Granting Silence to Avoid Wireless Collisions

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***Abstract*—We describe grant-to-send, a novel collision avoidance algorithm for wireless mesh networks. Rather than announce packets it intends to send, a node using grant-to-send announces packets it expects to hear *others* send.**

We present evidence that inverting collision avoidance in this way greatly improves wireless mesh performance. Evaluating four protocols from 802.11 meshes and 802.15.4 sensor networks, we find that grant-to-send matches or outperforms CSMA and RTS/CTS in all cases. For example, in a 4-hop UDP flow, grant-to-send can achieve 96% of the theoretical maximum throughput while maintaining a 99.9% packet delivery ratio. Grant-to-send is also general enough to replace protocol-specific collision avoidance mechanisms common to sensor network protocols.

Grant-to-send is simple. For example, incorporating it into 802.11 requires only 11 lines of driver code and no hardware changes. Furthermore, as it reuses existing 802.11 mechanisms, grant-to-send inter-operates with current networks and can be incrementally deployed.

I. Introduction

Collisions are a significant design challenge for wireless mesh protocols. Traditionally, wireless MAC layers improve collision avoidance by trading off throughput. Simple schemes such as CSMA/CA introduce very little throughput overhead, but exhibit significant collisions under load. More complex schemes, such as RTS/CTS, avoid collisions better but reduce throughput when there is no contention. In practice, this tradeoff has led mesh protocol designers to choose CSMA [12], [24] and deal with the challenges collisions introduce, such as highly variable and severe packet loss [7].

More recently, network coding at the physical layer has emerged as a way to sidestep the tradeoff between collision avoidance and throughput. Approaches such as analog network coding [22] or ZigZag decoding [19] have shown that nodes can recover collided packets using simple signal processing and redundant information. The downside of these approaches is that they require new chipsets and hardware: they cannot be easily deployed in existing networks.

Can we improve collision avoidance without sacrificing throughput or requiring new hardware? Given the maturity of research in collision avoidance, a positive answer might seem unlikely. The sheer number of CSMA/CA backoff schemes [8], [11], [13], [29] and RTS/CTS variations [6], [9], [20], [30], [31] implies that the problem has been put to rest, suggesting the only way forward is through better signal processing, cross-layer optimizations, and network coding.

This paper presents evidence to the contrary. It shows that inverting collision avoidance's information flow can significantly reduce collisions without lowering throughput. More precisely, this paper proposes grant-to-send (GTS), a novel collision avoidance primitive. Grant-to-send "inverts" collision avoidance because a grant announces what a node expects to hear other nodes transmit. It embeds its collision avoidance information in data packets, and so uses no control packets.

When sending a packet, a node may specify an interval for which it "grants" its local channel to the recipient. The granter and all overhearing nodes remain silent for this interval. A grant allows the recipient to transmit without causing collisions at the granting node. Grants do not protect the packet they are in; they avoid collisions between future packets sent by other nodes.

Grants are a suppression mechanism: they are not a precondition for transmission. If all grants are zero, grant-to-send behaves identically to CSMA. Existing work has shown that the default 802.11 MAC protocol designed for access point networks is ill-suited for wireless mesh networks [24]. Grant-to-send is a simple extension to adapt the 802.11 protocol for mesh networking, and it does not incur any overhead for traditional AP networks.

Long grants avoid collisions but reduce throughput through channel idleness. Short grants do not waste the channel but suffer from more collisions. So how long should a grant be? To answer this question, we derive an analytical expression of grant-to-send's behavior for a simple UDP flow. The analysis shows that a grant should be as long as a node expects the recipient to use the channel: the optimal grant is a packet time for this case. Simulation and testbed results support this analysis. We examine how complications such as broadcast protocols, variable bit rates, and link-layer retransmissions affect this rule. In cases where the optimal grant is not known, we present simple conservative heuristics that select the optimal grant 98.8% of the time.

We evaluate grant-to-send by examining four different protocols from two network regimes, 802.11 meshes and 802.15.4 sensor networks. We measure the performance benefits over traditional approaches such as CSMA/CA and RTS/CTS. This paper makes four research contributions:

- It presents the design of grant-to-send, a novel collision avoidance mechanism. Using simulation and testbed experiments as a guide, it derives an analytical formulation of grant-to-send's behavior and performance.
- Grant-to-send matches or outperforms the throughput and delivery ratio of CSMA and RTS/CTS for all protocols in all testbed and simulation cases. For example, in a 4-hop route, grant-to-send increases UDP throughput by up to 23%, achieving 96% of the maximum possible throughput, while simultaneously reducing end-to-end

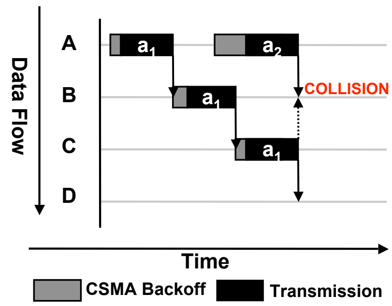


Fig. 1. The hidden terminal problem in a simple flow. Node A must wait for node C to forward a_1 before transmitting a_2, or both will collide at B.

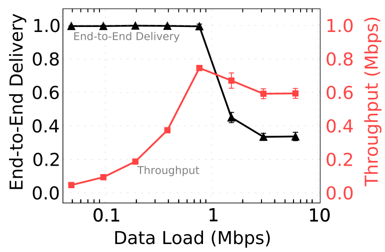


Fig. 2. The effect of the hidden terminal problem within a single CSMA flow. End-to-end delivery does not count dropped packets due to queue overflow at the source node. When load passes the threshold the path can sustain, self-interference becomes significant and the delivery ratio drops accordingly. Furthermore, throughput also drops: sending more packets causes fewer packets to arrive.

losses by >95%.
- Contrary to common wisdom in existing literature [12], [14], [24], CSMA is not always superior to RTS/CTS: RTS/CTS's UDP throughput is up to 38% higher for flows longer than 3 hops.
- Grant-to-send is general enough to implement and replace existing collision avoidance mechanisms in sensor network protocols with no loss of performance.

Grant-to-send can reuse existing 802.11 MAC protocol mechanisms, such that it is completely inter-operable with existing CSMA and RTS/CTS networks. This inter-operability enables grant-to-send nodes to be incrementally deployed with an 11-line change to existing 802.11 drivers.

For 802.15.4, replacing protocol specific collision avoidance mechanisms at the network layer with grant-to-send at the MAC layer enables the collision avoidance mechanisms to work across protocols. This is a crucial property for 802.15.4 in order to prevent complex inter-protocol interactions [16].

The next section provides background on wireless collision avoidance. Section III presents grant-to-send and details two implementations (802.11 and 802.15.4). Section IV analyzes grant-to-send's behavior and provides guidance for how long grants should be. Sections V–VII explore and evaluate grant-to-send for a variety of network protocols. Section VIII discusses limitations of the mechanism. Section IX presents prior related work and Section X concludes.

II. Wireless Collisions

CSMA collision avoidance is inexpensive but susceptible to the hidden terminal problem. The hidden terminal problem happens when two nodes that cannot hear each other (are "hidden") transmit at the same time. A third node hearing both transmissions receives neither because they collide. The hidden terminal problem is common in real-world wireless meshes and is a dominant source of packet losses especially with CSMA [15]. Hidden terminals can cause packets within a flow to self-collide as shown in Figure 1. Nodes separated by 2 hops cannot hear each other, so their transmissions collide at the node in the middle. This behavior is well-known, and bounds a flow's throughput to one third of the single-hop throughput [35], as a node must wait for a packet to progress out of interference range before transmitting the next one.

Bitrate	CSMA	RTS/CTS	Overhead
1 Mbps	0.79	0.76	4.0%
2 Mbps	1.44	1.35	6.6%
5.5 Mbps	3.36	2.89	14.1%
11 Mbps	5.89	4.42	25.1%

TABLE I
Single-hop UDP throughput (Mbps) on a high quality 802.11b link. RTS/CTS overhead ranges from 4-25%.

Figure 2 shows this effect experimentally in a single flow in an 802.11b mesh testbed. Section IV-A provides greater details on the experimental setup, but in summary, one node sends UDP traffic along a static 4-hop route with a fixed bitrate of 5.5Mbps. As the data rate surpasses the path's capacity, the end-to-end delivery ratio and throughput drop due to collisions. This experiment validates earlier simulation results by Li et al. [27] and Vyas et al. [32] that pushing a path beyond what it can support increases collisions and reduces performance. The plots flatten at 3.0 Mbps because link layer queuing prevents sending faster.

RTS/CTS avoids collisions through a control packet exchange before each data packet. The improved data delivery ratio with RTS/CTS has a cost: a data packet requires a control packet exchange, reducing throughput. In practice, many protocol designers have found that RTS/CTS's costs outweigh its benefits [14], [24], and AP vendors suggest disabling it [2], [4].

To quantify this cost, we measure UDP throughput between two nearby 802.11b nodes. In this experimental setup, the packet drop rate and collision rate are very low. The RTS/CTS exchange is pure overhead. Table I shows the results. RTS/CTS overhead is 4-25%. The overhead increases with the bitrate because data packets at higher bitrates are faster, but the fixed-duration control packets sent at 1 or 2 Mbps consume a larger portion of the packet exchange time.

III. Grant-to-Send

This section provides an intuitive and formal description of grant-to-send. Through a simple example of a flow, it illustrates how grant-to-send avoids collisions. Later sections examine more complex protocol interactions. The section concludes with details on the two implementations (802.11 and 802.15.4) we use in the rest of the paper.

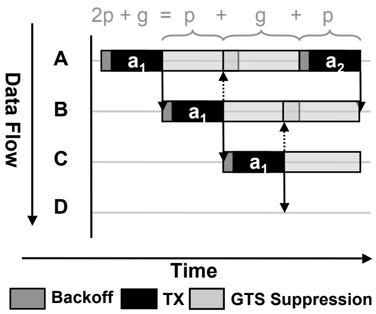


Fig. 3. A packet flow using grants slightly longer than a packet time. The grants avoid intra-flow collisions by forcing nodes to wait until a forwarded packet clears the channel of their next hop.

A. Intuitive Description

Grant-to-send's primitive is simple. When a node sends a packet, it can tell nodes around it to be quiet so they do not collide with the recipient's future transmission. For unicast routing, that transmission is to forward the received packet. Given an estimate of what a recipient will do in response to a transmission, a node shares this information with neighbors to help them avoid collisions.

Grant-to-send sits on top of a CSMA/CA layer providing local node fairness and basic single-hop collision avoidance.

B. Formal Description

Each node i maintains a local quiet time q_i, which states the point in time when channel grants end and it may send a packet. The variable t_i refers to the current time on i's clock. When node i overhears or transmits a grant-to-send packet with a grant of length g, it extends its quiet time to $max(q_i, t_i + g)$. A packet's recipient considers g to be zero. While $q_i > t_i$, a node assumes the channel is busy. If $q_i \leq t_i$, then a node transmits using the underlying CSMA layer. A grant recipient may be unable to transmit immediately: outstanding grants to other nodes can make $q_i > t_i$.

For a transmitter, t_i is when the last bit is sent. For a receiver, t_i is when the last bit is received. As propagation time is typically below 1μs, the difference in timing between the two is irrelevant in practice.

If all packets have $g = 0$, then it is always the case that $q_i \leq t_i$: grant-to-send does not affect packet scheduling or timing and behaves identically to CSMA.

C. Avoiding Collisions

Figure 1 shows how the hidden terminal problem causes a packet flow to self-interfere. Figure 3 shows the same flow using grant-to-send where grant durations are slightly longer than one packet time. There are no intra-flow collisions.

The example begins with Node A granting B its channel. This grant prevents A from transmitting for a single packet time, and so B does not have to compete with A for channel access. B forwards the packet collision-free to C. This packet, in turn, grants B's channel to C. A hears the grant from B to C and extends its quiet time. C forwards the packet, granting its channel to D. As B overhears this grant, it extends its quiet time. Node A's quiet time, however, has expired, so it can now transmit to B.

Every time A transmits a packet to node B, it waits just over two packet times before transmitting again: the first from its own grant and B's transmission, the second from B's grant. Grant-to-send enforces the basic rate limiting (one third) needed in multihop flows. The last hop in a flow has a grant of zero, as it does not expect a retransmission, so grant-to-send does not force idleness on shorter flows.

This example makes many simplifying assumptions: it assumes that the interference range is the same as the transmit range, that there is a single transmitter in a unicast flow, and that a granter somehow knows the correct grant duration for the next hop. We relax these assumptions in later sections by examining how grant-to-send affects four different protocols on testbeds with two different link layers.

D. Grant-to-send Implementation in 802.11

The 802.11 duration header field states the expected length of the current packet exchange between two nodes in terms of microseconds. For example, an 802.11 data packet's duration is the length of an ACK response, while an 802.11 request-to-send packet states the expected length of the CTS-DATA-ACK exchange. Nodes can assume the channel is busy during duration intervals without sensing the channel.

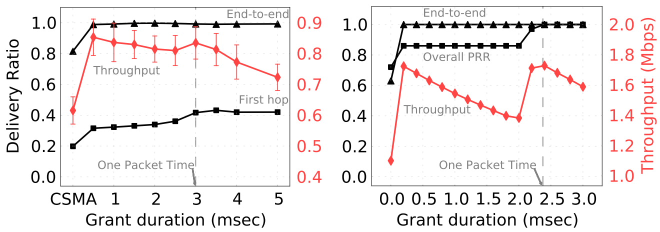
The 802.11 duration field is similar to a grant, but differs in mechanism and use. As a mechanism, the duration field does not suppress a transmitter, so that a node can transmit data after an RTS. Grant-to-send, in contrast, suppresses transmitters. In terms of use, 802.11 uses the duration field to state the duration of future transmissions *between the communicating pair*, while in grant-to-send it states the duration of future transmissions *to any destination*.

Implementing grant-to-send requires two modifications to existing 802.11b drivers. First, the driver must place grant intervals into the duration field. Second, the driver must suppress packet transmitters. These two changes represent a total change of 11 lines in the driver code. Reusing the duration field and NAV means existing 802.11 nodes respect grants that they hear and grant-to-send respects RTS/CTS exchanges. We defer discussing how a routing layer addresses 802.11b's variable bitrate to Section V.

We have modified the current MadWifi [3] and ath9k [1] drivers to provide grant-to-send on Atheros-based 802.11b/g and 802.11b/g/n cards. The experiments in Section V use the MadWifi driver running on Atheros based 802.11b/g cards and dual antennas. The 802.11 stack has a maximum link retransmission count of 11.

E. Grant-to-send Implementation in 802.15.4

802.15.4 is a low-power link layer that operates in the same 2.4GHz band as 802.11b/g. The maximum transfer unit, including header, is 127 bytes, with a bitrate of 250Kbps. The packet header has no analog to 802.11's duration field. Supporting grant-to-send requires inserting a one-byte header



(a) 5-node linear topology in testbed. (b) 7-node linear topology in ns-2.

Fig. 4. The effect of grant duration on UDP throughput, link delivery and end-to-end delivery. In the testbed, "first hop" is the link frame delivery ratio for the first hop. Both exhibit two peaks, at the minimum grant interval and at one packet time.

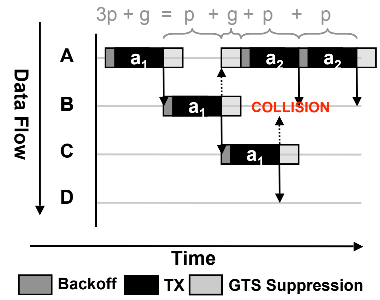


Fig. 5. A UDP flow using a short grant. A short grant gives a forwarder CSMA priority over the first transmitter, avoiding simultaneous transmissions. However, the source still encounters the hidden terminal problem at the first hop, and so has to transmit each packet twice.

between layer 2 and layer 3, specifying a grant duration between 0 and 255 milliseconds.

We implemented grant-to-send on 802.15.4 nodes with TI/ChipCon 2420 (CC2420) radio chip, running TinyOS [26] version 2.0.2. The underlying CSMA layer is the standard TinyOS 2.0.2 MAC. All experiments use the Intel Mirage testbed [17], which has MicaZ nodes. The implementation constitutes 50 lines of TinyOS code and adds nine bytes of state for a timer that marks when q_i expires.

IV. Grant Duration

Longer grants improve collision avoidance but shorter grants have higher channel utilization. This raises the question: how long is *long enough* for a grant? To answer this question, we examine the most basic case of a multihop protocol, a single UDP flow with a static bitrate.

A. Small Testbed

To experimentally determine the best grant duration, we deploy a seven-node 802.11b/g testbed in our building's hallways. In this experiment, each node uses a fixed 5.5Mbps bitrate and runs on channel 1, which was cleared for the purposes of the experiment. A few wireless APs in nearby buildings within reception range remain on channel 1. We use 5.5 Mbps because it is the highest bitrate that our logging facility permits. The routing layer uses Srcr [5], implemented using Click [25]. The packet source has a reasonably stable but not static route to the gateway that is typically 4 hops. We run iperf for 90 seconds with a payload of 1470 bytes to measure UDP's performance. As the last hop does not expect the destination (or the gateway if the destination is outside the multihop wireless network) to transmit wirelessly, it always specifies a grant of zero.

We use three metrics to evaluate the effect of grant-to-send. Throughput is the rate at which UDP delivers data. End-to-end is the percentage of transport-layer segments that arrived at the destination. This metric is important as many higher layer protocols, such as TCP, respond to end-to-end loss. First hop is the percentage of link-layer frames that arrived successfully at the first hop. In this case retransmissions via ARQ are considered separate frames and end-to-end delivery is higher than first hop due to ARQ. The first-hop metric is important because of its effect on mesh routing protocols; packet losses imply self-interference.

Figure 4(a) shows the results. CSMA sustains a throughput of 0.62 Mbps while having an end-to-end delivery ratio of 81%. A small grant of 500 μs increases throughput to 0.85 Mbps, a 37% improvement. End-to-end delivery ratio increases 98.8%, reducing losses by 94%.

Increasing the grant past 500 μs decreases throughput until it reaches 3 ms, at which point throughput jumps to 0.84Mbps, well within the experimental error of the throughput at 500 μs. Furthermore, a grant of 3 ms has an end-to-end delivery ratio of >99%, a >95% reduction in losses over CSMA and a 31% reduction over a 500 μs grant.

3 ms is the expected transmit time of a 5.5 Mbps packet, including CSMA backoff. A small grant greatly improves throughput and end-to-end delivery; a grant of a single packet time has the same throughput but even better end-to-end delivery. Intermediate values, while better than CSMA, are inferior to these two grant durations.

Unlike throughput, first-hop delivery increases steadily with larger grant durations. While CSMA has a first-hop delivery ratio of 20%, a small grant boosts this to 32%, and a full packet grant boosts it further to 42%. Increasing the grant past 3 ms does not improve the chance that the first hop will successfully receive a link-layer frame.

These results are from a single route in a somewhat controlled wireless network. Blindly generalizing them to all networks is dangerous. Instead, we turn to the repeatability, control and visibility of simulation to understand the cause of these peaks, and to see if they are fundamental or an artifact of the experimental setup. Simulation removes uncontrollable variables, such as external 2.4GHz interference.

B. Simulation

We simulate a 7-node chain topology in ns-2 with the 802.11Ext MAC layer at 6Mbps and a link MTU of 1500 bytes. The physical layer model consists of logical links, where nodes can communicate perfectly with the two adjacent nodes. The interference range is the same as the transmit range: packet reception fails only when two adjacent nodes transmit at the same time. In these experiments, we look at the overall PRR of all link layer segments, because of ns2's simplification of the wireless channel, where the increased forwarding load of grant-to-send causes all collisions to occur on the first link, unlike in real networks.

Figure 4(b) shows UDP's throughput and end-to-end network delivery ratio as a function of grant duration. While the values are different than in Figure 4(a) and the peaks are steeper, the simulation shows the same trends. The second peak is at 2.4 ms rather than 3ms because of the differences in preamble length and bitrate.

At the minimum grant, 200μs, both throughput and delivery are significantly higher than CSMA. From Figure 3, we know that a grant longer than a packet time avoids intra-flow collisions. Why does a short grant help?

Examining the simulation logs, we find that a small grant's benefit comes from delaying a transmitter slightly, so the forwarder is likely to win CSMA. Small grants do not avoid hidden terminal collisions. Packet a_2 still collides in Figure 5, as node A believes it can transmit at the same time as node C. Furthermore, grants longer than the CSMA backoff window harm throughput. A's first transmission of a_2 starts after B's grant concludes, but collides at B. A retransmits a_2, and this second transmission succeeds. A's first transmission will always fail as long as B's grant is shorter than a packet time, and it delays when A's second, successful, transmission occurs.

This explains why throughput declines between the two peaks. It also explains why overall PRR increases with a small grant, but does not reach 100% until 2.4 ms. The significant increase at 2.2 ms is because the actual packet time for 6 Mbps is between 2.2 and 2.4 ms.

C. Analysis

The simulation results allow us to describe grant-to-send analytically. In this analysis, p is the length of a packet, g is the grant duration in terms of p, and B is the maximum single-hop throughput of the link layer. In real networks g is in absolute time units such as microseconds; here it is in terms of p for simplicity.

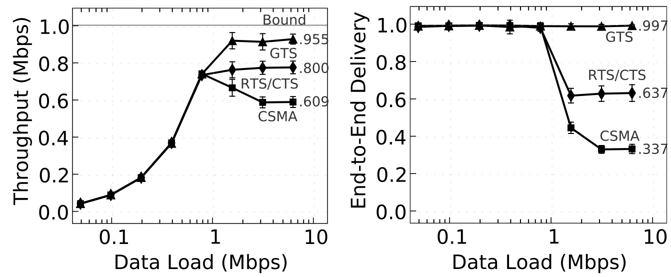
When $g = 0$ (CSMA, Figure 1), A and B contend for the channel. Prior work by Vyas et al. shows that such a flow can sustain a throughput of $\frac{B}{3+k}$, where k is in the range of 0.3 to 3, is typically well above 1, and depends on load as well as physical parameters [32].

When $g < p$ (Figure 5), A and B do not contend, but A's first transmission is lost due to hidden terminal C. A's inter-packet interval is $3p + g$: B's forwarding, B's grant, A's first transmission, and A's retransmission. The flow can sustain a throughput of $\frac{B}{3+\frac{g}{p}}$.

When $g \geq p$ (Figure 3), A transmits collision-free. A's inter-packet interval is $2p + g$: B's forwarding, B's grant, and A's transmission. The flow throughput is $\frac{B}{2+\frac{g}{p}}$.

Therefore, the throughput T of a grant g is

$$T(g) = \begin{cases} \frac{B}{3+k} & \text{if } g = 0 \\ \frac{B}{3+\frac{g}{p}} & \text{if } g < p \\ \frac{B}{2+\frac{g}{p}} & \text{if } g \geq p \end{cases}$$



(a) Throughput. The bound is 1/3 of the throughput of the bottleneck link.

(b) End-to-end delivery.

Fig. 6. UDP performance in a testbed for a single flow with varying load. Each data point is averaged over 21 runs. Error bars show 1-standard deviation.

From this analysis, the highest throughput is when $g = p$. This falls under case 3, such that the throughput is $\frac{B}{3}$, which is the maximum achievable throughput in flows longer than 2 hops [35]. As $g \rightarrow 0$, case 2 approaches but does not reach $\frac{B}{3}$. In real networks, grants smaller than the CSMA backoff interval cause B to sometimes lose CSMA, so as $g \rightarrow 0$ the network starts to behave as a mix of cases 1 and 2.

Figure 4(b) supports this analysis. In this simulation, $p =$ 2.4ms. The two peaks have a throughput of 1.72 Mbps, which is approximately one third of the single hop throughput of 5.5 Mbps. For example, for a 2ms grant (the worst grant in the plot), $3+\frac{g}{p} = \frac{18}{6}+\frac{5}{6} = \frac{23}{6}$. Therefore $T(2ms) = \frac{5.5Mbps \cdot 6}{23}$, or 1.4Mbps. The results in Figure 4(a) are in a real network with other contenders. They violate assumptions in the analysis so do not match the equation. For example, real networks exhibit the capture effect due to which some colliding packets may also be received [28]. Also, the grant duration used in the experiment has assumed the interference range is the same as the reception range. For the larger interference range, the optimal grant duration would also increase. In spite of these assumptions in the analysis and simulations, these experiments show a similar trend.

V. UDP in a Large Testbed

The prior section makes four simplifying assumptions: the transmit and interference range are equal, a node knows the next hop's transmission duration, routes are static, and there are few contenders. Evaluating UDP in a large testbed allows us to validate these controlled results in an uncontrolled environment. It also provides a basis for understanding more complex protocols in later sections.

These experiments use a 24-node testbed in the Gates Computer Science building at Stanford University. Unlike the controlled experiments in Section IV, the testbed shares the 802.11 spectrum with the building's heavily used wireless network. The 24 nodes are spread across 6 floors.

A. CSMA, RTS/CTS, and Grant-to-send

Figure 6 shows the throughput and end-to-end delivery ratio of CSMA, RTS/CTS, and grant-to-send (GTS) between a single node pair as the offered load increases. The route was typically 4 hops. Nodes used a 5.5Mbps fixed bitrate.

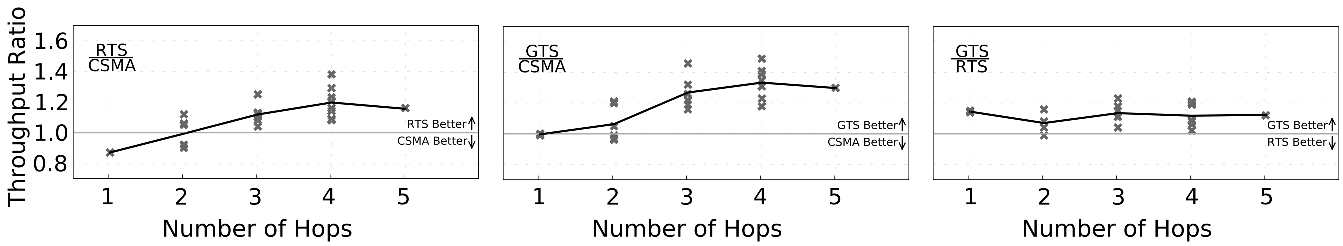


Fig. 7. Comparison of UDP throughput for node pairs on a 24-node testbed; the solid line traces the mean. Shorter routes favor CSMA and longer ones favor RTS/CTS. Grant-to-send maintains efficiency of CSMA in shorter routes, and outperforms RTS/CTS in longer routes, showing up to 49% gain over CSMA and 23% over RTS/CTS.

Hops	**# Pairs**	**GTS**	**CSMA**	**RTS/CTS**
1	2	2.60	2.60 (0%)	2.27 (15%)
2	6	1.19	1.12 (6%)	1.11 (7%)
3	6	0.90	0.70 (28%)	0.79 (13%)
4	8	0.77	0.57 (35%)	0.69 (15%)
5	1	0.65	0.50 (30%)	0.58 (12%)
Total	23	1.06	0.92 (15%)	0.96 (10%)

TABLE II
UDP THROUGHPUT (MBPS) FOR 23 NODE PAIRS AVERAGED FOR EACH HOP COUNT. PERCENTAGES SHOW GRANT-TO-SEND'S IMPROVEMENT. GRANT-TO-SEND HAS HIGHER OR EQUAL THROUGHPUT IN ALL CASES.

As in Figure 2, CSMA's throughput and delivery degrade after it is pushed past approximately 800Kbps, dropping to 608Kbps and a delivery ratio of 34%. RTS/CTS flattens at 800Kbps, maintaining a delivery ratio of 64%. Grant-to-send is able to sustain a throughput of 956Kbps and a delivery ratio of 99.7%. Under load and in the presence of other interfering transmitters, grant-to-send's throughput is 20% higher and it reduces end-to-end losses by over 99%.

The bound line in Figure 6(a) represents the theoretical throughput bound of the topology. We compute this by starting with the link-layer throughput measurement in Table I of 3.36 Mbps. As the route is longer than 2 hops, the bound is one third the link throughput [35]. Furthermore, packet losses reduce throughput: the bottleneck link has a PRR of 90%, cutting the throughput by one tenth, leading to an overall throughput of 1.01 Mbps. Grant-to-send achieves 965Kbps, 96% of this upper bound.

B. *Effect of Hop Count*

In this section, we measure the performance of grant-to-send using the full testbed. We pick one source that has a reasonable distribution of hop counts to other nodes, and measured the throughput of all 23 possible pairs. Each measurement is a 1 minute run of iperf. We measure each pair using CSMA, RTS/CTS, and grant-to-send, repeating this ten times. Each data point is the average of 10 runs. This comprises over ten hours of measurements.

Figure 7 shows the throughput ratios between collision avoidance schemes, grouped by hop count. Table II presents the raw results, averaged for each hop count. As these results are taken on a dynamic routing topology decided by Srcr, the hop count between two nodes can change over time. We sample the hop count between each pair before the experiment. Therefore, the number of hops shown is just for reference, and might not reflect the actual number of hops taken.

The top plot in Figure 7 shows CSMA has higher throughput than RTS/CTS in and 1- and 2-hop routes. This follows from the measurements in Table I; when collisions are rare, RTS/CTS imposes unnecessary overhead. At 3 hops, the hidden terminal comes into play and RTS/CTS sustains a higher throughput than CSMA – up to 38% – on a 5.5 Mbps link. This contradicts a common belief in the research literature [12], [14], [24] that CSMA is superior to RTS/CTS in wireless meshes; the primary experimental study, Srcr [12], only examined TCP on routes of up to 3 hops.

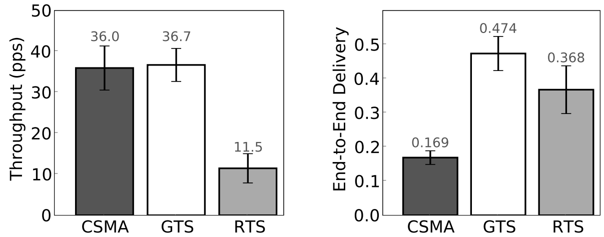
The middle plot shows that grant-to-send matches the throughput of CSMA for one-hop networks and is superior – up to 49% – on longer routes. The bottom plot shows that grant-to-send outperforms RTS/CTS for all hop counts.

C. *Variable Bit Rate*

So far, all nodes used the same bitrate, 5.5 Mbps, making the forwarder's packet duration predictable. However, routing layers often use bitrate adaptation to minimize transmit time.

Our modified Srcr implementation includes a grant adaptation scheme. A node maintains a hashtable keyed by the (next hop, destination) pair. The hashtable stores the last bitrate the node heard that entry use. Destination is necessary because it can change what link and bitrate the next hop uses. When selecting a grant duration, grant-to-send assumes the last bitrate heard. If there is no entry, grant-to-send assumes the fastest bitrate: the analysis in Section IV-C shows that underestimating is better than greatly overestimating.

This approach assumes that bitrates are stable. To check the validity of this assumption, we run Srcr with variable bit rates on top of grant-to-send and log when a grant does not match the subsequent transmission. This experiment is unfavorable for bitrate stability as nodes go through a startup settling period of finding the best rate. Across the 23 node pairs, 1.2% grants did not match. Of these, 66% were underestimates. Grant-to-send overestimates grants on 0.4% of transmissions.



(a) Throughput. (b) End-to-end delivery ratio.

Fig. 8. Event-driven collection on CSMA, GTS, and RTS/CTS. GTS delivers throughput comparable to CSMA's, while increasing end-to-end delivery.

VI. Collection Trees

In this section, we evaluate whether grant-to-send can replace a protocol-specific collision avoidance mechanism without loss in performance. In sensor networks, collection protocols construct minimum-cost trees to data sinks. These trees are unidirectional: they do not maintain reverse sink-to-source routes. Like UDP, collection protocols are connectionless and unreliable. Since multiple nodes can report data at once, collection protocols can be viewed as multiple UDP flows converging at a gateway.

Under this abstraction, however, collection protocols use very different mechanisms than 802.11 meshes in order to cope with environmental dynamics and energy constraints. For example, they use distance vector, rather than link-state algorithms. More generally, the importance of energy efficiency causes most layer 3 sensornet protocols to have custom built-in collision avoidance mechanisms.

A. CTP

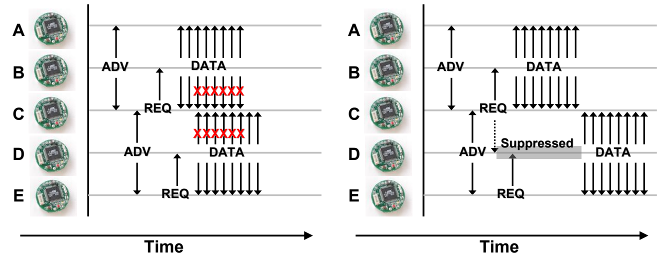
CTP is the standard collection protocol in TinyOS 2.1 [18]. It uses a transmit timer to avoid self-interference along a route. When a CTP node transmits a data packet, it waits approximately 2 packet times before sending another packet or retransmitting. This timer is local to a node. It does not prevent other nodes from immediately sending to the same next hop and colliding.

Grant-to-send can provide a superior mechanism to CTP's timer: it can avoid collisions with all nearby nodes, not just a single transmitter. We modify CTP by removing its transmit timer and instead having it send all data packets with a grant of one packet time (10ms). As with UDP, data packets to a data sink (the last hop) carry a grant of zero.

B. Evaluation

We evaluate grant-to-send in an event-driven collection scenario, where a subset of nodes detect an event and stream a large data report. Volcanic seismic monitoring is one example of an application that has such a workload [34]. The assumption in this scenario is that the low-power sensor network wakes up for a burst of activity: collision avoidance is not a major concern when the network is asleep.

We run CTP on 64 nodes in the Mirage testbed [17]. A radio packet simulates a triggering event, and 14 nodes that hear the packet begin streaming data to a sink. The source nodes are fixed throughout the experiments to minimize variations between runs. Source nodes stream packets for 15 minutes. Each result is the average of five runs.



(a) Standard Deluge. (b) V-Deluge and GTS-Deluge.

Fig. 9. A simple example of Deluge with and without collision avoidance, running on a chain topology.

Figure 8(a) shows throughput under CSMA, RTS/CTS and grant-to-send. Grant-to-send's throughput is 220% higher than RTS/CTS and within experimental error of CSMA. Grants can replace an existing layer 3 collision avoidance mechanism with no appreciable effect on throughput.

Figure 8(b) shows CTP's end-to-end delivery ratio. Grant-to-send's delivery ratio is 180% higher than CSMA's, and 29% higher than RTS/CTS. This improvement comes from the natural rate-limiting that grant-to-send provides. For example, while each CSMA node sends at most once every three packet times, the aggregation of this load towards the root causes queue drops. While grant-to-send does not completely solve this problem, it limits load in terms of broadcast regions, rather than individual nodes. Therefore, a group of nodes close to one another impose an aggregate load of at most one transmission every three packet times.

An astute reader will notice that the results in Figure 8 demonstrate a major difference between 802.11 and TinyOS's MAC layer. The throughput benefit of grant-to-send is much smaller in collection than in UDP. This can be explained by two observations. First, the CSMA and RTS/CTS results include CTP's transmit timer, providing better collision avoidance than UDP. Second, the default CSMA backoff interval in the TinyOS MAC layer dominates a packet time. An actual frame transmission takes approximately 1 ms, while backoff is 1-9 ms. Correspondingly, while routes do self-interfere, the interference is much less pronounced than with 802.11.

VII. Dissemination

In sensor networks, a dissemination protocol reliably delivers a piece of data to every node. This section examines Deluge [21], a dissemination protocol for data items much larger than node RAM. Deluge's typical use is distributing new node binaries into a network for in-situ reprogramming.

Deluge uses a three-way handshake to deliver a burst of data broadcasts. It is an evolution of wireless dissemination protocols such as SPIN [10]. Like CTP, Deluge uses protocol-specific suppression mechanisms at layer 3 to avoid data collisions and deliver data faster. This section examines whether grants are general enough to implement these mechanisms and achieve equivalent or superior performance.

A. Deluge and V-Deluge

Deluge periodically broadcasts what binary version a node has. When a node hears a newer version, it sends a unicast request for the data to the advertising node. A node receiving a request broadcasts a flurry of packets in response. When a node has part of the new image, it advertises quickly, such that neighbors with the older version request it.

Prior studies of the original Deluge protocol showed that sending bursts of data packets can cause long periods of high collision, as shown in Figure 9(a). A Deluge variant called Visible Deluge (V-Deluge) solves this problem by having requests suppress other traffic, as shown in Figure 9(b). These suppressions reduce dissemination time by 31% while simultaneously sending 46% fewer packets [33].

This suppression is a grant: when a node sends a request, it grants for how long it expects the flurry of data packets to take. Request packets already state how many data packets they need, so computing a grant duration is trivial. Data packets and advertisements have grants of zero.

This suppression through requests is not perfect. In Figure 9(b), for example, D cannot respond immediately to E's request, so E's grant will not cover all of D's data transmissions. However, if D is delayed long enough E will re-request and grant again.

B. GTS-Deluge

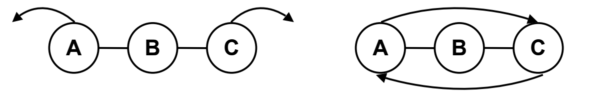
We modify Deluge in TinyOS 2.0.2 to grant as described above: the change involved adding a single parameter to the 3 function calls that send a packet (advertisement, request, and data). We call this version of Deluge GTS-Deluge.

We obtained the V-Deluge source code from its authors. We compare V-Deluge and GTS-Deluge with the same methodology and testbed (Mirage) used to compare standard Deluge and V-Deluge. Each experimental run involves injecting a new binary at one corner of the network. We measure two metrics, dissemination time and packet transmissions, as the average of ten runs. V-Deluge and GTS-Deluge perform equivalently; their latency and transmission counts are within 3%, a variation well within experimental error.

V-Deluge's mechanism can be easily expressed as a grant in GTS-Deluge, and the two have indistinguishable performance. GTS-Deluge requires 3 function call changes to Deluge. In contrast, V-Deluge modifies 247 lines of code, five times the entire implementation of grant-to-send! These results, together with the results from Section VI provide evidence that grant-to-send is more broadly applicable than unicast flows, and is general enough to describe existing higher-layer collision avoidance mechanisms.

VIII. Best Effort

The philosophy behind grant-to-send is to have a simple and lightweight but generally applicable collision avoidance mechanism. As grant-to-send takes a best effort approach, it has limitations and edge cases, which this section examines.



(a) A and C are hidden and grant other nodes.

(b) A and C are not hidden and grant each other.

Fig. 10. A and C take turns transmitting overlapping grants such that $tq_B > t_B$ casing starvation at B.

A. Inter-flow Collisions

Since grant-to-send is an intra-flow collision avoidance mechanism, the network is still vulnerable to inter-flow collisions. As discussed in Section VI, grant-to-send can still benefit inter-flow collisions when multiple flows share the same direction. However, grant-to-send does not address general inter-flow collisions.

For example, TCP traffic has two flows in opposite directions, one for data packets and the other for TCP ACK packets. For TCP, grant-to-send gets a modest 28% throughput gain with a marginal improvement in link-layer packet reception ratio. Since grant-to-send addresses collisions among data packets, it reveals that the bottleneck of wireless TCP lies in the collisions between data-ACK packets. Experiments with a reduced rate of TCP ACK packets show a 45% throughput increase with grant-to-send in a small testbed.

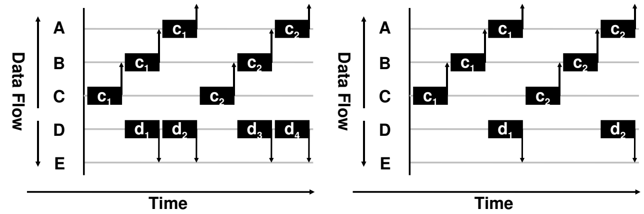
Inter-flow collisions are hard to address in the MAC layer, since dealing with hidden terminals requires two-hop reservation as in RTS/CTS, which introduces excessive overhead. We believe the network layer must address inter-flow collisions. For example, network coding protocols such as COPE [24] can be used to code TCP ACK packets with data packets, so that the network traffic looks like a single directional flow. Grant-to-send has benefits with multiple flows if they share the same traffic direction. Thus, grant-to-send, on top of network coding that converts opposing flows to single directional flows, can mitigate hidden terminals in a general scenario.

B. Starvation

Since grant-to-send suppresses transmissions, a natural concern is whether a node can get starved, such as node B in Figures 10(a) and 10(b). In both cases however, a single packet loss will break the starvation, as B will be able to fairly enter CSMA at the end of the last grant it heard. Needless to say, most wireless networks exhibit significant packet losses. In Figure 10(a) such an event could be due to the hidden terminal problem; in Figure 10(b) a loss could occur due to external interference, a random packet drop, or any of the other vagaries of wireless. These topologies also assume that no other nodes contend for the channel: if either A or C has to compete with neighbors, grants can suppress them while B transmits.

C. Fairness

Since grants can be multiple packet times, they can harm fairness. One node can receive large grants and use more than its fair share of the channel. Furthermore, grant-to-send as described in this paper simply transmits packets in FIFO order. Large grants can give a larger channel share.



(a) CSMA (b) Grant-to-send

Fig. 11. An edge case where grant-to-send exacerbates the exposed terminal problem and shows 33% throughput drop over ideal CSMA scheduling. C and D send packets in opposite directions.

Incorporating fairness mechanisms into grant-to-send is a natural extension to this work. Prior work by Choi et al. has used existing fair queueing mechanisms to implement protocol fairness while preventing inter-protocol interference using grant-to-send in 802.15.4 [16]. This work can be extended to provide other types of fairness on top of grant-to-send. Incorporating these fairness schemes can also alleviate starvation problems.

D. Exposed Terminals

The exposed terminal problem occurs when two nodes think they cannot transmit concurrently because they hear each other, but their transmissions would not collide at the intended receivers. Grant-to-send suffers more from the exposed terminal problem than CSMA, as Figure 11 shows. In this linear topology, C send multihop packets to A through B and D sends single-hop packets to E. Figure 11(a) shows the optimal schedule for CSMA, where B uses two thirds of the link throughput. Figure 11(b) shows how grant-to-send only gives D one third of the link throughput, as C's grant suppresses D. Allowing B and D to transmit concurrently would require knowledge of B's destination: if it is C, D cannot transmit.

While the exposed terminal is an issue in this and similarly constructed examples, its importance and prevalence in mesh workloads is unclear. Nearby nodes in access meshes use the same gateways, making this diverging traffic pattern uncommon. In the presence of other flows, neither C nor D would be able to use the link throughput as shown in Figure 11(a). Additionally, the throughput gains grant-to-send observes is comparable to the 33% reduction seen in Figure 11(b), such that its benefit balance out its costs.

E. Imperfect Grants and Retransmissions

Grant durations are the expected duration of the recipient's transmission(s). A recipient cannot guarantee that its transmissions will complete before the grant expires. There are many cases where a transmission takes longer than the grant: CSMA backoff due to external interference, link-layer retransmissions, and outstanding grants to other nodes (such as in Figure 9(b)) can all delay transmission.

Like CSMA and RTS/CTS, grant-to-send *avoids* collisions: it does not *prevent* them. The analysis in Section IV-C and experimental results in Section IV-A showed that shorter-than-optimal grants are superior to CSMA. Therefore, while an adaptive scheme to estimate transmission duration could improve performance, small grants are still better than no grants at all. An adaptive scheme that considers expected transmissions (ETX) is a possible future direction.

The optimal grant duration also depends on the interference/reception ranges that vary from node to node. For example, if the interference range is twice the reception range, the optimal grant should be two packet times instead of one. The current implementation does not consider this effect. A possible extension to this work may incorporate picking the optimal grant durations for different interference ranges across the network.

IX. Related Work

RTS/CTS as described in Section II is only the most basic instance; there is a long history of research and a plethora of variants. A full survey is beyond the scope of this paper so we merely mention a few prominent approaches. One well-understood limitation of RTS/CTS is that it is less effective when interference range is larger than the communication range [36]. BTMA [31] and DBTMA [20] solve this issue by introducing a sideband channel. In multihop wireless networks, collision avoidance is equivalent to the problem of physical layer spatial reuse. POWMAC [30] improves spatial reuse by exchanging signal information with RTS/CTS. MACA-P [6] accumulates multiple RTS/CTS exchanges to reduce unnecessary RTS/CTS suppression.

Grant-to-send has similarities to 802.11 fast-forward scheduling [9], which embeds an RTS in an acknowledgment packet to enable the receiver to forward immediately. Since fast-forward is built on top of RTS/CTS, it inherits the overhead for short routes. Furthermore, as fast-forward RTS packets do not go through CSMA, it sacrifices fairness between contending transmitters. As fast-forward requires different packet formats, it requires new hardware and is not compatible with existing networks. Alternatively, one might consider using short backoffs for forwarding packets. While this has a similar effect as fast-forwarding without altering packet frame formats, using shorter backoffs leads to excessive collisions in the network.

Network coding between the link and network layers has emerged as a way to increase throughput by having a single frame contain coded packets for multiple destinations. Grant-to-send is complementary to this work. Protocols such as MORE [14], MIXIT [23], and COPE [24] require receiving complete packets or at least uncorrupted packet fragments: reducing collisions boosts their performance. COPE, for example, notes that hidden terminals prevent it from achieving any coding gain in TCP, and so evaluates TCP in a single-hop, collision-free network with a logical routing topology.

Approaches such as ZigZag [19] and analog coding [22] can recover collided packets. ZigZag, for example, is designed for one hop AP-client networks, so APs can mitigate the hidden terminal problem between clients. Grant-to-send, in contrast, addresses the problem of collisions in a multi-hop mesh. A combination of these schemes, where grant-to-send runs on commodity mesh nodes and ZigZag runs at gateways with special hardware, could achieve both benefits.

X. Conclusion

Grant-to-send provides a simple and inexpensive way to avoid collisions in multi-hop wireless networks. It is easy to implement and is effective in many protocols and traffic patterns. It does not have the overhead associated with other schemes like RTS/CTS. This paper examined various traffic patterns in 802.11 and 802.15.4, and grant-to-send matches or outperforms both CSMA and RTS/CTS in all cases.

Grant-to-send has a very low barrier to adoption. As grant-to-send uses the 802.11 duration field, standard 802.11 nodes respect grants and grant-to-send respects RTS/CTS. Many of our experiments occurred in the midst of a busy 802.11 network during working hours. Furthermore, as grant-to-send reverts to simple CSMA at the last hop, so act identically to standard CSMA devices when talking to an AP.

Grant-to-send is able to achieve these results by rethinking the information flow in collision avoidance. Rather than avoid loss of its own packets due to collisions, a grant-to-send node helps others avoid collisions. Networks have traditionally been modeled as individuals that compete, at time selfishly, within certain rules. Grant-to-send's efficacy suggests that, at least in wireless meshes, perhaps these rules should enforce more collaborative relationships.

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