Applied Space Technology Laboratory (ApSTL)

Time to Agree

Time synchronisation across Satellite Networks

A. BOUIS, R. A. CLARK, M. MACDONALD

University of Strathclyde Glasgow

agathe. bouis@strath.ac.uk

Read more in: Bouis et al, (2024), "An autonomous distributed timing signal in space as alternative to GNSS time synchronisation" in IAC 2024 conference proceedings.

A. Satellite Time Synchronisation

Accurate synchronised time is key for many Earth- and space-based services: telecomms, sensor data, bank systems...

Currently, the primary source of this time data comes from GPS. **BUT**, the past years have shown GPS' vulnerability to space weather and attacks which caused widespread disruptions.

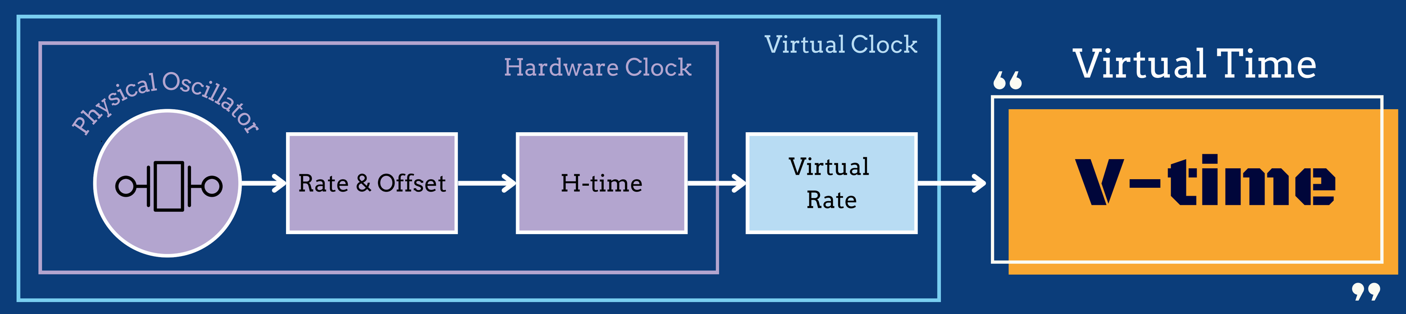
With the number of satellites launched increasing exponentially and satellites becoming increasingly interconnected, satellite constellations are being re-imagined as Internet of Things (IoT) networks.

This shift in thinking towards IoT approaches enables a re-think of Time Synchronisation where current centralised methods are failing. Bringing **Space** and **IoT** together, this project presents a **resilient, distributed, and space-based time synchronisation** algorithm enabling satellites to synchronise despite of disruptions and without the need for an external reference source.

B. 2 Clocks, 1 Satellite !

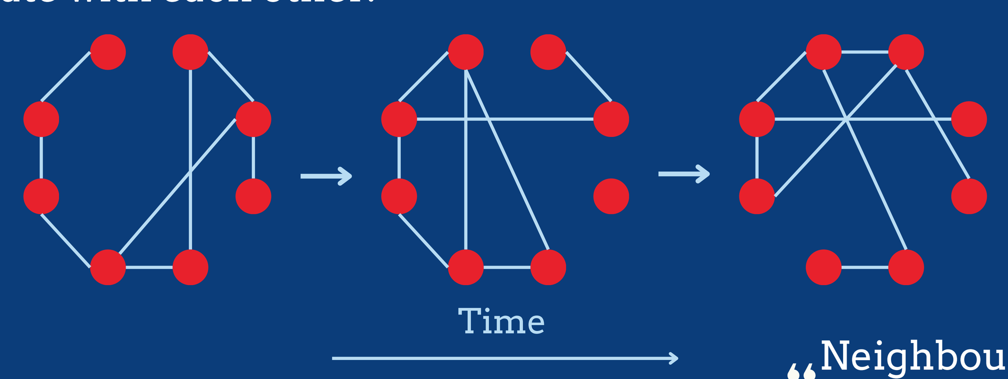
Two clocks are distinguished on board satellites:

- The **Hardware clock (H)**: satellite's physical oscillator. The H-time is the results of the oscillator frequency (f), its ticking rate (t), and offset (o) with respect to the ground standard, H = t*(1/f) + o. H-clocks may drift over time due to aging, heat, damage...
- The **Virtual time (V)**: software time created by adapting the H-time with a virtual rate (r), V = r*H. **Time Synchronisation is performed over V-clocks** by correcting the virtual rate to avoid modifying the physcial clocks as this damages their long-term durability.



C. Satellite Networks

Satellites can communicate with each other using Inter-Satellite Links (ISLs). Much like IoTs, this interconnectedness allows satellite systems to be abstracted as **time-varying dynamic networks**, where nodes represent satellites and edges represent satellites close enough to communicate with each other:



Satellites receive **V-time data** from their **neighbours** and store it into a database on board the satellite: Neighbours'-times.

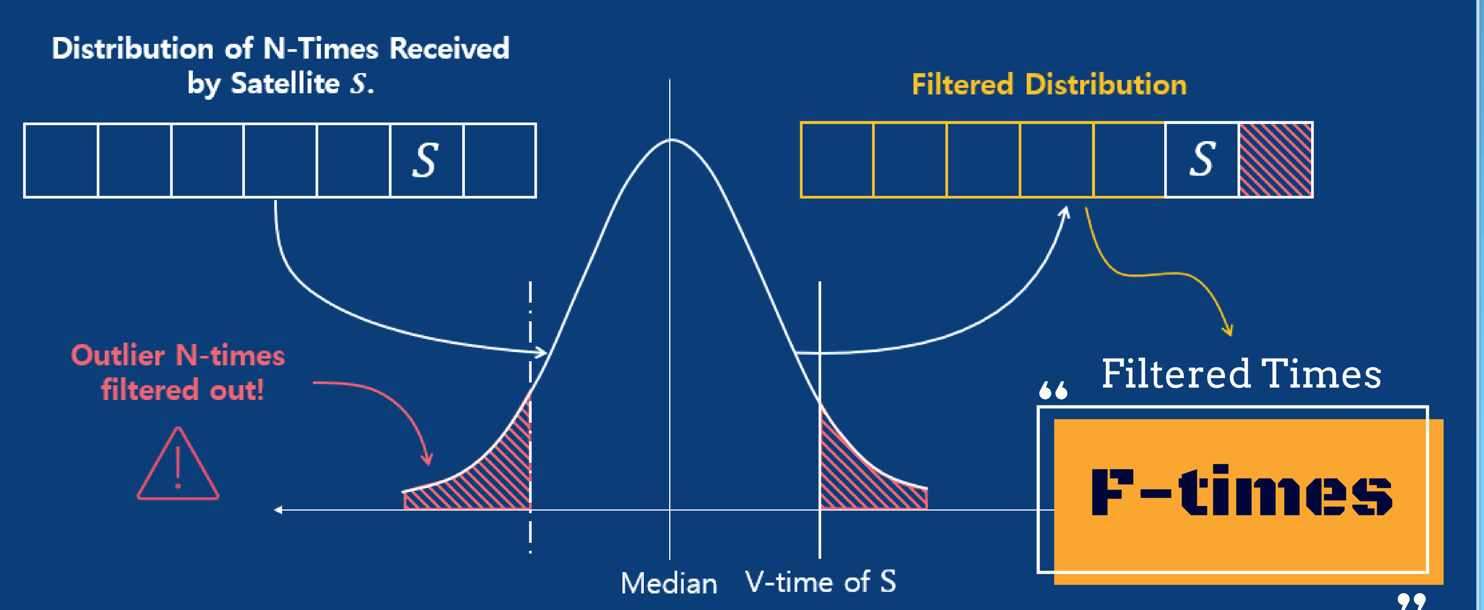
"Neighbours' Times **N-times**"

D. Preventing Divergence

Time synchronisation is achieved by **satellites reaching a consensus on a shared distributed time**. To do so, satellites exchange their on-board V-times with their neighbours, and adapt their virtual rates to allow them to tick at a same frequency

Malicious or faulty satellites with **extreme on-board V-times** can **disrupt the consensus process**. To mitigate these disruptor nodes' influence, the time values sent by the satellite's neighbours, **N-times, are filtered**.

Using a protocol (ODDI-C) inspired by the Opinion Dynamics of social systems [1], extreme nodes are dynamically filtered out during each Consensus Cycle. The nodes remaining following this step are the **Filtered Times** (F-times) and are used for the update.



E. An Agreed Time !

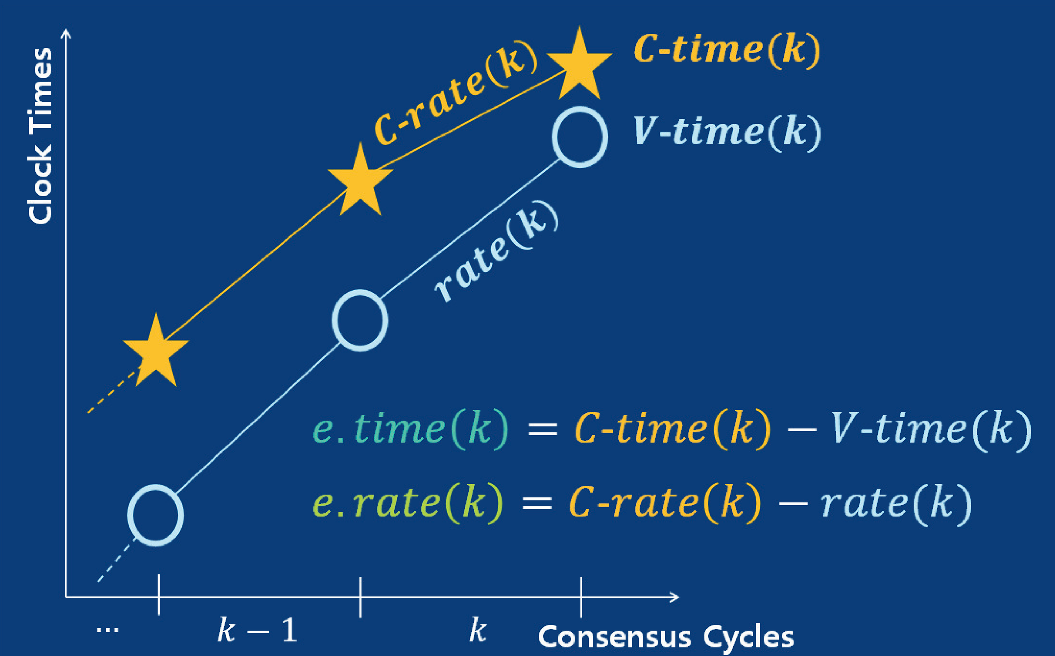
Following the removal of disruptive values a **Consensus-time** is calculated*. **The satellite's goal is to match its V-time to this value by changing its virtual rate.**

"Consensus Time **C-time**" = mean of F-times **

*If all N-times are filtered out (F-times is empty), C-time is the satellite's own V-time!

**If S.'s V-time is not an outlier, it is included in the F-times

From the C-time, **2 errors** are calculated. These indicate **discrepancies between the satellite's V-time** and the **consensus value** it should reach.



$$e.time(k) = C\text{-}time(k) - V\text{-}time(k)$$

$$e.rate(k) = C\text{-}rate(k) - rate(k)$$

These **errors** are then used to calculate the **new rate** to allow the satellite to match the consensus time.

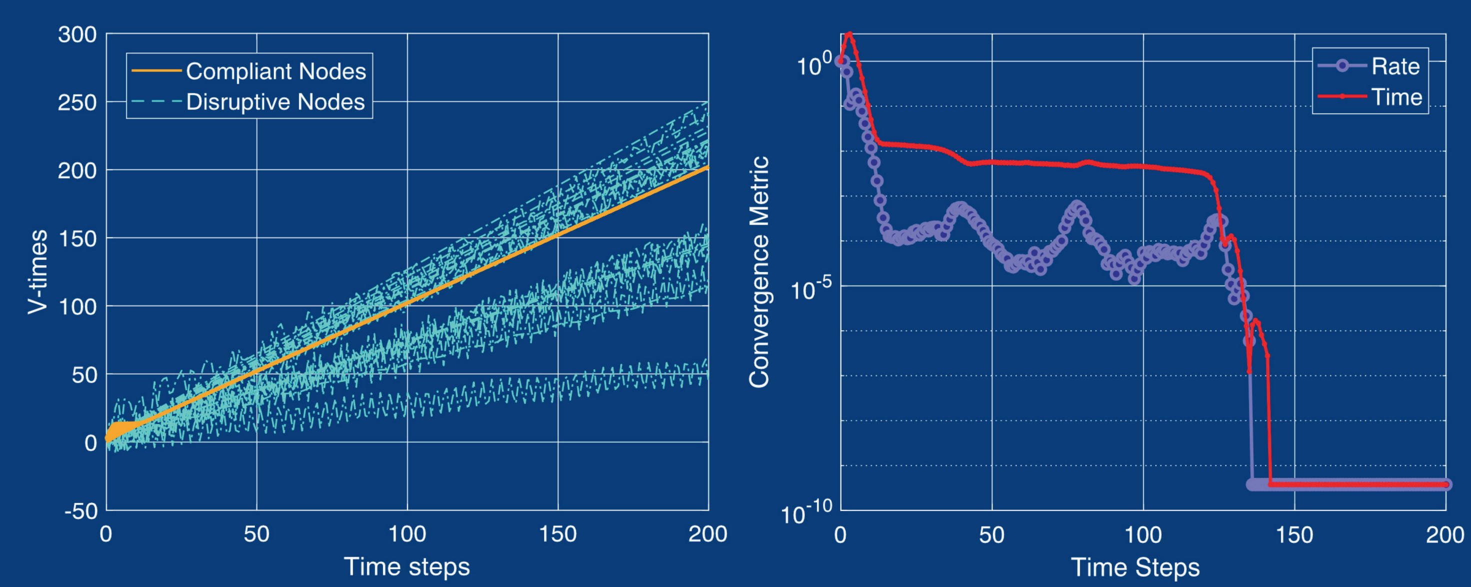
"**New Rate**" = rate (k) + 0.5 e.time (k) + e.rate (k)

The consensus process is repeated with new data over multiple consensus cycles, reducing the errors in rate and time at each step.

F. Success !

Tests show that **robust and distributed synchronisation in time and rate** can be obtained for satellite networks, without the need for any terrestrial reference time,

Example below: (right) evolution of the V-times of a 500-satellite network attacked by 20 disruptive nodes, (left) convergence in time and rate between non-disruptive satellites.



[1] BOUIS A. et al, (2024) "Engineering Consensus in Static Networks with Disruptors" in Applied Network Science.

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