capturing the best user, and (ii) what power mapping function (defined in terms of the adversary order and the support) to use for the nodes that do transmit. Intuitively, controlling the number of nodes that transmit is important because more steps will be required to find the best user if too few users transmit in each step. If too many users simultaneously transmit, the interference increases and reduces the odds of a successful capture. As we have already seen, another important factor for the probability of successful capture is the power mapping.

The multiple access algorithm proceeds through a sequence of steps to guarantee that the first successful capture is that of the packet transmitted by the best user. In each step, only those nodes whose metrics lie within an interval calculated by the algorithm transmit. At the end of each step, the sink broadcasts one of three outcomes to all nodes: idle, collision, or success. Depending on the outcome, the intervals are updated, as described below. This updating can be done independently by each node without any additional feedback from the sink.

We present the VP-MAS algorithm for the case when the metric is uniformly distributed in $[0, 1)$.

Definitions: To specify the protocol precisely and optimize its performance, we first define the following three state variables: $\mu_{\text{base}}(k)$, $\mu_{\max}(k)$, and $\mu_{\min}(k)$. $\mu_{\text{base}}(k)$ and $\mu_{\max}(k)$ are the lowest and highest possible values of the best metric at the beginning of step k. In step k, only nodes with metrics between $\mu_{\min}(k)$ and $\mu_{\max}(k)$ transmit. Hence, the supports at step k that determine the receive power level are

$$m_i = \mu_{\min}(k) + \left(\frac{\mu_{\max}(k) - \mu_{\min}(k)}{L+1} \right) i, \tag{12}$$

for $0 \leq i \leq L+1$. We also define $z(k)$ as the probability that an arbitrary node will transmit in step k. Finally, $m(k)$ denotes the most likely estimate of the number of nodes with metrics between $\mu_{\text{base}}(k)$ and $\mu_{\max}(k)$.

Basic relationships: Given $m(k)$ and $z(k)$, the probability of success in step k is lower bounded by

$$P^{\text{succ}}(k) = \sum_{r=1}^{m(k)} S_{r-1} \binom{m(k)}{r} z(k)^r (1 - z(k))^{m(k)-r}. \tag{13}$$

Initialization: In the beginning, the best metric can lie anywhere between 0 and 1. Therefore, $\mu_{\text{base}}(1) = 0$ and $\mu_{\max}(1) = 1$. And, $m(1) = N$ since the metrics of all N nodes lie between $\mu_{\text{base}}(1)$ and $\mu_{\max}(1)$, and $z(1)$ follows from (14) below.

The key rule is that the parameters are updated so as to maximize the probability of success in each step. From (13), it follows that the transmission probability, $z(k)$, needs to be set as follows to achieve this:

$$z(k) = \arg\max_{z} \sum_{r=1}^{m(k)} S_{r-1} \binom{m(k)}{r} z^r (1 - z)^{m(k)-r}. \tag{14}$$

Given that all nodes with metrics that lie between $\mu_{\min}(k)$ and $\mu_{\max}(k)$ transmit, $z(k)$ is entirely determined by the state variables through $z(k) = \frac{\mu_{\max}(k) - \mu_{\min}(k)}{\mu_{\max}(k) - \mu_{\text{base}}(k)}$. Therefore,

$$\mu_{\min}(k) = \mu_{\max}(k) - (\mu_{\max}(k) - \mu_{\text{base}}(k)) z(k). \tag{15}$$

VP-MAS Algorithm: At each time slot k, the VP-MAS algorithm proceeds as follows:

1) A node i with metric μ_i transmits only if μ_i lies in the range $[\mu_{\min}(k), \mu_{\max}(k))$. If it transmits, it uses power mapping $\pi(\mu_i)$ defined in (9) and the support defined in (12).
2) If the outcome is a success, then the best node has been captured and the algorithm terminates.
3) If the outcome is idle, then no node transmitted. This implies that all of the nodes, and thus also the best node, have metrics that lie between $\mu_{\text{base}}(k)$ and $\mu_{\min}(k)$. Hence, $\mu_{\max}(k+1) = \mu_{\min}(k)$ and $\mu_{\text{base}}(k+1) = \mu_{\text{base}}(k)$. Thus, the estimate of the number of nodes with metrics between $\mu_{\max}(k+1)$ and $\mu_{\text{base}}(k+1)$ remains unchanged: $m(k+1) = m(k)$. Therefore, from (14), it also follows that $z(k+1) = z(k)$. $\mu_{\min}(k+1)$ is calculated from (15).
4) If the outcome is a collision, it implies that the best metric definitely lies between $\mu_{\min}(k)$ and $\mu_{\max}(k)$. Hence, $\mu_{\max}(k+1) = \mu_{\max}(k)$ and $\mu_{\text{base}}(k+1) = \mu_{\min}(k)$. Furthermore, $m(k+1)$, the most likely number of nodes between $\mu_{\text{base}}(k+1)$ and $\mu_{\max}(k+1)$ can is the argument r that maximizes $\binom{m(k)}{r} z(k)^r (1 - z(k))^{m(k)-r} (1 - S_{r-1})$. Values of $z(k+1)$ and $\mu_{\min}(k+1)$ follow from (14) and (15).

We demonstrate all the possibilities of the algorithm using the following contrived example with $N = 6$ nodes, $\bar{\gamma} = 10$ dB, $\sigma^2 = -110$ dBm, and $P_{\max} = -70$ dBm. The optimal receive power levels are then given by -100 dBm, -84.9 dBm, and -70 dBm. The metrics of nodes 1 to 6 are assumed to be 0.1548, 0.2731, 0.4324, 0.5749, 0.6440 and 0.7011, respectively. In slot 1, with $\mu_{\text{base}}(1) = 0$, $\mu_{\max}(1) = 1$, $m(1) = 6$, the algorithm computes $\mu_{\min}(1) = 0.71$. Since none of the metrics exceeds 0.71, an idle slot results. The algorithm then sets $\mu_{\text{base}}(2) = 0$, $\mu_{\max}(2) = 0.71$, and $m(2) = 6$, which leads to $\mu_{\min}(2) = 0.5041$. This implies that the mapping function in slot 2 maps metrics in $[0.5041, 0.5727)$ to -100 dBm, in $[0.5727, 0.6414)$ to -84.9 dBm, and $[0.6414, 0.71)$ to -70 dBm receive power. Hence, the receive powers from nodes 4, 5 and 6 are -100 dBm, -70 dBm and -70 dBm, respectively, which leads to a collision. The algorithm then sets $\mu_{\text{base}}(3) = 0.5041$, $\mu_{\max}(3) = 0.71$, and computes $m(3) = 2$ and $\mu_{\min}(3) = 0.5556$. This implies that the mapping function in slot 3 maps metrics in $[0.5556, 0.6071)$ to -100 dBm receive power, $[0.6071, 0.6585)$ to -84.9 dBm, and $[0.6585, 0.71)$ to -70 dBm. Now, the receive power from nodes 4, 5 and 6 are -100 dBm, -84.9 dBm, and -70 dBm, respectively, which leads to the desired successful capture of best node 6's packet.

V. SIMULATIONS

We consider a network of multiple transmitting nodes and a common information sink. Each node has a metric that is uniformly distributed in the range $[0, 1)$. The SINR threshold for successful decoding is set as $\bar{\gamma} = 10$dB. The effective noise floor is taken to be $\sigma^2 = -110$dBm. Hence, $P_{\min} = \sigma^2 \bar{\gamma} = -100$dBm. For each set of parameters, data are collected over 10^5 independent trials.

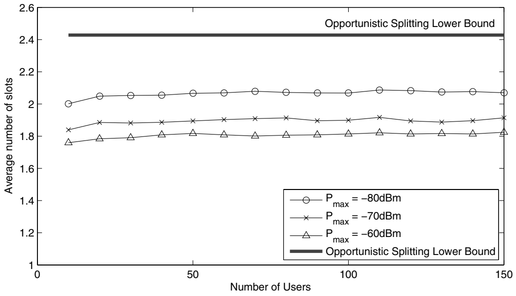

Fig. 2. Average number of slots required to select the best node with the best metric using VP-MAS algorithms ($\sigma^2 = -110$ dBm, $\bar{\gamma} = 10$ dB). Also shown is the 2.43 slot lower bound of opportunitistic splitting algorithm.

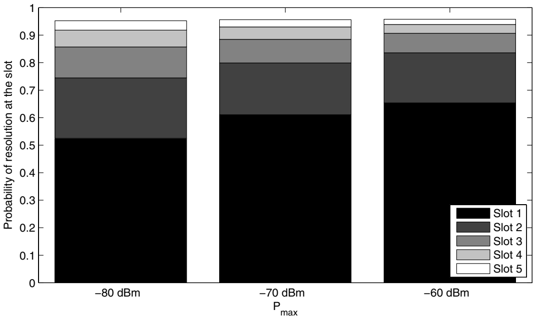

Fig. 3. Probability of finding the best user as a function of the steps (slots) for VP-MAS ($N = 50$, $\sigma^2 = -110$ dBm, and $\bar{\gamma} = 10$ dB).

We examine the performance of the system when there are 10 to 150 nodes in the network. Figure 2 plots the average number of slots required to select the best user as a function of the number of users. It can be seen that even with as many as 150 users, 2.1, 1.9, and 1.8 slots are required for $P_{\max} = -80$ dBm, -70 dBm, and -60 dBm, respectively. The improvement in performance as $P_{\max}$ increases occurs because the number of levels supported increases from 2 for $P_{\max} = -80$ dBm to 3 for $P_{\max} = -70$ dBm to 4 for $P_{\max} = -60$ dBm. Also plotted in the figure is the 2.43 slot lower bound on the average number of slots required by the opportunistic splitting algorithm that is designed only for collisions [13] and does not have the concept of a metric-to-power-mapping function. This, to the best of our knowledge, is the lowest value known to date. We see that adding just one additional power level shaves off 0.3 slots, while adding two levels shaves off 0.5 slots.

We now study the reason behind the remarkable efficiency of the algorithm. Figure 3 plots the probability of a successful capture as a function of the number of steps (slots) of the algorithm for $N = 50$ users. At $P_{\max} = -80$ dBm (20 dB dynamic range), the probability of success in the first slot is 53.5%. It increases to 61.1% for $P_{\max} = -70$ dBm (30 dB dynamic range), and to 65.0% for $P_{\max} = -60$ dBm (40 dB dynamic range). Thus, the asymmetric receive power levels enable the algorithm to readily capture the best user more than half of the time in the first slot itself.

VI. CONCLUSIONS

The key insight and contribution of this work is that using power control to enable capture can drastically improve the performance of multiple access selection when the channel state information is available locally to the transmitting nodes. We showed that the metric-to-power mapping that uses a discrete set of receive power levels is optimal in terms of maximizing the probability of successful capture. Based on our theoretical results, we introduced the VP-MAS algorithm that dynamically adjusts the power levels depending on whether the outcome of the previous transmission attempts resulted in capture, idle channels, or collisions. VP-MAS could select the best user in less than 2 slots on average regardless of the number of contending users. This is much less than the 2.43 slot average achieved by the best algorithm known to date, which did not exploit metric-based power control. The results of this paper can be used in a wide range of scenarios, including user selection in systems with multiuser diversity, and fast relay selection in cooperative communication systems.

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