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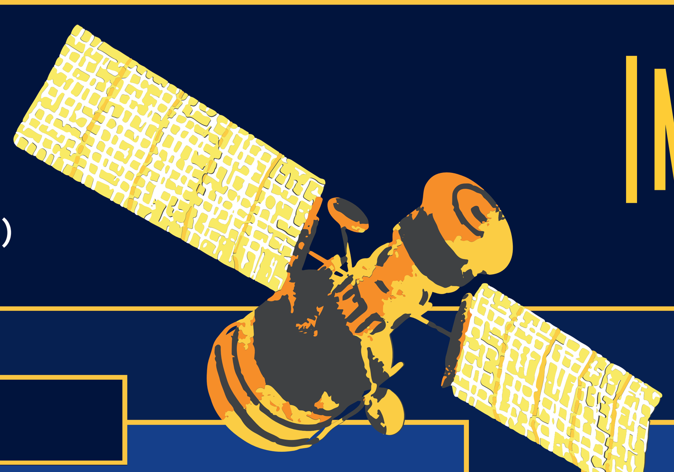


INTEGRATED SPACE COMMUNITIES

DO NOT REQUIRE TRUST

University of Strathclyde Glasgow

Abstract

As space becomes increasingly contested, the terrestrial vulnerabilities of GPS will extend into orbit. The resulting inability to rely on GPS for time synchronisation on ground and in space will cause a fundamental shift in the approach to space networks. The AUDITS (AUtonomous DIstributed Time-signal In Space) project aims to design an autonomous, distributed, robust timing signal in space as an alternative method to GPS time synchronisation. Building upon prior work in consensus algorithms, this project has developed a Disruption-Tolerant Social-Dynamics inspired approach to consensus. This work is being adapted for time synchronisation and space networks which involve dynamic effects, time delays, and relativity effects.

Motivation

GPS signals are used for Earth- and Space-based positioning, and time synchronisation. Many applications rely on these signals to function and coordinate their actions. To be of use, these GPS signals must be time synchronised, with all GPS atomic clocks showing the same time.

However, this reliance faces two issues:

- GPS's centralised approach ("server-client") makes it vulnerable to single point failures (incorrect or spoofed signals), causing all downstream applications to suffer.
- GPS atomic clocks are expensive, yet still suffer from drift and error:
  - As such, GPS clocks must still be corrected from ground.

GPS are vulnerable and expensive - an alternative must be proposed.

Consensus & Time Synchronisation

Methods of network control are shifting from centralised to distributed approaches to avoid communication overheads, and their associated latencies and single point failures.

New theory must cope with issues of:

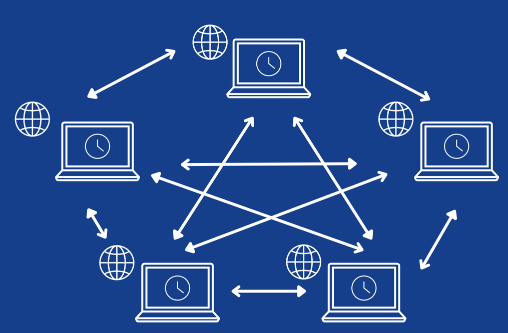
- Security and resilience to faults and deliberate attacks
- Dynamic Systems with shifting nodes
- Realistic Systems with unknown network topologies and delays

Distributed control relies on Consensus building - for nodes within a system to reach a common shared state. Consensus Protocols must be Robust, Reliable, and Adaptable.

Time Synchronisation is Consensus between Clocks - a requirement for action and communication coordination. Time Synchronisation is needed to manage Clock Drift caused by clocks counting time at slightly different rates.

In distributed control, Virtual Clocks are contrasted against Hardware Clocks.

Hardware clocks (Ω) are the result of the physical oscillator housed in the satellite (ω), its ticking rate (α), and offset (β) from a given reference.



Virtual (software) clocks (ψ) take as input the output time of hardware clocks (Ω) and adjusts it with a virtual rate (φ) and offset (μ):

$$\Omega = \alpha^{*}\omega + \beta$$
$$\psi = \varphi^{*}\Omega + \mu$$

Time Synchronisation is performed over virtual clocks to avoid directly modifying hardware clocks since doing so reduces their health and longevity.

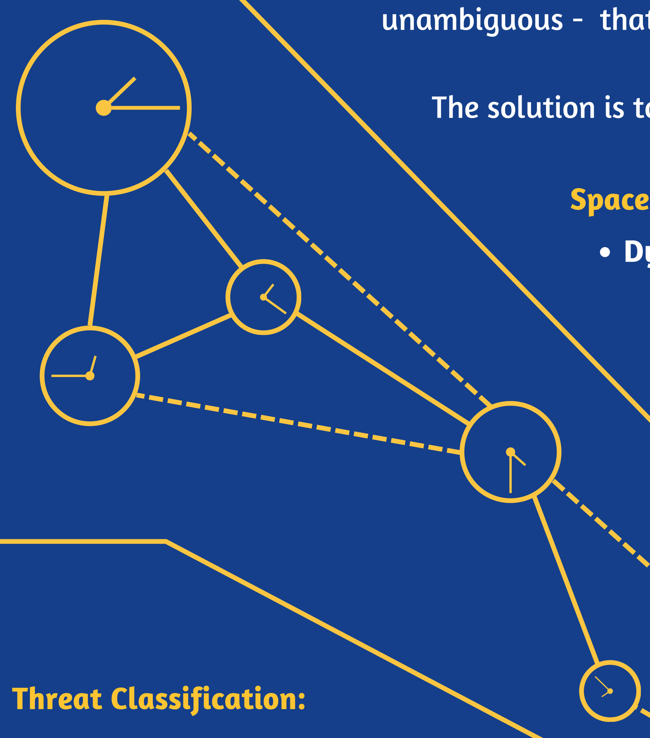
Space IoTs

If in the 1970s satellites supplemented ground networks, new projects are now integrating satellites as integral pieces of the future Internet for new 5/6G Technology. In the new space age (cheap launches and quick procurement of small, inexpensive, and standardised CubeSats), IoT architectures can now be extended to space for increase scale and flexibility. Space IoTs are the evolution of the increasing interconnectedness of space. This extension matches general trends in IoTs: lower power, longer range of data transmission and processing, higher reliability, and better security and privacy.

In the light of these developments, it is now possible to conceive space networks as communities of distributed processing actors.

However, for such environment to emerge, one problem must be solved: time synchronisation. In a centralized system, time is unambiguous - that is not the case for distributed systems.

The solution is to develop an autonomous, distributed, robust timing signal in space. To do so, 2 key areas must be addressed:



Space Networks:

- **Dynamics**: Unspecified Network Topologies incorporating deterministic motion from their timing nodes.

Delays: Space Communications deal with large delays, intermittent connectivity, and asymetric links.

Relativity: Space Networks are subject to both Special and General Relativity due to the satellites' velocity and altitude.

AUTONOMOUS

Threat Classification:

- **Attacks**: Can target different system levels and features, most commonly: Confidentiality, Integrity, and Availability (CIA) - all of which affect the client.

ROBUST

- **Defences**: What is the expected level of performance?
  - Prevention - attack does not cause damage,
  - Resilience - system bounces back from an attack,
  - Detection - system can detect malicious nodes,
  - Intelligence - system learns from attacks.

DISTRIBUTED

- **Robustness and Resilience:** Terms used as umbrella terms bringing together notions of dependability, fault tolerance, reliability, security and survivability.

  However, for this project it is important to characterise these terms.
  - Is it a behaviour or a static network metric?
  - Where in the system do robustness and reslience emerge?
  - What perspectives matter most for the analysis: component level, information systems infrastructure, service/end-users, or design integration?

(Left) Newer generations of connectivity (5/6G) see increasing levels of integration, with mobile networking technologies realising Space, Air, Ground Integrated Networks (SAGINs)

This Project's objective is the design of a robust distributed time synchronisation consensus protocol, aiming to function over dynamic satellite networks, bringing together:

- Satellite Networks
- Time Synchronisation Protocols
- Cybersecurity Considerations

Up until now, this work has focused on Consensus Protocols and the defining of what Robustness and Resilience mean in the context of space networks.

A Social Dynamics Approach to Consensus

Love, Hate, and Propaganda, or how opinion dynamics can engineer consensus for synchronisation

Social dynamics models characterise the underlying behaviour of social interactions and seek to answer the following questions:

- How do people's opinions change based on their social interactions?
- How can minority opinions dominate social groups?

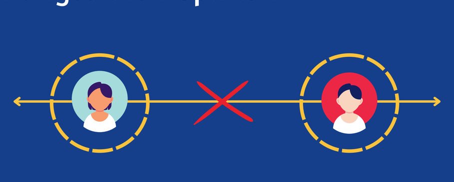
Mathematical models are used to describe the dynamics of opinion diffusion. They model the outcomes of opinion sharing in social networks, notably:

- Consensus (1 opinion dominates)
- Polarisation (2 opposite opinions dominate)
- Fragmentation (no clear opinion dominates)

A key focus is the modelling of inflexible and extremist agents who create conflicts and sway their more open-minded peers, fragmenting communities.

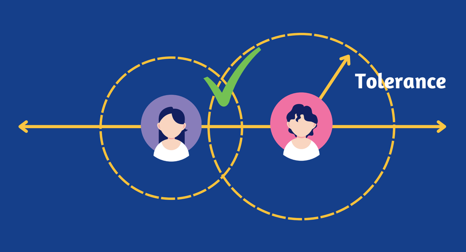
The most common Social Dynamics model is the Deffuant Model. Agents are modelled with a tolerance. If:

- Two agents have sufficiently close opinions (within each other's tolerance) -> their new opinions evolve closer
- Two agents have radically different opinions (no tolerance overlap) -> their opinions do not change
- One agents accepts the other's idea, but not the reverse (one agent's tolerance is larger than the other) -> only one agent changes their opinion



(Left) Disagreement - No Opinion Change

(Right) Agreement - New Opinions will Converge



Tolerance is based on extremism levels. The more extreme an agent's opinion, the lower their tolerance (see above).

Based on the similarities in mechanics between Social Dynamics and Consensus Protocols, a **SOCIAL DYNAMICS INSPIRED PROTOCOL** has been designed, tested, and concluded to be **DISRUPTION-TOLERANT.**

Social Dynamics

Extremists Agents have Low Tolerance

Extremists Agents cause Fragmentation

=

Consensus Protocols

Disruptive Nodes cannot be ignored

Disruptive Nodes cause Fragmentation

→

Social Dynamics Protocols

Exploits and Inverts Tolerance Mechanism

Nodes' Tolerance is now INVERSLY linked to their extremism

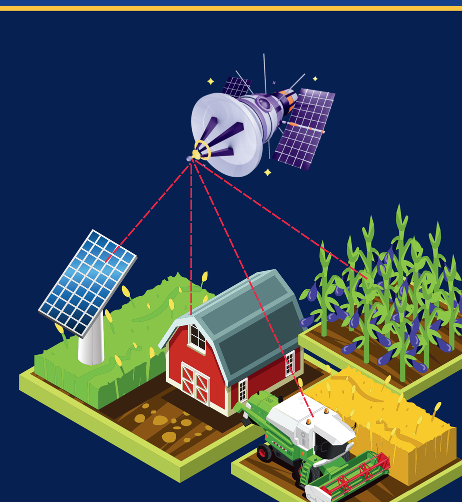
Applications

This Project will slot itself in the current framework of satellite network communications and offer an alternative to GPS time synchronisation and position. The Project:

- can operate on lower quality clocks compared to typical high precision GPS clocks (lower costs).
- is robust to disruption within the network (faults and malicious actors).
- is not trust-based, its design preventing disruptive agents from impacting its consensus while still allowing new members to join the consensus and connect to the network.
- will integrate in the existing architecture of satellite communications, requiring no adaptation.

This enables a higher level of integration of satellites and satellite constellations, resulting in an augmented architecture which will allow for:

- improved service coverage, reliability, performance, and efficiency.
- a more cohesive use of space resources benefiting ground applications and end-users, but also earth- and space-based sustainability efforts.
- an incentive for cooperation and collaboration within the network.
- a unified and harmonised perspective of space networks, promoting regulations and standardisations.



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