Performance Analysis of Cooperative Random Access with Long PN Spreading Codes*

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***Abstract*— A novel cooperative spread spectrum random access (CSSRA) protocol has been recently proposed. It is shown that thanks to user cooperation the novel protocol can capture part of the available diversity and achieve a marked increase in maximum stable throughput over its non-cooperative counterpart. In this paper, we study the finite-user behavior of a one-packet-buffering CSSRA system with Poisson packet arrivals and derive pertinent performance metrics including throughput, packet loss rate and average packet delay. With the proposed analysis framework, we compare the performance of CSSRA with that of non-cooperative SSRA for a Rayleigh fading channel to illustrate the advantage of user cooperation in terms of throughput as well as delay.**

I. INTRODUCTION

Cooperative networking in wireless communication has been receiving increasing attention as a new diversity enabler, whose advantages in fixed point-to-point and multiple access links are well appreciated, [4], [5]. In a Random Access (RA) setting it has been shown that due to the fact that only a fraction of the users is active at any time, user cooperation is a very well suited form of diversity providing a significant throughput increase with negligible costs in terms of bandwidth and power consumption [3].

Besides throughput, delay is another metric of interest in RA networks particularly important for delay sensitive packet communications. Thus, the purpose of the present paper is to study the delay metric of the cooperative spread spectrum random access (CSSRA) protocol introduced in [3]. Unfortunately, the throughput analysis in [3] is based in a dominant system approach that while being a powerful tool for studying such metric cannot be used to study the delay performance, [7].

Moreover, delay analysis requires considering a finite-user RA system leading to intractable mathematical descriptions due to queue interactions that arise in such setting, [8], [10], [11], [12], [13]. A possible approach to avoid this intractable models is to consider one-packet buffers as introduced in [9]. Consequently, the present paper considers a finite-user one-packet-buffering CSSRA system. Assuming the packet arrival process for each user node is Poisson, we analyze the system with a embedded Markov chain and derive the performance metrics including throughput, packet loss rate and average packet delay. With this results in hand we compare the performance of CSSRA with that of non-cooperative SSRA for a Rayleigh fading channel to illustrate the advantage of user cooperation in terms of throughput and delay.

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II. COOPERATIVE SPREAD SPECTRUM RANDOM ACCESS

Consider a set of J users, $\mathcal{J} \quad \{U_j\}_{j=1}^J$, communicating with an access point (AP) in a wireless RA network. User j and its position in a coordinate system centered at the AP will be denoted by U_j. The average power received at the AP from a source U_j transmitting with power $P(U_j)$ is given by an exponential pathloss model

$$P_R(U_j) \quad \frac{\xi \; P(U_j)}{\|U_j\|^\alpha}, \tag{1}$$

with ξ, and $\alpha \geq$ constants.

Each of the J users has a one-packet buffer for storing L-bit fixed length packets that arrive at a rate of λ packets per packet duration. The packet arrival processes are independent identically distributed (i.i.d.). The L bits of each packet are spread by a factor S (a.k.a. spreading gain) to construct a transmitted packet of $T \quad SL$ chips. Spreading is implemented using a long PN sequence $\mathbf{c} \quad \{c(t)\}_{t\in\mathbb{Z}}$ with period $\mathcal{P} \quad T$. If $\mathbf{d}_{U_j} \quad \{d_{U_j}(l)\}_{l=0}^{L-1}$ denotes a *data* packet of user U_j, and $\mathbf{x}_{U_j} \quad \{x_{U_j}(t)\}_{t=0}^{T-1}$ the corresponding *transmitted* packet we have

$$x_{U_j}(Sl+s) \quad \sqrt{P(U_j)}\; d_{U_j}(l)c(Sl+s-\tau_{U_j}), \tag{2}$$

where $\mathbf{c}$ is a common long PN sequence *shared* by all users, τ_{U_j} is a user-specific shift applied to $\mathbf{c}$ and $P(U_j)$ is the power transmitted by node U_j.

We are now ready to define the CSSRA protocol considered in this paper by the following rules:

[R0] Users are paired so that elements in a pair have agreed to cooperate with each other. This pairs are denoted (U_j, R_j) with R_j denoting the user cooperating with U_j. Users generate random quantities using a random number generator with seed $s(U_j)$.

[R1] Time is divided into slots, each comprising T chip periods. If users decide to transmit, they do so at the beginning of a slot. Let t_i denote the i^{th} time slot.

[R2] If a given user's queue is not empty, the user transmits the first queued packet in the next slot with probability p.

[R3] **First-try**: Packets are spread for transmission according to (2). The shift $\tau_{U_j} \quad \tau_f$ is selected at random by each user; and $P(U_j) \quad P_0\|U_j\|^\alpha/\xi$ effects average power control so that all users are received at the AP with the same average power $P_R(U_j) \quad P_0$ [c.f. (1)]. The random number generator seed $s(U_j)$ is included in the packet header to assist cooperation in a later stage.

[R4] **Relay-assisted**: If the first-try packet is not successfully decoded, the packet is retransmitted by U_j and R_j with shift $\tau_{U_j} \quad \tau_{R_j} \quad \tau_r$ chosen at random and powers $P(U_j) \quad P_0/ \ \|U_j\|^\alpha/\xi$, $P(R_j) \quad P_0/ \ \|R_j\|^\alpha/\xi$ so that they are received at the AP with power $P_R(U_j) \quad P_R(R_j) \quad P_0/$. Note that U_j and R_j will choose to transmit in the same slot with the same shift if R_j uses the seed $s(U_j)$ in its random number generator.

Note that at any time slot t_i the users are in one of three states; F_i of them are first-try active users (FAU); $U_i - F_i$ are relay assisted active users (RAU) so that the total number of active users is U_i; and $J - U_i$ are idle users (IU).

The details of how the CSSRA protocol just described achieves diversity and the throughput increase relative to non-cooperative SSRA are studied in [3]. For our purposes suffices to note that CSSRA consists of a first-try in which the packet is transmitted by the user alone and a relay assisted phase in which the transmission attempt benefits from user cooperation. Defining $\rho(x) \quad \sqrt{x/(\ + x)}$, this diversity benefit translates into a reduction of the bit error probability from

$$q^{(0)}(S, U_i + \ ) \quad - \quad - \rho(S/U_i) \ , \tag{3}$$

during the first try, to

$$q^{(1)}(S, U_i + \ ) \quad - \left[\ - \rho\left(\frac{S}{U_i + \ /}\right)\right]^2 \left[\ + \rho\left(\frac{S}{U_i + \ /}\right)\right] \tag{4}$$

during the relay assisted phase.

In the remaining discussion we will consider packet error probabilities, that are determined by $q^{(k)}(S, U_i + \ ) \ k$, and the Forward Error Correcting (FEC) code used. For illustration purposes, we consider block codes capable of correcting ϵ errors; e.g., BCH codes [1, p.437]. In this case,

$$P_e^{(k)}(S, U_i) \quad - \sum_{k=0}^{t} \binom{L}{k} q^{(k)}(S, U_i)^k \quad - q^{(k)}(S, U, i)^{\ (L-k)}. \tag{5}$$

III. Performance Analysis of CSSRA

It is well known the queueing behaviors of the users in a finite-user slotted ALOHA system are interacting [8], [10], [11], [12], [13]; i.e., the activity of one user will affect the queueing behaviors at other users, giving rise to a statistical dependence among queues in the system. To mathematically describe the J-interacting queues with a Markov chain, as many as b^J states may be needed, where b could be, e.g., in [8], one plus the buffer size of a single user if all the users have the same buffer sizes for their incoming packets. Then to analyze the queueing of the slotted ALOHA system with such a Markov chain, the eigenvalue decomposition of a $b^J \times b^J$ state transition matrix may be involved, which is practically untractable except for very small J. In the interacting queues, the major reason for the prohibitive size of their states is that the buffer status of each user has to be tracked to guarantee the queueing a Markovian process. By assuming each user has only one-packet buffer, Tobagi bypassed this difficulty and analyzed the resultant J-user one-buffering slotted ALOHA system with a Markov chain of only J states [9]. Tailoring the framework of [9] for our CSSRA protocol, we analyze the delay performance of CSSRA in this section.

To simplify the analysis, we make the following assumptions:

AS1) The relay R_j can always successfully decode the corresponding source's packet $\mathbf{x}_{U_j}$.

AS2) Each user has a one-packet buffer. When the buffer is loaded, subsequently arriving packets are dropped.

AS3) User's packets are generated according to a Poisson source with intensity λ packets/slot.

AS4) The probability $\quad \{\tau_{U_{j_1}} \quad \tau_{U_{j_1}}\}$ for $j_1 \ / \ j_2$ is negligible.

The key to performance analysis is the steady state distribution of users between FAU, RAU and IU. Let (U_i, F_i) denote the state of the network with $\ \le U_i \le J$ and $\ \le F_i \le U_i$ and note that the time evolution from state (U_i, F_i) to (U_{i+1}, F_{i+1}) can be modelled with a Markov chain since the state transitions are independent of the past states. We can, thus, define the stationary distribution vector of the state pairs (U_i, F_i) at t_i as

$$\pi \quad \left[\pi_{(0,0)}, \pi_{(1,0)}, \pi_{(1,1)}, \cdots, \pi_{(J,0)}, \cdots \pi_{(J,J)}\right] \tag{6}$$

where $\pi_{(u,f)}$ denote the stationary probability of the queueing state pair being (u, f) at t_i.

The distribution π in (6) can be computed by standard techniques. For that matter we let $c \quad (u_1 - f_1) - (u_2 - f_2)$ and $B(u, U, s) \quad \binom{U}{u} s^u (\ - s)^{U-u}$ denote the probability mass of a Binomial random variable with U trials and success probability s, evaluated at u and establish the following claims.

Proposition 1 *The stationary state distribution vector π can be computed from the equation:*

$$\pi \quad \pi \mathbf{P}_t, \quad \sum_{u=0}^{J} \left[\sum_{f=0}^{u} \pi_{(u,f)}\right] \tag{7}$$

where the non-zero entries of the state transition matrix $\mathbf{P}_t$ are specified by (8) with $i_{min} \quad \{ \ , f_1 - f_2, -c\}$, $i_{max} \quad \{f - \ , J - u_1 + f_1 - f_2\}$, $j_{min} \quad \{ \ , c\}$, $j_{max} \quad J - u_1$, $e_{min} \quad \{ \ , -c\}$, and $e_{max} \quad \{i, j - c\}$.

Proof: Following our CSSRA protocol, a user transits between different statuses at t_i as in Fig. 1:

1) A FAU keeps silence in current slot and stays as a FAU in the next slot with probability $\ - p$; or it transmits, and accordingly transits to an IU with probability $pP_e^{(0)}(N/n)$ or an RAU with probability $p(\ - P_e^{(0)}(N/n))$.
2) An RAU transits to an IU upon a successful packet transmission with probability $p(\ - P_e^{(1)}(N/n))$; otherwise, it stays as an RAU in the next slot.
3) An IU stays as an IU in the next slot if no packets arrive at it during current slot, with probability $e^{-\lambda}$, and

$$((u_1, f_1) \rightarrow (u_2, f_2)) \quad \sum_{i=i_{min}}^{i_{max}} \sum_{j=j_{min}}^{j_{max}} \sum_{e=e_{min}}^{e_{max}} B(i, f_1, p) B(f_2 - f_1 + i, J - u_1, \; - e^{-\lambda}) \times B(j, u_1 - f_1, p) B(e, i, P_e^{(0)}(N/(i+j))) \times B(c+e, j, \; - P_e^{(1)}(N/(i+j))) \tag{8}$$

$$\text{for} \quad \leq f_2 \leq J - u_1 + f_1, \quad f_2 \leq u_2 \leq \quad \{J, u_1 + f_2\}.$$

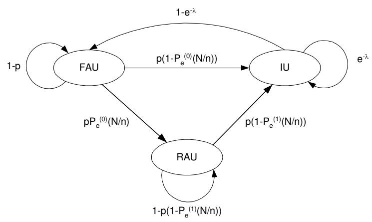

Fig. 1. User status transition in CSSRA protocol.

transits to a FAU upon packet arrival with probability $- e^{-\lambda}$ (under Poisson arrival assumption *AS3)*).

If we just look at the set of t_i time points, the queueing process of state pair (U_i, F_i) is Markovian[1]. To start with, we suppose that the Markov chain is always stable and investigate the transition probability from state pair $((U_i, F_i) \quad (u_1, f_1))$ at t_i to state pair $((U_{i+1}, F_{i+1}) \quad (u_2, f_2))$ at t_{i+1}. In the ALOHA protocol, an active user can opt to transmit or defer with probabilities p and $- p$. Let integers i, j and a (all of which are random variables) denote the number of transmit FAUs, the number of transmit RAUs and the number of IUs with packet arrivals in the i-th slot, respectively, with $\leq i \leq f_1$, $\leq j \leq u_1 - f_1$ and $\leq a \leq J - u_1$. Moreover, given i and j, let integers e and s denote the failed transmit FAUs (whose transmitted packets fail at the destinations) and the successful transmit RAUs, respectively, with $\leq e \leq i$ and $\leq s \leq j$. Then according to the user statuses transition in Fig. 1, the investigated pair transition follows

$$f_2 \quad f_1 - i + a \tag{9}$$
$$u_2 - f_2 \quad u_1 - f_1 + e - s. \tag{10}$$

From (9) and (10), given a state pair (u_1, f_1) ($\leq u_1 \leq J$ and $\leq f_1 \leq u_1$), the feasible state pair (u_2, f_2) must satisfy:

$$\leq f_2 \leq J - u_1 + f_1, \quad f_2 \leq u_2 \leq \quad \{J, u_1 + f_2\} \tag{11}$$

where the lower bound 0 for f_2 is imposed when $i \quad f_1$ and a while the upper bound $J - u_1 + f_1$ for f_2 is imposed when i and $a \quad J - u_1$; and the upper bound $u_1 + f_2$ for u_2 is imposed when $e \quad f_1$ and s .

As shown in (9) and (10), a state pair transition $(u_1, f_1) \rightarrow (u_2, f_2)$ can be realized through different paths specified by different i, a, e and s. Note that the probability mass functions of e and s depend on the number of total transmit users $n \quad i + j$. Given (u_1, f_1) and (u_2, f_2), a is coupled with i by (9) while s is coupled with e by (10). Therefore, a particular transition path for $(u_1, f_1) \rightarrow (u_2, f_2)$ can be specified by a triplet (i, j, e). Let (x) and $(x|y)$ denote the probability mass of x and conditional probability mass of x given y, respectively. Using the notation $B(u, U, s)$, we have the probability $P_1 \quad ((u_1, f_1) \rightarrow (u_2, f_2), (i, j, e))$ of a particular transition path (i, j, e) for $(u_1, f_1) \rightarrow (u_2, f_2)$ as

$$P_1 \quad (i) \quad (a \quad f_2 - f_1 + i) \quad (j) \times \quad (e|(i,j)) \quad (s \quad c + e|(i,j)) \tag{12}$$

where

$$(i) \quad B(i, f_1, p),$$
$$(a \quad f_2 - f_1 + i) \quad B(f_2 - f_1 + i, J - u_1, \; - e^{-\lambda}),$$
$$(j) \quad B(j, u_1 - f_1, p),$$
$$(e|(i,j)) \quad B(e, i, P_e^{(0)}(N/(i+j))),$$
$$(s \quad c + e|(i,j)) \quad B(c+e, j, \; - P_e^{(1)}(N/(i+j))),$$

with $c \quad u_1 - f_1 - (u_2 - f_2)$. Note that in (12), we implicitly define $P_e^{(0)}(N/\ )$, ^{0} and $\binom{0}{0}$.

To calculate the overall transition probability $((u_1, f_1) \rightarrow (u_2, f_2))$, we need to count all the possible transition paths, thus calling for the ranges of i, j and e.

1) We first look at the range of i: i) From (9), we have $i \quad a + f_1 - f_2$; since $\leq a \leq J - u_1$, we subsequently have $f_1 - f_2 \leq i \leq J - u_1 + f_1 - f_2$. ii) From (10), we have $e \quad s + u_2 - f_2 - (u_1 - f_1) \quad s - c$; since $e \leq i$ and $s \geq$, we subsequently have $i \geq -c$. Using i) and ii) along with the natural bounds $\leq i \leq f_1$, we arrive at
$$i_{min} \quad \{\ , f_1 - f_2, -c\} \leq i \leq \quad \{f_1, J - u_1 + f_1 - f_2\} \quad i_{max} \tag{13}$$
2) From (10), we have $s \quad e + u_1 - f_1 - (u_2 - f_2) \quad e + c$. Since $s \leq j$ and $e \geq$, we subsequently have $j \geq c$. Together with $\leq j \leq u_1 - f_1$, we further have
$$j_{min} \quad \{\ , c\} \leq j \leq J - u_1 \quad j_{max}. \tag{14}$$
3) From (10), we have $e \quad s + u_2 - f_2 - (u_1 - f_1) \quad s - c$. Using $\leq s \leq j$, we have $-c \leq e \leq j - c$. Then along with $\leq e \leq i$, we obtain
$$e_{min} \quad \{\ , -c\} \leq e \leq \quad \{i, j - c\} \quad e_{max}. \tag{15}$$

With (12), (13), (14) and (15), we obtain the non-zero state transition probability (8). Considering the overall queueing

[1] Since the number of state pairs in this Markov chain is equal to $(J+1)(J+2)/2$, the resultant queueing analysis is tractable for non-huge J.

process, the stationary state distribution vector π can then be computed from the equation (7). By mimicking the proof of [14, Appendix, Theorem 1], we can establish that a stationary distribution π exists and is unique. This justifies our assumption that the stability of this Markov chain is guaranteed, and the proof is completed. □

From equation (7) we can obtain π as the left eigenvector of $\mathbf{P}_t$ corresponding to the eigenvalue 1; and from there derive the steady-state performance metrics of interest as we detail next.

Proposition 2 *Let D, S and ξ denote average packet delay (in slots), throughput (in packets/slot), and packet loss rate respectively. Then, we have*

$$\xi \qquad - \frac{J-u}{J} e^{-\lambda} \tag{16}$$

$$S \qquad J\lambda(\quad -\xi) \qquad \frac{J-u}{\lambda} e^{-\lambda} \tag{17}$$

$$D \qquad \frac{u}{S} + \quad - \frac{}{\ - e^{-\lambda}} \left(\frac{}{\lambda}(\ - e^{-\lambda}) - e^{-\lambda} \right) \tag{18}$$

where $u \quad \sum_{u=0}^{J} \sum_{f=0}^{u} \pi_{(u,f)} u$.

Proof: Packet loss in the one-buffering system occurs from blockage due to buffer overflow; i.e., the packet loss rate ξ is given by

$$\xi \qquad \frac{N_b}{J\lambda} \tag{19}$$

where N_b denote the expected number of blocked packets during one slot, and $J\lambda$ is the average number of arriving packets in a slot. Since except the first arriving packets of idle users, all the remaining packets are blocked, we have

$$N_b \quad J\lambda - \sum_{u=0}^{J} \sum_{f=0}^{u} \pi_{(u,f)} (J-u)\lambda e^{-\lambda} \tag{20}$$

where $\pi_{(u,f)}$ are the entries of π computed from (7). Define the average number of active users

$$u \qquad \sum_{u=0}^{J} \sum_{f=0}^{u} \pi_{(u,f)} u. \tag{21}$$

Then (20) can be rewritten as

$$N_b \quad J\lambda - (J-u)\lambda e^{-\lambda}. \tag{22}$$

And subsequently,

$$\xi \qquad - \frac{J-u}{J} e^{-\lambda}. \tag{23}$$

Given the packet loss rate ξ, it is clear that we can express the throughput S as

$$S \quad J\lambda(\quad -\xi) \qquad \frac{J-u}{\lambda} e^{-\lambda}. \tag{24}$$

As in [15], the total average delay D (in slots) for a packet in this system can be broken into two parts: the average buffering delay D_b, which stands for the time the packet has to wait in buffer from when it arrives until the beginning of the next slot, and the average service delay D_s; i.e.,

$$D \quad D_b + D_s. \tag{25}$$

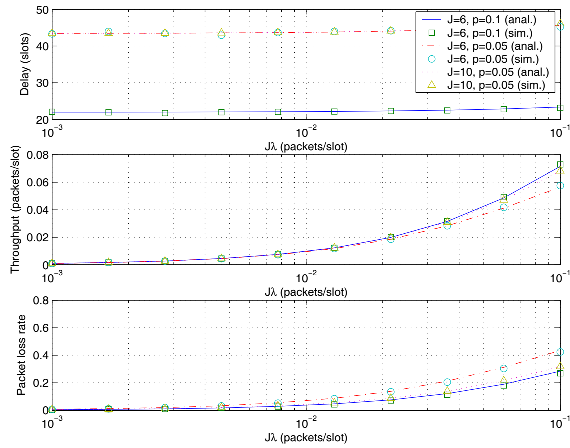

Fig. 2. Comparison of analytical and simulated results.

By Little's result [2, Chapter 2], the average service delay is given by

$$D_s \qquad \frac{u}{S}. \tag{26}$$

And we show in the appendix that

$$D_b \qquad - \frac{}{\ - e^{-\lambda}} \left(\frac{}{\lambda}(\ - e^{-\lambda}) - e^{-\lambda} \right). \tag{27}$$

Substituting (26) and (27) into (25), we can obtain the average packet delay D. □

IV. Simulation Results and Comparisons

In this section we set L , S , and block codes capable of correcting ϵ errors for FEC coding. Simulations were carried out for three different sets of parameters i) total number of users J and transmit probability p . ; ii) J and p . ; and iii)J , p . . Buffers were fed with independent Poisson sources having intensity λ packets/slot for different values of λ and in each case the result shown is the average of 10 independent runs encompassing ^{6} slots. Fig. 2 compares analytical results for average delay, throughput and packet loss rate in Proposition 2 with corresponding simulated results. It can be seen that the simulated behavior is accurately predicted by the results in Proposition 2.

The delay analysis of the non-cooperative SSRA (NSSRA) can be done with a similar framework as in Sec. III. Since no relay cooperations are available, all transmit active users have the same packet error probabilities given by $P_e^{(0)}(N/n)$. Therefore we only need the number of active users u ($\leq u \leq J$) to capture the queueing. Let i, s and a denote the number of transmit active users, the number of successful transmit active users and the number of IUs with packet arrivals in the i-th slot, respectively, with $\leq i \leq u_1$, $\leq s \leq i$ and $\leq a \leq J - u_1$. Then the state transition follows

$$u_2 \quad u_1 - s + a. \tag{28}$$

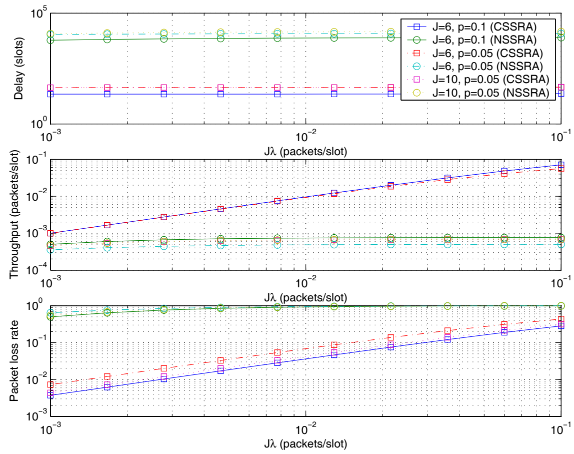

Fig. 3. Comparison between CSSRA and non-cooperative SSRA.

The transition probability $(u_1 \rightarrow u_2)$ can be similarly derived as

$$(u_1 \rightarrow u_2) \quad \sum_{i=i_{min}}^{u_1} \sum_{s=s_{min}}^{s_{max}} B(i, u_1, p) B(s, i, \quad - P_e^{(0)}(N/i)) \times B(u_2 - u_1 + s, J - u_1, \quad - e^{-\lambda})$$

where i_{min} $\{ \ , u_1 - u_2\}$, s_{min} $\{ \ , u_1 - u_2\}$ and s_{max} $\{i, J - u_2\}$. With $(u_1 \rightarrow u_2)$, we can then construct the state transition matrix and in turn calculate the stationary state probability vector π' $\pi'_0, \pi'_1, \cdots, \pi'_J$ where π'_u denote the stationary probability of the queueing state being u at t_i. Similarly, the average packet delay, along with the throughput and packet loss rate for the one-buffering NSSRA can be derived as in Sec. III.

Comparison of analytical results for CSSRA and non-cooperative SSRA are shown in Fig.3 where it can be seen the significant improvement of CSSRA with respect to non-cooperative SSRA in terms of delay, throughput and packet loss rate.

V. Conclusions

In this paper, we proposed an analysis framework for a finite-user one-packet-buffering CSSRA network. This framework can serve as a complement to the dominant throughput analysis in [3], analyzing and demonstrating the performance gain of CSSRA when the total packet arrival rate is less than the dominant throughput. By comparing the derived performance metrics of CSSRA with those of NSSRA under certain simplifying assumption, we established that diversity provided through user cooperation largely enhances the throughput as well as packet delay performance for long PN-spread ALOHA random access network.[2]

[2]The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.

Appendix I
Proof of (27)

According to the Poisson distribution, the probability that the first packet is generated before t_g is given by

$$(t < t_g) \qquad - e^{-\lambda t_g}. \tag{29}$$

Therefore, given that at least one packet is generated in a slot, the conditional probability density of the first packet being generated at t_g is given by

$$p(t_g) \quad \frac{d}{dt_g} \frac{(t < t_g)}{- e^{-\lambda}} \quad \frac{\lambda e^{-\lambda t_g}}{- e^{-\lambda}}. \tag{30}$$

Then we in turn have

$$\begin{aligned} D_b \quad E\{ \ - t_g\} & \quad - \int_0^1 t_g p(t_g)\, dt_g \\ & \quad - \frac{}{- e^{-\lambda}} \int_0^1 t_g \lambda e^{-\lambda t_g}\, dt_g \\ & \quad - \frac{}{- e^{-\lambda}} \left(\frac{}{\lambda} (\ - e^{-\lambda}) - e^{-\lambda} \right). \end{aligned}$$

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