On the Impact of Coordination on Local Delay and Energy Efficiency in Poisson Networks

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***Abstract*—The local delay characterizes the number of time slots required for a node to successfully transmit a packet to its target receiver. In this letter, we explore the impact of coordinated transmission on the mean local delay and the energy efficiency, in a Poisson network model. Leveraging tools from point process theory, we derive analytical expressions of the mean local delay and the long-term energy efficiency, without and with coordinated transmission. We find that coordinated transmission greatly decreases the mean local delay and also improves the long-term energy efficiency under certain network configurations.**

***Index Terms*—Coordinated transmission, energy efficiency, local delay, poisson point process, stochastic geometry.**

I. Introduction

Delay is a crucial performance metric that affects user experience. Recently, tools from point process theory have been applied to study access delay performance in wireless networks. In this letter, we explore potential benefits of coordinated transmission for the local delay of Poisson networks. Meanwhile, as coordinated transmission incurs additional cost in terms of energy consumption, we also conduct a comparative study between the energy efficiencies without and with coordinated transmission.

Related works on local delay are as follows. The general framework for local delay analysis has been established in [1]–[3], wherein a notable observation is that for static networks, local delay may have diverging mean and variance, in the absence of coordination. The work in [4] evaluated the local delay for the case of finite mobility. In [5], power control policies were proposed to minimize the local delay. In [6], local delay was studied for clustered networks.

II. System Model

We model the spatial distribution of the transmitters as a Poisson point process (PPP) $\Phi = \{x_i\} \subset \mathbb{R}^2$ of intensity λ. Throughout this letter, the analysis is conditioned on $x_0 \in \Phi$, which is the considered transmitter. We assume that its corresponding receiver is located at the origin o and thus $R = |x_0|$ is the distance between the considered transmitter and receiver. The network topology is static throughout the entire process under consideration.

For simplicity, we assume that the transmit power is P for all transmitters, and that the thermal noise is negligible, i.e., an interference-limited scenario.[1] Time is divided into discrete time slots with equal duration Δt. Let α be the path loss exponent, and consider spatially independent Rayleigh fading, i.e., $h_{x,k} \sim \mathcal{CN}(0,1)$ denoting the fading coefficient between transmitter x and the considered receiver in time slot k. We further adopt a block-fading model in which the fading is constant within each time slot and changes independently among time slots. We adopt an SIR-thresholding reception model with a threshold of θ; that is, as long as the SIR exceeds θ, transmission is successful with spectral efficiency $\log_2(1+\theta)$ bits/s/Hz. For normalization purposes, we assume that a packet needs exactly one successful transmission, and the amount of information per packet is $W\Delta t \log_2(1+\theta)$ bits, where W denotes the bandwidth. For coordinated transmission, we adopt the non-coherent joint transmission scheme considered in [7], in which the signal-to-interference ratio (SIR) of the considered receiver in time slot k is

$$\mathrm{SIR}_k = \frac{\left|\sum_{x\in A} P^{1/2}|x|^{-\alpha/2} h_{x,k}\right|^2}{\sum_{x\in A^c} P|x|^{-\alpha}|h_{x,k}|^2}, \tag{1}$$

wherein all the transmitters in the coordinating set A jointly serve the considered receiver by sending the same signal so that their signals are superimposed, and A^c is the set that cause interferences, which are mutually independent and thus are combined as power superposition. For simplicity we assume an infinite-capacity backhaul and perfect synchronization among the coordinating transmitters.

We let A consist of $\{x_0\}$ and the n transmitters in Φ that are nearest to the considered receiver at the origin.[2] Note that when $n = 0$, there is no coordination and the model degenerates into non-coordinated transmission. We also consider a silencing scheme, in which all transmitters except $\{x_0\}$ in A are silent, and thus in the SIR expression (1) the numerator is simply $P|x_0|^{-\alpha}|h_{x_0,k}|^2$.

We can further incorporate random access into the transmission model. For tractability we focus on a slotted ALOHA

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[1]The effect of noise can be readily addressed; see, e.g., [3]. The resulting expressions will contain an additional scaling factor which depends on the noise power only, thus having relatively mild impact on the main findings of this letter.

[2]Other choices of A are also possible. For example, A may be a region surrounding the considered receiver of a given radius, and for that case a similar analysis can be conducted and the results are qualitatively similar to those presented in this letter.

protocol in this letter. The receiver is oblivious, i.e., its decoding is only based on the signal received in the current time slot without mutual information accumulation. Each transmission attempt occurs with probability p, and a retransmission will be attempted, with probability p as well, if the previous transmission attempt fails. The local delay is defined as the number of time slots for a packet to be successfully received, and in this letter we focus on the mean local delay [1]–[3]. When considering coordinated transmission, the random access protocol is modified so that in a time slot, all transmitters in A simultaneously transmit to the receiver with probability p or keep silent with probability $1-p$. The SIR in time slot k in which the transmitters in A are scheduled to transmit thus is

$$\mathrm{SIR}_k = \frac{\left|\sum_{x\in A} P^{1/2}|x|^{-\alpha/2}h_{x,k}\right|^2}{\sum_{x\in A^c} P|x|^{-\alpha}|h_{x,k}|^2\mathbf{1}(x\in\Phi_k)}, \tag{2}$$

where $\Phi_k \in \Phi$ is the transmitting set in time slot k and $\mathbf{1}(\cdot)$ is the indicator function. Note that when $p=1$, (2) degenerates into (1).

The preceding models may be used to describe ad hoc networks, wireless LAN, or randomly deployed small cells, among other possibilities.

For transmitting a packet, the failed time slots can be classified into two types: those that have not been scheduled by ALOHA and hence are in sleep mode,[3] and those that have been scheduled but failed due to SIR $<\theta$. Suppose that the mean local delay is $D(n,p)$. On average, $p(D(n,p)-1)$ time slots have been scheduled for transmission but failed, and $(1-p)(D(n,p)-1)$ time slots have been in sleep mode. The expectation of the total energy consumption for a packet hence is

$$E(n,p)=[D(n,p)-1]\,[p\cdot P_1+(1-p)\cdot P_2]\,\Delta t+P_1\Delta t, \tag{3}$$

where P_1 and P_2 are the consumed powers when a transmitter is in transmit and sleep modes, respectively.

The energy efficiency η is defined as the ratio between the amount of information in a packet and the expectation of the total energy consumption for successfully transmitting the packet. For non-coordinated transmission and silencing, we have

$$\eta(n,p) = \frac{W\log_2(1+\theta)}{[D(n,p)-1]\cdot[p\cdot P_1+(1-p)\cdot P_2]+P_1}. \tag{4}$$

Throughout this letter, we use subscripts jt and sil to denote the performance metrics for the joint transmission scheme and the silencing scheme, respectively. On the other hand, letting $n=0$ corresponds to non-coordinated transmission. For the joint transmission scheme, there is an additional factor of $1/(n+1)$, because the energy consumption is multiplied when $(n+1)$ transmitters simultaneously serve one receiver, i.e.,[4]

$$\eta_{\mathrm{jt}}(n,p)=\frac{1}{n+1}\frac{W\log_2(1+\theta)}{[D_{\mathrm{jt}}(n,p)-1]\cdot[p\cdot P_1+(1-p)\cdot P_2]+P_1}. \tag{5}$$

[3]Here we assume that when a transmitter is not scheduled to transmit it enters a sleep mode, which is a favorable condition for energy efficiency.

[4]This scaling also exists when the coordinating transmitters serve $n+1$ receivers through round-robin time division, because then the mean local delay for each receiver is increased by a factor of $n+1$.

In this letter, the numerical study is based on the following parameters: $P_1 = 8.8$ W, $P_2 = 5$ W, $\lambda = 0.0001$ m^{-2}, $n=1$, $\theta = 0$ dB, and $|x_0| = R$ as a tunable parameter.

III. The Case Without Random Access

The performance for the SIR model (1) without random access is given by the following proposition.

Proposition 1: Without random access (i.e., l), $D(0,1) = D_{\mathrm{sil}}(n,1)=\infty$ while $D_{\mathrm{jt}}(n,1)<\infty$ for $n>1$. Correspondingly, $\eta(0,1)=\eta_{\mathrm{sil}}(n,1)=0$ while $\eta_{\mathrm{jt}}(n,1)>0$ for $n>1$.

Proposition 1 reveals that joint transmission achieves finite mean local delay. This is a surprising result, in view of the fact that $D(0,1)$ diverges for non-coordinated transmission, which is partly the reason why random access (i.e., $p<1$) was necessitated in [3]. Furthermore, silencing nearest interferers is ineffective in reducing the mean local delay.

A consequence of divergent $D(0,1)$ and $D_{\mathrm{sil}}(n,1)$ is that their corresponding energy efficiencies vanish since the average energy consumption for successively transmitting a packet also diverges with the mean local delay.

IV. The Case With Random Access

A. Mean Local Delay

For non-coordinated transmission, the mean local delay has been obtained in closed form [3, Eq (14)], as

$$D(0,p) = \frac{1}{p}\exp\left(\frac{pB}{(1-p)^{1-\delta}}\right), \tag{6}$$

where $B=\lambda\pi R^2\theta^\delta C(\delta)$, $\delta = 2/\alpha$, and $C(\delta)=1/\mathrm{sinc}(\delta)$.

For joint transmission and silencing, the mean local delays are given by the following proposition.

Proposition 2: With random access ALOHA, the mean local delay for joint transmission is

$$D_{\mathrm{jt}}(n,p) = \frac{1}{p}\int\limits_{0<d_1<\cdots<d_n<\infty}\exp\left\{2\pi\lambda\int_{d_n}^{\infty}\frac{p\theta K_n r^{-\alpha}}{1+(1-p)\theta K_n r^{-\alpha}}r\mathrm{d}r\right\}\mathrm{e}^{-\lambda\pi d_n^2}(2\pi\lambda)^n\prod_{i=1}^{n}(d_i\cdot \mathrm{d}d_i), \tag{7}$$

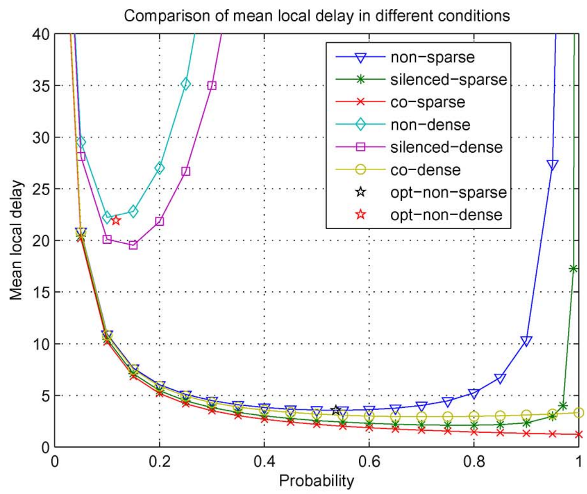
where $K_n = (R^{-\alpha}+\sum_{i=1}^n d_i^{-\alpha})^{-1}$; the mean local delay for silencing, $D_{\mathrm{sil}}(n,p)$, is also given by the right hand side of (7), except for replacing K_n with $K_0 = R^\alpha$.

B. Analysis of Results

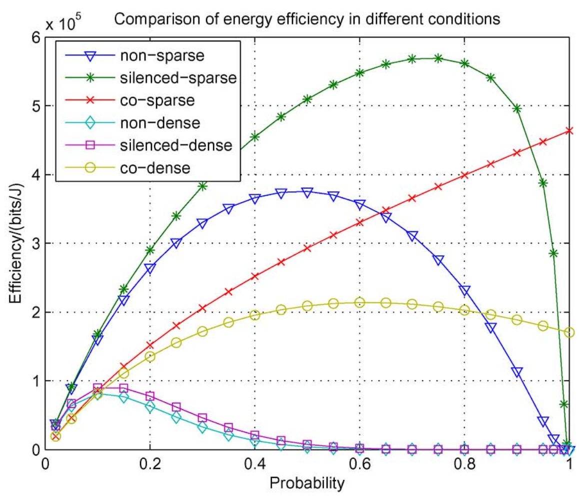
A property of non-coordinated transmission and silencing is given by the following proposition.

Proposition 3: There exists a unique $p\in(0,1)$ at which $D(0,p)$ is minimized and thus $\eta(0,p)$ is maximized. The same statement also holds true for $D_{\mathrm{sil}}(n,p)$ and $\eta_{\mathrm{sil}}(n,p)$.

The minimizing p can be obtained by a standard one-dimensional line search algorithm such as bisection. Take $D(0,p)$ as an example: from $\partial D(0,p)/\partial p = 0$ we have $-1/p + B(1-p\delta)/(1-p)^{2-\delta}=0$, in which the left hand side is monotonically increasing with p so the solution can be solved by bisection. In Fig. 1(a) we indicate using stars the



(a)



(b)

Fig. 1. Comparison of mean local delays and energy efficiencies: non-coordinated transmission vs. joint transmission vs. silencing. We set $R = 40$ m (sparse) or 120 m (dense). The critical distance is $R_0 = 82.2$ m. (a) Mean local delay; (b) Energy efficiency.

values of the minimizing p, which coincide with the numerical curves.

On the other hand, several properties of joint transmission are given by the following proposition.

Proposition 4: For joint transmission, $D_{\rm jt}(n,p)$ has the following properties:

(a) $D_{\rm jt}(n,p)$ decreases with n and increases with λ.
(b) $D_{\rm jt}(n,p) < D_{\rm sil}(n,p) < D(0,p)$ for every $n \ge 1$ and $p \in (0,1]$, and $D_{\rm jt}(n,p)$ is always finite;
(c) there exists a critical distance R_0 such that: in the regime of $R \le R_0$, $D_{\rm jt}(n,p)$ decreases monotonically with $p \in (0,1]$, and in the regime of $R > R_0$, $D_{\rm jt}(n,p)$ is minimized by some $p \in (0,1)$.

Fig. 1(a) displays the mean local delays in (6) and Proposition 2. We can observe that $D(0,1)$ and $D_{\rm sil}(n,1)$ go to infinity while $D_{\rm jt}(n,1)$ remains bounded. Interestingly, the gap between $D_{\rm jt}(n,p)$ and $D_{\rm sil}(n,p)$ is largely negligible for the regime of $R \le R_0$, except for p near one. The gap becomes substantial for the regime of $R > R_0$, implying that then coordinated transmission is more robust against interference correlation than silencing.

Inspecting Proposition 4, Properties (a) and (b) coincide with our intuition that coordinated transmission decreases the local delay compared with non-coordinated transmission. Indeed, joint transmission always achieves finite $D_{\rm jt}(n,p)$, even for $p = 1$, so it does greatly help improve the local delay performance, in a fundamental way. We also remark that, nevertheless, if the SIR threshold θ is chosen inappropriately, $D_{\rm jt}(n,1)$ can very large. For example, taking θ as 5 dB, 10 dB, 15 dB and 20 dB, the corresponding mean local delays are 1.47, 3.52, 88.51 and 9.18×10^6 time slots, respectively.

As for Property (c), the value of the critical distance R_0 can be calculated numerically. For example, with the parameters listed in the end of Section II, we have $R_0 = 82.2$ m. As illustrated in Fig. 1(a), in the regime of $R \le R_0$, $D_{\rm jt}(n,p)$ decreases monotonically with p, leading to the optimal $p = 1$, i.e., without random access. This regime may be called the "access-limited" regime, in that the optimal performance demands a full access to the channel. In the regime of $R > R_0$, however, the interference correlation due to non-coordinating transmitters is still substantial as p gets large, so the optimal choice is to tune p appropriately below one, using random access. Therefore, this regime may be called the "interference-limited" regime. Alternatively, when fixing R, there exists a critical intensity λ_0 which divides the network intensity into a "sparse" regime ($\lambda \le \lambda_0$) and a "dense" regime ($\lambda > \lambda_0$).

Given the mean local delay, the energy efficiency can be evaluated as displayed in Fig. 1(b). We observe that $\eta(0,p)$ and $\eta_{\rm sil}(n,p)$ initially increase but then decrease towards zero with p, while $\eta_{\rm jt}(n,p)$ either monotonically increases (in the regime of $R \le R_0$) or initially increases and then decreases towards a positive value with p (in the regime of $R > R_0$). The curves of $\eta(0,p)$ (or $\eta_{\rm sil}(n,p)$) and $\eta_{\rm jt}(n,p)$ intersect at one point denoted by p_0 (or $p_{0\rm sil}$). When $p > p_0$ (or $p_{0\rm sil}$), we have $\eta_{\rm jt}(n,p) > \eta(0,p)$ (or $\eta_{\rm sil}(n,p)$). But when $p \le p_0$ (or $p_{0\rm sil}$), the mean local delay does not benefit much from joint transmission, while the energy consumption is multiplied due to coordination. Hence the impact of joint transmission on energy efficiency becomes negative, and it is preferable to adopt silencing. When $p > p_0$ (or $p_{0\rm sil}$), joint transmission becomes necessary to withstand the excess interference correlation, and even though it incurs multiplied energy consumption, such cost is outweighed by the advantage of decreasing the mean local delay.

V. Conclusion

In this letter, we have studied the mean local delay and energy efficiency without and with coordinated transmission, in a static Poisson network. Our conclusions are as follows.

(a) For non-coordinated transmission, the mean local delay is unbounded and correspondingly the energy efficiency vanishes, unless a random access protocol like ALOHA is employed to mitigate the interference correlation.

(b) Joint transmission substantially decreases the mean local delay and increases the energy efficiency. In particular the mean local delay is bounded even without random access. There exists a critical hop distance, dividing the network configuration into two regimes with distinct behaviors.

(c) Interference silencing is insufficient to reduce the mean local delay from infinity without random access. But when random access is employed, it may lead to improved energy efficiency performance compared with joint transmission.

APPENDIX
PROOFS

1) Proof of Proposition 1: For non-coordinated transmission, from (6) it is apparent that $D(0,p)$ diverges as $p \to 1$.

For silencing and joint transmission, this proposition is a corollary of Proposition 2. Letting $p = 1$ in (7), we have

$$D_{\rm sil}(n,1) = \frac{2(\pi\lambda)^n}{(n-1)!}\int_0^\infty \exp\left\{\frac{2\pi\lambda\theta R^\alpha}{\alpha-2}r^{2-\alpha}\right\}\mathrm{e}^{-\pi\lambda r^2}r^{2n-1}\mathrm{d}r,$$

which is divergent because it has a discontinuity point of the second kind at $r = 0$.

Regarding $D_{\rm jt}(n,1)$, since $K_n = \left(R^{-\alpha} + \sum_{i=1}^n d_i^{-\alpha}\right)^{-1} \leq (R^{-\alpha} + d_n^{-\alpha})^{-1}$, we have

$$D_{\rm jt}(n,1) \leq M\int_0^\infty \exp\left\{\pi\lambda\left[\frac{2\theta}{(\alpha-2)(1+R^{-\alpha}r^\alpha)} - 1\right]r^2\right\}r\mathrm{d}r,$$

where $M = 2(\pi\lambda)^n/(n-1)!$. Letting $r_{\rm c} = \left(\frac{2\theta}{\alpha-2} - 1\right)^{1/\alpha}R$, the integral upper bounding $D_{\rm jt}(n,1)$ above can be divided into $D_{\rm jt}(n,1) < M\int_0^{r_{\rm c}}(\cdot)\mathrm{d}r + M\int_{r_{\rm c}}^\infty(\cdot)\mathrm{d}r$, in which, according to the integral mean value theorem, the first integral is bounded; since the exponent is negative when $r > r_{\rm c}$ and $\int_0^\infty x^s\mathrm{e}^{-tx}\mathrm{d}x$ is convergent for all $s,t > 0$, the second integral is also bounded. This proves that $D_{\rm jt}(n,1)$ is bounded.

2) Proof of Proposition 2: For joint transmission, the success probability conditioned on Φ is

$$\mathbb{P}(C_\Phi) = p\mathbb{P}(\mathrm{SIR}_k > \theta|\Phi) = p\mathbb{P}\left\{\left|\sum_{x\in A}P^{1/2}|x|^{-\alpha/2}h_{x,k}\right|^2 > \theta\sum_{x\in A^c}P|x|^{-\alpha}|h_{x,k}|^2\mathbf{1}(x\in\Phi_k)\,\middle|\,\Phi\right\}.$$

Since $|\sum_{i=1}^n P^{1/2}|x_i|^{-\alpha/2}h_{x,k}|^2 \sim \mathrm{Exp}((\sum_{i=1}^n P|x_i|^{-\alpha})^{-1})$,

$$\begin{aligned}\mathbb{P}(C_\Phi) &= p\mathbb{E}\left\{\exp\left[-\frac{\theta\sum_{x\in A^c}P|x|^{-\alpha}|h_{x,k}|^2\mathbf{1}(x\in\Phi_k)}{\sum_{d\in A}P|d|^{-\alpha}}\right]\middle|\,\Phi\right\}\\ &= p\prod_{x\in A^c}\left\{p\mathbb{E}_h\left[\exp\left(-\frac{\theta|x|^{-\alpha}|h_{x,k}|^2}{\sum_{x\in A}|d|^{-\alpha}}\right)\middle|\,\Phi\right] + 1 - p\right\}\\ &\overset{(a)}{=} p\prod_{x\in A^c}\left\{\frac{p}{1+\theta K_n|x|^{-\alpha}} + 1 - p\right\},\end{aligned}$$

where $K_n = (R^{-\alpha} + \sum_{i=1}^n d_i^{-\alpha})^{-1}$, and (a) follows from that $|h_{x,k}|^2$ are i.i.d. Exp(1). Now let us evaluate the mean local delay $D_{\rm jt}(n,p) = \mathbb{E}_\Phi(1/\mathbb{P}(C_\Phi))$. For this, let us first condition upon the n nearest transmitters in A, to obtain

$$\mathbb{E}_\Phi\left(\frac{1}{\mathbb{P}(C_\Phi)}\middle|\,A\right) \overset{(b)}{=} \frac{1}{p}\exp\left\{-2\pi\lambda\int_{d_n}^\infty\left[1 - \frac{1}{\frac{p}{1+\theta K_n r^{-\alpha}} + 1 - p}\right]r\mathrm{d}r\right\},$$

where (b) follows from the probability generating functional (PGFL) of the PPP. Then, let us use the joint distribution of the nearest points in a PPP [9]: $f(d_1,\ldots,d_n) = \mathrm{e}^{-\pi\lambda d_n^2}(2\pi\lambda)^n\prod_{i=1}^n d_i$, $0 < d_1 < \cdots < d_n$, to obtain

$$D_{\rm jt}(n,p) = \int\limits_{0<d_1<\cdots<d_n<\infty}\mathbb{E}_\Phi\left(\frac{1}{\mathbb{P}(C_\Phi)}\middle|\,A\right)\cdot f(d_1,\ldots,d_n)\mathrm{d}d_1\ldots\mathrm{d}d_n,$$

which is exactly (7) after some algebraic manipulations.

For silencing, the evaluation of $D_{\rm sil}(n,p)$ is analogous, and the only difference is to replace $K_n = (R^{-\alpha} + \sum_{i=1}^n d_i^{-\alpha})^{-1}$ with $K_0 = R^\alpha$ due to the lack of coordinating transmitters.

3) Proof of Proposition 3: From (6) we observe that $D(0,p)|_{p=0,1} = \infty$, and from (4) we get $\eta(0,p)|_{p=0,1} = 0$. The existence and uniqueness of the optimal $p \in (0,1)$ is readily verified by taking derivatives. The verification for silencing is similar.

4) Proof of Proposition 4: For Property (a), the monotonicity of $D_{\rm jt}(n,p)$ with λ follows from (7); regarding n, letting $D^{(n+1)}$ and $D^{(n)}$ denote the mean local delays with $n+1$ and n coordinating transmitters, then we can show the monotonicity property with n via a comparison argument.

For Property (b), first, in (7) we can see that $D_{\rm jt}(n,p)$ increases monotonically with $K_{\rm c}$. Replacing K_n with K_0 and expanding the integration range inside the exponent to $(0,\infty)$, we get exactly $D(0,p)$ [3, Eq. (16)]. Therefore it holds that $D_{\rm jt}(n,p) < D(0,p)$ for $n \geq 1$. Similar bounding techniques can be applied to show $D_{\rm sil}(n,p) < D(0,p)$ and $D_{\rm jt}(n,p) < D_{\rm sil}(n,p)$ for $n \geq 1$. To show the finiteness of $D_{\rm jt}(n,p)$, the same technique used in proving Proposition 1 applies, from examining an upper bound by ignoring the term $(1-p)\theta K_n r^{-\alpha}$ in the denominator inside the exponent of (7).

For Property (c), since $\partial^2 D_{\rm jt}(n,p)/\partial p^2 > 0$, $\partial D_{\rm jt}(n,p)/\partial p$ increases monotonically with p. As $\partial D_{\rm jt}(n,p)/\partial p|_{p\to 0^+} < 0$, the sign of $\partial D_{\rm jt}(n,p)/\partial p|_{p\to 1}$ determines whether $D_{\rm jt}(n,p)$ decreases monotonically or not. It can be verified that $\partial D_{\rm jt}(n,p)/\partial p|_{p\to 1}$ increases monotonically with R. Given that $\partial D_{\rm jt}(n,p)/\partial p|_{p\to 1,R=0} < 0$ and $\partial D_{\rm jt}(n,p)/\partial p|_{p\to 1,R\to\infty} > 0$, the existence and uniqueness of threshold R_0 readily follow.

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