# REDUCING TERMINAL SLOT CONTENTION BY APPLYING SET THEORY TO THE INTEGRATED WAVEFORM (DAMA UHF SATCOM)

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## ABSTRACT

*The Integrated Waveform (DAMA UHF SATCOM), specified in MIL-STD-188-181C/182B/183B/185A, defines a TDMA communication system in an attempt to improve satellite bandwidth utilization over conventional SATCOM waveforms. To overcome some of the limitations of statically defined user communications (UCOM) services in MIL-STD-188-183A, the flexibility to assign services nearly anywhere within a frame was introduced in MIL-STD-188-183B. Unfortunately, though the flexibility to locate services in nearly any location within a channel has the ability to greatly improve bandwidth utilization, the benefits of this feature have a tendency to be greatly diminished, especially for half-duplex terminals, by limitations attributable to terminal slot contention. Fortunately, through the efficient allocation and relocation of Downlink and Uplink support services, it becomes possible for the IW Network Management System to minimize the system performance impact due to terminal slot contention by allowing the allocation of UCOM services wherever necessary to achieve optimal satellite channel utilization.*

*This paper will discuss the application of set theory to the allocation of Downlink and Uplink support services within a TDMA communications system to reduce the impact of slot contention and improve the utilization of satellite bandwidth.*

## 1. INTRODUCTION

Through the utilization of geostationary satellites, terminals are capable of achieving beyond the line-of-sight communications nearly anywhere within the footprint of a satellite system. Unfortunately, because of the enormous cost of deploying each satellite, there are a very limited number of Military Satellite Communications (MILSATCOM) channels available. To circumvent the limitation of having to allocate a dedicated channel to each terminal, or group of terminals, one or more channel access techniques are typically employed.

One channel access technique that is currently employed in UHF SATCOM systems is Time Division Multiple Access (TDMA). TDMA protocols, such as MIL-STD-188-181B/182A/183A (DAMA)[1,2,3], allow multiple terminals to simultaneously utilize a single MILSATCOM channel by splitting each channel into frames, dividing those frames into timeslots, and then distributing those timeslots to terminals in the form of multiple-access services (Figure 1). Through the careful creation of services, by allocating only the bandwidth that is required, several terminals are capable of simultaneously utilizing a single channel with minimal degradation in performance.

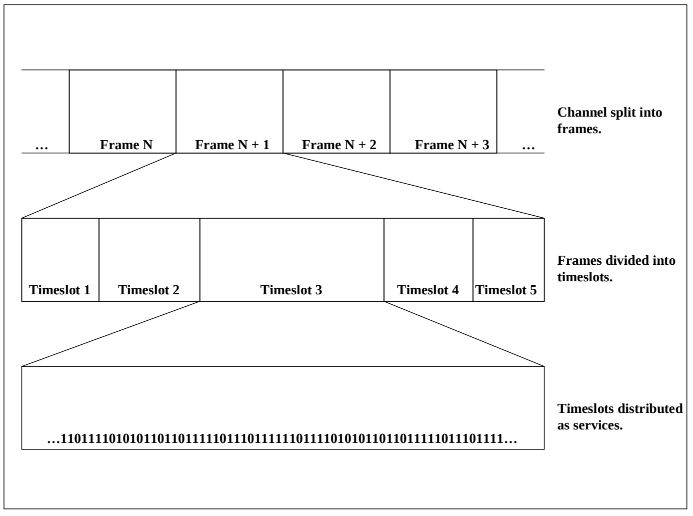


**Figure 1: TDMA Frame Structure**

Though the DAMA protocol has been in use for several years to improve the communications capabilities of the existing UHF satellite constellation, an increasing emphasis on information superiority has led to a rise in demand that can not be supported with the currently deployed satellite system. Additionally, the degradation of satellite resources due to age has further reduced the capabilities of the existing MILSATCOM system to the point where current mission requirements are no longer being fulfilled.

Although the Mobile User Objective System (MUOS) was designed to provide MILSATCOM users with additional satellite resources and communication capabilities, eventually replacing the existing UHF MILSATCOM system, full operational capability is years away[1] and a stopgap measure was needed in the interim.

[1] The first MUOS satellite is scheduled for launch in late 2009 with on-orbit capability achieved in 2010.

## 2. THE INTEGRATED WAVEFORM (IW)

The Integrated Waveform (IW) was developed to further improve the utilization of the existing UHF MILSATCOM constellation until MUOS was deployed and fully operational. Through the support of multi-h continuous phase modulation (CPM), the IW protocol allows more services to be allocated within a single satellite channel than with the legacy DAMA protocol [4,5]. Additionally, the elimination of service configuration and channel format restrictions within the IW protocol provides the Network Management System with the flexibility to select from a nearly limitless number of multiple-access service configurations (Figure 2). By empowering the Network Management System with the ability to allocate each service practically anywhere within an IW TDMA frame, the IW protocol facilitates the reuse of channel space that has been historically wasted while utilizing the legacy DAMA protocol.

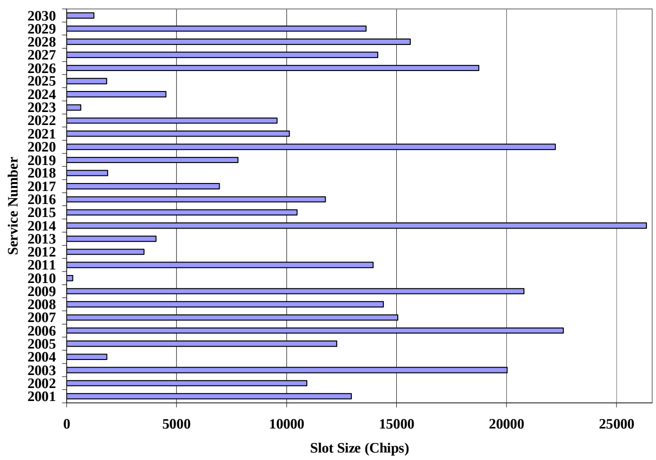


**Figure 2: Example of IW TDMA Timeslots**

## 3. SUPPORT SERVICES

While the use of a TDMA protocol allows multiple terminals to simultaneously utilize a single MILSATCOM channel, by splitting each channel into distinct services, the employment of such a protocol does incur some additional overhead in the form of Uplink and Downlink support services. Regrettably, in addition to decreasing the effective channel utilization of an IW communication, due to the need of support services to consume channel space, the use of support services introduces further complications for terminals wishing to utilize user communication services.

### 3.1. DOWNLINK SERVICES

Because of the need to maintain synchronization with the IW communications system's TDMA frame timing, terminals need to continuously monitor Downlink support services, such as forward orderwires (FOW), in order to achieve and maintain Downlink acquisition[2] while participating in an IW communications system. If Downlink acquisition is lost, the terminal will cease utilizing any user communication services that it was connected to and will attempt to reacquire Downlink acquisition. Furthermore, because the Network Management System is allowed to spontaneously update any active service, by announcing the update within each Downlink support service a certain number of times, a terminal must successfully monitor these services to avoid failing to notice an update cycle. Should a terminal not receive and process Downlink support services frequently enough to ensure that an update cycle has not been missed, the terminal is required to cease transmitting in all services until the terminal is certain that an update has not occurred to any of the services that the terminal was utilizing.

### 3.2. UPLINK SERVICES

While Downlink support services provide a terminal with the ability to synchronize with an IW communications system's TDMA frame timing, giving a terminal the timing precision to receive any other service within the system, achieving Downlink acquisition is not usually sufficient to permit a terminal to transmit.

Since the IW communications system relies on the use of geostationary satellites to relay transmitted RF signals between terminals, and therefore system timing is based on the timing of Downlink support services at the satellite, knowledge of the precise RF propagation delay from the terminal's current position to the geostationary satellite on which it is operating is necessary. Therefore, most terminals must continuously utilize Uplink[3] support services to initially determine the precise RF propagation delay from their current position to the geostationary satellites which relay the transmitted RF signals. Additionally, since RF propagation delay can vary based on terminal location, and the majority of terminals are capable of moving, the initial RF propagation delay measurement must be periodically updated to ensure that the terminal's transmission does not slowly drift into an adjacent timeslot of another service.

## 4. SLOT CONTENTION

Unfortunately, the need to utilize Downlink and Uplink support services places an additional burden on terminals operating in an IW communications system, especially single channel half-duplex terminals, as the need to achieve and maintain Downlink and Uplink acquisition can begin to interfere with a terminal's ability to efficiently and effectively utilize user communications services.

[2] Downlink acquisition is lost if a terminal has not successfully received, and processed, a Network Data Element in 2 minutes.

[3] Uplink acquisition is lost if a terminal's uplink uncertainty exceeds the guard time of a UCOM service that it is connected to.

Slot contention occurs when two or more services that a terminal is required to utilize are positioned in a TDMA frame such that the terminal is only capable of operating on one of the necessary services at any given time. Though occasionally only a minor inconvenience, such as when a forward orderwire (FOW) is required to be missed for a single frame for active ranging to be performed, slot contention becomes a serious issue when a terminal desires to utilize a UCOM service that completely interferes with the terminal's ability to maintain Downlink or Uplink acquisition. Therefore, because of the aforementioned consequences of losing Downlink or Uplink acquisition, if a terminal operator attempts to connect to a UCOM service that is in slot contention, the operator will be denied the ability to connect to the requested service until the Network Management System relocates one or more services such that the terminal can operate on the desired service and continue to maintain both Downlink and Uplink acquisition. As a result it is imperative that the Network Management System allocate services such that each terminal is able to connect to any UCOM service that it wishes to, and still utilize whichever services are essential to maintaining Uplink and Downlink acquisition.

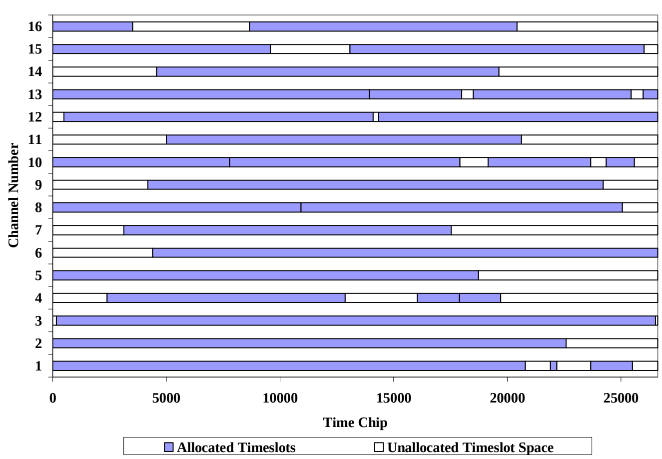


**Figure 3: Initial User Communication Service Allocation**

Since locating a single timeslot to allocate a service has a tendency to be extremely difficult in a congested system, the additional complexity due to slot contention typically forces the Network Management System to utilize the first available timeslot which does not place the requesting terminal into contention. By not pursuing the most optimal timeslot location when allocating services (Figure 2), and taking into account how the service placement will affect the ability of the Network Management System to allocate additional services to fulfill future requests, channel space is needlessly wasted and future service allocation becomes unnecessarily difficult (Figure 3).

## 5. ALLOCATION FLEXABILITY

Fortunately, the Network Management System can utilize the enhanced service allocation flexibility provided by the IW protocol to overcome some of the issues with slot contention between user communication and support services.

By leveraging the ability of the IW protocol to allocate services practically anywhere within a frame, the Network Management System can attempt to allocate Downlink and Uplink support services to timeslot positions that will cause slot contention with the least amount of user communication services. Furthermore, because the implementation of most terminals is intelligent enough to select the combinations of services that would place the terminal into the least amount of slot contention, the Network Management System could allocate a large number of support services to reduce the chances that a future user communication services will be in slot contention. Consequently, there are currently two methods a Network Management System may utilize to select the location and number of support services within an IW communications system.

## 6. CURRENT ALLOCATION METHODS

The first method of support service allocation entails an operator providing the Network Management System with a predefined location for the necessary Downlink and Uplink support services and allowing the allocation of user communication services with this fixed placement in mind. While this is the most straight forward approach, and provides the most predictable service allocation outcome, the Network Management System will be forced to allocate user communication services to non-optimal timeslot location in order to avoid slot contention. Consequently, the IW communications system will become fragmented as sections of each TDMA channel become unused due to the avoidance of slot contention between the allocated support services and the user communication services (Figure 4).

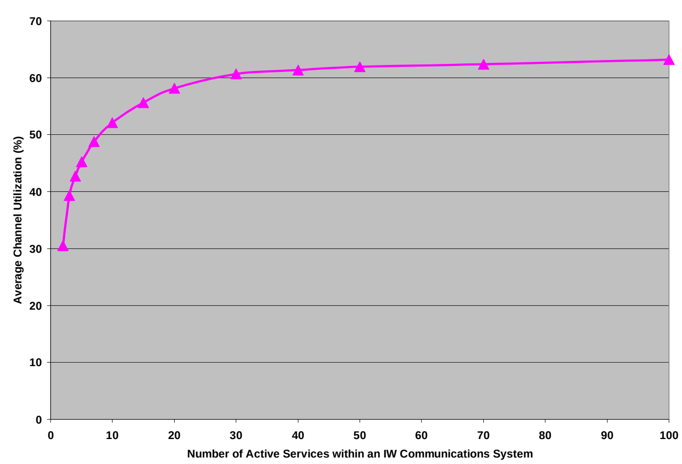


**Figure 4: Fixed Support Services Allocation Channel Utilization**

Because of the issue of channel fragmentation while utilizing fixed support service placement, the other support service allocation method that is typically employed entails the allocation of additional support services to reduce slot contention. While allocating additional support services so that user communication services can be allocated without slot contention does reduce channel fragmentation, this method leads to an increased number of support services as the number of user communication services increases (Figure 5). Consequently, because support services consume a non-trivial amount of channel space, the channel utilization of an IW communications system will inevitably be reduced as support services are continuously allocated. Additionally, since the allocation of some support services is restricted to certain channels, the haphazard allocation of support services will inevitably lead to circumstances when no additional support services can be beneficially allocated. When this occurs, the IW communications system will revert to the situation described in the first allocation method, where channel space becomes fragmented due to increased slot contention (Figure 6).

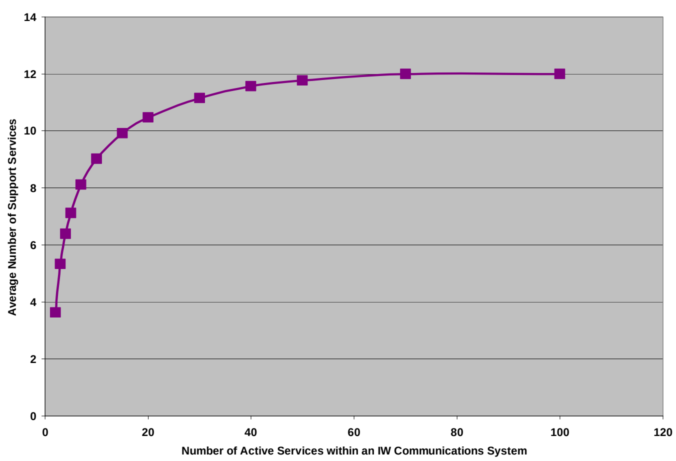


**Figure 5: Progressive Allocation Number of Support Services**

Although allowing the Network Management System to allocate additional support services to reduce the amount of slot contention between support and user communication services has been shown to be non-optimal, the idea of allowing the Network Management System to control the available support services based on the allocated user communication services is still sound. Because one of the primary issues of allocating additional support services is due to the selection of non-ideal timeslot positions, and the subsequent allocation of superfluous support services, a method of selecting the optimal number and location of support services would mitigate these issues by minimizing the number of support services utilized in order to avoid slot contention between support and user communication services.

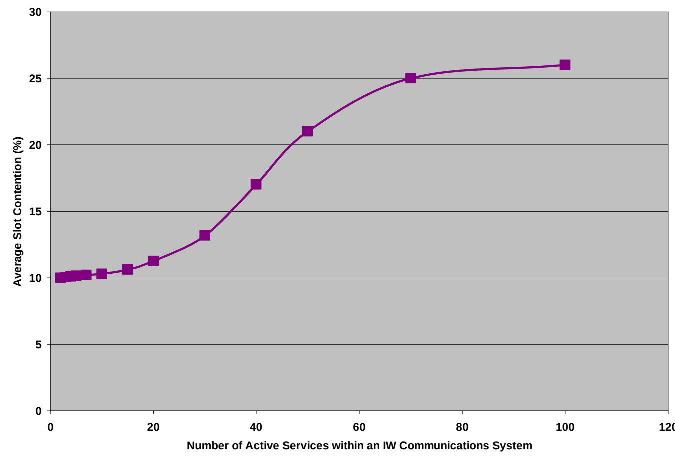


**Figure 6: Progressive Allocation Slot Contention**

## 7. SET THEORY

Given that computing the optimal number and timeslot location for support services can be classified as an NP-Hard[4] problem, and therefore is unable to meet the real-time constraints imposed on the Network Management System, this problem must first be reduced into one that can be resolved within deterministic polynomial time.

Because the allocation of support services while minimizing slot contention with user communications services is similar to the traditional set covering problem, the utilization of approximation algorithms can hypothetically be applied to the allocation of support services within an IW communications system. However, in order to utilize this category of algorithms, the allocation of support services must first be representable utilizing set algebra. Fortunately, by creating a weighted matrix (Figure 7) of the valid support services positions for each user communication service, the goal of representing the allocation of support services using set algebra is indeed achievable. Furthermore, once converted to matrix form, it is readily apparent that the allocation of support services can be represented utilizing a classical set covering problem.

| | Support Service Timeslot Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Service Number | 1 | 2 | 3 | 4 | … | N-4 | N-3 | N-2 | N-1 | N |
| 2001 | 7 | 8 | 7 | 6 | 7 | 6 | 6 | 6 | 5 | 6 |
| 2002 | 3 | 3 | 3 | 4 | 3 | 4 | 3 | 4 | 4 | 4 |
| 2003 | 7 | 5 | 6 | 6 | 5 | 6 | 6 | 6 | 5 | 5 |
| 2004 | 7 | 6 | 5 | 6 | 4 | 5 | 5 | 6 | 4 | 5 |
| 2005 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 2 | 3 | 3 |
| 2006 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 2007 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 |
| 2008 | 7 | 9 | 7 | 8 | 7 | 9 | 8 | 10 | 8 | 8 |
| 2009 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| 2010 | 5 | 6 | 5 | 6 | 6 | 7 | 8 | 9 | 10 | 10 |

**Figure 7: Weighed Slot Contention Matrix**

[4] NP-Hard problems are intrinsically harder than those that can be solved by a nondeterministic Turing machine in polynomial time [8].

## 8. SET COVERING

Set covering is a classical computer science and computational complexity problem where the objective is to find, from a family of subsets of a finite universe, the smallest subfamily of sets whose union provides the greatest degree of coverage of the initial universe. Although the allocation of support services within an IW communications can be transformed into a set covering problem, calculating the optimal solution to this type of problem is still classified as NP-Hard. Given that arriving at a perfect solution to an NP-Hard problem is not likely without attempting every possible combination, approximation algorithms are typically applied to achieve sub-optimal solution in polynomial time. Through the selection of an approximation algorithm with a provable lower bound, we can be assured that an arbitrarily bad solution will not be generated during the allocation of support services.

### 8.1. WEIGHTED GREEDY SET COVERING

Although there are many approximation algorithms that could be employed to allocate support services within a TDMA communications system, the Weighted Greedy Set Covering (WGSC) algorithm is especially useful in the allocation of support services within an IW communications system as it attempts to select a minimum number of sets. Additionally, since overlapping coverage by support services does not impact an IW communications system, the main drawback of the WGSC algorithm is of little concern. Furthermore, it has been proven that set covering cannot be approximated in polynomial time to within a factor of $(1-o(1))\bullet\ln n$ [6], unless NP has quasi-polynomial time algorithms, which essentially matches the approximation ratio achieved by the WGSC algorithm of $c\bullet\ln n$ [7]. Finally, the computational complexity of $O(n\bullet\log n)$ ensures that the WGSC algorithm minimally impacts the run time performance of support service allocation.

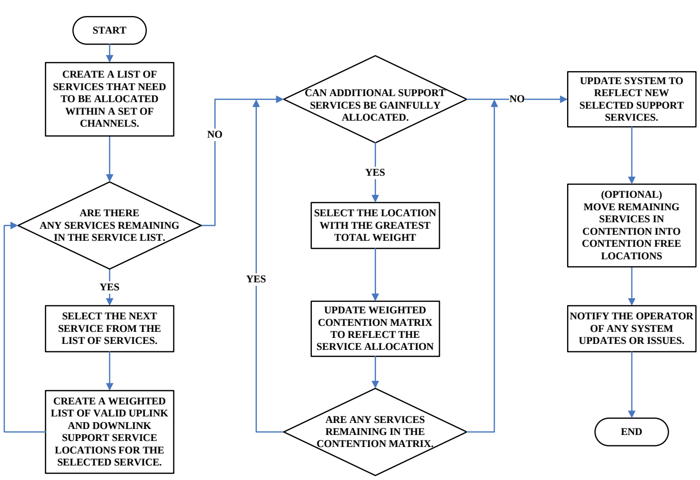


**Figure 8: Greedy Set Covering Flow Diagram**

When utilizing the WGSC algorithm in the allocation of support services, the Network Management System will first iterate over the list of user communication services that need to be allocated within a given IW communications system and create a weighted matrix of the valid support services positions for each user communication service (Figure 7). Once the weighted matrix has been completed, the Network Management System will select the timeslot location from the matrix which achieved the greatest total weight and allocate a support service to that location. After updating the matrix to reflect the allocation of the support services, by removing the rows of all user communication services whose need of support services was fulfilled by the service placement, the Network Management System will continue to allocate support services to the greatest weighted position until no more support services can be allocated or all user communication services have been removed from the matrix. If the allocation of support services terminates before the support service needs of every user communication service has been fulfilled, the optional step of relocating these services into non-contending timeslot positions can be performed. Once the Network Management System has allocated all services, and optionally moved the remaining user communication services out of slot contention, the operator will be informed of the change and any issues that might have been encountered.

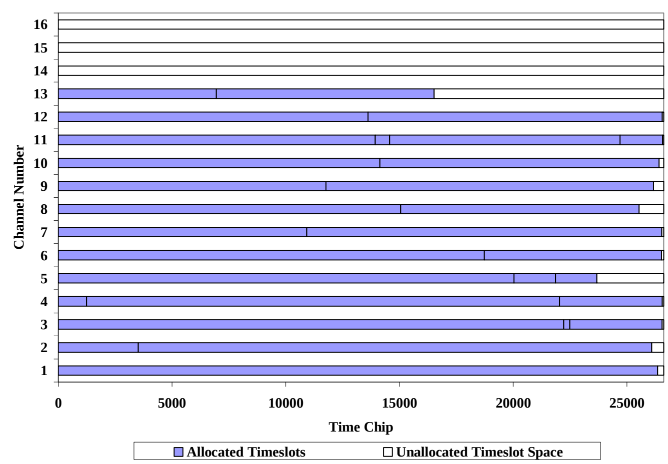


**Figure 9: Greedy Set Covering User Communication Service Allocation**

Through the minimization of the number of support services necessary, and the reduction in the amount of slot contention between support services and user communication services, the WGSC algorithm is able to reduce the number of channels necessary for the allocation of a given set of services by allowing the Network Management System to disregard slot contention when allocated user communications services (Figure 9). Consequently, the effective channel utilization of the IW communication system can be increased dramatically.

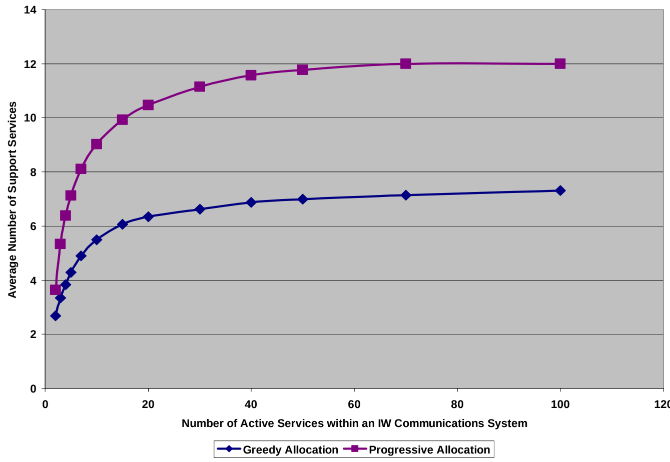


**Figure 10: Progressive Allocation vs. Greedy Set Covering Number Support Services**

By simulating the allocation of services within an IW communications system while employing the aforementioned WGSC algorithm for support service allocation, and comparing the results to that of the typical support service placement methods, it is possible to evaluate the effectiveness of utilizing the WGSC algorithm for support service allocation. As shown in Figure 10, the average number of support services necessary to fulfill the needs of the user communication IW communications systems is substantially reduced, thereby reducing the amount of channel overhead due to support services and increasing channel utilization. Furthermore, not only did the Network Management System not experience a sharp increase in slot contention as the number of user communication services increased, due to the lack of valid locations to allocate additional services, but the level of slot contention was reduced by 4 - 5% over that of the previously illustrated progressive support service allocation method (Figure 11).

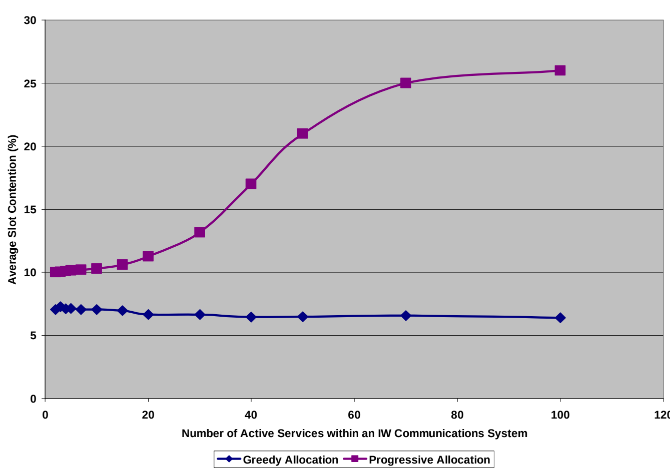


**Figure 11: Progressive Allocation vs. Greedy Set Covering Average Slot Contention**

## 9. SUMMARY

Through the use of the IW protocol it is possible to greatly improve the communications capabilities of the existing UHF MILSATCOM constellation by allowing more terminals to simultaneously utilize a single MILSATCOM channel than with the legacy DAMA protocol. Regrettably, slot contention between support services and user communications services decreases channel utilization and diminishes the benefits of transitioning from the legacy DAMA protocol to the state-of-the-art IW protocol. Fortunately by utilizing the enhanced service allocation flexibility in the allocation of support services the Network Management System is empowered with the ability to control the number and timeslot position of the available support services based on the Network Management Systems knowledge of the allocated user communication services. While the optimal allocation of support services would be desirable, the allocation of support services is classified as an NP-Hard problem, and consequently an approximation algorithm should be employed to avoid impacting the run-time performance of the Network Management System. Therefore, by integrating the Weighted Greedy Set Covering algorithm into the allocation of support services within an IW communications system, in conjunction with the employment of the service allocation flexibility, the Network Management System can reduce the number of channels necessary for the allocation of a given set of services by effectively disregarding slot contention between support services and user communication services when allocating user communications services (Figure 9). Consequently, the Network Management System can improve the utilization of limited satellite resources by 10 - 20% over that of an IW communications system utilizing typical support service allocation methods (Figure 12).

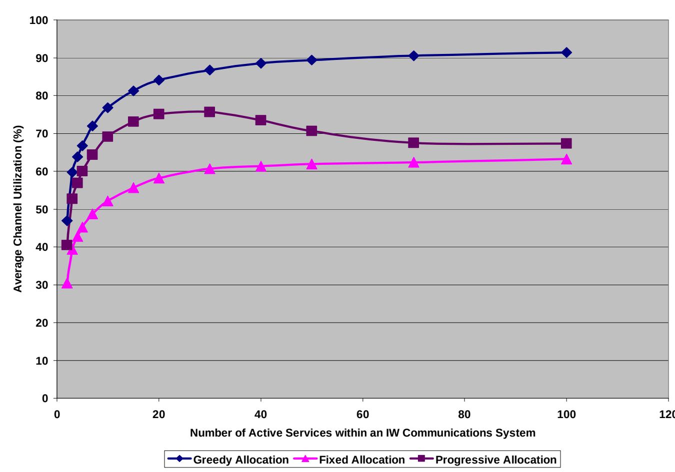


**Figure 12: Fixed Allocation vs. Greedy Set Covering Channel Utilization**

## 10. REFERENCES

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