Analysis of Intra-flow Interference in Opportunistic Large Array Transmission for Strip Networks

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***Abstract*—The Opportunistic Large Array (OLA), a simple form of concurrent cooperative transmission that extends range, is known to provide fast and reliable broadcasting of a single packet on both disk- and strip-shaped networks. This paper studies multi-packet OLA transmission within a single flow along a strip-shaped network, which also models an OLA-based cooperative route in a large multi-hop network. One packet makes interference on many other packets in the same flow, which generally retards OLA sizes for all packets, and can cause some packets to die off. However, by using the continuum and deterministic channel assumptions, which correspond to high node density, the authors show that multi-packet transmission can be made reliable and throughput can be optimized, by selecting the correct inter-packet spacing.**

I. Introduction

Concurrent Cooperative transmission (CCT) is a physical layer technique, which combines multiple copies of the same message simultaneously received over independently fading diversity channels. CCT provides an SNR advantage through array and diversity gains [1]. One form of CCT is the Opportunistic Large Array (OLA), where groups of relays are formed without coordination by their nodes' successful decoding of a message from a single nodes or another OLA [2]. The diversity channels can be formed using orthogonal waveforms [3], distributed space-time block codes [4], or phase dithering [5]. OLA-based broadcasts and unicasts are known to be fast, reliable, power-efficient and less susceptible to the network partition problem [6]. However, while most of these benefits are derived by the range extension property, one negative aspect of range extension is increased interference. A packet transmitted in the network generally suffers from co-channel interference from other packets propagating at the same time. In this paper, we investigate "*intra-flow interference*" of OLA transmission, which is generated by multiple OLAs transmitting different packets from the same source and heading for the same destination within a single flow.

The amount of interference from an OLA transmission depends on the shape of the OLA and its distance to the receiver. In disk-shaped networks, OLA broadcasts form concentric rings around the source [7]. In [8], the authors analyzed intra-flow interference in OLA broadcasts for the disk network, and showed that the interference produced by a ring is significant around the source, regardless of the radius of the ring. Consequently, spatial pipelining (i.e., broadcasting a co-channel packet before the previous one has cleared the network) always degrades the network throughput. Therefore, if multiple packets are to be broadcasted by OLAs in a disk network, the only option is that they are transmitted in orthogonal channels. This paper examines the strip-shaped network, which can be considered as an idealization of a cooperative route constructed by the CCT-based routing scheme such as [9][10]. The strip network has differently shaped OLAs compared to the disk network [11], [12], and in this paper, we show that spatial pipelining of co-channel packets is beneficial. Also, optimal spacing of co-channel packets is shown for both finite and infinite length networks. To our knowledge, this is the first study of the intra-flow interference in strip networks.

II. System Model

We consider a strip network with length of L and width of W, which is expressed by $\mathbb{S} = \{(x, y) : 0 \leq x \leq L, |y| \leq \frac{W}{2}\}$, where decode-and-forward (DF) wireless nodes are uniformly and randomly distributed with average density of ρ. As shown in Fig. 1, the source node is at the origin, while the destination is at the right end separated by L. The other nodes are operating DF relays that forward the packet only when the decoding is successful and the node has not transmitted the packet before [2]. Let P_s and P_r denote the SNRs received by a node at unit distance from the source and relay, respectively. Assuming a path loss exponent of two, the SNR received from the source is $\frac{P_s}{(x^2+y^2)}$, when (x, y) is the distance between the transmitter and the receiver in Cartesian coordinates. Following [11], [7], we make the "continuum assumption," where $\rho \rightarrow \infty$ while $\overline{P_r} = \rho P_r$ is held constant. Also following [11][7], we assume the deterministic channel model, which assumes that the power received at a node is the sum of the powers from each of the transmitting nodes. For the fading channel, [7] shows that the system with cooperative orthogonal transmission, despite the existence of fading and randomness in the channel, has a deterministic SNR (or SINR) in the limit by continuum assumption, which ultimately gives the same result as the deterministic channel assumption.

With these assumptions, the first OLA for the ith packet is the area denoted by $\mathbb{O}_{(i;1)}$ with boundary $x_{(i;1)}$, which satisfies $P_s/x^2_{(i;1)}=\tau$. Subsequent OLAs $\mathbb{O}_{(i;k)}$ of this packet without interference for $k \geq 2$ form by SNR condition, which is given by

$$\mathbb{O}_{(i;k)} = \{(x, y) \in \mathbb{S} \setminus \bigcup_{n=1}^{k-1} \mathbb{O}_{(i;n)} : \iint_{\mathbb{O}_{(i;k-1)}} \overline{P_r} / \left[(x - x')^2 + (y - y')^2\right] dx'dy' \leq \tau\} \quad (1)$$

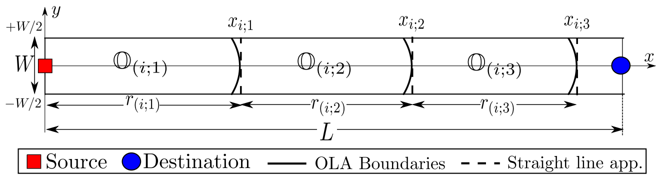


Fig. 1. The OLA transmission on the strip network based on Continuum assumption and straight line approximation

As shown in [11], when the width W is small enough, the curved boundaries of the OLAs can be approximated by straight lines indicated by the dashed lines in Fig. 1. Therefore, the approximated OLA, $\tilde{\mathbb{O}}_{(i;k)}$, is the area that satisfies $x_{(i;k-1)} \leq x \leq x_{(i;k)}$ and $|y| \leq \frac{W}{2}$. Suppose the location of a receiver is $(z, 0)$ such that $z < x_{(i;k-1)}$ or $z > x_{(i;k)}$ at the time that OLA $\tilde{\mathbb{O}}_{(i;k)}$ is transmitting. The SNR at this receiver is denoted as

$$P(\tilde{\mathbb{O}}_{(i;k)} \to z) = \int_{-W/2}^{W/2} \int_{x_{(i;k-1)}}^{x_{(i;k)}} \frac{\overline{P_r}}{(x-z)^2 + y^2} dxdy = \int_{x_{(i;k-1)}}^{x_{(i;k)}} \frac{2\overline{P_r}}{(x-z)} \arctan\left(\frac{W}{2(x-z)}\right) dx, \quad (2)$$

where $k = 1, 2, 3, ...$ and $x_0 = 0$. Therefore, the outer boundary of $(k+1)$st OLA, $x_{(i;k+1)}$ is the solution of $P(\tilde{\mathbb{O}}_{(i;k)} \to z) = \tau$ such that $z > x_{(i;k)}$. Let $r_{(i;k)} = x_{(i;k)} - x_{(i;k-1)}$ be the step-size of ith packet for kth level. [11] derived the sufficient condition for the broadcast to the infinite length strip network, in the absence of interference; this condition is $\mu < 2$, where $\mu = \exp(\kappa^{-1})$ and $\kappa = \frac{\pi \overline{P_r}}{\tau}$ can be interpreted as the node degree of the network [6]. Therefore, $\mu < 2$ implies a lower bound on the node degree $\kappa > (\ln 2)^{-1}$. When the condition holds, as the OLA level goes to infinity, the step-size converges to a positive number $r_{(i,\infty)}$, which satisfies $\frac{W(\pi \ln 2 - \overline{P_r}/\tau)}{4} \leq r_{(i;\infty)} \leq \frac{W \overline{P_r}}{2\tau}$ [11].

III. Signal Model of Intra-Flow Interference

We consider multiple packets transmitted from the source to the destination, with no interference from any other flows in the network. Suppose n is the total number of packets to be sent with a packet insertion period M (i.e., the source sends a new data packet into the network every M time slots). We are interested in the network throughput $\eta = 1/M$ for large n. In the conventional network with single-input-single-output (SISO) links, the source inserts another packet when carrier sensing determines that the channel around the source is available. However, carrier sensing is not desirable for OLA transmission because of the autonomous and distributed control in each node. Instead, the condition for transmission is simply that a node has successfully decoded the packet for the first time; hence, all nodes that decoded the same packet should forward the message simultaneously [2].

Suppose only two packets are broadcasted, so that the second one is transmitted by the source M time slots after the first. The shaded areas in Fig. 2 indicate two OLAs that could be transmitting at the same time. Suppose the smaller one, $\tilde{\mathbb{O}}_{(2;k)}$, transmits the 2nd packet in its $k+1$st hop, and $\tilde{\mathbb{O}}_{(1;k+M-1)}$, transmits the first packet in its $k+M$st hop. We

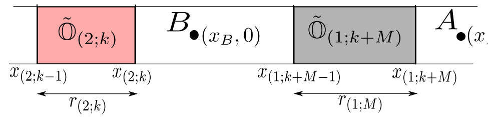


Fig. 2. The snapshot of multiple-packet OLA broadcast

are interested to know if receivers at Points A at $(x_A, 0)$ and B at $(x_B, 0)$ will be able to decode Packets 1 and 2, respectively. We note that $x_{(1;k+M)} < x_A$ and $x_{(2;k)} < x_B < x_{(1;k+M-1)}$.

For the receiver at Point A, we have,

$$\mathbf{SINR}_{(1;k+M+1)}(x_A) = \frac{\mathbf{S}}{\mathbf{I} + \mathbf{N}} = \frac{P(\tilde{\mathbb{O}}_{(1;k+M)} \to x_A)}{P(\tilde{\mathbb{O}}_{(2;k)} \to x_A) + 1}. \quad (3)$$

We will assume that if this SINR is greater than τ, the receiver can decode. For the receiver at Point B, the interference comes from $\tilde{\mathbb{O}}_{(1;k+M)}$, which is to the right of Point B. Thus, for the receiver at Point B, the SINR is

$$\mathbf{SINR}_{(2;k+1)}(x_B) = \frac{P(\tilde{\mathbb{O}}_{(2;k)} \to x_B)}{P\left(\tilde{\mathbb{O}}_{(1;k+M)} \to x_B\right) + 1}. \quad (4)$$

Therefore, $x_A = x_{(1;k+M+1)}$ satisfies $\mathbf{SINR}_{(1;k+M+1)}(x_A) = \tau$, while $x_B = x_{(2;k+1)}$ satisfies $\mathbf{SINR}_{(2;k+1)}(x_B) = \tau$.

IV. Multi-packet Propagation Dynamics

In this section, we present some properties of the OLA propagation along a strip network. As an example to show the impact of the co-channel interference, we numerically calculate the propagation dynamics with $P_s = 100, \overline{P_r} = 100, \tau = 10, W = 1$, and $L = 200$. If the source sends only one packet, there is no intra-flow interference; the numerical results in Fig. 3 show this case with the horizontal axis representing the distance (from the source to the destination) on the x-axis, similarly to Fig. 1. We denote the OLA boundaries and step sizes of this single packet case by $x_{(0;k)}$ and $r_{(0;k)}$, respectively. The '+' markers indicate the outer boundaries of the OLAs $x_{(0;k)}$, and the numbers just above them indicate the hop count. Because the step-size is defined by $r_{(0;k)} = x_{(0;k)} - x_{(0;k-1)}$, the gaps between adjacent '+' markers mean the step-sizes of the OLAs. As shown in the figure, the single packet OLA broadcast takes 41 hops to reach the destination. Therefore, with a fixed packet insertion period M, if the source injects new packets, interference will occur if $M \leq 40$; we refer to this situation as *pipelining*.

Figs. 4 and 5 show the numerical results of the OLA broadcast with ten packets (M=10). Similarly to Fig. 3, Fig. 4 displays the hop counts and step-sizes of the ten packets with the vertical axis indicating the packet index. Fig. 5 shows the packet propagations as time evolves, where the x-axis indicates time, and the y-axis denotes the propagation distance in terms of the horizontal distance from the source $x_{(i;k)}$. The black solid curves represent the numerical results of M=10, while the red dashed lines are the reference curves showing the interference-free situation in Fig. 3. Figs. 6 and 7 show the numerical results of a different packet insertion period M=5, where we observe that Packets 3, 6, and 8 are lost, because they quit propagating.

1) Upper Bounds on Hop Counts and Step-sizes : Because of the co-channel interference, the step-sizes of the pipelined OLA transmissions are smaller than the step-sizes of a single packet OLA broadcast, where co-channel interference does not exist. In Figs. 5 and 7, the step-size decrease causes the slope of the black curves to be lower than the red dashed curves. Also, because $x_{(i;k)}$ is the accumulated value of the step-sizes, it is bounded by $x_{(0;k)}$. We can observe this property by comparing $x_{(i;k)}$ having same hop counts k in Figs. 4 and 6 with $x_{(0;k)}$ in Fig. 3. Therefore, regardless of the packet insertion period, it always holds that $r_{(i;k)} \leq r_{(0;k)}$ and $x_{(i;k)} \leq x_{(0;k)}$. This property is important to estimate the range of the OLA boundaries, which is required to numerically calculate the SINR equation.

2) Packet Insertion Period : If the final hop count at the destination for the single packet case is M_0, the range of the packet insertion period M for the spatial pipelining is $3 \leq M \leq M_0 - 1$, assuming a half-duplex system. In this range, the intra-flow interference increases as M decreases, because smaller M means the shorter inter-packet distances. However, if M is too small, some packets die-off in the middle of the sequence as Packets 3, 6, and 8 in Figs. 6 and 7, which results in a waste of time and energy. Therefore, it is significant to choose the appropriate M to maximize the network throughput without causing any packet loss. Also, while Fig. 7 shows the time-varying slopes, the slope of each packet curve in Fig. 5 is almost stable, because the step-sizes change between adjacent hops is very small.

3) Worst Case Packet : Depending on the packet index, packets have different propagation patterns in terms of the hop distance and hop count. As long as no packets are lost, the first packet always shows the fastest propagation, because it does not experience interference until the second packet comes into the network. For a similar reason, the first and last few packets undergo relatively less interference, because the number of the co-channel packets is smaller compared to the packets with the intermediate index. For example, in Fig. 4, among the 10 packets, Packet 1 shows the smallest final hop count of 43, and its slope in Fig. 5 is also the highest. Packets 2 and 10 also show relatively smaller hop counts of 46, while Packet 5 to 9 have 48. If looking at the curve of Packet 5 in Fig. 5, the instantaneous slope is minimized around when $x_{(5;k)} = 100$, which is the horizontal mid-point of the strip network. Suppose there are three consecutive co-channel packets along a strip network as a simplified example. Among the three packets, the one in the middle always has the highest total interference. In conclusion, if no packets are lost, a packet experiences the highest interference, when it is the middle one of the sequence (i.e., i=50, if total number of packets is 100), and when it is in the middle of the strip (i.e., $x_{(i;k)} \approx L/2$).

V. Optimal Packet Insertion Period

The most important issue in the pipelined OLA transmission is the selection of M; we want the smallest of M that causes no packet loss. In this section, we consider first the infinite length network and second the finite length network.

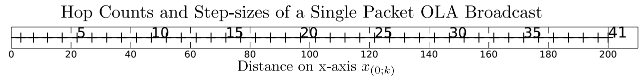


Fig. 3. OLA broadcast of the single packet

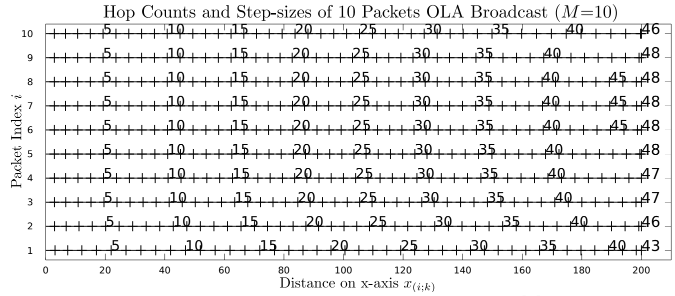


Fig. 4. OLA broadcast of ten packets, when M=10

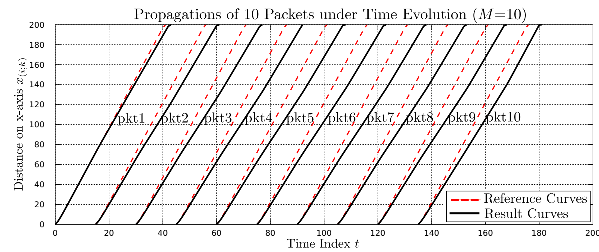


Fig. 5. The time evolution of the distances, when M=10

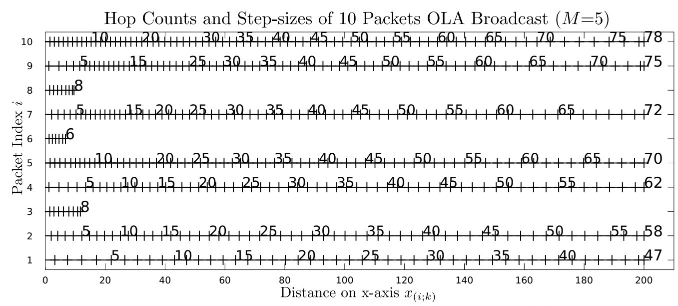


Fig. 6. OLA broadcast of ten packets, when M=5

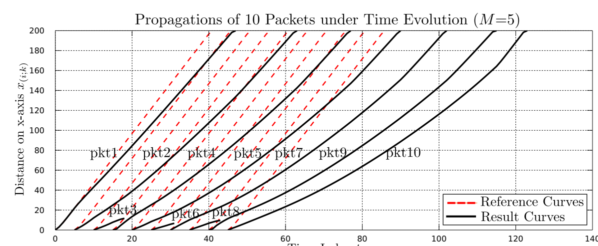


Fig. 7. The time evolution of the distances, when M=5

A. Infinite Strip Network

In this section, we explore steady state throughput for the infinite strip network. While there may be other possible steady state solutions, we will investigate the existence of solutions in which an infinite sequence of simultaneously active OLAs, each of width Δ, are equally separated by $(M-1)\Delta$, as shown in Fig. 8. Under this assumption, the condition for infinite OLA propagation is the same as that for a single isolated packet (i.e., μ<2 as in Section II), with unity noise power replaced by noise-normalized interference power plus one:

$$\exp\left(\tau(1 + \mathbf{I}_{inf})/(\pi \overline{P_r})\right) < 2, \qquad (5)$$

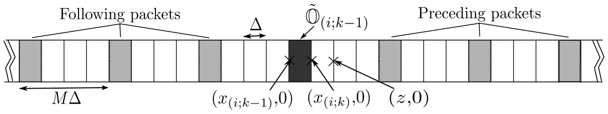


Fig. 8. Illustration of a steady state in infinite strip networks

where $\mathbf{I}_{inf}$=$\sum_{j\neq i} P\left(\tilde{\mathbb{O}}_{(j;k+jM)} \to x_{(i;k+1)}\right)$, which always converges[1] for $M\geq 3$. A solution pair (M,Δ) must satisfy (5) as well as the step-width condition:

$$\mathbf{SINR}_{(i;k+1)}(z) = P(\tilde{\mathbb{O}}_{(i;k)} \to z)/\left(\mathbf{I}_{inf}+1\right) = \tau, \quad (6)$$

where z=$x_{(i;k+1)}$=$x_{(i;k)}$+Δ for all i and $|x_{(i;k)} - x_{(j;k)}| = M\Delta|i-j|$ for all k.

Finding closed form solutions for (5) and (6) is very difficult, so for this paper, we do a numerical approximation by considering the center of a sufficiently long but finite network of length L. Our approach is to fix the step-size Δ and then search for the smallest integer value of M, denoted by $\hat{M}_{inf}$, that satisfies (5) and (6) for the finite network.

For given M and Δ, the maximum number n of packets pipelined in the network is $\lceil \frac{L}{M\Delta} \rceil$. Hence, for Packet i in the middle, the number n_p of its preceding co-channel packets is $\lceil \frac{n-1}{2} \rceil$, while the number n_f of its following packets is $\lfloor \frac{n-1}{2} \rfloor$. Therefore, when $(n-1)$ is odd, n_p= n_f+1, which is because we consider the worst case scenario and it gives higher interference than n_f= n_p+1, considering the propagation direction. Thus, with the number of co-channel packets n_p and n_f, we are able to test if the given Δ and M satisfy (5) and (6).

B. Finite Strip Network

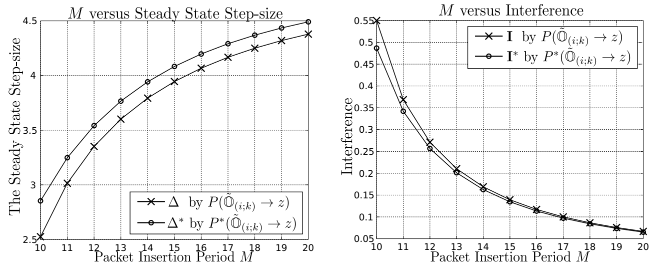
If the network is finite, then the OLAs will not be equidistant and will not have equal step-size, because the interference near the ends is not as high as the interference in the center. Finding the optimal packet insertion period $M_{L,opt}$ (the minimum M that does not cause packet loss for finite L) requires numerical calculation for the OLA boundaries $x_{(i;k)}$ for the all packet indices i and levels k at each time unit. Also, this numerical calculation should be repeated for different M starting from 3, to see whether there is packet loss. To avoid this exhaustive search, we propose upper and lower bounds of $M_{L,opt}$, which gives an appropriate range for the search. $\hat{M}_{inf}$ serves as an upper bound, since it satisfies a condition of interference (i.e., center with steady state) that would be higher than actual interference in a finite network.

To estimate the lower bound of $M_{L,opt}$, the equal step-size and equi-spaced OLA assumptions are the same as in the previous section, but we will use different path-loss function and reduce the number of co-channel packets in the network. The basic idea is to use these mechanism to artificially inflate the SINR calculation, making it possible for a smaller value of M to satisfy the solution conditions.

· *Simplified Path-loss Function :* First, using Taylor series with a single term for $\arctan(\alpha)$≈α for $|\alpha| \leq 1$, we simplify the path-loss function (2) into

$$P^*(\tilde{\mathbb{O}}_{(i;k)} \to z) = W\overline{P_r}\left[1/(z-x_{i;k}) - 1/(z-x_{i;k-1})\right]. \quad (7)$$

[1]We have proved this, but space constraints do not allow including it here.



(a) Comparison of Δ and Δ^* (b) Comparison of $\mathbf{I}$ and $\mathbf{I}^*$

Fig. 9. Impact of the approximation using $\tilde{P}(\mathbb{O}_{(i;k)} \to z)$

Since $\arctan(\alpha)$<α for 0<α<1, (7) gives greater received power than the actual obtained by (2). If we use (7) instead of (2), it gives the signal power $\mathbf{S}^*$=$P^*(\tilde{\mathbb{O}}_{(i;k)} \to z)$ and interference power $\mathbf{I}^*$=$\sum_{j\neq i} P^*\left(\tilde{\mathbb{O}}_{(j;k+jM)} \to x_{(i;k+1)}\right)$, where the number of summation terms of $\mathbf{I}^*$ is n_p^*+n_f^*, which is reduced as explained in the next subsection. In the steady state with equi-distant OLAs, the use of (7) gives larger step-size Δ^* than Δ derived by (2). For example, assuming n_p=n_f=1 just for simplicity with P_s=100, $\overline{P_r}$=100, τ=10, W=1, 9(a) shows Δ^* (indicated by the 'o' markers) is larger than Δ (the 'x' markers) with the x-axis of M and the y-axis of the steady state step-sizes. The increased step-size means all the OLAs have larger areas including both the signal source and the interfering OLAs. However, the distances to the interfering OLAs increase for a given M because of the larger step-size. Because the effect of the distance is more significant than the increase in the OLA size, (7) eventually reduces the interference $\mathbf{I}^*$. Fig. 9(b) shows that $\mathbf{I}^*$ (the curve with 'o' markers) is always smaller than $\mathbf{I}$ (the curve with 'x' markers) for the same M, where the parameters are same to Fig. 9(a).

By the simplified path-loss function and the truncation, the new SINR equation modified from (6) is given by

$$\mathbf{SINR}^*_{(i;k+1)}(z) = \mathbf{S}^*/\left(\mathbf{I}^*+1\right) = \tau, \quad (8)$$

where z=$x_{(i;k+1)}$=$x_{(i;k)}$+Δ^* for all i and $|x_{(i;k)} - x_{(j;k)}| = M\Delta^*|i-j|$ for all k by the equal step-size condition. For large enough L, the solutions should satisfy the inequality, which is modified from (5):

$$\exp\left(\tau(1+\mathbf{I}^*)/(\pi\overline{P_r})\right) < 2. \quad (9)$$

Among the solution pairs (M,Δ^*) of both (8) and (9), the smallest M is used as the lower bound $\hat{m}_{L;opt}$.

· *Number of Packets Reduction :* In this section, we derive the number of co-channel packets, which contributes to the SINR inflation. In [11], the simplified path-loss function (6) gives increased limiting step-size $r^*_{(0;\infty)}$=$\frac{W\overline{P_r}}{2\tau}$ in the absence of interference, which is bigger than the actual limiting step-size $r_{(0;\infty)}$. By using $r^*_{(0;\infty)}$, we can guarantee the reduction in the number of co-channel packets to n^*=$\lceil \frac{L}{Mr^*_{(0;\infty)}} \rceil$. Then, we use n^* for the calculation of $\mathbf{I}^*$ and apply the steady state network conditions (5) and (6) to obtain the lower bound of $M_{L,opt}$. Therefore, we have n_p^* = $\lceil \frac{n^*-1}{2} \rceil$ and n_f^*= $\lfloor \frac{n^*-1}{2} \rfloor$ to get the lower bound, $\hat{m}_{L;opt}$.

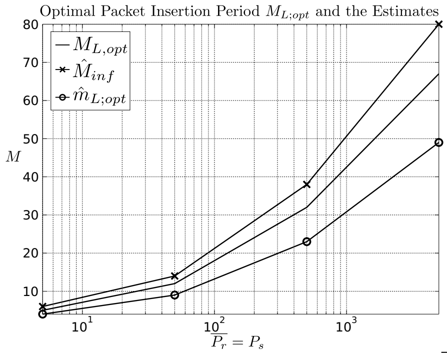


Fig. 10. Numerical results for the same node degree, (P_s,$\overline{P_r}$,τ)=(5,5,1), (50,50,10), (5×10^2,5×10^2,10^2), (5×10^3,5×10^3,10^3), L=200, and W=1

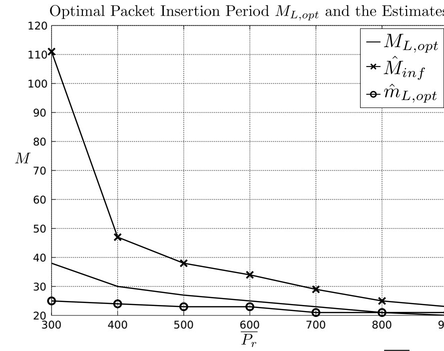


Fig. 11. Numerical results for different P_s=100, $\overline{P_r}$=300∼900, τ=100, L=100, and W=1

C. Numerical Results

We performs numerical calculation to obtain the optimal packet insertion period $M_{L;opt}$ by exhaustive search and verify the bounds, $\hat{M}_{inf}$ and $\hat{m}_{L;opt}$. Fig.10 shows the numerical results with 50 packets, and L=200, and W=1 and fixed node degree κ=$\frac{\pi \overline{P_r}}{\tau}$=5$\pi$. We consider four different sets of parameters, (P_s,$\overline{P_r}$,τ) = (5,5,1), (50,50,10), (5×10^2,5×10^2,10^2), (5×10^3,5×10^3,10^3), which correspond to increasing SINR, because the noise becomes negligible. The x-axis of Fig. 10 represents P_s=$\overline{P_r}$ in log scale, and the y-axis represents M in linear scale. The solid line with no marker is the optimal value, $M_{L,opt}$, obtained by exhaustive search, while $\hat{M}_{inf}$ and $\hat{m}_{L,opt}$ are the curves with 'x' and 'o' markers, respectively. In the graph, $\hat{m}_{L,opt}$≤$M_{L,opt}$≤$\hat{M}_{inf}$ always holds, which verifies the two bounds.

If we look at the trend of the three curves, they are increasing as the parameter sets move from first: (5,5,1), to the last: (5×10^3,5×10^3,10^3). The increase in SINR means smaller inter-packet spacing is possible. At the same time, however, by the increase of τ, SINR requirement becomes more demanding, which exceeds the influence of the increase in $\overline{P_r}$. Thus, the simultaneous increases of $\overline{P_r}$ and τ result in the increase of M (i.e., inter-packet spacing).

Fig. 11 shows the numerical results with 30 packets, L=100, W=1, P_s=100, τ=100 and $\overline{P_r}$ ranges from 300 to 900 on the linear scale x-axis, while y-axis is M. Since τ is fixed, the node degree increases with $\overline{P_r}$, which implies SINR increases, because noise becomes insignificant. However, τ is relatively low, which means smaller M (i.e., more interference) can be accommodated. As a results, M_{opt} decreases, as $\overline{P_r}$ increases.

Also, the inequality, $\hat{m}_{L,opt}$≤$M_{L,opt}$≤$\hat{M}_{inf}$, is satisfied except only when $\overline{P_r} = 900$. The reason for exceptional case is that L and the number of packets is not large enough. The asymptotic inequalities in (5) and (9) assume the large enough L, and long-lasting interference with large enough number of packets. However, the two estimates can still give a good guideline for the search of $M_{L,opt}$.

VI. Conclusion

In this paper, we analyze the impact of the intra-flow interference in OLA transmission for strip networks using continuum and deterministic channel assumptions, which pertain to the high node density. We present the signal model and the properties of spatially pipelined OLA transmission bounded by a strip where the length is much greater than the width. Different from disk networks, it is feasible to improve the network throughput by inserting a new packet before the previous packet clears the network. The optimal packet insertion period that maximizes the throughput over a finite network without causing packet loss is found numerically, facilitated by upper and lower bounds.

Acknowledgment

The authors gratefully acknowledge partial support for this research from the National Science Foundation, grant number CNS-1017984.

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