RANDOM CELLULAR NETWORKS FOR TACTICAL COMMUNICATIONS

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ABSTRACT

Most wireless networking communications systems are prone to suffer congestion collapse. Current approaches to avoid this adverse effect seek solutions in scheduled access protocols and in architectures that reduce the effect of contention. The tradeoff in these designs is reliability for losses in capacity and flexibility. We propose a new access mechanism that retains the flexibility and capacity that is required for tactical communications yet is very robust to congestion. Better yet, this protocol orchestrates spatial reuse by creating a cellular like layout of contenders that can communicate simultaneously. This geometry also enables the exploitation of capacity increasing technologies of cellular telephony.

1. INTRODUCTION

The paradigms most normally used to design tactical communications systems combine either asynchronous contention based or scheduled access mechanisms with flat, hierarchical, or fixed architectures. Efficiency, flexibility and reliability are the tradeoffs between these choices. In Section 2, we list several examples of the limitations of these choices and attempt to make the point that none are all that attractive. We then propose a new paradigm in Section 3 that is built upon a synchronous contention based access mechanism called Synchronous Collision Resolution (SCR)[1]. In Section 4, we demonstrate that this protocol not only avoids the limitations of the other architectures but that it can orchestrate a spatial reuse of the wireless channel that is highly efficient. In Section 5, we describe how this same protocol creates the conditions that enable the exploitation of the capacity increasing communications technologies of cellular telephony. We call the resulting networking approach, random cellular networking.

2. COMMUNICATIONS DEFICIENCIES

The most serious failure mechanism of wireless medium access control (MAC) protocols is congestion collapse. Congestion collapse is a phenomenon that causes a decrease in performance as a result of load. We illustrate the phenomenon in Figure 1. As load increases, throughput decreases. Congestion collapse occurs when three conditions occur: 1. service attempts may result in failures, 2. the rate of failures increases with offered load, and 3. failed packets are regenerated. The most critical of these conditions is the dependence of failure rates on load.

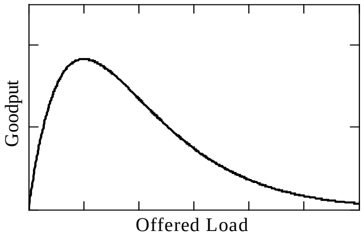

Figure 1. The congestion collapse effect

The events that cause failures are collisions, interference, and blocking. A collision occurs when a node within range of a destination attempts to access the channel while that node is already receiving a packet. Collisions are most commonly associated with aloha protocols where there is no effort to carrier sense before access attempts. Carrier sensing is no guarantee either as nodes outside the range of a transmitter, a.k.a. hidden nodes, may transmit resulting in a collision at the destination. Proposed solutions have included the use of unique spread spectrum codes, the use of a request-to-send (RTS) – clear-to-send (CTS) handshakes to cause virtual carrier sensing around the destination, and scheduled access. None of these approaches eliminates the load-based failures. Using spread spectrum codes defeats the carrier sensing mechanism, so although collisions do not occur in the same channel, there is interference across channels. In Figure 2, we illustrate a deficiency of the RTS-CTS handshake. In the illustration, N2 fails in its contention to send a packet to D2 since D2 is virtually carrier sensing after hearing the CTS from D1. N2 will defer and contend again. If D2 continues to be in a carrier sensing or virtual carrier sensing mode, N2 will continue to fail. At some point, N2 may drop the packet. Scheduling mechanisms generate access schedules that prevent neighbors from communicating on the same channel. The disadvantage of this approach is that it is inefficient. Dividing a channel a priori amongst users will lead to wasted capacity when a node has no traffic to send. Additionally, there is overhead associated with creating schedules that further decreases capacity. Although congestion collapse may be avoided in the access mechanism, scheduling simply pushes the problem into other networking layers where collapse occurs because of the limited capacity on links.

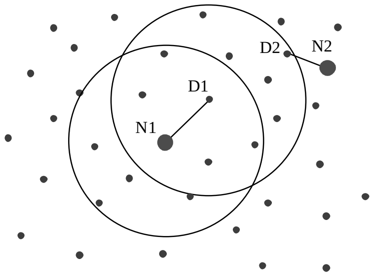

Figure 2. Blocking as a result of virtual carrier sensing. D2 does not respond to N2’s transmission since it is deferring after receiving D1’s CTS transmission. Circles represent the range of virtual carrier sensing.

Architectural approaches have been proposed to reduce the effects of congestion. The idea is to group clusters of nodes onto common channels and then to connect these clusters by some sort of backbone network. Keeping the number of nodes in clusters small mitigates access congestion. The Tactical Internet (TI) and the proposed wideband networking waveform (WNW) of the Joint Tactical Radio System work on this principle. The shortcoming of the TI approach is the inflexibility of the architecture, which prevents operational flexibility as well as making the network very prone to catastrophic failure when nodes are lost. The

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[1] Patent pending.

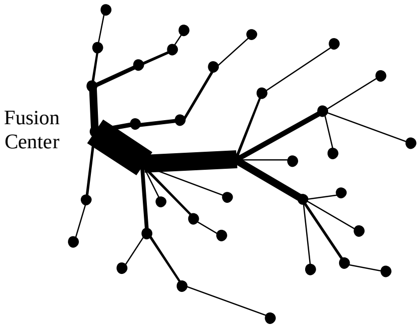

Figure 3. Traffic fusion. The size of the links corresponds to the quantity of traffic across those links to and from the fusion center

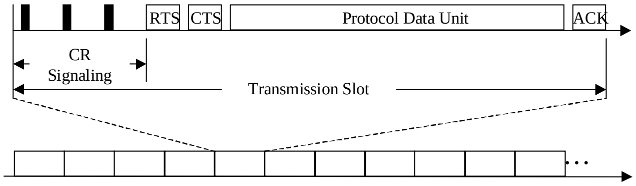

Figure 4. The Synchronous Collision Resolution Protocol

WNW attempts to create a more flexible architecture where clustering and a scheduled channel assignment are done dynamically. The authors are not privy to the specific algorithms but typically clustering protocols require a lot of overhead to create and maintain the clusters. Overhead, and thus capacity is dependent on the volatility of the network topology.

Another source of congestion is traffic fusion. Fusion centers occur where network traffic tends to converge. Figure 3 illustrates the effect of converging traffic. Traffic converges to nodes that provide access to network backbones, command and control centers, and to critical data servers.

We conclude that congestion is a spatial phenomenon that is caused by network use and network design. Design approaches that attempt to prevent access congestion problems tend to reduce network flexibility and to waste channel capacity. We now propose an access mechanism that is contention based, does not suffer congestion collapse, and supports a completely flat architecture.

3. SYNCHRONOUS COLLISION RESOLUTION (SCR)

Figure 4 illustrates the SCR protocol. The network channel is time slotted into transmission slots. Each of these transmission slots is preceded by a period of signaling called collision resolution signaling (CRS). CRS is highly effective at resolving collisions. CRS can be designed in many ways but the easiest to describe and the most effective consists of a series of signaling slots. Contenders randomly determine in each slot whether they will or will not signal. If a contender hears another node contend when it does not, it defers from contending in that transmissions slot. Performance is designed by selecting the probabilities that contenders will signal in each slot. Figure 5 illustrates the performance of a 9 slot signaling design. With better than .99 probability more than 200 nodes can contend simultaneously with just one survivor remaining at the end. Since the signaling process has no memory, the protocol is completely fair in granting access.

4. ORCHESTRATING SPATIAL REUSE

SCR has an even greater significance in an ad hoc network. In addition to resolving contentions locally, it enables multiple nodes to access the channel simultaneously. Figure 6 illustrates the effect. The protocol takes a set of contenders and then identifies a subset of these contenders that are spatially separated from each other. With .99 probability, these surviving nodes are further than the range of their transmitter from any other survivor. Adjusting the power used in signaling can control separation distance.

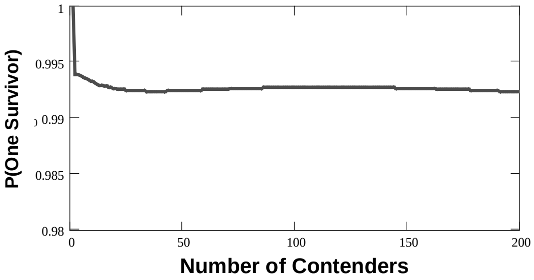

Figure 5. Performance of a 9 slot collision resolution signaling design

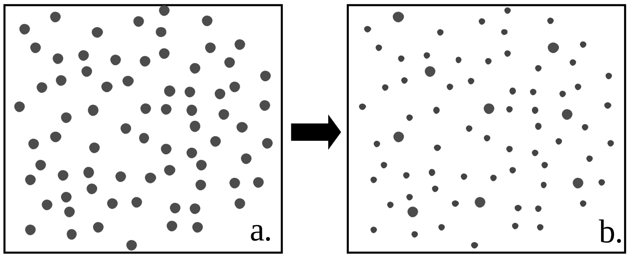

Figure 6. The effects of signaling. All nodes are contenders in panel a and then signaling resolves a subset of these contenders in panel b, where all the surviving contenders are separated from each other by at least the range of their signals. Large nodes are contenders.

5. RANDOM CELLULAR NETWORKS

The final distribution of surviving contenders can be best described as a random cellular network where survivors, like base stations, are separated from each other and numerous non-contending nodes, like cellular phones, are within their range. This geometry is the feature that enables exploitation of cellular communications technologies. Surviving contenders can send packets to multiple destinations simultaneously just as base stations in cellular networks. The technologies developed for cellular telephony, such as orthogonal code division multiple access (OCDMA) and smart antennas can be applied in the network. The network retains its ad hoc nature as the random cellular distribution of contenders changes at a rate of hundreds to thousands of times a second.

6. CONCLUSION

We briefly discussed failure mechanisms in wireless networks and identified congestion collapse as a chief cause of failure. We then proposed a new access mechanism that does not suffer congestion collapse. Better, this mechanism orchestrates high spatial reuse of a channel and creates the conditions that enable exploitation of the capacity increasing technologies of wireless telephony. Even better, as is described in [Stine et. al. 2002], this protocol provides the foundation where quality of service can be guaranteed.

REFERENCES

J. Stine, B. Durst, and K. Grace, “Methods to Achieve Capacity and Quality of Service in Ad Hoc Networks,” Proceedings of the Army Science Conference, 2002.