USAP Multiple Access: Dynamic Resource Allocation for Mobile Multihop Multichannel Wireless Networking

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Abstract-**A number of tactical military and commercial applications require self-organizing, wireless networks that can operate in dynamic environments and provide peer-to-peer, multi-hop, multi-media communications. Rockwell Collins developed the Soldier Phone to meet these needs as part of the WireCom Engine Technology Reinvestment Program jointly sponsored by DARPA and CECOM [1]. USAP Multiple Access is the part of the system that manages the TDMA slot and channel assignments for optimal operation in the face of changing topologies and traffic requirements.**

I. INTRODUCTION

Key to adaptive TDMA is the ability of neighboring nodes to transmit without interference. They do this by choosing time slots and channels that do not cause collisions at the intended unicast or broadcast receivers. This functionality is provided by the patented Unifying Slot Assignment Protocol (USAP) [2] which monitors the RF environment, allocates the channel resources on demand from higher level heuristics, and automatically detects and resolves contention resulting from changes in connectivity. As depicted in Fig. 1, USAP Multiple Access (USAP-MA) is a new type of channel access that results from the integration of USAP with a family of heuristics that enable it to satisfy the requirements of the Soldier Phone.

Wireless channel access schemes traditionally come in two flavors: **contention** and **reservation**. Contention has been a favorite for ad hoc broadcast networks because its lack of structure makes it easy to accommodate a mobile environment. However, a reservation TDMA like USAP-MA can achieve much higher efficiencies under heavy loading by adapting the transmission schedules. Another dichotomy is the tradeoff between **broadcast** and **unicast**. A case can be made for both, depending on the application, so ideally either technique would be available. USAP-MA supports both in a flexible fashion so that the best instantaneous mix can be achieved to match the applications, the loading, and the topology. Also, the ideal channel access would support both **reserved circuits** and **datagrams** in whatever combination is required. USAP-MA does this by providing for the establishment and maintenance of virtual circuits as well as a permanent datagram service that can allocate soft circuits in response to traffic surges. It does all of this while optimizing for densities ranging from **fully connected to sparse** and, because it relies only on local information, **scaling to large networks**.

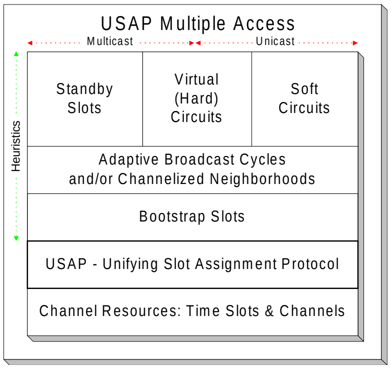


Fig. 1. USAP Multiple Access

II. USAP FUNDAMENTALS

Since the problem of optimally assigning slots in this environment is intractable, prior to USAP a heuristic approach was typically taken to design an application specific protocol that both chose the number of slots to assign to each neighboring node and coordinated their activation (see [3] for example). The USAP approach separates the slot assignment mechanism from the heuristic and creates a single generalized protocol for reliably choosing the slots and coordinating their activation. This can then be used to support many different higher layer heuristics for selecting the number of slots to be activated with which neighbors. Because of its ability to tie together diverse higher layer protocols, it is called the “Unifying Slot Assignment Protocol”.

Traditionally, there are two methods in which a node transmits to its neighbors. The first, known in the literature as “node activation”, has a transmitter broadcast to all of its neighbors at once rather than individually. When a transmitter has only one intended receiver it is known as “link activation”. The former allows only one active transmitter in a neighborhood while the latter can potentially have several, as depicted in Fig. 2. Node activation is especially well suited for applications like address resolution and conferencing. Link activation on the other hand lends itself better to high volume point-to-point traffic. USAP-MA has

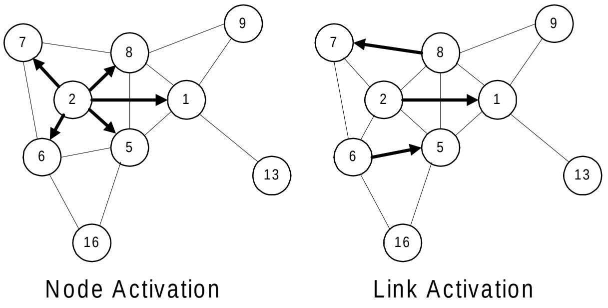


Fig. 2. Activation Schemes

heuristics to support both under the more common names of broadcast and unicast.

Since it will be useful to have a way of referring to an ordered pair of RF channel and time slot, the word “allocation” will be used for this purpose. When a node chooses an allocation, USAP enforces certain constraints to avoid interference within 2 hops of the transmitter. For unicast from node i to neighbor j it must be an allocation:

- that has not already been assigned to either node
- i’s neighbors are not receiving in
- j’s neighbors are not transmitting in

For broadcast a node i must choose an allocation:

- that has not already been assigned to node i or any of its neighbors
- none of i’s neighbors’ neighbors are transmitting in.

As described in [2], a node insures that its allocations satisfy the above constraints by sharing the following USAP slot sets with its neighbors:

STi - allocations where a node is transmitting
SRi- allocations where a node is receiving
NTi- allocations where a node’s neighbors are transmitting

To minimize the size of the control packets needed to share this information, it may be more efficient to encode these sets as bit maps or as lists, depending on the number of slots and channels being managed and the density of the network. By exchanging these control packets, USAP has the information it needs to choose non-conflicting transmit allocations consistent with the most recent topology measurements and detect and report conflicts caused by topology changes.

After a transmit allocation is chosen, a node has the option of either using it immediately or waiting until a confirmation is received from each neighbor. The unconfirmed mode is appropriate when it is tolerable to have momentary conflicts due to coincident changes in connectivity or conflicting allocations. The confirmed mode verifies that all neighbors are aware of the allocation and that nothing has happened in the meantime to make it inconsistent with the current topology or other nodes’ allocations.

The broadcast constraints can be modeled in graph theory as a distance 2 vertex-coloring problem; that is, in an undirected graph no vertices connected by 1 or 2 edges have the same color. In Soldier Phone the colors are applied to both time slots and frequency channels so transmitters within 2 radio hops of each other must color their slots or channels (or both) to prevent interference at their intended receivers. Indeed, for broadcast the half-duplex Soldier Phone transceivers within 2 hops of each other must choose different slots for the sake of the neighbors they have in common. Thus, transmitters using the same slot must be at least 3 hops apart. But if they are 3 hops apart then they are allowed to have the same color so they might as well use the same channel. Thus, the channels would not seem to play a useful role in coloring for broadcast. However, USAP-MA does use them effectively to deal with dense networks as described in the section on channelized neighborhoods.

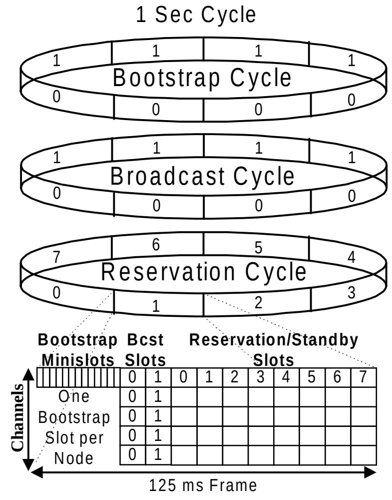
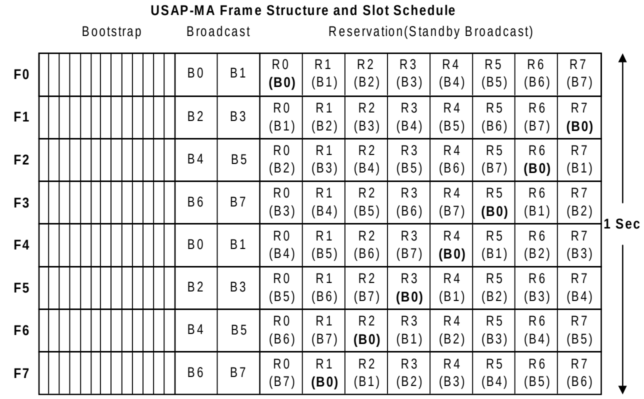


Fig. 3. USAP-MA TDMA Frame

III. TDMA STRUCTURE

The objectives of the Soldier Phone system are to support both datagrams and on demand circuits, low latency voice, and network size, density, and mobility consistent with the tactical battlefield. After all of the tradeoffs were taken into consideration, USAP-MA ended up with the TDMA structure of Fig. 3, although other structures are possible and, given other constraints, more optimal.

The frame length of 125 milliseconds was chosen because it was deemed acceptable for voice latency, it divides evenly into 1 second, and it allows a manageable number of slots per frame. The bootstrap minislots are for sharing the critical USAP information necessary to dynamically assign the rest of the slots. With 13 bootstrap slots per frame and a bootstrap cycle of 4 frames, up to 52 nodes can be supported although a technique for managing larger nets will also be presented. The broadcast slots are node allocations made to support the datagram service and any other control traffic that nodes need to share. With a broadcast cycle of 4 frames, up to 8 nodes can transmit in the 2 broadcast slots or a total of up to 40 nodes on 5 different channels in a neighborhood. The reservation slots repeat every frame so their latency is 125 milliseconds. When a reservation slot has not been allocated it acts as a standby broadcast slot assigned to the same



USAP-MA Frame Structure and Slot Schedule

	Bootstrap	Broadcast		Reservation(Standby Broadcast)							
F0		B0	B1	R0 **(B0)**	R1 (B1)	R2 (B2)	R3 (B3)	R4 (B4)	R5 (B5)	R6 (B6)	R7 (B7)
F1		B2	B3	R0 (B1)	R1 (B2)	R2 (B3)	R3 (B4)	R4 (B5)	R5 (B6)	R6 (B7)	R7 **(B0)**
F2		B4	B5	R0 (B2)	R1 (B3)	R2 (B4)	R3 (B5)	R4 (B6)	R5 (B7)	R6 **(B0)**	R7 (B1)
F3		B6	B7	R0 (B3)	R1 (B4)	R2 (B5)	R3 (B6)	R4 (B7)	R5 **(B0)**	R6 (B1)	R7 (B2)
F4		B0	B1	R0 (B4)	R1 (B5)	R2 (B6)	R3 (B7)	R4 **(B0)**	R5 (B1)	R6 (B2)	R7 (B3)
F5		B2	B3	R0 (B5)	R1 (B6)	R2 (B7)	R3 **(B0)**	R4 (B1)	R5 (B2)	R6 (B3)	R7 (B4)
F6		B4	B5	R0 (B6)	R1 (B7)	R2 **(B0)**	R3 (B1)	R4 (B2)	R5 (B3)	R6 (B4)	R7 (B5)
F7		B6	B7	R0 (B7)	R1 **(B0)**	R2 (B1)	R3 (B2)	R4 (B3)	R5 (B4)	R6 (B5)	R7 (B6)

Fig. 4. Slot Schedule

transmitter as the corresponding broadcast slot. In addition, the correspondence is shifted by 1 slot every frame as shown in Fig. 4 to minimize the impact on the broadcast capacity and latency of any one node when a reservation slot is allocated.

The upshot of this TDMA schedule is that when no reservations are active all slots are fully utilized in support of a broadcast channel that can be used for user datagrams or control traffic. As unicast reservations become active they gradually decrease the capacity of the broadcast channel.

IV. BOOTSTRAP SLOTS

For small networks it is most efficient to assign one permanent bootstrap slot per node, but as network size increases this method results in less and less traffic capacity. Thus, it is desirable to have a technique for dynamically assigning these slots. However, since the bootstrap packets carry the USAP information necessary for contention-free assignment, how does a node coordinate things initially? The answer is that it simply listens for bootstraps from its neighbors before assigning itself a slot and transmitting its own bootstraps. If a conflict occurs, the effected nodes will learn this from their neighboring nodes via the USAP information and choose another slot.

Now, the choice of using a fixed or dynamic assignment and, if the latter, which bootstrap cycle length to use, depend on the maximum expected neighborhood density. Assuming a network of size N with a maximum degree D (the most neighbors any one node can have), the following formula can be used:

$$L = \min(D^2+1, N) \tag{1}$$

The D^2+1 term is a simple upper bound on the number of colors it takes to do a distance-2 vertex coloring of an undirected graph and this corresponds to the maximum number of bootstrap slots a neighborhood needs for every node to get a slot. One can see that small and/or fully connected networks are best handled by fixed assignments.

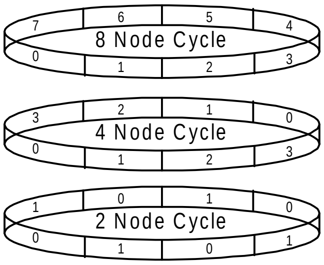


Fig. 5. Adaptive Bootstrap Cycle

However, for large networks of reasonable degree the D^2+1 term yields a smaller cycle. Indeed, this demonstrates that USAP-MA can manage very large networks with a resource management latency that depends only on the maximum neighborhood density. In fact, that latency can be improved significantly for sparser neighborhoods by simply assigning more slots to each node as described below.

An efficient but flexible way to assign more or less slots is to do it in blocks whose size is a power of 2 and whose slots are evenly distributed in the bootstrap cycle. This allows the block to be specified by the first slot index and N where 2^N is the size of the block. In fact, if the first slot indices are chosen to be as small as possible then the size of the blocks can be adjusted up or down with maximum flexibility. This technique is very similar to the Adaptive Broadcast Cycle and Slot Poaching to be described shortly but it deserves its own treatment here. Consider Fig. 5 depicting a short broadcast cycle that can accommodate up to 8 nodes.

Sparser neighborhoods could optimize down to 4 or 2 node cycles if the nodes continually assign themselves the lowest available slot index, thereby packing themselves into the lower portion of the cycle. Under certain conditions a node can reuse unassigned slots in the latter part of the cycle if they correspond to its transmit slot on a shorter cycle. A node gleans this knowledge about its neighbors from the USAP information in their bootstraps, as described in the section on slot poaching. A sample network where this optimization is possible is shown in Fig. 6.

The nodes are numbered by their slot index and the ones

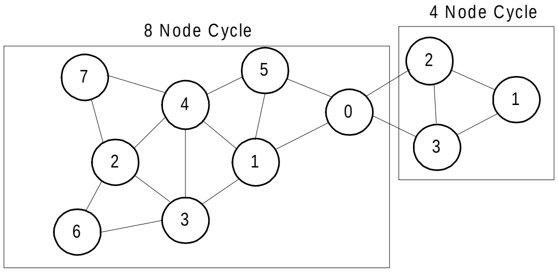


Fig. 6. Adaptive Broadcast Cycle Example

toward the right have packed themselves in the lower half of the 8-node cycle. This allows the 3 nodes furthest to the right to use a 4-node cycle.

V. ADAPTING TO NETWORK DENSITY

One of the hardest problems to solve in broadcast networks is how to efficiently manage network densities ranging from sparse to fully connected. USAP-MA uses a combination of techniques to solve this problem. To handle sparse neighborhoods the Adaptive Broadcast Cycle (ABC) employs nested subdivisions of the fixed length cycle to allow nodes to reuse unused slots. At the other end of the spectrum, neighborhoods whose density exceeds the capacity of the broadcast cycle utilize Channelized Neighborhoods (CN) to create parallel cycles on other channels so that multiple neighboring transmitters can be active in any given slot. The fusion of these methods results in efficient channel utilization over the entire range of connectivity.

A. Adaptive Broadcast Cycle (ABC)

A number of possible broadcast schedules are presented in Fig. 7, each for a different neighborhood density, that is, the maximum number of nodes before CN takes effect. A number in a slot corresponds to the assigned broadcast slot. In other words, if a node has chosen broadcast slot N, the standby slots with the number N are also it's transmit opportunities. They are designed to have the following properties:

- They maximize overlap such that a schedule has half of its slots in common with both the previous schedule (shown shaded) and the next schedule. This eases transitions from one schedule to the next as the density changes.
- The standby slots are shifted from frame to frame to minimize the impact a reservation slot has on broadcast latency.

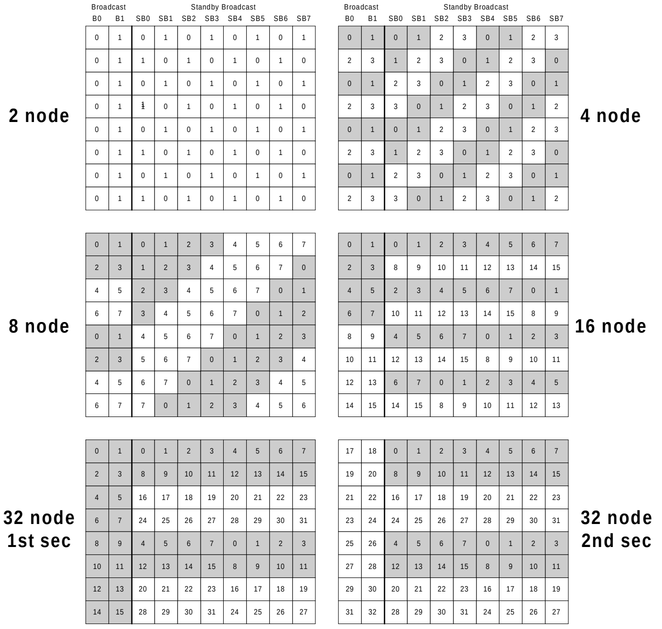


Fig. 7. Adaptive Broadcast Cycles

A schedule is chosen based on the location of the assigned broadcast slot and any open slots that come after it in the broadcast cycle. If there are open slots corresponding to the assigned slot on a shorter cycle, the node may be able to adopt the shorter cycle as described in the next section. To make this work a node would continually look for empty slots earlier in the cycle and try to move its broadcast allocation to that slot. This has the effect of packing the allocated slots into the earlier part of the cycle and allowing the cycle to be shortened as density decreases.

B. Channelized Neighborhoods

If the number of broadcast slots is limited to 8, communication with more than 7 neighbors requires the use of additional broadcast cycles, where cycles can be separated by time or channel. USAP-MA uses the latter approach to maximize channel utilization. For a receiver to hear from each transmitter, it rotates from one channel to another according to the schedule in which a 2-second epoch is broken into 4 cycles, each of 4 frames. Fig. 8 presents the schedules for the 8, 16, 24, and 32 node cases. A Rotating Receiving Group (RRG) is made up of the 4 pairs of nodes that share the same frame on each channel. An RRG will visit a different channel each frame so that at the end of an epoch each receiver will get a chance to receive from up to 28 transmitters in a 32-node neighborhood. The reason that not all 31 transmitters are heard at every receiver is that the nodes

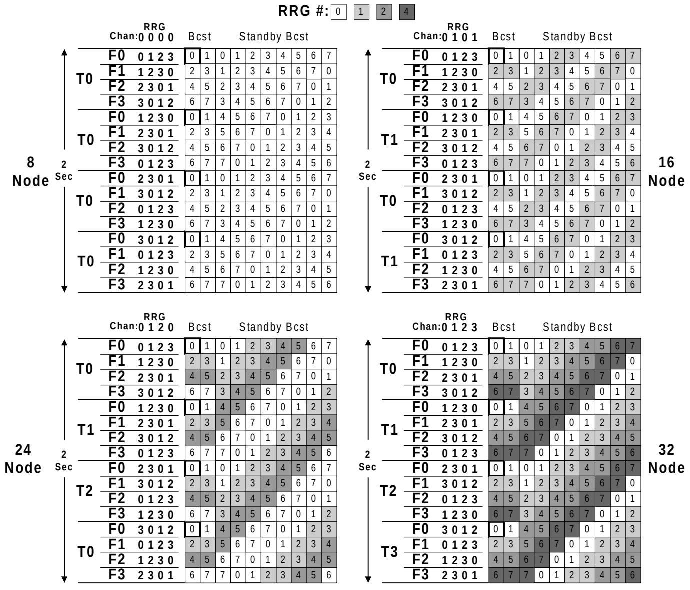


Fig. 8. Channelized Neighborhoods

with the same transmit slot will never receive from each other. This has the result that these nodes will not be recognized as logical neighbors even if they are physical neighbors. Communication between them can be achieved over relays or a further optimization can be made to change the RRG memberships each epoch in such a way as to evenly distribute the receive opportunities over time. For brevity this will not be described.

The {T0,T1,T2,T3} schedule presented for the 32-node neighborhood can be optimized for sparser neighborhoods. In particular, an 8-node neighborhood uses {T0,T0,T0,T0} for single channel operation, a 16-node neighborhood uses {T0,T1,T0,T1} for 2-channel operation, and a 24-node neighborhood uses {T0,T1,T2,T0} for 3-channel operation. Since the perception of neighborhood density can change from one node to the next, the nodes must let each other know each other's schedules. This is done via a couple of bits in the bootstrap. Now when a node goes to transmit, it can calculate which of its neighbors will be listening at that time according to the schedule in effect at each neighbor. Note that each node always transmits in its allotted time slot and channel. The receivers are the ones that rotate among the transmitters on different schedules depending on the neighborhood density and the RRG they belong to.

VI. BOOTSTRAP PACKET FORMAT

The bootstrap packet consists almost entirely of the USAP assigned slot sets STi, SRi, and NTi. The broadcast and reservation slots are managed separately and encoded slightly differently. There is a map of 2 bit fields that correspond to every slot, yielding *2 bits * 8 slots * 5 channels = 80 bits* for the reservation slots and *2 bits * 8 slots = 16 bits* for the broadcast slots. The 2 bit fields are combined into what is called the Assigned Slots Record (ASR) and are interpreted as follows:

Broadcast:	Reservation:
0: unassigned	0: unassigned
1: self transmit	1: self transmit
2: self receive	2: self receive
3: conflict	3: neighbor transmit or conflict

USAP regenerates the STi, SRi, and NTi sets from the ASR when it receives a bootstrap packet from a neighbor. In addition, there are

2 bits to indicate which of 4 channels the broadcast slots are used on
2 bits for channelized neighborhood cycle (8, 16, 24, or 32-node)
4 bits for 16 second synchronization
24 bits to identify up to 4 6 bit receiver Ids for unicast reservations

In this way the entire functionality of USAP-MA described up to this point is packed in about 16 bytes.

VII. SOFT CIRCUITS

One of USAP's strong points is its ability to make unilateral allocations on the fly. Since it constantly maintains up-to-date knowledge via the bootstrap packets of the active allocations its it neighborhood, it is always ready to allocate a new transmit slot. Nominally the new allocation must be announced in only one bootstrap before it can be used. Certain types of applications can take advantage of this to eliminate the setup delays and inflexibility of hard circuits, that is, reserving slots all along a path from source to destination before turning on the traffic. In particular consider voice and video. Once started they continuously supply data that loses its value if it is not delivered very quickly. They are also both tolerant of small amounts of dropped data and data arriving out of order, resulting in small glitches of little consequence to the users.

Now consider a heuristic that simply assigns enough slots on its outgoing links to satisfy the requirements of the traffic entering it. This would allow traffic to push its way through the network reserving the channel resources along the way. When the traffic stops the allocations are automatically released. Called a "soft circuit", this heuristic has essentially the same effect as a dedicated circuit setup: if enough slots are available, they are allocated to support the traffic stream. The difference is that it is executed locally at each node rather than coordinated at the end points. Also, the soft circuit heuristic will attempt to fix a broken link locally by routing around it if possible instead of reporting the failure all the way back to the source. Thus, by taking advantage of certain characteristics of the data streams and effectively utilizing the capabilities of USAP, soft circuits provide fast, robust support for certain applications.

VIII. CONCLUSION

USAP-MA is an integrated family of USAP heuristics that supports the requirements of the tactical environment. It does this by providing broadcast and unicast transmissions, datagrams for bursty data and hard and soft circuits for high capacity or low latency streams, sparse and dense neighborhood optimizations, and the ability to scale to large networks. Thus, the applications of USAP-MA are many; they span the gamut from low latency voice to delay tolerant data, from bursty transactions to high throughput streams, and from multicast conferencing to point-to-point circuits.

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