Adaptive Frequency Hopping and Synchronization-Based Algorithms for Rendezvous*

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Problem Statement

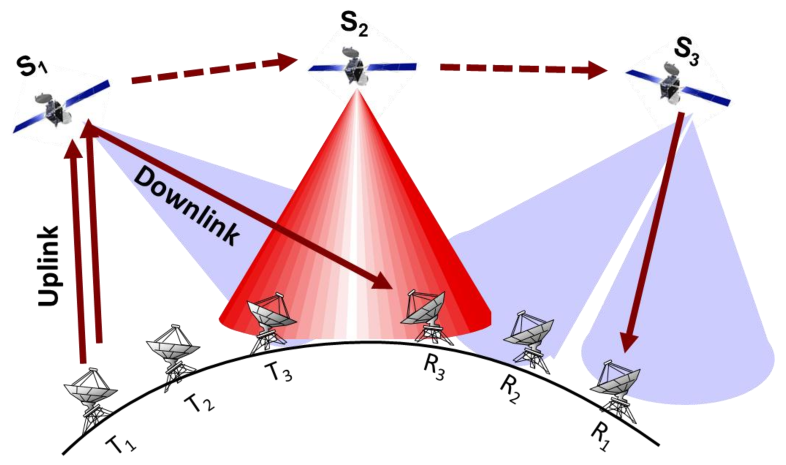
Establishing unicast and multicast communications between agents in satellite networks (i.e., rendezvous in satellite networks).

Constraints:

(1) Agents are asynchronous.
(2) Agents are uncoordinated (i.e., blind rendezvous).

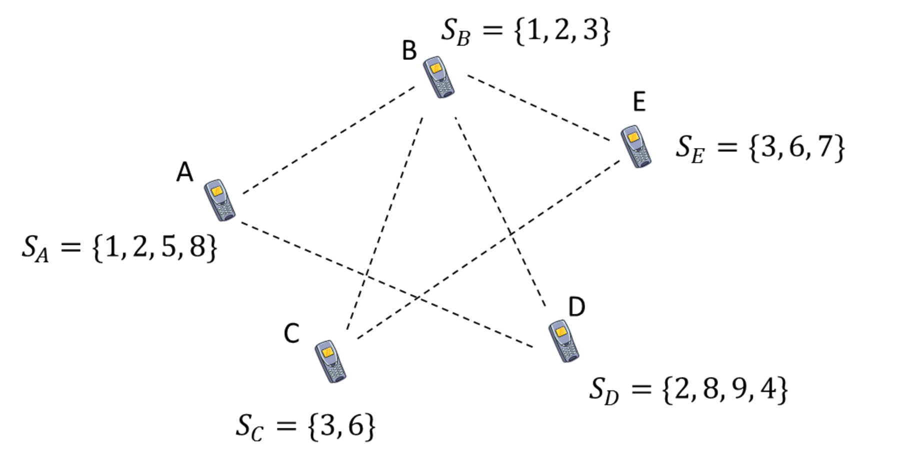
Network models:

(1) Dynamic spectrum access (DSA) networks.
(2) Networks operating in a hostile environment with multiple jammers.



Network Models/ Motivational Scenarios

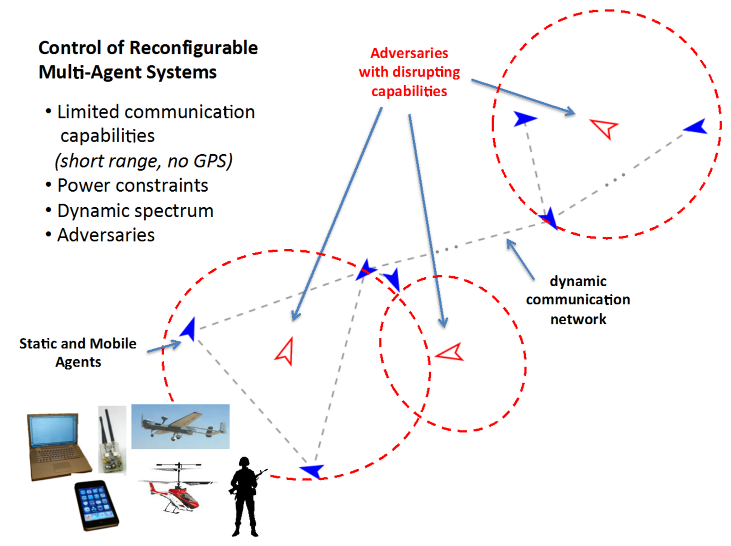
Dynamic Spectrum Access Networks



⋯⋯ Temporal links. Connectivity is time-varying.

S_K: set of channels available at node K in the current time.

Networks operating in a Hostile Environment



Adaptive Frequency Hopping Algorithms for Rendezvous[1]

Background (Quorum Systems)

A quorum system Q is a collection of non-empty intersecting subsets of a set. Ex.: Q = { {0, 1, 2}, {0, 1, 3}, {0, 2, 3}, {1, 2, 3} }.

Grid Quorum System

Grid quorum system arranges the elements of Z_n as a $\sqrt{n} \times \sqrt{n}$ array. A quorum is formed from the elements of any column plus any row of the grid.

Example:

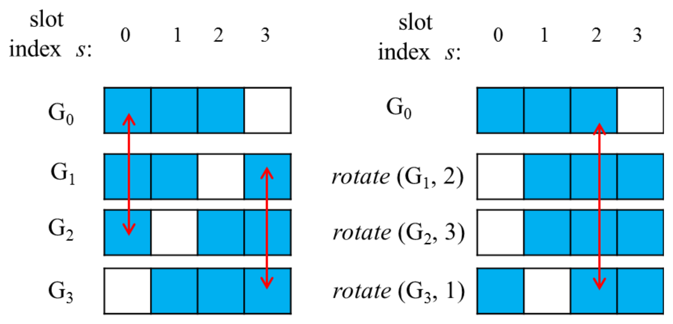
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Uniform k-arbiter Quorum System

Q is a uniform k-arbiter quorum under Z_n if:

$$Q = \left\{ G \subseteq Z_n : |G| = \left(\left\lfloor \frac{kn}{k+1} \right\rfloor + 1 \right) \right\}$$

Example:

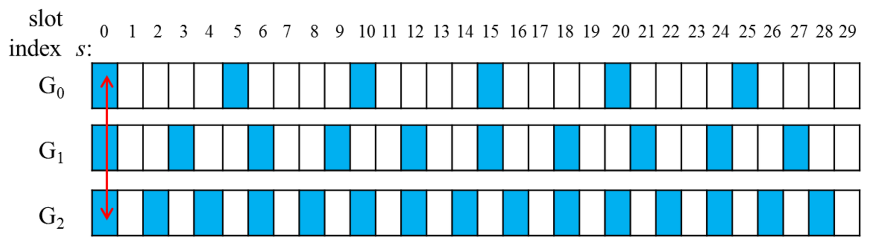


Chinese Remainder Theorem (CRT) Quorum System

Let $x_1, x_2, \ldots, x_k$ be k positive integers that are pairwise relatively prime, and let $y = x_1 x_2 \ldots x_k$. Then, the quorum system Q under Z_y is called the CRT quorum system.

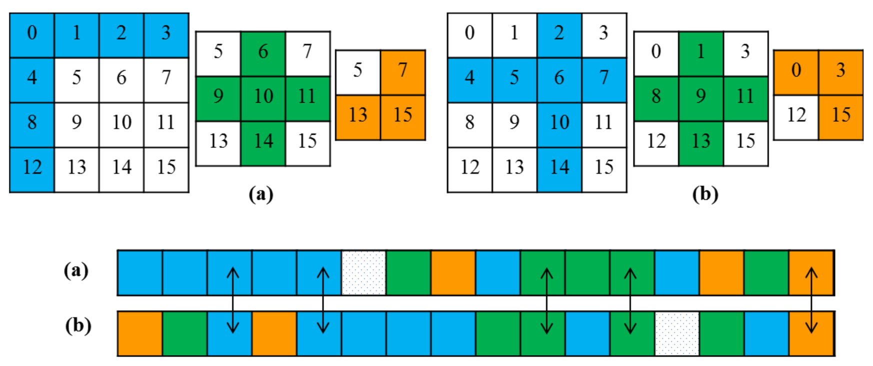
$$Q = \{G_1, \ldots, G_k\}, \text{where } G_i = \{x_i c_i, c_i = 0, \ldots, \frac{y}{x_i} - 1\}$$

Example:

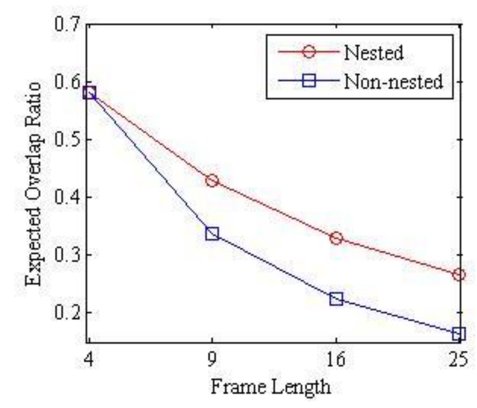


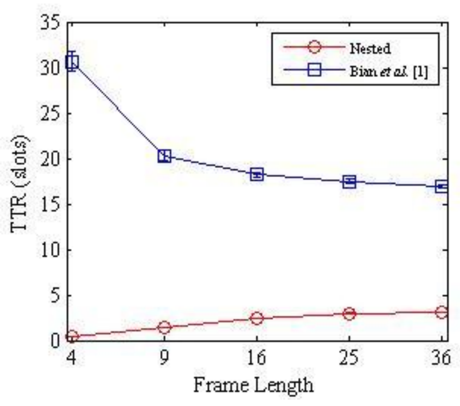
Nested Grid Quorum-Based FH Algorithm for Pairwise Rendezvous (NGQFH)

Approach:



Results:





Quorum-Based FH Algorithms for Multicast Rendezvous (AMQFH, CMQFH, and nested-CMQFH)

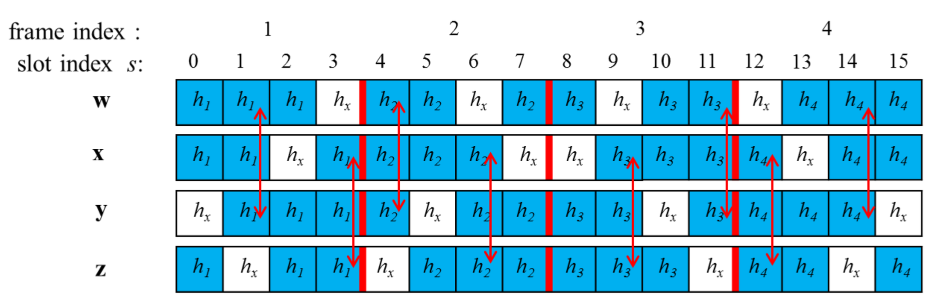
Common Approach

Step 1: Construct a universal set $Z_n = \{0, 1, \ldots, n-1\}$.
Step 2: Construct a quorum system Q under Z_n.
Step 3: Construct an FH sequence w using Procedure 1.
Step 4: Repeat Step 3 to construct the other FH sequences.

Procedure 1

(1) Select a quorum G from the quorum system Q.
(2) Assign frequency h to the FH slots that correspond to G, and assign a random frequency h_x to the other slots, where h and $h_x \in \{f_1, f_2, \ldots, f_L\}$.
(3) Repeat the above procedure for the other frames.

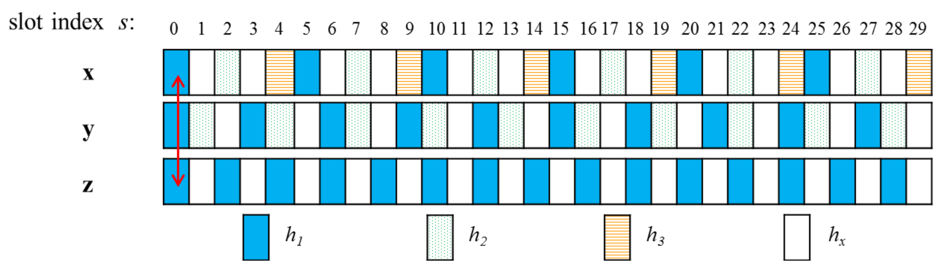
Uniform k-arbiter Based FH Algorithm (AMQFH)



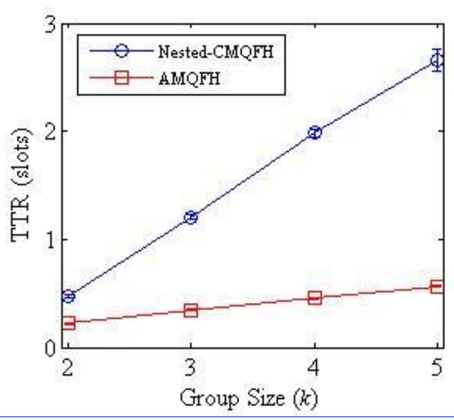
Nested CRT Based FH Algorithm (Nested-CMQFH)

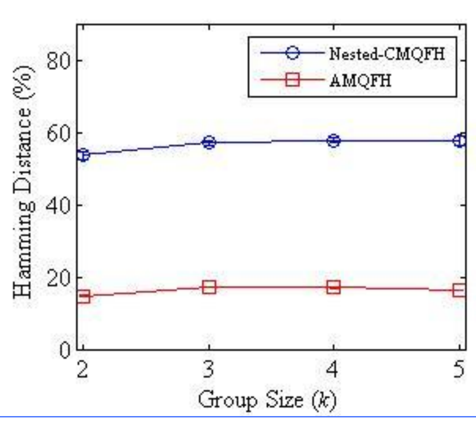
CMQFH: Similar to AMQFH

Nested-CMQFH



Results:





Synchronization-based Algorithms for Decentralized Rendezvous[2]

Reformulation as a Synchronization Problem

Goal: Design a decentralized control algorithm that steers every radio to the same communication channel, that is, for every initial configuration of the radios the channel selection converge to

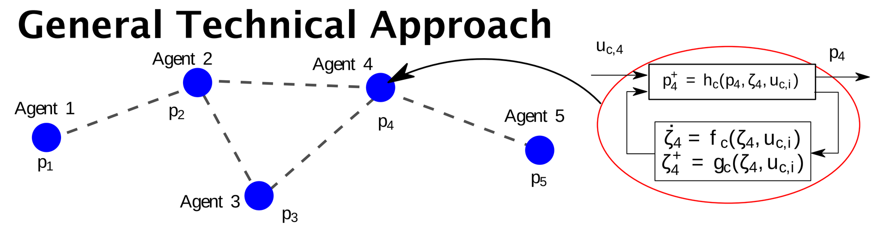
$$p_1 = p_2 = \ldots = p_N$$

under the potential presence of adversaries jamming the channels.

This is not an easy goal to accomplish since

- Common low bit-rate control channel is unavailable
- Frequency hoping algorithms rely on common seeds and could be reverse engineered by adversaries:
  - Frequency hoping [Ephremides ea 87]
  - Frequency rendezvous [DaSilva and Guerrero 08]
  - Frequency rendezvous for CR [Silvius ea 09]
- Broadcast of information should be minimized

General Technical Approach



- Each agent will have a channel selection state $p_i \in \{f_1, f_2, \ldots, f_N\}$ updated discretely by $p_i^+ = h_c(p_i, \zeta_i, u_{c,i})$.
- An internal controller can be dynamic, i.e.
  $\dot{\zeta}_i = f_c(\zeta_i, u_{c,i}) \qquad \zeta_i^+ = g_c(\zeta_i, u_{c,i})$
  where ζ_i is the controller state and $u_{c,i}$ is the input.
- The goal of the controller is to drive the channels to synchronous channel switching, i.e. the set
  $\{(p, \zeta) : p_1 = p_2 = \ldots = p_N\}$
  is rendered asymptotically stable

Proposed Solution

Consider the case N = M = 2 and a hybrid controller for each radio with state

$$\zeta_1, \zeta_2 \in [0, 2T] \qquad T > 0$$

evolving as timers triggering a channel change when reaching T.

Decentralized synchronization strategy:

- Each radio timer ζ_i increases until it reaches T.
- When it reaches T, the radio sends a packet, resets its timer to zero, and switches channel.
- If any other radio is on the same channel and receives the packet, then its timer is advanced by some value ε > 0.

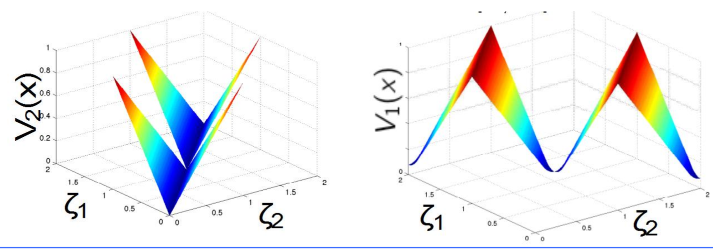
Theorem

The augmented hybrid system model of two radios on two channels is such that

$$A := \{(\zeta_1, p_1, \zeta_2, p_2) : p_1 = p_2 \ \zeta_1 = \zeta_2\}$$

is asymptotically stable with basin of attraction containing every level set of V except $\{x : V(x) = T\}$.

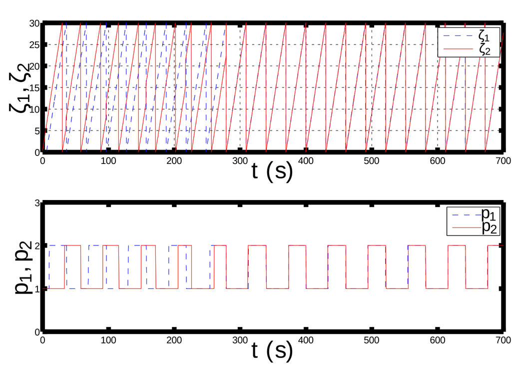
Lyapunov Function given as a piecewise defined function



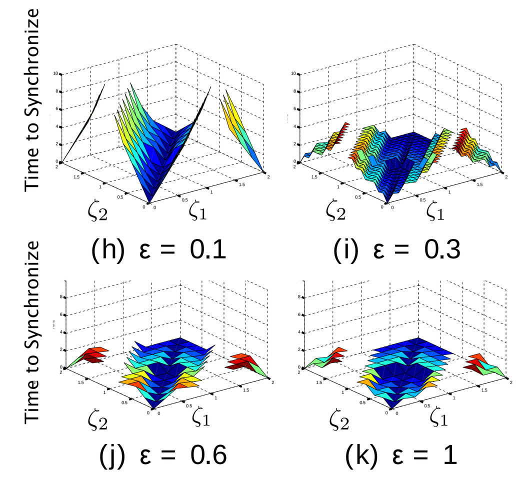
Basin of attraction $\zeta_1 = \zeta_2$

Dynamical Properties of Synchronization Algorithm

Temporal response:

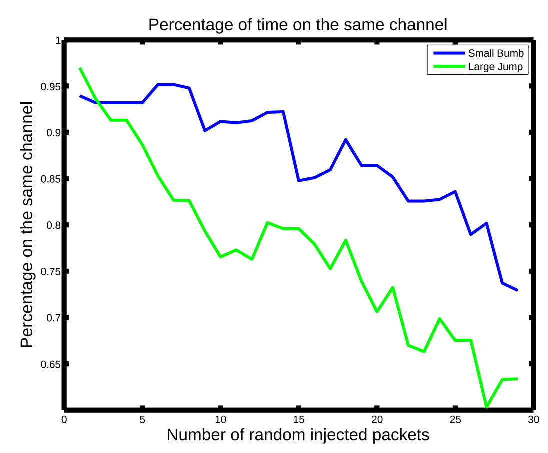


Performance as a function of ε:



(h) ε = 0.1 (i) ε = 0.3 (j) ε = 0.6 (k) ε = 1

Robustness to adversarial packets:



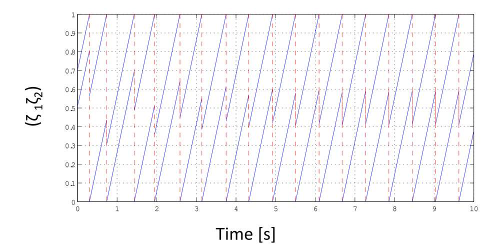
Algorithm for multiple agents (cooperative and adversarial settings)

Proposed algorithm:

- If no packet was received in the T window, agent i jumps to a random channel.
- Radios get an ACK once they transmit a packet at the end of their period (if their packed was received).
- If a transmitted packet is received by another radio and its corresponding ACK was received by the transmitter, then these radios jump to the next channel.

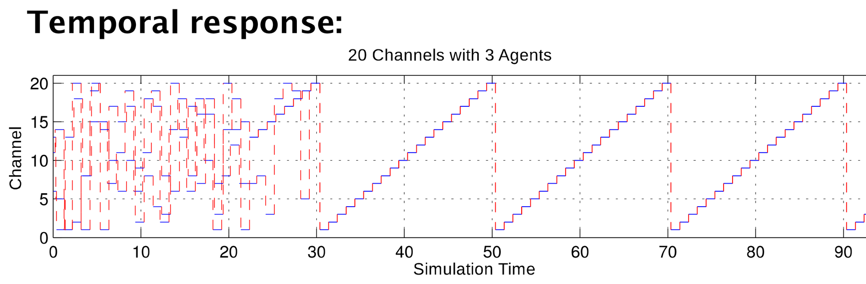
Desynchronizing from jammers:

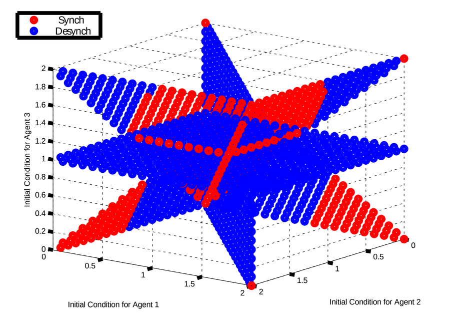
In adversarial settings, cooperative agents can desynchronize themselves from the channels selections of adversarial jammers.

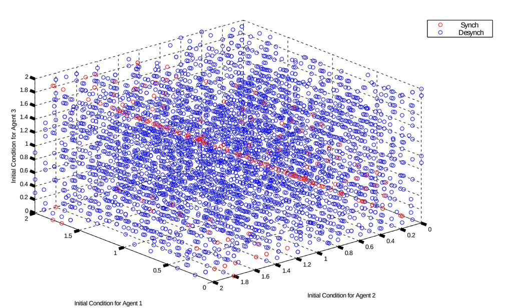


For the case of two cooperative agents and one jammer, the goal is to synchronize the actions of the cooperative agents and, simultaneously, desynchronize such actions from those of the jammer.

Temporal response:







Acknowledgement

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References

[1] Mohammad J. Abdel Rahman, Hanif Rahbari, and Marwan Krunz, "Adaptive frequency hopping algorithms for multicast rendezvous in DSA networks," accepted for the *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN 2012)*, Oct. 2012.
[2] Sean Phillips, Ricardo G. Sanfelice, and R. Scott Erwin, "On the Synchronization of Two Impulsive Oscillators under Communication Constraints," In *Proceedings of the American Control Conference (ACC)*, 2012.