Barrage Relay Networks: System & Protocol Design

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***Abstract*—Barrage relay networks (BRNs) are mobile ad hoc networks designed from the ground up to meet the demands of tactical edge communications. The fundamental building block of BRNs is not a point-to-point wireless link, but rather a rapid and robust broadcast mechanism that employs an autonomous cooperative communications scheme. Following a summary of basic BRN concepts, this paper demonstrates how the efficient barrage broadcast mechanism can be contained for unicast traffic via controlled barrage regions (CBRs). In particular, a protocol for CBR establishment is defined and formally verified.**

I. Introduction

Communications at the *tactical edge* provides perhaps the most compelling potential application for mobile ad hoc network (MANET) technology. A squadron of soldiers seeking to maintain connectivity in a challenging RF propagation environment (e.g., urban canyons, ships, subterranean structures, etc.) is an example of edge networking; first-responder communications, such as remote search and rescue, is another. Much like ad hoc or sensor networks, this *tactical* MANET application assumes no fixed infrastructure (cf., [1]); however, the operating environments and usage considerations for tactical MANETs pose unique design challenges. For example, since nodes are both mobile and typically in rich scattering environments, link-level connectivity is unreliable and the network topology is highly dynamic. Furthermore, low-latency, network-wide broadcast – as opposed to latency-tolerant, randomly-paired unicast – and robust connectivity are the primary requirements of tactical MANET systems, with typical traffic including interactive push-to-talk (PTT) voice, real-time streaming video from a small set of source nodes, and a limited amount of unicast traffic (e.g., text messaging).

Section II of this paper describes the basic concepts of *barrage relay networks* (BRNs), which are a type of MANET developed specifically for tactical edge communications. BRNs utilize autonomous cooperative communications in order to define a rapid, robust, and scalable broadcast mechanism. This barrage broadcast mechanism is topology agnostic (i.e., neighbor and routing tables need not be maintained) and the fundamental physical layer resource to which access must be controlled in a BRN is therefore not the link, but rather the barrage broadcast mechanism in both space and time.

While prior work has shown that BRNs scale optimally for broadcast data rate and latency [2], the focus of this paper is developing a method of containing the inherent flooding of barrage to enable concurrent unicast flows that are spatially separated. As described in Section III, this containment can be achieved via controlled barrage regions (CBRs). Briefly, a CBR comprises a set of buffer (or sentry) nodes that isolate interior nodes that transport data from source to destination via a spatially contained barrage broadcast mechanism. Section III describes a multi-hop request-to-send (RTS) / clear-to-send (CTS) protocol that establishes which nodes relay and buffer for a given source-destination pair. A detailed verification of the correctness of the proposed CBR establishment protocol is contained in Section IV. Specifically, it is shown under a graph theoretic deterministic network model that: (i) the proposed protocol provably establishes the desired CBRs; and, (ii) once a CBR has been established, the barrage broadcast mechanism can be directly employed for collision-free, multi-hop data transmission from source to destination.

II. Barrage Relay Networks

Before focusing on unicast traffic, the basic barrage broadcast mechanism is summarized. This section relies heavily on descriptions previously provided in [2–4]. In particular, [2] discusses the relationship between specific components of BRNs and related concepts that have been proposed independently – and in isolation – in the literature (e.g., [5–7]).

A. Barrage Relay via Example

While there are a number of network capabilities required by BRNs, only two are critical to this example: time division multiple access (TDMA) and a method of *autonomous cooperative communication*. The assumption that all nodes utilize a common *TDMA framing* format requires coarse slot-level synchronization, which can be accomplished using low overhead pilot signaling [3]. As detailed in Section II-B, autonomous cooperation ensures that the concurrent transmission of packets carrying identical data results in neither collisions nor destructive superposition, but rather in a form of cooperative diversity; this is achieved with no coordination beyond the TDMA-level synchronization.

With these assumed capabilities, the BRN broadcast mechanism is illustrated in Figure 1. Generally, M-slot TDMA framing is assumed for some $M \geq 3$; Figure 1 assumes that $M = 3$ with slots labeled A, B, and C. Suppose the black node transmits a packet on slot A of the first TDMA frame. All nodes that successfully receive this packet are, by

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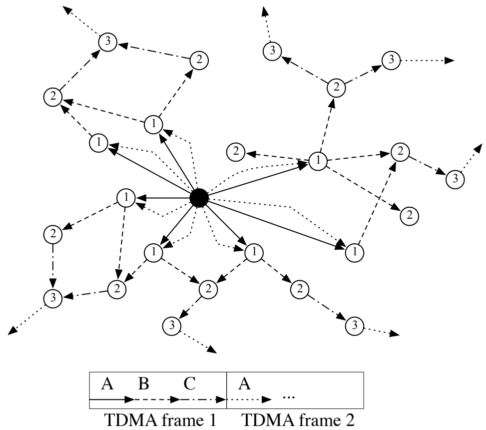


Fig. 1. Barrage relay network broadcast protocol for a three slot ($M = 3$) TDMA frame format. The source node is black while relay nodes are numbered by their distance in hops from the source.

definition, one hop away from the source node. These nodes then transmit the same packet on slot B, thus relaying to the nodes that are two hops away from the source, which in turn transmit the same information on slot C. Nodes that are 3 hops away from the source relay on slot A of the second TDMA frame. Packets thus propagate outward from the source via a decode-and-forward approach. To prevent the relay transmissions from propagating back towards the source, each node relays a given packet only once. For example, one-hop nodes will receive the first broadcast packet on slot A and again on slot C but only relay on slot B. Figure 1 shows that a number of two-hop nodes receive the same packet on the same slot, but from different one-hop nodes via the assumed autonomous cooperative communications. In fact, all nodes at a given hop count cooperate to communicate to nodes at the next level; for simplicity, Figure 1 shows only the most significant contributions.

The spatial reuse of time slots enables packets to be pipelined into the source for transmission every M slots. For example, in Figure 1, the one-hop nodes will not receive the packet transmitted by the three-hop nodes during slot A of the second TDMA frame. Thus, the source can safely transmit a second packet during that slot. It is readily verified that M must be at least 3 in order to allow such *spatial pipelining*. Larger values of M can be chosen so as to trade throughput for enhanced robustness to topological variation.

B. Autonomous Cooperation

It is well-understood that the use of cooperative communications can yield significant performance improvements in MANETs (cf., [8]). Conventional approaches to cooperative communications (e.g., distributed space-time coding), however, require a significant amount of inter-node coordination. This coordination typically includes team-forming and may also include other tasks such as channel identification and codebook assignment. In networks with highly dynamic topologies, frequent updates of the inter-node coordination information would be required, thereby impacting overhead and increasing the latency required for packet relay. Furthermore, it is unclear how to efficiently design coordinated schemes that allow for a single node to simultaneously cooperate with several, possibly overlapping, sets of other nodes (i.e., in multiple cooperative *teams*) in transmitting to multiple receivers.

In contrast to such *coordinated* cooperative communications, barrage relay networks utilize an *autonomous* scheme that does not require inter-node coordination (including the explicit formation of teams). An autonomous scheme in which each transmitting node pseudo-randomly dithers its carrier phase so that the superposition of these signals will induce a time-varying channel characteristic at a receiving node is described in [9]. A *modern* forward error correction code can then be used to extract the time diversity provided by this induced time-varying fading channel (cf., [10]). Strategies for realizing this basic concept in practical systems are described in [2]; suffice it to say presently that transmitters require neither any channel state information nor is there any explicit formation of teams, while receivers process the received signal without regard to the number of transmitters. Furthermore, as illustrated in Figure 1, a given node may cooperatively transmit to multiple receivers simultaneously – a task that is not directly possible in conventional, team-based approaches. Finally, in as much as all nodes at a given hop count in Figure 1 represent a spontaneously formed team, this set of nodes can change on a packet-by-packet basis according to whether successful packet reception occurs.

There are several other assumptions regarding autonomous cooperation in BRNs that are more subtle. First, networking stacks typically modify protocol header information at each relaying node so that even if two relay nodes transmit identical payload data, the resulting on-air packets may be different. In order to support autonomous cooperation, node-specific packet transformation must be suppressed: protocol headers can be modified only in a manner that is hop-dependent. Second, cooperating nodes must relay identical packets on identical time slots. Relaying decisions are traditionally made at the network layer, introducing processing delays that are unpredictable and node-dependent. To minimize delay and ensure that relays occur on the same slot, relay decisions must be made at the physical layer. Finally, cooperating nodes transmitting on the same TDMA slot may incur different propagation delay due to the heterogeneous propagation environment. The receiver must thus accommodate a total effective delay spread that is the sum of the *cooperative delay spread* induced by the network geometry and the channel-induced physical delay spread.

C. Barrage Access Control

The barrage broadcast mechanism described above provides a low-latency, robust mechanism for flooding from a *single* source node. In order to provide networking with multiple sources, some form of access control is required. The simplest scenario is PTT voice in which an operator accesses the channel by keying down the transmitter and collisions are resolved by standard manual operational protocols. For data transmission, this operator control is not sufficient. Nonetheless, it illustrates the fundamental physical layer resource to be controlled: the barrage broadcast fabric for some period of time. This is in stark contrast to the standard layered architecture for network design which controls access to a node-to-node link via a collision avoidance MAC protocol.

While MAC may still be an applicable term to describe algorithms controlling access to barrage resource, the term *barrage access control (BAC)* was introduced in [4] to emphasize that BRNs are not based on a link abstraction. As an example of the basic structure for a BAC protocol, assume that the TDMA structure employed by the BRN partitions time slots into two independent logical channels: the *contention* logical channel (CLC) and the *data* logical channel (DLC). Control traffic transmitted on the CLC is used to coordinate access to the DLC; the bandwidth reserved for the CLC therefore constitutes the overhead associated with this protocol. In practice, the overhead required by a specific BAC protocol depends heavily on the design constraints it must meet (e.g., how rapidly new sources must be able to access the DLC).

Future access to the data logical channel is tabulated in a *DLC schedule* that lists which node (if any) is the designated source on each DLC slot. When a node is the designated source, it injects packets on the DLC every M slots; otherwise, nodes relay what they receive (i.e., relay decisions are made at the physical layer). In this manner, multiple data flows are time-multiplexed on the DLC so as to provide shared access to the efficient barrage broadcast mechanism.

The CLC is used to maintain the DLC schedule in response to time-varying traffic demands. Nodes announce their desire to source data (and how much) via a packet broadcast on the CLC. A common *schedule control* node responds to this packet by broadcasting a scheduling update packet on the CLC that incorporates the new data source. Observe that the receipt (or not) of a concomitant scheduling update can be used as an implicit positive (or negative) acknowledgement of the successful transmission of a request packet to the schedule control node, thereby enabling the use of Ethernet-like backoff and retry schemes to mitigate collisions on the CLC.

III. Controlled Barrage Regions

It was shown in [2] that an abstract BAC protocol similar to that described above provides a broadcast function that scales optimally: $\Theta(1)$ scaling of the sum transmit rate (over any number of sources) is achieved in dense networks (cf., [11]). Unicast transmission can of course be achieved via the same network-wide flooding protocol (i.e., all nodes relay but only intended recipients pass the received packet up the stack from the physical layer); however, the ability to support multiple, contemporaneous localized unicast streams can enhance the network capacity offered by BRNs. This section describes *controlled barrage regions* (CBRs), which are a building block for just such spatially separated unicast transmissions. The basic CBR concept was discussed previously in [4] and [2]; in the present work, a protocol for CBR establishment is detailed.

A. Cooperative Links, Paths, and CBRs

In a traditional network, a link is defined by a transmit/receive radio pair that share a suitably reliable point-to-point communications channel. A unicast route is simply a series of these links connecting a source-destination node pair. In a BRN, however, links are *cooperative* and comprise one or more transmitters and one receiver as illustrated in Figure 2(a). A cooperative path, as illustrated in Figure 2(b), is formed by series of braided cooperative links between the source and destination nodes.[1] A controlled barrage region is simply the union of one or more such cooperative paths (of distinct lengths). Figure 2(c) illustrates a CBR comprising two cooperative paths. As shown quantitatively in [4] and [12], controlled barrage regions afford a mechanism for unicast transport that is more robust than both traditional unicast routing and non-cooperative multipath variants.

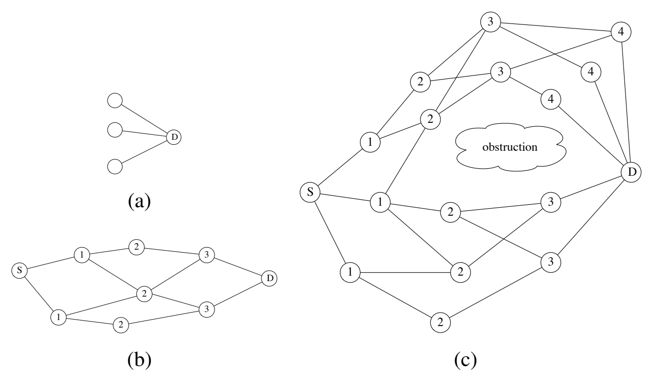


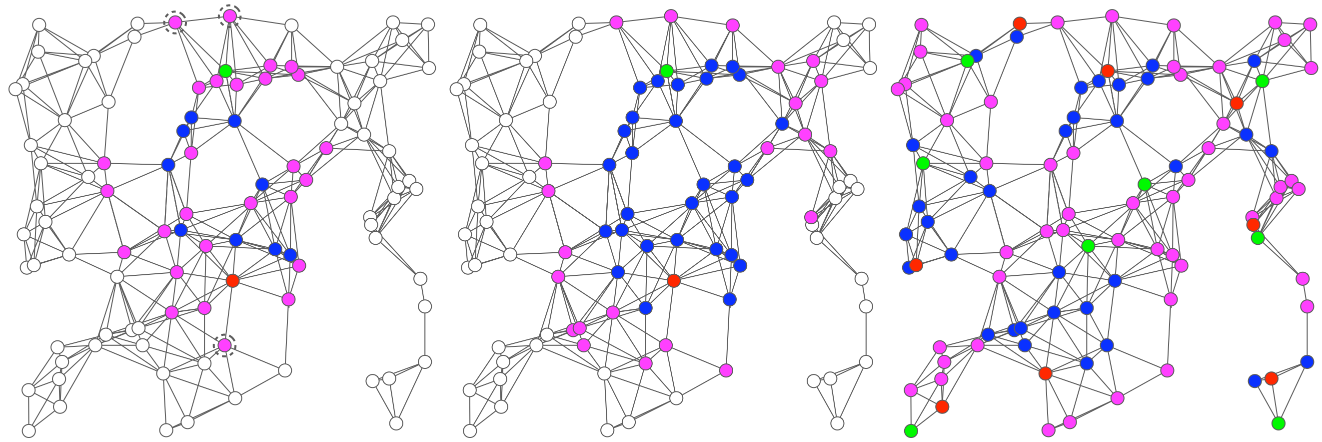
Fig. 2. Examples of (a) a (3 to 1) cooperative link; (b) a (length 4) cooperative path; and (c) a controlled barrage region comprising two cooperative paths, one of length 5 hops and another of length 4.

B. CBR Establishment

CBRs can be established by specifying a set of buffer nodes around a set of cooperating *interior* nodes. The relay function of buffer nodes is suppressed so that external packets do not propagate into the control region, nor do internal packets propagate to the rest of the network. In this way, multiple unicast transmissions may be established in different portions of the network. It is precisely the action of these buffer nodes that inspired the name *controlled* barrage region. The buffer and interior nodes corresponding to a given source-destination unicast pair can be specified via the broadcast of request-to-send (RTS) / clear-to-send (CTS) packets on the CLC.

RTS Packet Broadcast: CBR establishment is initiated by a source node that transmits a RTS packet that contains (i) the destination node's identity and (ii) a hop count field that is incremented by every relaying node (i.e., a hop-dependent transformation). This packet is broadcast network-wide; all nodes thus ascertain their distance (in hops) from the source.

[1] Again, all nodes at a given hop count cooperate in relaying to all potential receivers. The lines shown between nodes in Figure 2 notionally indicate the most significant contributors. In fact, the concepts of cooperative links and paths are used largely to draw comparisons to existing notions in the wireless networking community and are not, strictly speaking, applicable in BRNs.



(a)

(b)

(c)

Fig. 3. In these illustrations, source, destination, interior (relay), buffer, and exterior nodes are colored green, red, blue, pink, and white, respectively. Examples of (a) a width $N = 0$ CBR and (b) a width $N = 1$ CBR for the same source/destination pair as (a). The buffer nodes is (a) that require the use of BUF packets to be properly set are highlighted with a concentric dotted circle. Eight concurrent CBRs are shown in a network that is nearly identical in (c).

CTS Packet (Controlled) Broadcast: Upon receipt of the RTS packet, the destination node waits a prescribed number of CLC slots (the value of which is derived in Section IV) before transmitting a CTS packet that contains (i) the source-destination hop distance ($d_{S\to D}$) obtained from the RTS packet and (ii) a hop count field that is incremented by every relaying node. Every node X that receives the CTS packet now knows its distance from the source ($d_{S\to X}$), its distance from the destination ($d_{D\to X}$), and $d_{S\to D}$. A CBR containing all braided shortest paths from source to destination can therefore be established by setting all nodes X satisfying $d_{S\to X} + d_{D\to X} \leq d_{S\to D}$ as interior nodes. Only such interior nodes relay the CTS packet. All nodes that receive but do not relay the CTS become buffer nodes for the CBR.

CBR Excess Width: As proven in Section IV, this concept is readily extended to CBRs that contain not only all shortest paths but also those of length $d_{S\to D}+1, \ldots, d_{S\to D}+N$ for any $N < M$, where N is the *excess width* of the CBR and M is the spatial pipelining factor (e.g., 3 in Figure 1). A larger excess width (larger N) provides more robustness at the expense of requiring a larger spatial region of the network.

BUF Packet: Potential collisions between the CTS and stray RTS packets on the CLC can be eliminated by the use of a third packet. Before transmitting the CTS, the destination node transmits a buffer assignment (or BUF) packet that is received, but not relayed, by its one-hop neighbors. Similarly, the source node transmits a BUF packet upon receipt of the CTS packet. Any node that receives a BUF packet but does not relay the CTS (i.e., a node that is *not* interior to the CBR) is also a buffer for the controlled barrage region.

Figure 3 illustrates CBRs in a 100-node random network. Figures 3(a) and 3(b) illustrate the difference between CBRs with excess widths of $N = 0$ and 1, respectively, between a common source-destination pair. The buffer nodes that require a BUF packet in order to be properly set are also highlighted in Figure 3(a) (i.e., RTS/CTS collisions can otherwise occur at these nodes). Figure 3(c) shows concurrent CBRs between eight unicast pairs that are separated by at most two hops.

C. CBR Coordination

The abstract BAC protocol described in Section II-C must clearly be extended in order to support unicast transmissions via CBRs. In particular, the *global* DLC schedule described for purely broadcast traffic can instead be replaced by *local*, node-specific schedules indicating whether nodes source packets, relay received packets (i.e., are interior to a CBR), or act as buffers for one or more CBRs on each DLC slot. While these schedules will not be identical at all nodes, they must be made *consistent* so as to avoid collisions between distinct flows.

IV. CBR Establishment Protocol Analysis

In this section, the CBR establishment protocol described above is specified and analyzed formally. In particular, the number of CLC slots that the destination node must wait before injecting BUF and CTS packets into the network is derived. The analysis assumes a simple deterministic network model for the sake of tractability. That is to say, the range extension afforded by cooperative transmission is neglected since the specific details of this range scaling depend highly on the propagation environment and receiver processing algorithms.

A. Graph Theoretic Model and Notation

A wireless network is modeled by a connected graph $G = (V, E)$, where the vertices $v \in V$ correspond to radios (nodes) and edges $e \in E$ correspond to reliable symmetric links. The distance $d(u, v)$ between two distinct vertices $u, v \in V$ is defined as the length of the shortest path connecting them. For any subset of nodes $U \subseteq V$, denote by $G_{\setminus U}$ the subgraph of G containing only the vertices in $V \setminus U$. Let u, v, and w be distinct vertices in G. The present work uses the notation $d(u, v; w)$ to denote the length of the shortest path from u to v that does not contain w. Equivalently, $d(u, v; w)$ is the length of the shortest path from u to v in $G_{\setminus\{w\}}$.

B. Formal CBR Establishment Protocol Summary

Suppose a CBR of excess width $N \geq 0$ is to be established between a source node $x \in V$ and (distinct) destination node $y \in V$. Without loss of generality, x transmits an RTS packet during CLC slot $t_{\mathrm{tx}}(x; \mathrm{RTS}) = 0$. A node $v \in V \setminus \{x, y\}$ receives an RTS packet for the first time during CLC slot

$$t_{\mathrm{rx}}(v; \mathrm{RTS}) = d(x, v; y) - 1, \tag{1}$$

uses the hop counter embedded in the RTS packet to acquire $d(x, v; y)$, and transmits an appropriately updated RTS packet during time slot $t_{\mathrm{tx}}(v; \mathrm{RTS}) = d(x, v; y)$. The distance measure in (1) is $d(x, v; y)$, rather than $d(x, v)$, because the destination y does not relay RTS packets. The destination node receives an RTS packet for the first time during slot $t_{\mathrm{rx}}(y; \mathrm{RTS}) = d(x, y) - 1$ and transmits a BUF packet on slot

$$t_{\mathrm{tx}}(y; \mathrm{BUF}) = d(x, y) + k_1 \tag{2}$$

for some $k_1 \geq 0$ that is to be determined. Recall that the BUF packet is not relayed by the neighbors of y. The destination node subsequently transmits a CTS packet during slot

$$t_{\mathrm{tx}}(y; \mathrm{CTS}) = d(x, y) + k_2 \tag{3}$$

for some $k_2 > k_1$ that, again, is to be determined. A node $v \in V \setminus \{x, y\}$ first receives a CTS packet for the during slot

$$t_{\mathrm{rx}}(v; \mathrm{CTS}) = t_{\mathrm{tx}}(y; \mathrm{CTS}) + d(y, v; x) - 1 \tag{4}$$

and uses information embedded in the CTS packet to ascertain both $d(y, v; x)$ and $d(x, y)$. The node v then will be *interior* to the established controlled barrage region only if

$$d(x, v; y) + d(y, v; x) \leq d(x, y) + N. \tag{5}$$

If v is indeed an interior node, then it relays an appropriately updated CTS packet during slot $t_{\mathrm{tx}}(v; \mathrm{CTS}) = t_{\mathrm{tx}}(y; \mathrm{CTS}) + d(y, v; x)$. Otherwise, the node does not relay a CTS packet and instead becomes a *buffer node* for the CBR. The source receives the CTS packet at time $t_{\mathrm{rx}}(x; \mathrm{CTS}) = t_{\mathrm{tx}}(y; \mathrm{CTS}) + d(x, y) - 1$ and transmits a BUF packet at time

$$t_{\mathrm{tx}}(x; \mathrm{BUF}) = t_{\mathrm{tx}}(y; \mathrm{CTS}) + d(x, y) + k_3 \tag{6}$$

for some constant $k_3 \geq 0$ that is to be determined. Recall that any node that receives a CTS packet – even those that did not receive an RTS packet – become either interior or buffer nodes according to (5). Similarly, any node that receives only a BUF packet becomes a buffer node.

C. Formal CBR Establishment Protocol Verification

A CBR is *proper* if: (i) every node $v \in V \setminus \{x, y\}$ satisfying $d(x, v; y) + d(y, v; x) \leq d(x, y) + N$ is interior to the CBR, and (ii) every non-interior node $v \in V \setminus \{x, y\}$ that is adjacent to x, y, or some other interior node r is a buffer node. Proper CBRs therefore have a well-defined set of buffer nodes that completely contains the interior unicast packet flow.

Theorem 1: The CBR established by the protocol described in Section IV-B is proper whenever k_1, k_2, and k_3 satisfy:

$$k_1 = \max(0, N - 1), \quad k_2 \geq \max(1, N) + 2, \quad k_3 \geq N$$

In order to prove Theorem 1, it need only be shown that (i) interior nodes successfully receive RTS and CTS packets, (ii) buffer nodes successfully receive either a CTS or BUF packet, (iii) the destination receives an RTS packet, and (iv) the source receives a CTS packet. Since a deterministic model is assumed, reception is successful provided that there are no extraneous (i.e., non-identical) packets received during the appropriate reception time slots listed in Section IV-B.

1) Interior RTS Verification: Let $r \in V \setminus \{x, y\}$ be a node that satisfies $d(x, r; y) + d(y, r; x) = d(x, y) + \alpha$ for some $\alpha \in \{0, \ldots, N\}$ so that it should be interior to the CBR. Since nodes only relay RTS packets once, the only potential collisions to consider are those between RTS packets and the BUF packet transmitted by the destination node. Thus, assume that r satisfies $d(y, r; x) = 1$ so that it is a neighbor of the destination (recall that BUF packets are not relayed). Collisions between RTS and BUF packets are avoided by ensuring that $t_{\mathrm{tx}}(y; \mathrm{BUF}) > t_{\mathrm{rx}}(r; \mathrm{RTS})$. Substituting definitions from Section IV-B establishes that such collisions are avoided whenever $k_1 > N - 2$. Since $k_1 \geq 0$ by definition, the smallest possible value for k_1 is simply $k_1 = \max(0, N - 1)$.

2) Interior CTS Verification: Again, assume that $r \in V \setminus \{x, y\}$ should be interior to the CBR. Since nodes only relay CTS packets once, there are only two potential collisions to consider: (i) collisions between CTS packets and stray RTS packets and (ii) collisions between CTS packets at neighbors of the source and the BUF packet transmitted by the source. The former are avoided if $t_{\mathrm{rx}}(r; \mathrm{CTS}) > t_{\mathrm{tx}}(v; \mathrm{RTS})$ for all $v \in V$ satisfying $d(r, v) = 1$. Since $d(r, v) = 1$, it is readily verified that $|d(x, r; y) - d(x, v; y)| \leq 1$. Furthermore, since it is assumed that r has already received an RTS packet, only the case where $d(x, v; y) = d(x, r; y) + 1$ need be considered. Substituting this result along with definitions from Section IV-B establishes that collisions between stray RTS packets and the first CTS packet received by r are avoided whenever

$$k_2 > \alpha + 2 - 2d(y, r; x). \tag{7}$$

Since $\alpha \leq N$ and $d(y, r; x) \geq 1$, such collisions are avoided whenever $k_2 > N$. Suppose next that r is a neighbor of x. Collisions between the CTS packet at r and the BUF packet transmitted by the source are avoided if $t_{\mathrm{tx}}(x; \mathrm{BUF}) > t_{\mathrm{rx}}(r; \mathrm{CTS})$. Substituting definitions from Section IV-B establishes that such collisions are avoided whenever $k_3 > N - 2$.

3) Buffer Verification: Recall that in order to become a buffer, a node need successfully receive either a CTS or BUF packet. There are two cases to consider: (i) neighbors of the destination node y, and (ii) all other buffer nodes.

Let $b \in V \setminus \{x, y\}$ such that $d(b, y) = 1$ and $d(x, b; y) + d(y, b; x) = d(x, y) + \beta$ for some $\beta > N$ so that b should be a buffer node. Using the value for k_1 established above, node b receives a BUF packet at time $t_{\mathrm{rx}}(b; \mathrm{BUF}) = d(x, y) + \max(0, N - 1)$ and a CTS packet at time $t_{\mathrm{rx}}(b; \mathrm{CTS}) = d(x, y) + k_2$. In the following, it is shown that for each of four sub-cases, either the BUF or CTS packet is successfully received provided $k_1 = \max(0, N-1)$ and $k_2 \geq \max(1, N)+2$.

- $N \geq 0$ and $\beta = N+1$:
  Consider some neighbor $w \neq y$ of b that transmits an RTS packet at time $t_{\rm tx}(w; {\rm RTS}) = d(x, w; y)$. A collision between the CTS from the source and this RTS packet is avoided provided that $t_{\rm rx}(b; {\rm CTS}) > t_{\rm tx}(w; {\rm RTS})$. Since $\beta = N+1$ and w is a neighbor of b, $d(x, w; y) \leq N + d(x, y) + 1$. Substituting in the definition for $t_{\rm rx}(b; {\rm CTS})$ establishes that b will successfully receive the appropriate CTS packet provided that $k_2 > N+1$.
- $N = 0$ and $\beta = N+2 = 2$:
  Following an argument similar to that of the $N \geq 0$, $\beta = N+1$ case, it is readily verified that b will successfully receive the appropriate CTS packet provided that $k_2 > 2$.
- $N = 0$ and $\beta > 2$:
  Recall that b receives a BUF packet in this case at time $t_{\rm rx}(b; {\rm BUF}) = d(x, y)$. If $\beta > 2$ then $t_{\rm rx}(b; {\rm RTS}) > d(x, y) + 1$ so b successfully receives the BUF packet.
- $N \geq 1$ and $\beta > N+1$:
  Recall that b receives a BUF packet in this case at time $t_{\rm rx}(b; {\rm BUF}) = d(x, y) + N - 1$. If $\beta > N+1$ then $t_{\rm rx}(b; {\rm RTS}) > d(x, y) + N$ so b successfully receives the BUF packet.

Consider next $b \in V \setminus \{x, y\}$ such that b and y are *not* neighbors (i.e., $d(b, y) > 1$). Suppose first that b is not adjacent to *any* interior node and is, therefore, adjacent to the source node x. In this case, b always receives the BUF packet from the source successfully. Suppose next that b is indeed adjacent to some interior node r. Following arguments similar to those employed above, it can be verified that the CTS packet at b does not collide with the BUF packet transmitted by the source provided $k_3 > N-1$, nor does it collide with any stray RTS packets provided $k_2 > N+1$.

4) Source & Destination Nodes: Finally, it can be verified that there are no collisions at the destination on slot $t_{\rm rx}(y; {\rm RTS})$, nor are there collisions at the source on slot $t_{\rm rx}(x; {\rm CTS})$ provided k_1, k_2, and k_3 are set as per Thm. 1.

D. Unicast Flow Operation

Suppose that a proper CBR of width N has been established between nodes x and y. Without loss of generality, suppose that the source x transmits the k^{th} data packet of a given multi-slot unicast transfer on DLC slot[2] Mk (so that packets are pipelined into the unicast flow every M time slots). An interior node r at a distance $d(x, r; y)$ from the source should receive this packet for the first time during slot

$$t_{\rm rx}(r; k) = Mk + d(x, r; y) - 1 \tag{8}$$

and relay it on the subsequent slot. The destination, similarly, receives this packet for the first time on slot $t_{\rm rx}(y; k) = Mk + d(x, y) - 1$. A collision will occur at the y only if during the intended reception of the k^{th} packet, a neighbor of y is concurrently transmitting some l^{th} packet for $l < k$. It can be verified that such collisions are avoided in proper CBRs provided $N < M$. Similarly, it is readily verfied that all collisions of non-identical packets at interior nodes (during the intended reception slot) are avoided if $M > 2$. In summary,

Theorem 2: Assuming a deterministic network model, a proper CBR with excess width $N < M$ permits collision-free, multi-hop data transmission from source to destination provided the spatial reuse factor M is at least 3.

V. Conclusion

While barrage relay networks have previously been shown to scale optimally for broadcast data rate and latency, this paper addressed the establishment of controlled barrage regions to spatially contain the barrage broadcast mechanism in order to support simultaneous unicast flows separated spatially. Under a deterministic network model, it was shown that a simple protocol provably establishes the intended CBR. Important topics of additional research include consideration of range extension effects associated with node cooperation and the design and analysis of distributed barrage access protocols (BACs) that enable simultaneous unicast flows in an efficient and robust manner.

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[2] Note that this section considers *data* slots rather than contention slots so that the numbering here is independent of that in Sections IV-B and IV-C.