Dynamical influence driven space system design

Ruaridh A. Clark, Ciara N. McGrath, Malcolm Macdonald
Department of Electronic & Electrical Engineering, University of Strathclyde
ruaridh.clark@strath.ac.uk

University of Strathclyde Engineering

COMPLEX NETWORKS

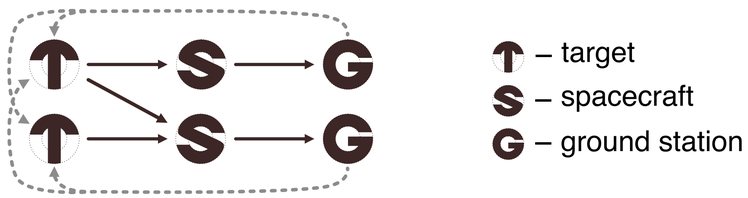
The problem

Emerging small-satellite constellations present as complex data transfer networks, due to the varying contact patterns between spacecraft, data sources (targets) and data sinks (ground stations). The data transfer network is therefore always evolving, requiring an evolving selection of ground stations that depend on spacecraft coverage of identified targets.

The solution

By modelling a constellation for a set period of time, a data transfer network can be created to guide space system designers. We highlight high-level insights from such a network by identifying **communities of dynamical influence**. We also propose **consensus leadership** as a method of sink node (ground station) selection for trading-off between high data flow and source node (target) coverage. This work is acting as the basis for a full space system design tool currently under development.

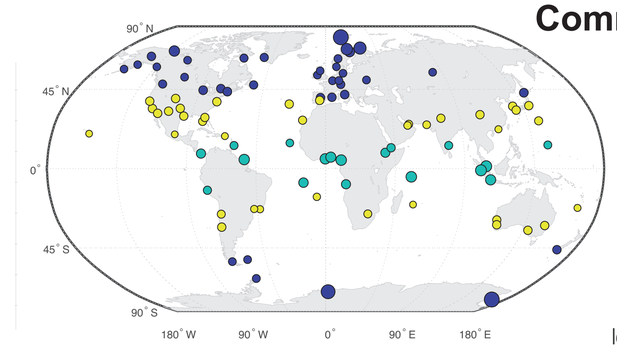
The network



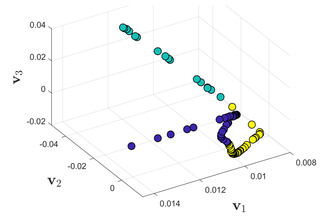
T – target
S – spacecraft
G – ground station

A data flow network is constructed based on data transfer capacity between ground stations, spacecraft, and targets. Spacecraft overfly targets uplinking data that is then downlinked to chosen ground stations. A toy example is shown above, where artificial edges are added between the ground stations and targets to enable network eigenvectors to identify influential ground stations.

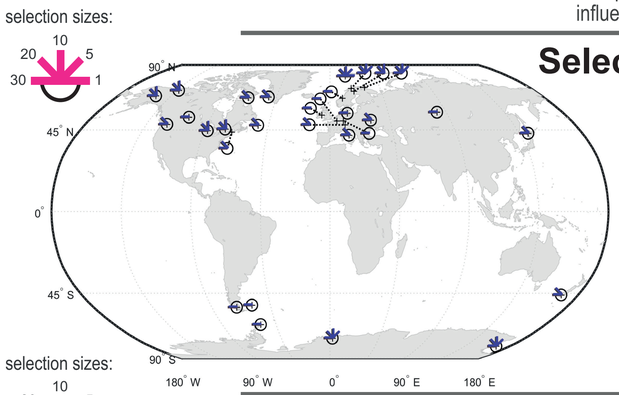
1 - Clark, R., Punzo, G. & Macdonald, M. Network Communities of Dynamical Influence. Sci Rep 9, 17590 (2019). https://doi.org/10.1038/s41598-019-53942-4



Communities of dynamical influence[1]

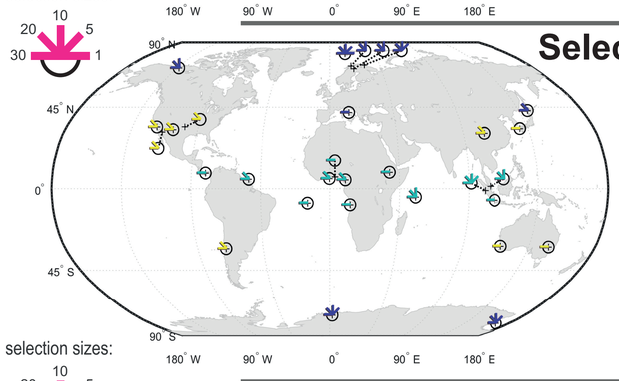


Communities emerge from embedding the network in a Euclidean space defined by the dominant eigenvectors (v_1,v_2,v_3). Ground stations (GS) form communities based on node alignment in this space. Communities form because of differing connectivity to targets, where v_1 corresponds to circle size (left figure) and highest v_1 entry determines community influence.



Selection method: Maximum flow

GS selected for maximum flow maximise the data transferred from targets, without considering data origin. Maximum flow selections of varying sizes (1 to 30) are detailed in the figure (left). Selected GS all belong to the most influential community (see above figures). These GS have the highest capacity data connections as they are near-polar GS with long periods of connectivity when spacecraft passing over the Earth's poles.



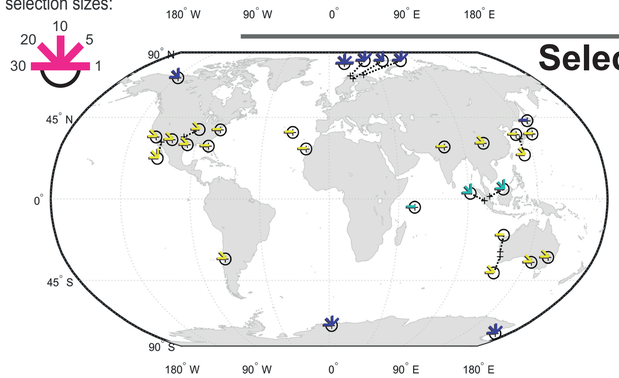
Selection method: Mean consensus leadership

Selections are based on GS leading all targets to a new state according to the linear consensus protocol and data transfer matrix:

$$u_i(t) = \sum_{v_j \in N_i} a_{ij}(x_j(t) - x_i(t))$$
$$x_i(t+1) = x_i(t) + \epsilon u_i(t)$$

matrix $(A = [a_{ij}])$, node state (x), time step (t), neighbours of node v_j (N_j)

This selection minimises the number of time steps required for the ***mean state*** of all targets to exceed a set value. The figure (left) displays a balanced selection across all communities (as shown in top figures) as this ensures all targets are connected.



Selection method: Minimum consensus leadership

The minimum consensus leadership differs in that the selection minimises the number of time steps required for ***all target states*** to exceed a set value. The objective function is tied to the least connected target. Hence, the figure (left) shows that this selection concentrates on the least influential community of GS (as shown in top figures).