Fast Flooding using Cooperative Transmissions in Wireless Networks

Marjan Baghaie A. and Bhaskar Krishnamachari

Department of Electrical Engineering - Systems, Viterbi School of Engineering
University of Southern California, Los Angeles, CA, 90089
Email: {baghaiea, bkrishna}@usc.edu

***Abstract*— Physical layer cooperation can be a powerful tool for enhancing the performance of multi-hop wireless networks. In this paper, we analyze the time to complete a cooperative broadcast to flood some information from one node to all nodes in a wireless network. We show that with cooperation the total time to complete the broadcast grows only logarithmically with the network diameter (unlike in traditional systems where time to flood increases linearly with the diameter). Simulation results validate the analysis, and show that the improvements in flooding time are more pronounced for higher density networks. We further compare the energy costs of cooperative and traditional flooding, and show that the improvements in flooding time with cooperation do not come at the expense of higher energy costs. These results, albeit based on an idealized form of cooperation, provide a strong motivation to develop and test practical schemes for cooperative flooding in multi-hop wireless networks.**

***Keywords*— Cooperative transmission, wireless networks, broadcast, flooding time.**

I. INTRODUCTION

A packet transmitted by a node in a wireless network is received by not only the intended recipient but also by other nodes in the nominal reception range of the transmitter. This innate property of the wireless medium can be a hurdle in point-to-point systems, where there is only one single intended recipient and the remaining neighboring nodes must treat that received packet as undesired interference. Nonetheless, broadcast systems can be designed to achieve potential performance gains by taking advantage of this property.

Many network protocols used in multihop wireless networks such as mobile ad hoc and sensor networks need to operate in broadcast mode to disseminate/flood certain control messages to the entire network (for instance, to initiate route requests, or to propagate a query). This can in turn amount to a significant portion of the network traffic, which may lead to a performance bottleneck. As such, the subject of broadcast transmission in multi-hop wireless networks has attracted a lot of attention from the research community (e.g., see [1], [2], [4], [5] and the references therein).

In this paper we consider a network operating in broadcast mode employing a *cooperative transmission protocol* whereby nodes in possession of a fully decoded packet transmit that packet together in each round of broadcast. Receiving nodes combine the information obtained from multiple transmitters to decode the packet. In conventional systems, the simultaneous transmission of identical information is considered a problem as it results in a packet collision[1]. In the case of cooperative systems, however, this redundancy is actually beneficial.

Cooperative transmission protocols for multi-hop wireless networks are being increasingly discussed in the literature in recent years (e.g., [3], [4], [5], [6], [7], [8]). The contribution of our work is that it provides the first analysis of the time required for cooperative flooding. Our results show that with cooperation, flooding times scale logarithmically with the diameter of the network, in contrast to linear scaling for traditional flooding; and that these gains do not come at the cost of higher energy costs.

Our study assumes an idealized setting for cooperation, where the powers from synchronous cooperating transmitters are assumed to be additive at a receiver. It

The work described here is supported in part by NSF through grants CNS-0347621, CNS-0627028, CCF-0430061, CNS-0325875, and by NASA through an AIST grant. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF or NASA.

---

[1] For instance, treating this problem of excessive collisions during flooding is the subject of the well-known work by Ni *et al.* [1]

can be argued that such an analysis provides only an upper-bound on real-world performance of cooperative strategies. Our optimistic results do suggest strongly, however, that there is sufficient motivation to further develop practical cooperation schemes and explore their performance, particularly for large, densely-deployed wireless networks, where flooding events are common.

II. SYSTEM MODEL

We consider a cooperative flooding protocol in which the broadcast is initiated by a source node transmitting one packet. All the nodes in the network that are within the transmission range of the source node, are assumed to *hear* the source with *sufficient* signal-to-noise ratio (SNR) to be able to decode the message correctly. In the following time interval, the same packet is transmitted by all the nodes that have successfully decoded it in the previous interval(s), but have not transmitted it so far, and the procedure is continued until all the nodes in the network have received the original packet. The receiving nodes are assumed to exploit the signals from not only from their immediate neighbors (i.e. those who have transmitted the message at the current time interval) but from all the nodes that have so far transmitted the message. The transmission power is kept constant for all nodes throughout the broadcast. Appropriate channel coding is assumed so that the decoding and re-transmission are done successfully, so long as the SNR is above some pre-determined threshold.

We assume that the N nodes in the network are distributed randomly and uniformly in a region. We assume an idealized cooperation setting in our analysis such that the received signal power of simultaneously transmitted packets is equal to the sum of the received powers of the individual packets had they been separately transmitted one at a time. This can be approximated in practice through synchronized transmissions and maximal ratio combining with channel estimation over orthogonal channels/codes/delay taps at the receiver end. These assumptions are commonly used in models employed in literature (e.g., [3], [5], [6], [7]).

III. FLOODING TIME IN COOPERATIVE BROADCAST

We consider a deterministic channel model, where the received signal power, on the medium is assumed to decay with distance with a constant path-loss exponent η. Successful reception at each node depends on the received signal power and the noise variance at that node.

If we define the transmission range of a single node transmitting with power P_s to be a disc of radius R, then assuming unit variance for noise, the corresponding received signal power at a receiving node, which is located at a distance d from the transmitting node can be expressed as $P_r = P_s.d^{-\eta}$. The reception threshold at each receiving node can be expressed as

$$\tau = P_s.R^{-\eta} \tag{1}$$

The message can be successfully decoded at a node if and only if the total received signal power at that node is greater than or equal to τ.

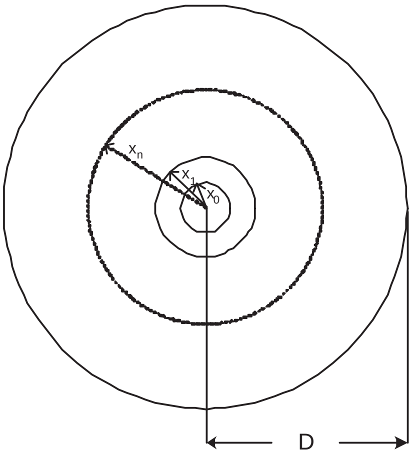

Fig. 1. Transmission propagation model for cooperative flooding

.

To study the effect of cooperative broadcast, and the amount of time it takes for a packet to be delivered to the entire network, let us consider a network defined by a mega-disc of radius D. Without loss of generality, assume that the transmission starts at time t_0 with a node located at the center of this mega-disc. At time t_1, all the nodes located in a disc of radius x_1 from the center have received the packet. The nodes located at the ring determined by inner radius x_0 and outer radius x_1 will start relaying data at t_2 covering a bigger disc with radius x_2 and so forth until the entire network is covered. The arrangement is pictorially presented in Figure 1.

The number of nodes, for any given radius, x, from the center can be represented by $n(x) = \pi x^2 \rho$, where ρ is the density [node/area]. In the analysis that follows, we consider a *continuum network* model [5], whereby the number of relay nodes N goes to infinity, while $P_s N$ is fixed. In the simulation section though, we consider a finite network with finitely many nodes, each of which transmits with a constant transmit power.

Here, we derive an approximate expression for T using the continuum network model, discussed in [5] (specifically, we base the following analysis on equation (74) of that work, pertaining to cumulative cooperation).

Based on that model for the case when the path loss exponent $\eta = 2$, we can write a recursive equation for x_t as,

$$x_t^2 = \frac{\mu}{\mu - 1} x_{t-1}^2 \tag{2}$$

where, $\mu = \exp\left(\frac{\tau}{\rho P_s \pi}\right)$ and the initial condition is given by $x_0 = R$. This can be re-arranged as

$$x_t = \left(\frac{\mu}{\mu - 1}\right)^{t/2} x_0 \tag{3}$$

substituting x_t and x_0, with D and R respectively and solving for T, we get

$$T = \frac{2 \log\left(\frac{D}{R}\right)}{\log\left(\frac{\mu}{\mu - 1}\right)} \tag{4}$$

The expression obtained in (4) clearly shows that with cooperation, the time to complete the flood is a logarithmic function of the hop-diameter of the network.

The analytical estimate of flooding time is plotted for different network radii in Figure 2. As can be seen from the figure, the flood time grows logographically (as opposed to linearly) with the network diameter. The continuum model, used in analysis, only provides closed form solutions for η values equal to 2 and considers infinitely many nodes with a constant sum-power. We explore other η values and look at finite network effects with a constant transmit power per node, using the simulation model presented in Section IV.

IV. SIMULATION RESULTS

In this section, we look at the performance of the cooperative broadcast in networks with finite number of nodes, where the nodes are uniformly distributed throughout the network. Throughout, D denotes the network radius, R is the transmission range of a single node and T is the number of cycles it takes to transmit the packet to the entire network. The results shown are average values, obtained by repeating the experiments multiple times. A customized simulation in MATLAB was used for producing the results.

A. Simulation setup

The transmission is initiated from a source node located in the center and we assume the detection time is negligible. The relay nodes decode and transmit the message if and only if their SNR exceeds a certain threshold τ. At every broadcast step, the set of nodes with reception power exceeding τ, which has not transmitted so far, transmits the message and so forth. Each node is assumed to have a *memory*, whereby it accumulates and exploits all the transmissions before them by storing the received signals from previous broadcast rounds and combining them via maximal ratio combining.

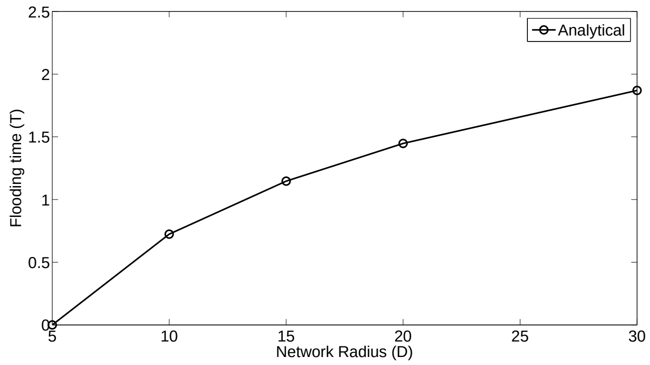

Fig. 2. The analytical flooding time of the cooperative scheme for varying values of network radius, $\rho = 0.08, R = 5$

We keep track of energy consumption costs of the cooperative scheme by calculating the transmission cost TC and the reception cost RC per broadcast. The former is calculated by accumulating the number of nodes that are in transmission mode in each step, for all broadcast steps and the latter is calculated by accumulating the number of nodes that are listening (are in reception mode) in each step, for all broadcast steps. We later compare these costs to those of a traditional flooding scheme. Notice in the cooperative scheme described, the total transmission cost will never exceed the number of nodes in the network, as each node can only transmit once. However, the reception cost might be more than the number of nodes in the network, since a node might have to remain in listening mode for a few rounds before being able to decode the message.

B. Effect of network parameters

Figure 3 shows the effect of η on the flooding time. As expected, the higher the value of η the longer it takes for the message to propagate throughout the network. The logarithmic relationship between the flood-time and the diameter of the network is also evident from the results.

As discussed previously, one advantage of using cooperative broadcast is that the collisions between different transmitting nodes can work to our advantage. This is shown in Figure 4, whereby — in contrast to traditional broadcast strategies — as the network density increases the time it takes for the packet to be transmitted to

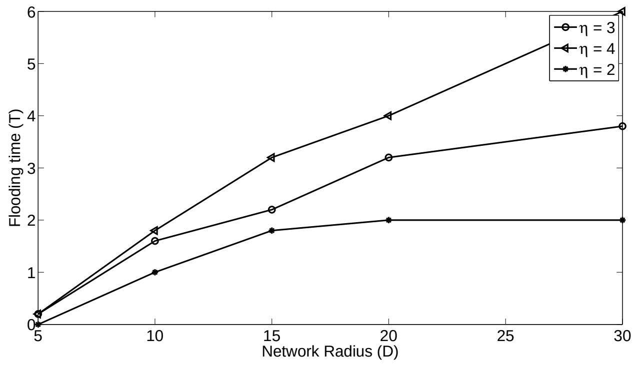

Fig. 3. Flooding time for varying values of network radius in the cooperative scheme, $\rho = 0.08, R = 5$

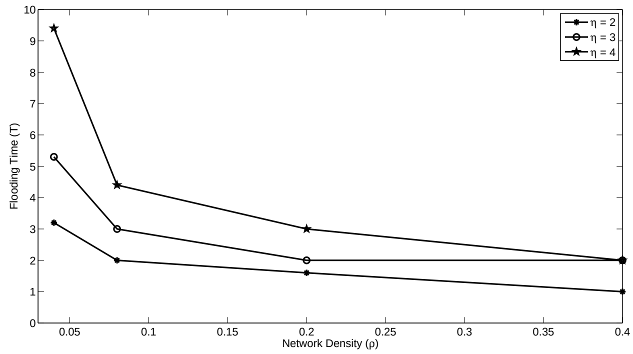

Fig. 4. Flooding time for varying values of network density in the cooperative scheme, $D = 20$, $R = 5$

the entire network decreases. The curve highlights in particular the advantages of using cooperative schemes in high density wireless networks.

C. Comparison with traditional flooding

In this section, we simulate a traditional collision-free flooding scheme, in order to provide a means of comparison between the time to flood and energy costs between the traditional and cooperative schemes. The simulations are done for arbitrary network parameters, whereby the network is chosen to be dense enough to ensure that the nodes are connected.

The traditional flooding protocol that we simulate works as follows: the transmission starts with a node at the center. All the nodes that can hear the message with a SNR above τ will decode the message successfully. A random priority queue will be formed from the nodes that have successfully decoded the message but have not transmitted it yet. In the next round of transmission the node with the (randomly assigned) highest priority from that queue will be assigned as the primary transmitter. Any other node, in the priority queue, in the order of their priority is either assigned to work in transmission mode or in contention mode. The former happens if the node is located in a distance greater than $2R$ from all the nodes that have previously been assigned as transmitter in that round, otherwise the node is said to be in contention mode in that round. The distance $2R$ is chosen to avoid collisions, in other words, the interference from adjutant transmitters is considered negligible if the node is not within the transmission range of the interfering transmitter. The priority queue is updated after each round of broadcast and it continues until the message has been delivered to the entire system. The network is chosen to be dense enough to be connected, so we can be sure that the message will get through to the entire network. The nodes that are yet to receive the message are considered to be in listening mode. Notice that each node can only transmit once, before the transmission is done the node is either in listening mode, in contending mode or in transmission mode.

In Figure 5, the flooding time is shown for the cooperative scheme vs the traditional flooding. As can be seen, unlike the cooperative scheme, the flood time grows almost linearly with the network diameter in traditional flooding. Figure 6 presents the energy consumption comparisons for the two schemes. The transmission cost TC and listening/reception cost RC are defined as described earlier in this section for both schemes. For traditional flooding, there is an additional contention cost, shown as CC, which is calculated as one unit per node for each round of broadcast at which the node is in contention mode. The results indicate that the cooperative scheme can flood the network more efficiently than the traditional flooding in terms of both the time and energy consumptions. Notice however that the receiver structure in the cooperative case needs to be more complex to deal with the memory issues and to decipher the signals received from multiple sources.

V. CONCLUSION

The use of cooperative transmission in broadcast wireless networks is becoming increasingly popular due to the advantages they offer over conventional schemes. In this paper, we provided the first analysis of the time required for broadcast flooding with cooperation. The analysis shows a logarithmic relationship between the flooding time and the ratio of the network radius to the transmission range of a single node (the hop-diameter of the network, in the traditional setting). Thus flooding using physical layer cooperation is fundamentally faster

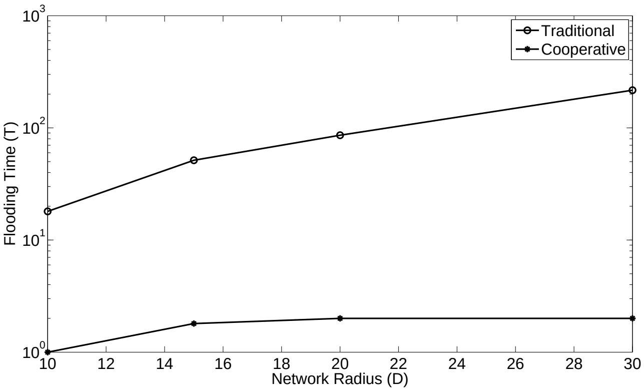

Fig. 5. Time comparison of cooperative flooding and a traditional flooding protocol, $\rho = 0.08, R = 5$

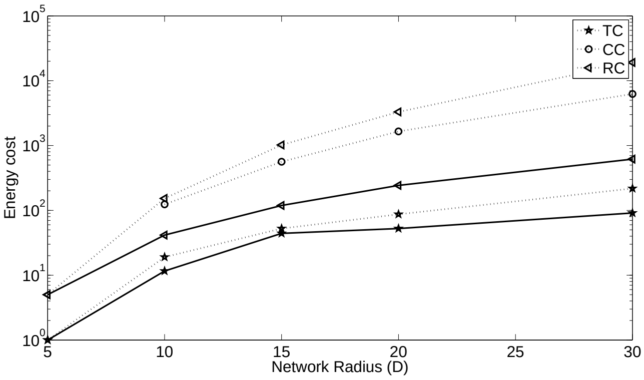

Fig. 6. Energy costs for cooperative flooding (solid lines) and traditional flooding protocol (dotted lines), $\rho = 0.08, R = 5$

than traditional flooding where the flooding time grows linearly with the hop-diameter.

We validate this analysis using a simulation model of a broadcast network with finite nodes. The results demonstrate the advantages of cooperative broadcast over traditional schemes in the sense that, unlike traditional schemes, in cooperative schemes the flooding time decreases as we increase the network density.

We compared the performance of the cooperative scheme to a traditional flooding scheme. The cooperative scheme was found, through simulation, to be superior both in terms of flood time and energy consumption. However, in practice some penalty must be paid for the additional complexity required by the receiver in a cooperative setting. Analyzing the complexity related issues are beyond the scope of this paper but could be a good venue for further investigation. Notice also that optimizing the traditional scheme was not considered in this work and can be a topic of further investigation.

The model considered in this paper represents an idealized scenario since we effectively assume perfect synchronization and maximal ratio combining using perfect channel state information at receivers from a large number of senders. Further, we have assumed a deterministic channel model. The analysis and simulations presented in this paper strongly suggest that a huge potential gain can be achieved by pursing cooperative designs and as such provide strong motivation for the development of more realistic simulations and practically implementable versions of these methods.

REFERENCES

[1] S.-Y.Ni, Y.-C. Tseng, Y.-S. Chen, J.-P. Sheu, “The broadcast storm problem in a mobile ad hoc network,” in *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking (MOBICOM)*, 1999.

[2] B. Williams and T. Camp, “Comparison of broadcasting techniques for mobile ad hoc networks,” in *Proc. Int. Symp. Mobile Ad Hoc Networking Computing (MobiHoc 2002)*, pp. 194-205, June 2002.

[3] A. Khandani, J. Abounadi, E. Modiano, Lizhong Zheng, “Cooperative Routing in Wireless Networks,” in the *Allerton Conference on Communications, Control and Computing*, October, 2003.

[4] I. Maric and R. D. Yates, “Cooperative multihop broadcast for wireless networks,” *IEEE J. Select. Areas Commun.*, vol. 22, no. 6, pp. 1080-1088, Aug. 2004.

[5] B. Sirkeci-Mergen, A. Scaglione, and G. Mergen, “Asymptotic analysis of multistage cooperative broadcast in wireless networks,” *IEEE J. Inform. Theory*, vol. 52, no. 6, pp. 2531 - 2550, June 2006.

[6] S. Chen, U. Mitra, and B. Krishnamachari, “Cooperative communication and routing over fading channels in wireless sensor network,” in *Proc. IEEE Int. Conf. Wireless Networks, Commun., and Mobile Computing (WirelessCom)*, June 2005.

[7] B. Sirkeci-Mergen, and A. Scaglione, “On the power efficiency of cooperative broadcast in dense wireless networks,” *IEEE J. Select. Areas Commun.*, vol. 25, no. 2, pp. 497 - 507, Feb. 2007.

[8] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, and P.V. Krishnamurthy, “On Broadcasting with Cooperative Diversity in Multi-hop Wireless Networks”, *IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Cooperative Communications and Networks*, February 2007.