Analysis of Spatial Pipelining in Opportunistic Large Array Broadcasts

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***Abstract*—The Opportunistic Large Array (OLA) is a simple form of cooperative transmission, in which a group of single-antenna nodes decode the same packet, then a short time later relay the packet simultaneously in orthogonal channels. The authors have previously shown that OLA transmissions can be adequately synchronized so they appear to a receiver as having come from a real array antenna doing transmit diversity. OLAs have been considered as a basis for rapid single-packet broadcasting in multi-hop networks, however, there are few studies that consider the long range, intra-flow interference produced by OLAs transmitting previous packets from the same source. We show that the broadcast throughput from a single source is always degraded if the source transmits a packet before previous co-channel packets have finished propagating across the network. The infinite disc case is treated theoretically, while the finite disc case is treated numerically.**

I. Introduction

The subject of broadcasting in multi-hop wireless networks has attracted the attention of many researchers over the years [1], and there are a number of popular techniques, such as flooding [2], the Probabilistic, Counter, and Location based schemes [3], and broadcast trees [4], [5]. Broadcasts that carry routine vehicle state information and emergency messages have inspired some new broadcast protocols for multi-hop in vehicular ad hoc networks (VANETs) [6], [7]. All of these methods rely on links between a single transmitter and a single receiver.

In contrast, some broadcasting schemes exploit cooperative transmission (CT), in which multiple single-antenna radios gang together to send the same message in independently fading channels so that a receiver can derive a signal-to-noise-ratio (SNR) advantage through diversity combining [8]. This class of schemes includes different ways to create diversity channels, such as orthogonal waveforms [9], distributed space-time block codes [10], or phase dithering [11]. Any of these diversity methods can be used with the opportunistic large array (OLA) [12]. An OLA is formed when a group of radios that can all decode the same packet next relay that packet at approximately the same time, as a virtual array. In an OLA broadcast, OLAs are formed in succession, as a new group of nodes are able to decode the OLA transmission from the previous group, forming ever-growing ring-shaped OLAs [13]. The OLA broadcasts are known to be fast and reliable, and able to overcome voids that would cause a partitions in networks that do non-cooperative transmission [14]. Because no topology information must be stored, OLA broadcasting is especially attractive for highly mobile networks [15]. The OLA broadcast has also been proposed as the route-request step in two reactive OLA-based unicast routing protocols [16], [15], [11].

The OLA-based works cited above all consider just a one-shot broadcast of a single packet. However, if more than just a single packet should be transmitted, for example, if a video file needs to be broadcasted over a tactical mobile ad hoc network, then broadcast throughput becomes important. This paper examines the “intra-flow interference” caused by multiple OLAs transmitting different packets from the same source at the same time in different rings of the broadcast. We do not consider “inter-flow interference” that would be caused by broadcasts from different sources.

To our knowledge, only one paper [17] treats intra-flow interference in OLA broadcasts. [17] assumes the perfect interference cancellation of the interference from preceding packets, and analyzes the effects of the interference from the following packets. However, for some types of networks, constraints on node processors and memory may preclude interference cancellation. Also, the presence of multiple time and frequency offsets of cooperators may make channel estimation very challenging. Therefore, we assume that none of the interference is cancelled.

Using multiple orthogonal channels for consecutive packets could eliminate the intra-flow interference. However, the number of such channels would be limited. Therefore, if a large file were being broadcasted over a large multi-hop network, channels may need to be reused, in which case, the results in this paper would still apply.

II. System Model

We assume that decode-and-forward (DF) wireless nodes are uniformly and randomly distributed with average density of ρ, and the source node is in the center of the network, at the origin of a two dimensional plane. When a node receives a packet, it forwards the packet only when the decoding is successful and the node has not transmitted the packet before [12]. 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 at a point of radius z is P_s/z^2. Following [13], we make the “continuum assumption,” where $\rho \to \infty$ while

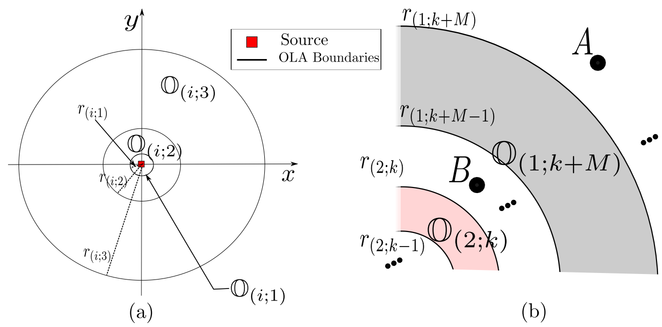

Fig. 1. (a) the coverage analysis based on Continuum approach and (b) the intra-flow interference of multiple packets OLA broadcast

$\overline{P_r} = \rho P_r$ is held constant. Also following [13], 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. With these assumptions, the SNR at a receiver at a distance z from the origin, receiving power from a disc-shaped OLA of radius r, centered at the origin, such that $r < z$, is $f(r,z) = \int_0^r \int_0^{2\pi} \overline{P_r} \cdot l(r\cos\theta - z, r\sin\theta) r dr d\theta$, where $l(x,y) = \frac{1}{(x^2+y^2)}$ [18], [13]. In the absence of interference, the decoding is assumed correct if the received SNR is greater than or equal to a certain threshold τ determined by the modulation and coding [13].

The first OLA for the ith packet is a disc denoted $\mathbb{O}_{(i;1)}$, with boundary $r_{(i;1)}$, which satisfies $P_s/{r_{(i;1)}}^2 = \tau$. Subsequent OLAs for this packet form concentric rings, centered at the origin. In general, $r_{(i;k-1)}$ and $r_{(i;k)}$ are the inner and outer boundaries, respectively, of the kth OLA $\mathbb{O}_{(i;k)}$ of packet i. We note that k is one less than the index of the hop in which $\mathbb{O}_{(i;k)}$ transmits. Thus, for the ith packet, the source transmits in the first hop and $\mathbb{O}_{(i;1)}$ transmits in the second hop.

Suppose z is the radius of a receiver such that $z > r_{(i;k)}$ at the time that OLA $\mathbb{O}_{(i;k)}$ is transmitting. The SNR at this receiver is denoted $P(z, \mathbb{O}_{(i;k)}) = f(r_{(i;k)}, z) - f(r_{(i;k-1)}, z)$, which can be expressed as [12]

$$P(\mathbb{O}_{(i;k)} \to z) = \pi \overline{P_r} \left| \ln \frac{\left| z^2 - r^2_{(i;k-1)} \right|}{\left| z^2 - r^2_{(i;k)} \right|} \right|, \quad (1)$$

where $k = 1, 2, 3, ...$ and $r_0 = 0$. [13] derived the necessary and sufficient condition for the broadcast to the infinite disc network, in the absence of interference; this condition is $\mu \leq 2$, where $\mu = \exp(\kappa^{-1})$, and κ, which can be interpreted as the node degree of the network, can be expressed as $\kappa = \frac{\pi \overline{P_r}}{\tau}$ [14]. Therefore, $\mu \leq 2$ implies a lower bound on the node degree $\kappa \geq 1/\ln 2$. As proven in [13], when $\mu < 2$, the thicknesses of the OLA rings grow with the hop index, as illustrated in Fig. 1(a); we refer to this as the "ring expansion case." As we will show below, the ring expansion means that OLAs for large k still make significant interference at the origin. Alternatively, when $\mu = 2$, the areas of all the OLAs are equal [13], implying that the thicknesses of the rings diminish with k.

III. Signal model of intra-flow interference

In this section, we consider multiple packets broadcasted from the source to the whole network. We define the broadcast throughput as $\eta = N/T$, where N is the total number of packets reaching the edge of the network, and T is the time duration between when the first packet is inserted into network and when the last packet reaches the edge of the network. In terms of throughput, the packet insertion rate at the source (i.e., how often the source can send a new data packet into the network) is more important than the end-to-end latency for a single packet. In the conventional network with SISO links, the packet insertion rate is determined by the time duration that the channel around the source is available again after sending a packet because carrier sensing is used. However, we note that the carrier sensing is not desirable for the OLA transmission because of the autonomous and distributed control in each node. Instead, all nodes that have decoded the packet for the first time should cooperatively forward the message simultaneously.

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. 1(b) indicate two OLAs that could be transmitting at the same time. Suppose the smaller one, $\mathbb{O}_{(2;k)}$, transmits the 2nd packet in its $k+1$st hop, and $\mathbb{O}_{(1;k+M-1)}$, transmits the first packet in its $k+M$st hop. We are interested to know if receivers at Points A at radius r_A and B at radius r_B will be able to decode Packets 1 and 2, respectively. We note that $r_{(1;k+M)} < r_A$ and $r_{(2;k)} < r_B < r_{(1;k+M-1)}$.

For the receiver at Point A, we have,

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

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 the ring, $\mathbb{O}_{(1;k+M)}$, which encloses Point B. We will denote that "backwards propagating" power by $P(r_B \leftarrow \mathbb{O}_{(1;k+M)})$, and it can be expressed as

$$P(r_B \leftarrow \mathbb{O}_{(1;k+M)}) = \pi \overline{P_r} \ln [\frac{\left| r^2_{(1;k+M)} - r^2_B \right|}{\left| r^2_{(1;k+M-1)} - r^2_B \right|}]. \quad (3)$$

Thus, for the receiver at Point B, the SINR is

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

Therefore, $r_{(2;k+1)}$ satisfies

$$\mathbf{SINR}_{(2;k+1)}(r_{(2;k+1)}) = \tau. \quad (5)$$

IV. Pipelined broadcast in the infinite disc network

In this section, we consider how the OLA propagation is affected in the infinite disc when a second packet is transmitted by the source M time slots after the first packet was transmitted. We assume that the transmit power and node density is such that one packet would be successful in the no intra-flow interference case (i.e., $\mu \le 2$). Therefore, we are interested in how this condition impacts the intra-flow interference.

Lemma 1: In the ring expansion case ($\mu < 2$), the interference from the first packet to the area around the Source has a non-zero lower bound regardless of the value of M.

Proof: With the packet insertion period of M, the interference from the first packet to a receiver at a radius z arbitrarily near the Source is

$$P(z \leftarrow \mathbb{O}_{(1;M-1)}) = \pi \overline{P_r} \ln[\frac{\left| r^2_{(1;M-1)} - z^2 \right|}{\left| r^2_{(1;M-2)} - z^2 \right|}], \tag{6}$$

where $r^2_{(1;k)} = \frac{P_s(\mu-1)}{\tau(\mu-2)}\left(1 - \frac{1}{(\mu-1)^k}\right)$ [13]. Therefore, $P(z \leftarrow \mathbb{O}_{(1;M-1)})$ is a decreasing function of M, and an increasing function of z, and has the limit

$$\begin{aligned} P(0 \leftarrow \mathbb{O}_{(1;\infty)}) &= \lim_{z\to 0, M\to\infty} P(z \leftarrow \mathbb{O}_{(1;M-1)}) \\ &= \pi \overline{P_r} \ln\left(\frac{1}{\mu-1}\right) > 0. \end{aligned} \tag{7}$$

■

This implies that no matter how long we wait for the first packet to "move away" from the source, the power from it is never less than $P(0 \leftarrow \mathbb{O}_{(1;\infty)})$. The reason is that the OLA widths grow without bound with hop index k. This can be observed by noticing that $r^2_{(1;k+1)} - r^2_{(1;k)}$ is proportional to $1/(\mu-1)^k$.

Lemma 2: For the ring expansion case, no node around the Source can ever decode the second packet, if

$$P_s < \tau[1 + \pi\overline{P_r} \ln\left(\frac{1}{\mu-1}\right)].$$

Proof: The maximum received SNR for Packet 2 is P_s. Therefore, based on *Lemma 1*, the maximum SINR around the source with the packet insertion period M is given by

$$\max \mathbf{SINR}_{2;1}(z \to 0) = \frac{P_s}{1 + \pi\overline{P_r}\ln\left(\frac{1}{\mu-1}\right)}. \tag{8}$$

Hence, if this maximum value is less than the decoding threshold, τ, the second packet cannot form its first OLA, $\mathbb{O}_{(2:1)}$. ■

Lemma 3: In the ring expansion case, when $\tau \ge 1$, the second packet always dies off. $\tau \ge 1$ corresponds to the class of bandwidth efficient waveforms [19], which would be desirable for large file transfers.

Proof: By "dies off," we mean the packet fails to be decoded after some finite number of hops. Let μ_2 be the version of μ for the interference case. In other words, let $\mu_2 = \exp\left(\frac{\tau(\mathbf{N}+\mathbf{I})}{\pi\overline{P_r}}\right)$. Then, *Lemma 2* implies μ_2 has a lower bound,

$$\mu_{2min} = \exp\left(\frac{\tau(1 + P(0 \leftarrow \mathbb{O}_{(1;\infty)}))}{\pi\overline{P_r}}\right). \tag{9}$$

By substituting (7),

$$\mu_{2min} = \frac{\mu}{(\mu-1)^\tau}. \tag{10}$$

However, $1 < \mu < 2$ implies $\mu_{2min} > 2$, when $\tau \ge 1$. Therefore, the second packet always dies off, because the condition for infinite broadcast fails. ■

These three lemmas show that the "ring expansion" property of the OLA broadcasts makes pipelined packet transmission impossible for $\tau \ge 1$. One might think that when $\mu = 2$, the pipelined packet transmission is feasible without the packet loss because the limit in (7) goes to zero by plugging the OLA boundary equation in [13], $r^2_{(1;k)} = \frac{P_s k}{\tau}$ into (6). However, this limit $P(0 \leftarrow \mathbb{O}_{(1;\infty)}) \to 0$ holds only when $M \to \infty$, which implies the insertion of Packet 2 should wait for an infinite time after Packet 1 transmission. Also, the following lemma shows that the finite packet insertion rate is not achievable, when $\mu = 2$.

Lemma 4: If $\mu = 2$ and $\tau \ge 1$, the pipelined packet transmission is impossible with a finite packet insertion period.

Proof: This can be proved by contradiction with the two-packet case as follows. Suppose two packets are successfully broadcasted in infinite network. Then, by the assumption $\mu = 2$ and $\mu_2 = 2$.

However, a finite packet insertion period results in $P(0 \leftarrow \mathbb{O}_{(1;M-1)}) = \epsilon$, where ϵ is infinitesimally small positive value. Because 2 is the upper bound of μ for the infinite OLA broadcast, even infinitesimally small decrease in SINR by $\epsilon(> 0)$ makes μ greater than the upper bound

$$\mu_2 = \exp\left(\frac{\tau(\mathbf{N}+\mathbf{I})}{\pi\overline{P_r}}\right) = \mu^{(1+\epsilon)} > \mu = 2. \tag{11}$$

Hence, the supposition is false, which implies at least one of the two packets dies off. Therefore, when μ=2, the pipelined transmission with a finite M is impossible, too, when $\tau \ge$1. ■

The four lemmas show that spatial pipelining of OLA broadcasts in the infinite disc network is infeasible with fixed relay transmission power.

V. Pipelined Broadcast in the Finite Disc Network

In finite networks, the interference from the preceding packet to the following packet does not last forever, because there is no more cooperative forwarding of the preceding packet after it reaches the edge of the network. For example, suppose the OLA broadcast of a single packet takes exactly W_0 hops to reach the edge of the network of radius R. If Packet 2 is inserted $M = W_0 - l$ time slots after Packet 1, where $1 \le l < W_0$, receivers of Packet 2 would experience interference from the first packet just for the first l time units, and the packet would propagate without the interference until the third packet comes into the network. The question is whether we can use this interference-free time and do the broadcast pipelining, ultimately to improve the network throughput η. However, even in this case, we will show that pipelined OLA broadcasting does not improve the network

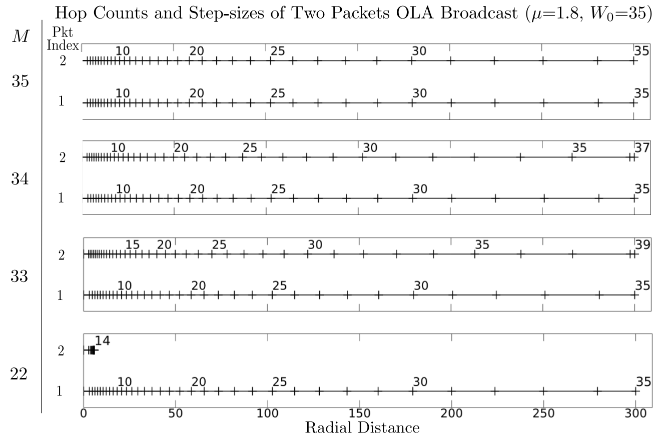

Fig. 2. OLA broadcast of two packets, when μ=1.8, W_0=35

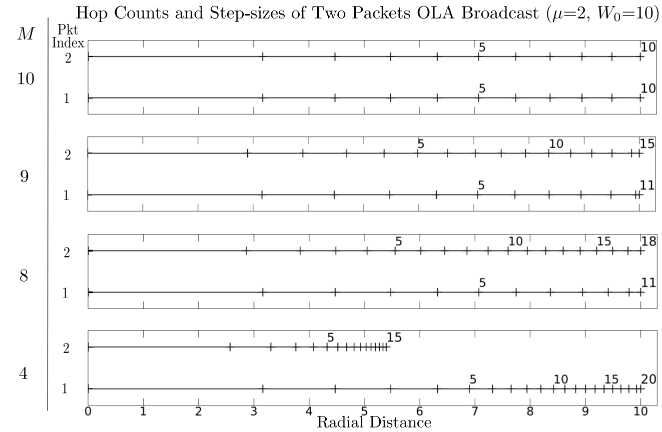

Fig. 3. OLA broadcast of two packets, when μ=2, W_0=10

throughput because the following packet hops are shorter. We will first show this with only two packets, and then show individual packet hop distances for 10 packets.

When a single-packet broadcast takes exactly W_0 hops to reach exactly the edge of the network, the radius of the disc network R satisfies $R^2 = P_s W_0/\tau$ when $\mu = 2$, and $R^2 = \frac{P_s(\mu-1)}{\tau(\mu-2)}\left(1 - \frac{1}{(\mu-1)^{W_0}}\right)$ when $\mu < 2$ [13]. In this case, if we send the two packets without pipelining, the OLA broadcast of each packet will take W_0 time units, so it takes $2W_0$ in total, which gives $\eta \leq \frac{2}{2W_0} = \frac{1}{W_0}$. If we insert the second packet at $t = W_0 - 1$ to save one time slot, the two packets coexist on the network, and interfere with each other, for just one time slot. The intra-flow interference during this one time unit overlap changes the last (Mth) hop-distance of the first packet, and also shortens the first hop-distance of the second packet. In particular, the outer boundary of the second packet is the r satisfying $\mathbf{SINR}_{(2;1)}(r) = \frac{P_s/r^2}{1+P(r \leftarrow \mathbb{O}_{(1;M-1)})} = \tau$. Therefore, the initial step of the second packet is smaller than the initial step of the first packet. The small size of the first OLA has a lasting effect; all the second-packet OLA boundary radii will be smaller than their first-packet counterparts. Therefore, the second packet takes at least one more hop than W_0 to reach the edge. Consequently, the required time to finish the two-packet OLA broadcast is at least $W_0 - 1 + W_0 + 1$, thereby $\eta \leq \frac{2}{2W_0} = \frac{1}{W_0}$.

A. Two-Packet Example

However, in fact, this one-time overlap usually makes the throughput η lower than $\frac{1}{W_0}$. Figs. 2 and 3 show the numerical results of the OLA broadcast with two packets, for $P_s = 10$ and $\tau = 1$. Fig. 2 is the ring expansion case with $\mu = 1.8$ and the radius of the network $R = 300$. To observe the effect of the pipelining, we change the packet insertion period M, where the four graphs in the figure have different values of M. On each graph, the propagations of the two packets are shown with the horizontal axis representing the radial distance (from the source to the edge of the network R), and the vertical axis is the packet index. Also, the '+' markers indicate the OLA boundaries ($r_{(i;k)}$, where the packet index $i = 1, 2$), the numbers just above each axis indicate the hop count. With the given parameters, a single packet OLA broadcast takes 35 hops to reach the edge of the network, which means $W_0 = 35$. Therefore, if we use the packet insertion period $M = 35$, the first and second packets propagate identically as shown in the first graph of Fig. 2. For $M = 34$, the first packet hop count is still the same, because the source transmission of the second packet is very weak, compared with the large and powerful 34th OLA transmission for Packet 1, $\mathbb{O}_{(1;34)}$, as observed by an intended receiver at $z > r_{(1;34)}$ for Packet 1, so the interference from the source is negligible. On the other hand, the intra-flow interference from $\mathbb{O}_{(1;34)}$ on the receivers near the source is significant compared to the source transmission, which reduces the initial hop distance $r_{(2;1)}$ and results in the two additional hops (total = 37) for the second packet to reach R. The numerical results in the second graph of Fig. 2 show that the total time slots to finish the OLA broadcast of the two packets is $T = 34 + 37 = 71 > 2W_0 = 70$. Also, as we decrease the packet insertion period M, the total time to finish the OLA broadcast increases. For example, when $M = 33$ as shown in the third graph of Fig. 2, the second packet takes 39 hops, which gives $t = 33 + 39 = 72$. Furthermore, if $M \leq 22$ as in the last graph of Fig. 2, the second packet dies off before reaching the edge of the network.

Fig. 3 shows the case of $\mu = 2$, which does not have the ring expansion property. Because the relay power corresponding to $\mu = 2$ is much lower than the $\mu = 1.8$ case of Fig. 2, we reduce R to 10, where the single packet OLA broadcast takes 10 hops as shown in the first graph of Fig. 3. For $M = 9$, the results are more dramatic than the example in Fig. 2 in that even the first packet gets one additional hop by the intra-flow interference. Because the first packet is in the network for an additional hop, its last OLA, $\mathbb{O}_{(1;M)}$, makes interference on the second hop of Packet 2, causing Packet 2 to require 5 additional hops. As in case of $\mu < 2$, the numerical results in Fig. 3 show that the reduction of M makes the throughput η worse at the edge of the network. Also, $M \leq 4$ causes the second packet to be lost in the middle of the propagation as in the last graph of Fig. 3.

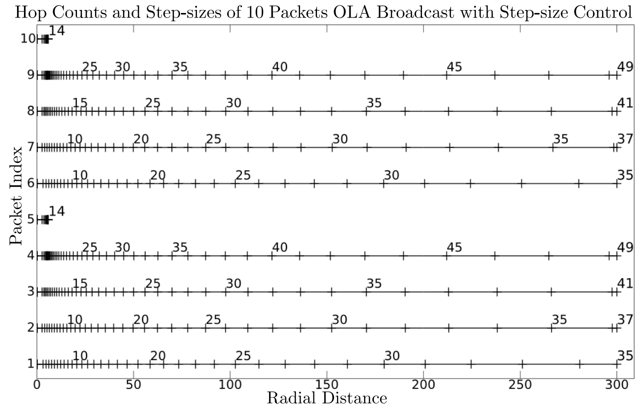

Fig. 4. OLA broadcast of ten packets, when μ=1.8, M=34

B. Ten-Packet Example

In the previous section, we observed how the interaction between just two packets could make both packets slow down considerably. Therefore, we may expect that with 10 packets, the interference effects will be compounded and cause even slower propagation. We assume the same two sets of parameters as in the $\mu = 1.8$ and $\mu = 2$ cases. This time. for each case, we will present the results using a pair of graphs, where the first graph is hop index versus distance, same as the last section, while the second plots the traces of all the 10 packets on the graph of distance versus time. Figs. 4 and 5 show the numerical results of the OLA broadcast with ten packets for the ring expansion case, where $\mu = 1.8$, $W_0 = 35$, $R = 300$, and $M = 34$, which are the same simulation parameters as in the second graph of Fig. 2. Fig. 4 shows that from the second to the fourth packets, the hop counts increase because the lagging second packet interferes with the third more than the the first packet interference with the second. The effects sequentially causes a more severe reduction in the hop-distances of the packets, until the fifth packet is lost; however, after that, the same pattern is repeated by the next five packets (from six to ten). Fig. 5 shows the effects of the gradual intra-flow interference accumulation as time evolves, where the x-axis indicates the time unit, and the y-axis denotes the propagation distance in terms of the radius. The slopes of the first to fourth packets are decreasing as the packet index increases, and finally the fifth packet is killed. As in Fig. 4, the next five packets (from six to ten) show the same pattern. It is a surprising result in that shortening the packet insertion period by just one slot, to $M = W_0 - 1$, makes multiple-packet pipelining impossible to achieve.

Figs. 6 and 7 show the case of $\mu = 2$, $W_0 = 10$, $R = 10$, and $M = 9$, which has the same parameters of the second graph of Fig. 3. Eight of the ten packets die off in the middle of the network, which is much worse than the ring expansion case. The reason is that the OLAs transmitting the leading and following packets are more balanced in size and not so far from each other, causing significant interference in both directions.

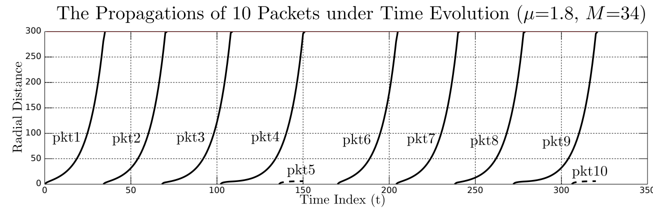

Fig. 5. The time evolution of the distances, when μ=1.8

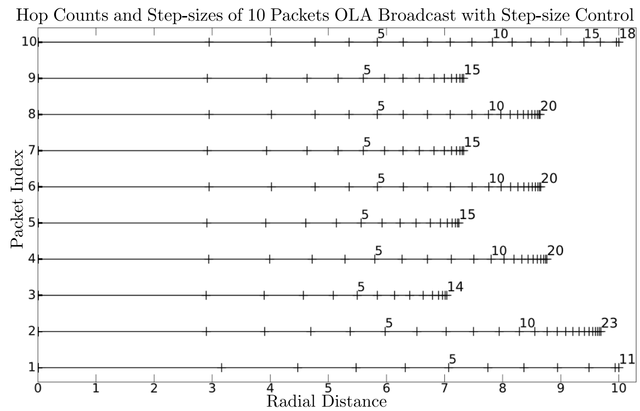

Fig. 6. OLA broadcast of ten packets, when μ=2, M=9

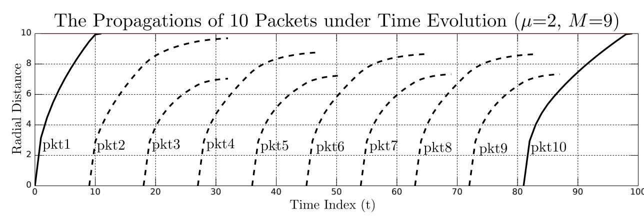

Fig. 7. The time evolution of the distances, when μ=2

C. Step-size Control

Because the large size of the OLAs of the first packet can be blamed for shortening the second-packet hop distances, we wondered if constraining OLA sizes would help the situation. It is straightforward to do power control as a function of hop count, to make OLA outer radii equally spaced. This "*step-size control*" approach was proposed in [14] for the purpose of regulating OLA sizes on the route reply phase of an OLA-based reactive routing scheme. In a single packet OLA broadcast, we can keep the same step-size of $\sqrt{(P_s/\tau)} = r_k - r_{k-1}$ for $k = 1, 2, \ ...$ by setting the relay transmission power at kth OLA to

$$P_r(k) \quad = \quad \frac{\tau}{\pi\rho \ln\left(4k/(2k+1)\right)}, \qquad (12)$$

which is readily derived by the OLA boundary condition that $r_k = \sqrt{(P_s/\tau)}k$. This equal step-size control technique is useful to suppress the intra-flow interference by avoiding the ring expansion problem. Figs. 8 and 9 show the numerical results of the OLA broadcast with ten packets following the step-size control power adaptation, where the parameters are same to the numerical analysis in Figs. 4 and 5. However,

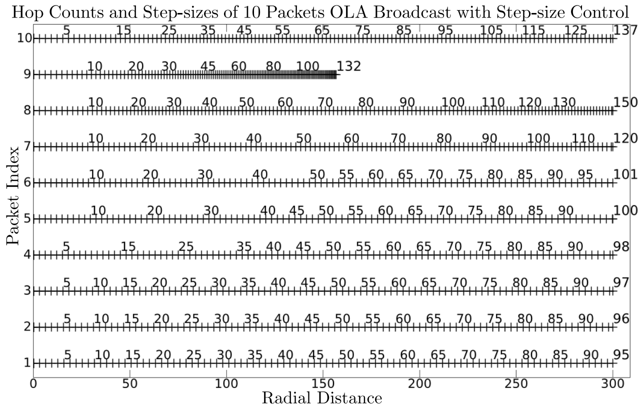

Fig. 8. OLA broadcast of ten packets with step-size control, when W_0=95, M=94, and R=300

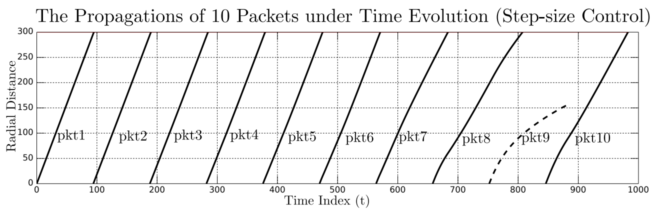

Fig. 9. The time evolution of distances with step-size control

because of the reduced total transmit power by the step-size control, a single packet OLA broadcast takes $W_0 = 95$ hops, so we use one less packet insertion period of $M = 94$ for the pipelining. Compared to the results in Fig. 4, the impact of the pipelining is smaller in the step-size controlled network, which shows the packet loss of the ninth packet, even though the transmit power level of each relay is decreasing with hop index, to avoid the ring expansion. However, as in the previous fixed relay power examples, the step-size of each packet decreases from the first to the eighth packets as indicated by the increasing total hop counts of the packets in Fig. 8 and the gradual slope variation in Fig. 9. Thus, the step-size of the ninth packet is being suppressed to tiny levels, and it dies off at the 132th hop.

VI. Conclusion

In this paper, we analyze the impact of the intra-flow interference in OLA broadcasts using the continuum and deterministic channel assumptions, which model the high node density situation. For the infinite disc network, we prove that the intra-flow interference of multiple OLA broadcasts discourages spatial reuse, because any co-channel pipelining causes shorter step sizes that greatly delay the second packet, and further addition of packets causes packet loss. By limiting the network size, we show that any kind of pipelined OLA transmission hurts network throughput, because each packet has smaller hop distances, or dies out depending on their interference loads. Therefore, we suggest that the best multiple-packet transmission strategy for OLAs is to wait to insert a packet until after the preceding co-channel packet has reached the edge of the network.

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