A Fault-Tolerant High Speed Network for Inter-Satellite Links (ISL)

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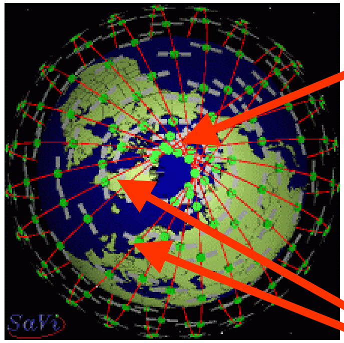
Introduction

- **Incorporating IP-compliant technologies could potentially allow seamless interoperability and connectivity between all subsystems in a single spacecraft as well as between spacecraft in a constellation or formation.**
- **A multi-satellite network based on IP-compliant wired and wireless protocols, which are implemented with commercial- off-the- shelf (COTS) components will contribute to the concept of Internet in the sky.**
- **COTS protocols such as IEEE 802.11 and SpaceWire will achieve fault-tolerant connectivity using intra and inter-satellite links providing less redundancy and more flexibility and which is of particular benefit to smaller spacecraft that are constrained by mass and volume.**
- **The main goal of this research is to build a communication platform for transfer of telecommand, telemetry and data information between satellites using inter-satellite links aiming at distributed small satellite missions.**
- **We propose that the bus and air interface structures of IEEE 802.11 and SpaceWire are combined to support a fault-tolerant and yet high performance network for the communication needs of autonomous distributed multi-spacecraft formations or constellations.**

IEEE 802.11 Optimisation for Inter-Satellite Links

This project is set to modify the IEEE 802.11 Physical and MAC layers for ISL range and frequency for the network and control connectivity in LEO constellations with variant geometry. The work will focus on:

- **Transmission at Ka-band: enabling high data rates and spatial reuse with small size high gain array antennas.**
- **Null Steered Reception: enabling receptions from one satellite to another satellite without interference from nodes transmitting simultaneously to the same node**
- **Variable Rate Cross-Links: enabling satellite to maintain connectivity over a wide range of distances.**
- **Medium Channel Access Mechanism: integrating physical carrier sensing and null steered transmission/reception.**
- **Neighbour Discovery : enabling a node to advertise itself, find nodes and achieve frame and initial frequency synchronisation.**
- **Interfacing with SpaceWire for spacecraft inter-module communications using wormhole routing.**



Limited Communication at poles due to satellite interference and frequency drift

Counter rotating Cross-Seam (The need for smart antennas)

Fig. 1 Polar Orbit LEO Constellation [5](SaVi Simulation)

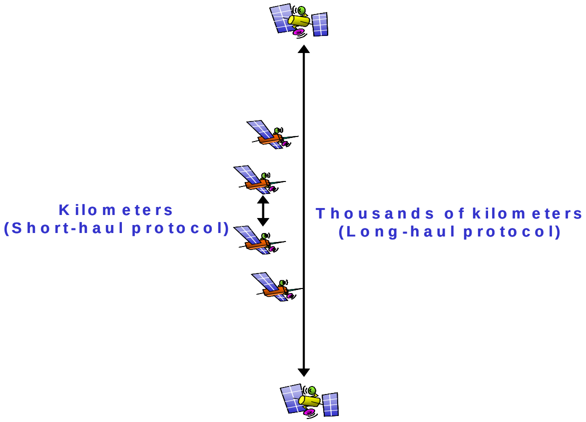


Fig. 2 Multi-Protocols Architecture for Short and Long haul ISL Distances [2].

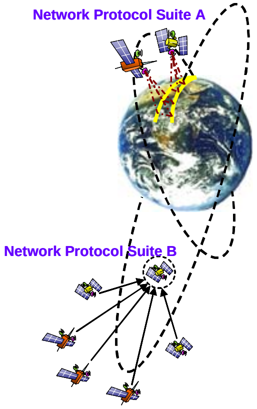


Fig.3 Satellite Distributed Networks [2]

Antenna Models for the IEEE 802.11 Physical Layer Optimisation

$$z(t)=\sum_{i=1}^{M} w_i S_i(t)+N(t)$$

$$= AS(t)\sum_{i=1}^{M} w_i e^{-J\beta(i-1)d\cos\theta}+N(t)$$

$$\beta=\frac{2\pi}{\lambda};\quad w_i=e^{J\beta(i-1)d\sin\theta_0}$$

Where $z(t)$ is the receiver input

w_i = beacon signal strength

$S_i(t)$ = signal arriving at antenna

β = phase propagation factor

d = distance between elements

$N(t)$ = white Gaussian noise

A = Amplitude of signal

$\lambda = \frac{\text{speed of light}}{\text{frequency}}$

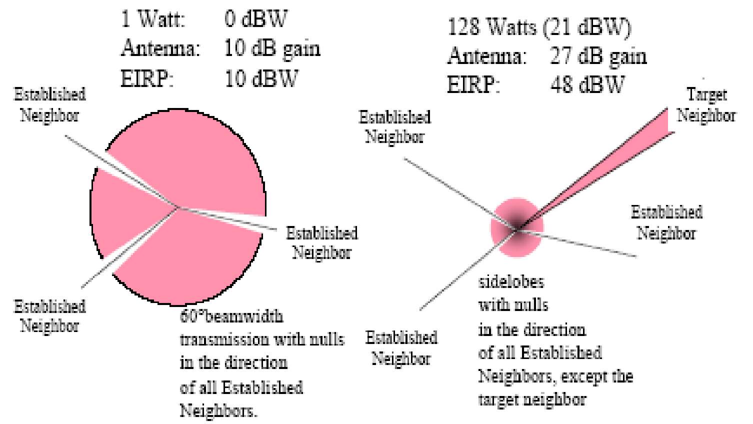


Fig. 5 a) Null-Steered Broadcast b) Null-Steered Point-to-Point

Source: Bergamo el. al.

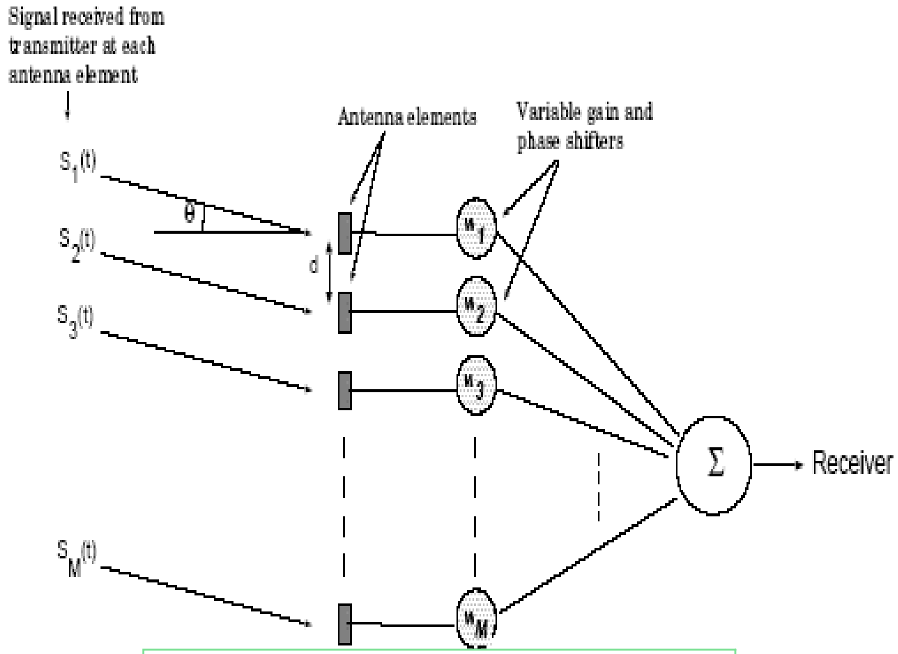


Fig.4 Antenna Phase Array Model

The integration of smart agile antenna with the IEEE 802.11 physical layer using these models will increase the range by an order of magnitude greater than the standard transmit power of 1 Watt without any modifications.

The null-steered broadcast and point-to-point will use the weighing factor, w_i to direct sharp beams towards target satellites with minimal interference from other satellites as shown in Fig 5.

Fig. 4 provides the schematic of an adaptive array smart antenna system with elements separated by distance d, providing a phase difference. Provided transmitters are located far enough away from the receiver then different signals $S(t)$ will arrive with different gains. The weighing factor w_i , which denotes the phase and gain that is added to each signal $S_i(t)$, only shifts the main beam to the desired direction leaving amplitude unchanged.

The effect of the LEO ISL Variance on the IEEE 802.11 Physical Layer

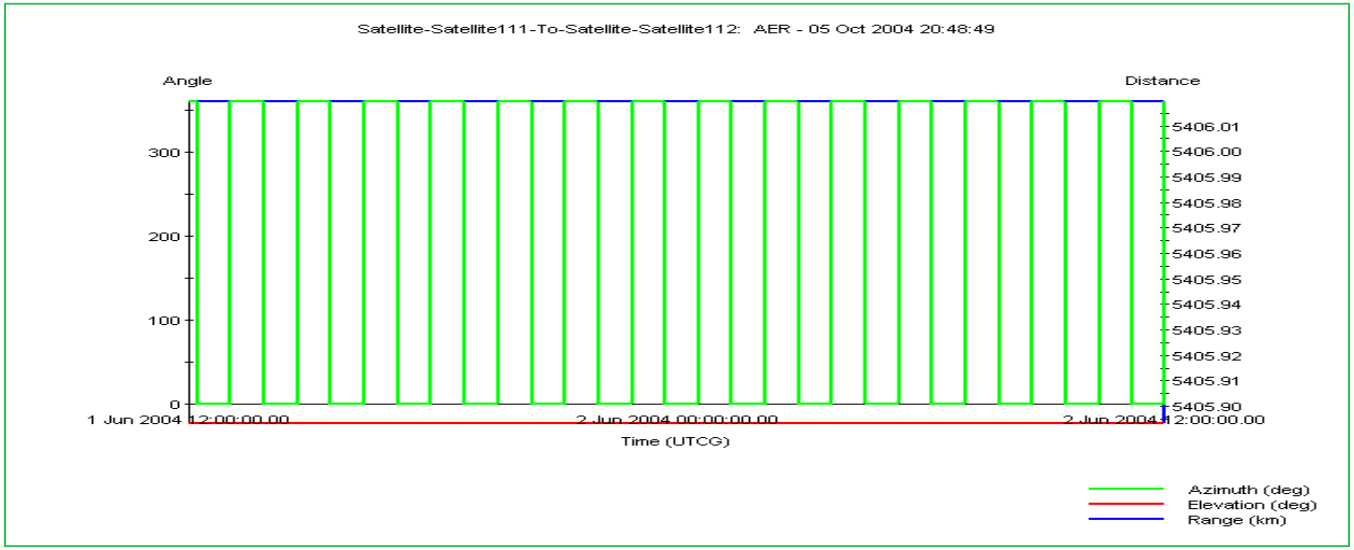


Fig.6 Intra-Plane Satellite Links

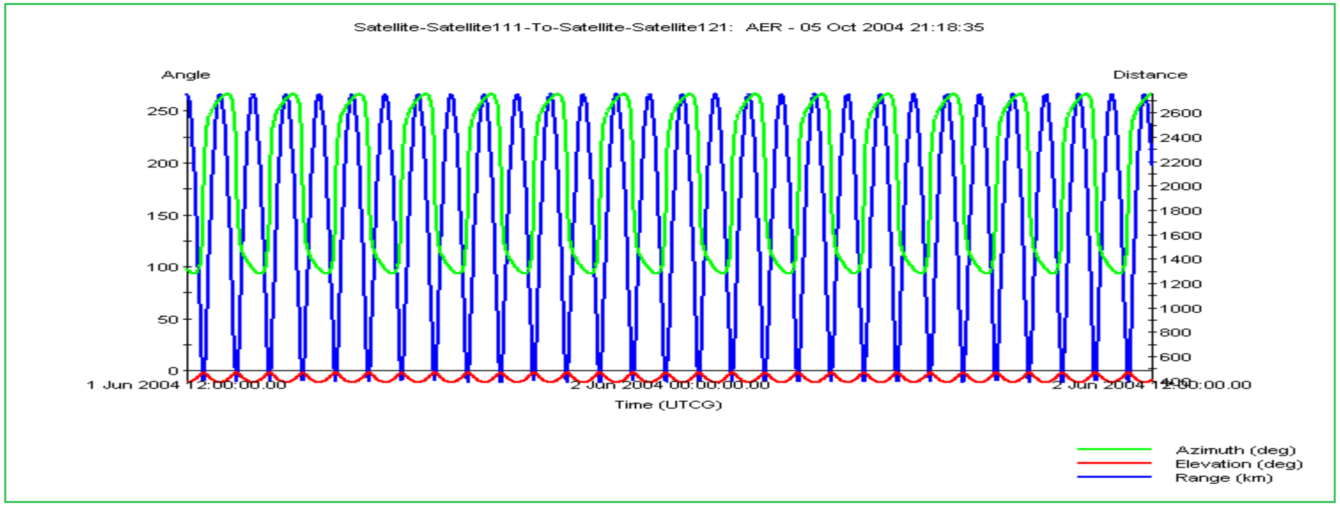


Fig.7 Inter-Plane Satellite Links

The LEO network geometry is dynamic in nature since the satellites are moving at high velocities in relation to rotating Earth and each other, the cross-link connections between two satellites are also varying with the network topology.

The impact of the geometry of inter-satellite links on the performance of the communication systems must be investigated.

In Fig. 6 there is minimal variation between satellites in the same orbital plane, which indicates a constant signal propagation.

The range is varying between 600 to 2600 km for satellites in different planes as shown in Fig.7, hence variable propagation delays and the need for smart agile antennas to track satellites.

The results indicate that the choice of ISL architecture has a significant effect on user-to-user delay and the communication system.

Performance Comparison of Different IEEE 802.11 Physical Layers for ISL Range

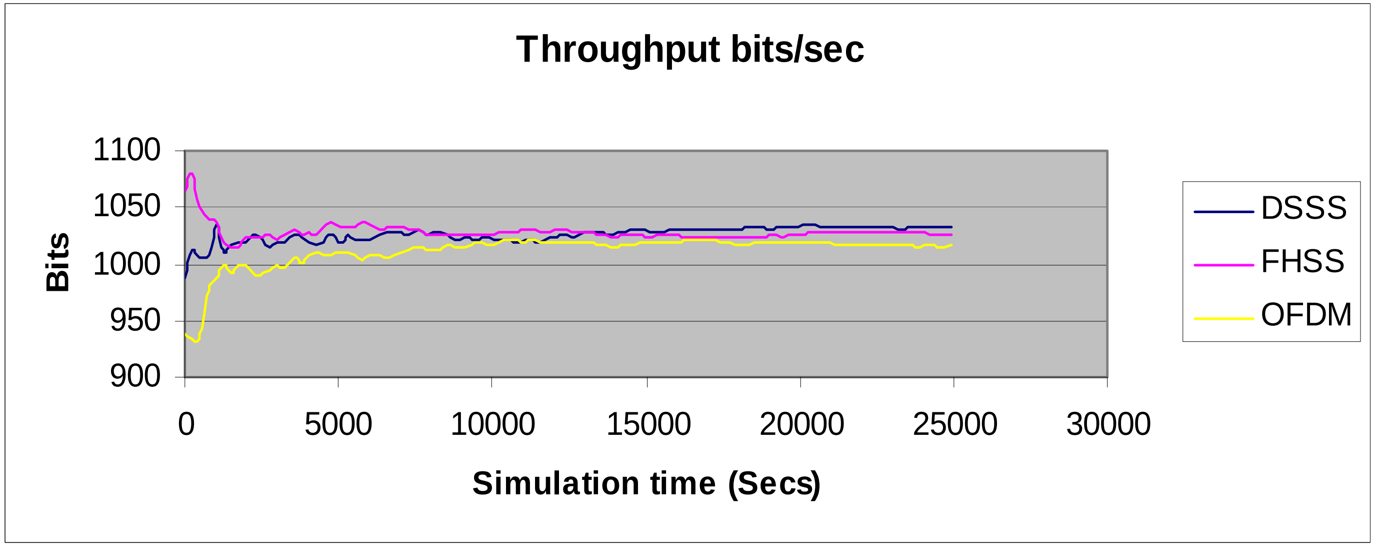


Fig. 8 IEEE 802.11 Throughput at 600 m

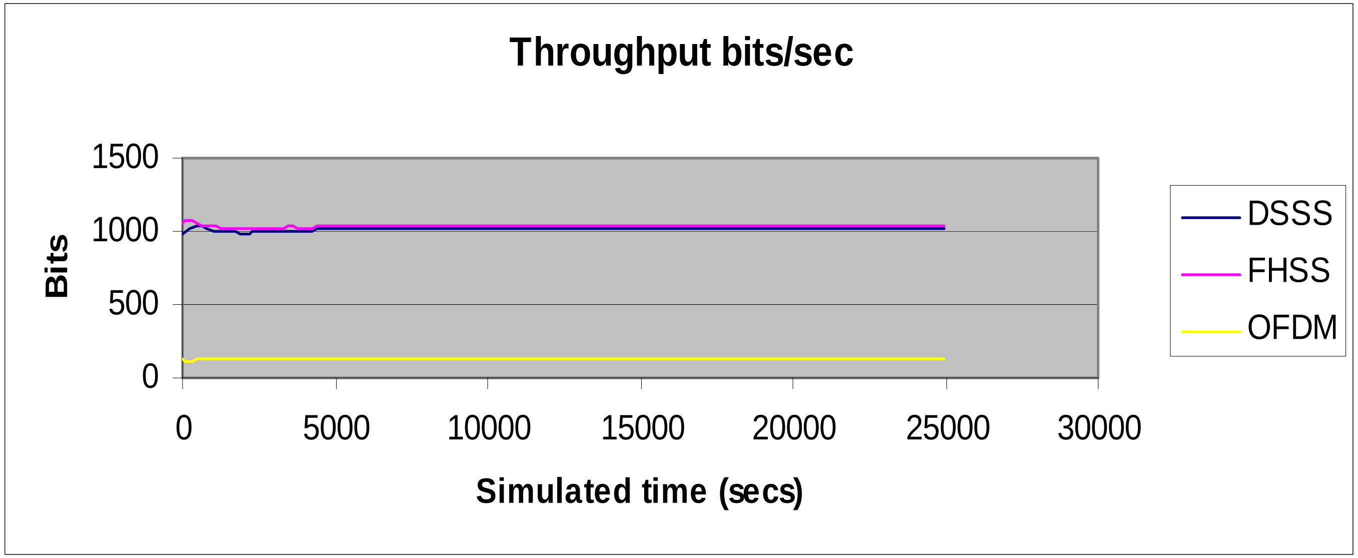


Fig. 9 IEEE 802.11 Throughput at 8 km

The IEEE 802.11 is designed for terrestrial application with a maximum transmit power of 1 Watt and outdoor distances of only 300 meters.

Fig. 8 & 9 compare the performance of three physical layers at a data rate of 1100 bits/sec. The results indicate that the DSSS has a better throughput at increased range, while OFDM needs high linear amplifiers and power for the same performance.

The impact of the LEO variance and range on different physical layers of the IEEE 802.11 standard will be investigated next in this research.

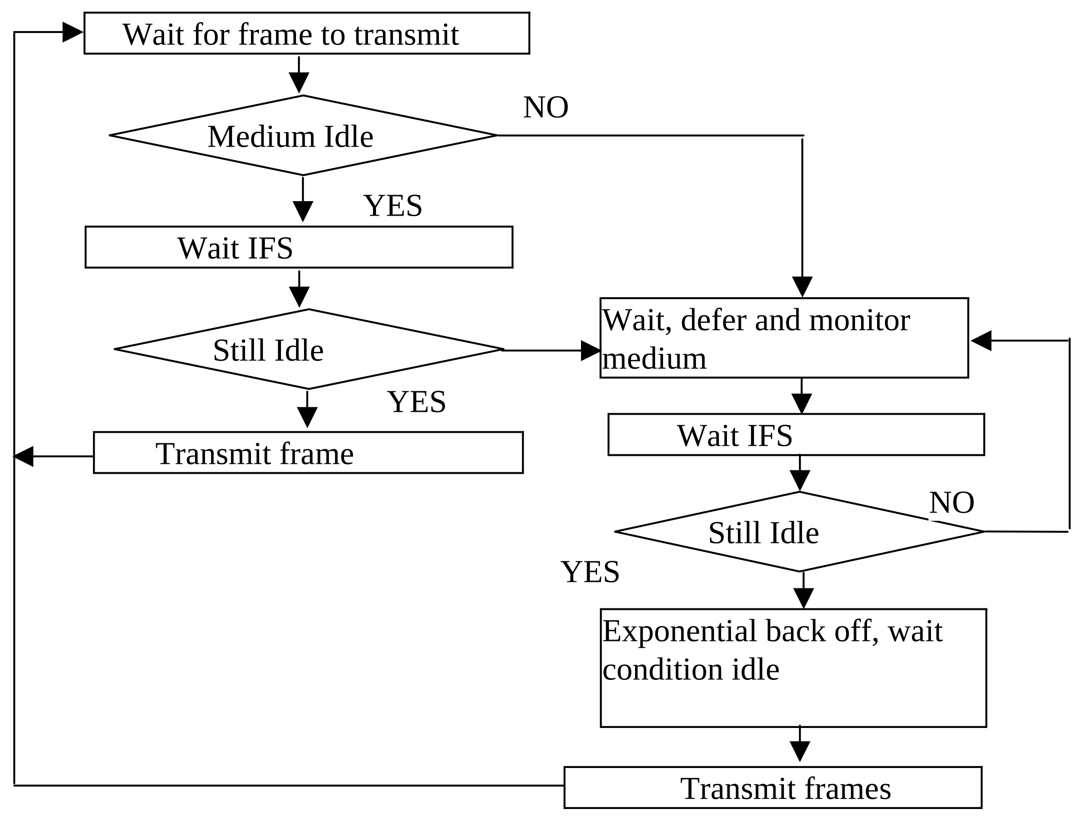
Legend:

DSSS *- Direct Sequence Spread Spectrum*

FHSS *- Frequency Hopping Spread Spectrum*

OFDM *– Orthogonal Frequency Division Multiplexing*

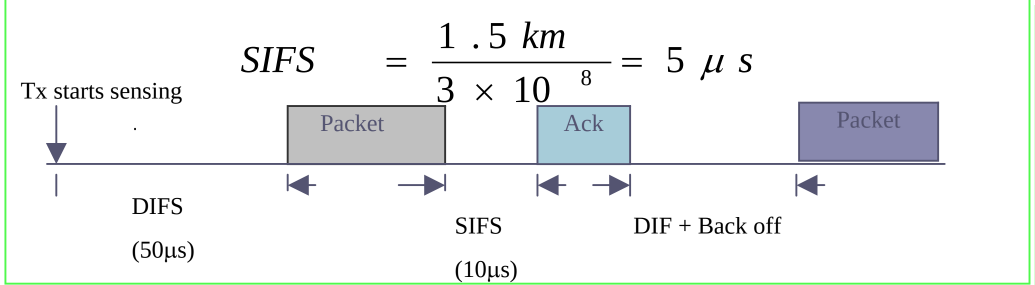
IEEE 802.11 MAC Optimizations



There are three main types of inter-frame spacing defined in 802.11 namely the Short Inter Frame space (SIFs ~ 10µS); DCF Inter Frame space (DIFs ~ 50µS) and PCF Inter Frame space (PIFs ~ 28µS). These inter frame spacings are provided to set different priority levels for access to the medium as shown in Fig 10. The SIFs is used to separate transmissions belonging to a single dialog like ACK, RTS and CTS. The PIFs is used for time bounded services in the Point Coordination function for nodes using infrastructures like Access points- to set polling priorities. The DIFs is used for the distributed services in the DCF for nodes using infrastructure less nodes like ad-hoc networks.

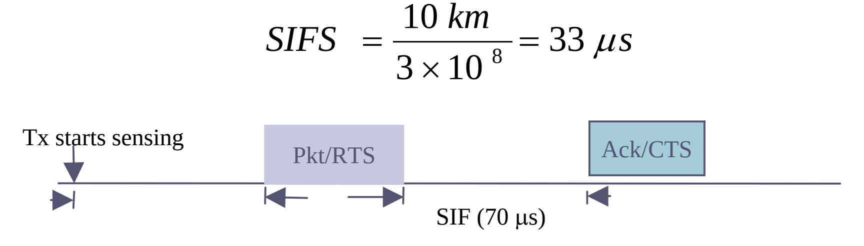
By exploiting the fact that the inter frame time out intervals are not explicitly specified in 802.11 and it is meant for indoor use of 100 meters range, the effect of increasing delay on the MAC and the physical layer, as the range increases up to 10 km were investigated.

The results show that IEEE 802.11 is feasible for ISL range for up 10 km by redefining the inter-frame delays without any modifications to the standard.



$$SIFS = \frac{1.5\ km}{3 \times 10^{8}} = 5\ \mu s$$

Fig. 10 The IEEE 802.11 Control Inter-frame Timing Definitions as Specified in the Standard



$$SIFS = \frac{10\ km}{3 \times 10^{8}} = 33\ \mu s$$

Fig. 11 Modifications to the Inter-Frame Control Signals for Increase Range

Integration of IEEE 802.11 MAC with Antenna Null Steering

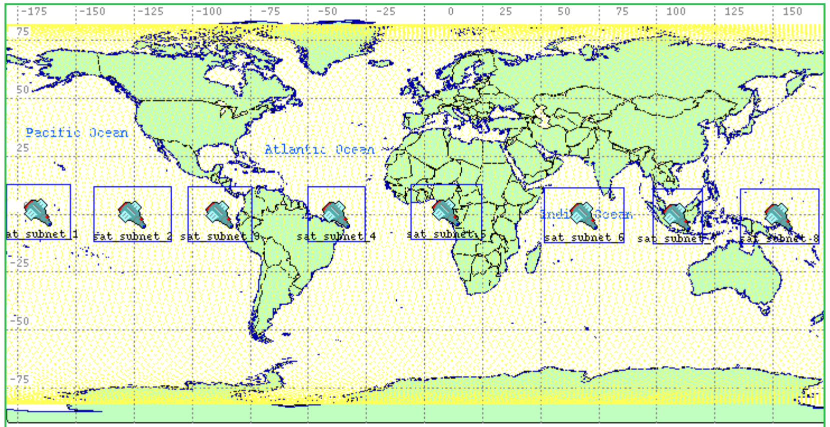


Fig. 12 IEEE 802.11 Network Model in OPNET

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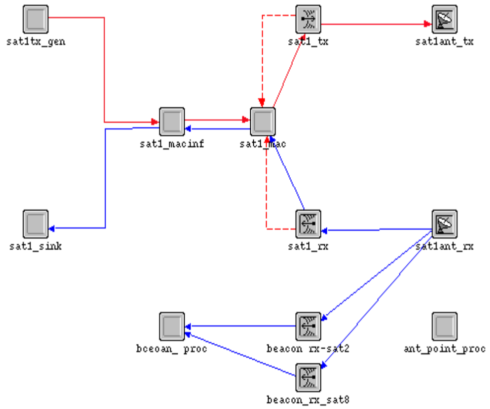

Fig. 13 IEEE 802.11 NODE Model in OPNET

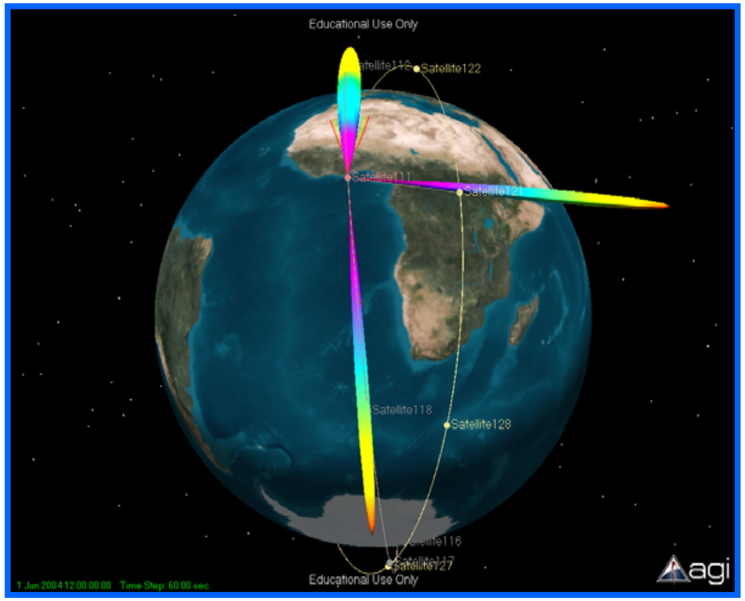

Fig. 14 Reception Null Steering Discovery in STK

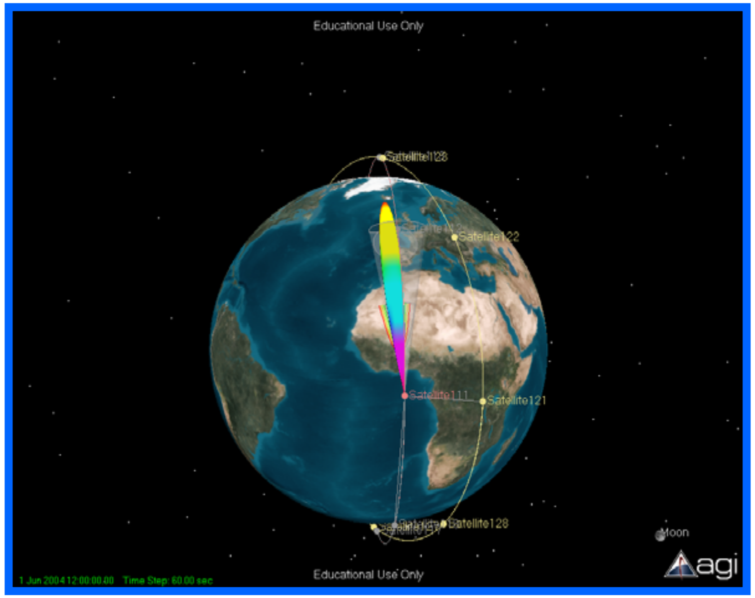

Fig.15 Target Discovery in STK

The main problem of using connectionless protocols such as IEEE 802.11 with MAC functions is the near and far end node interference problems especially when satellites are close to the poles where interference is inevitable.In present constellations using ISLs, satellites are handed-off at the poles and at cross-seams to reduce interference thus reducing the connectivity of satellites.

Fig. 12 shows an imported LEO orbit from STK to OPNET for IEEE 802.11 performance analysis using the node model in Fig. 13 for each satellite in the constellation. Continuous monitoring of IEEE 802.11 beacon signals strength from neighbouring satellites is achieved using antenna null steering and direction of arrival algorithms. Correct operation of pointing, acquisition and tracking of target satellites with signal strength above beacon threshold is shown in Fig. 14 & Fig. 15

IEEE 802.11 Performance Analysis

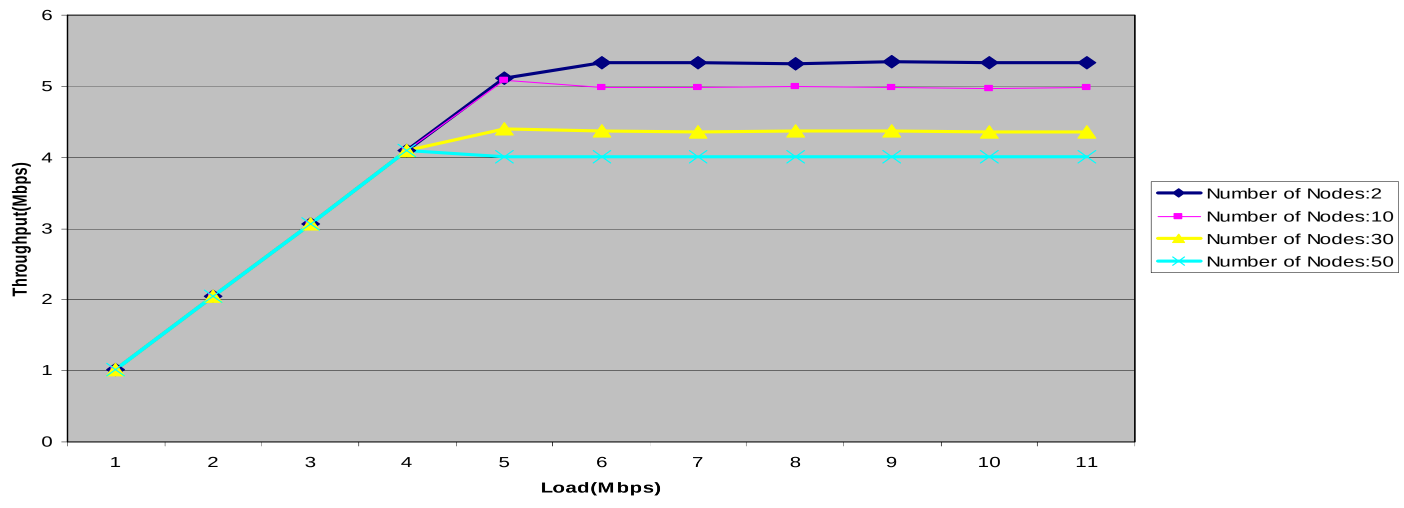

Fig. 16 The Effect of Nodes on IEEE 802.11 Throughput

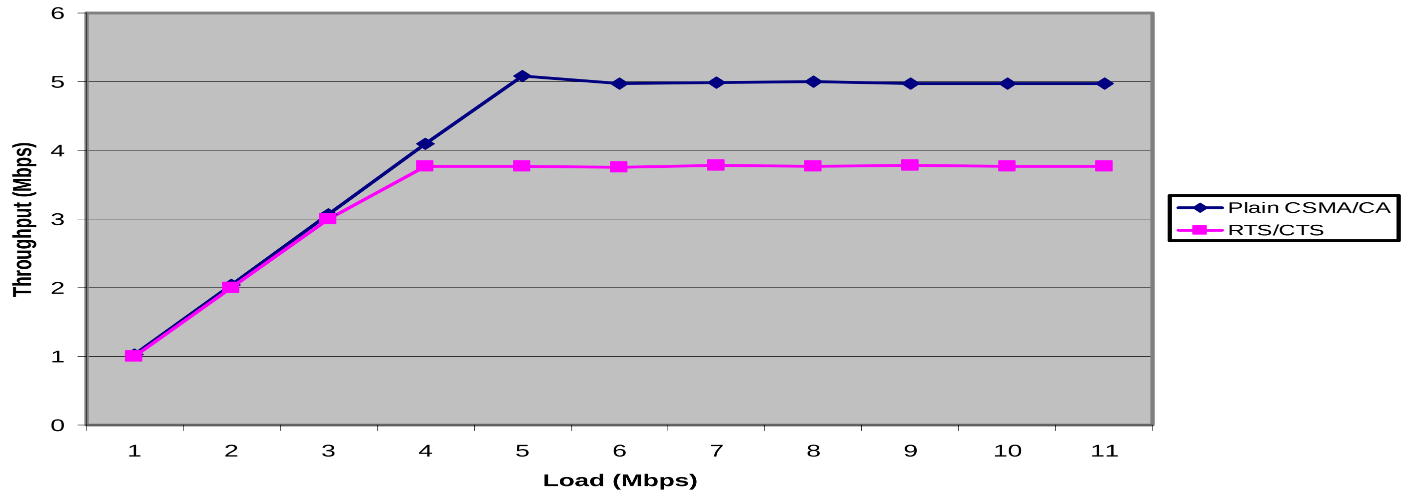

Fig. 17 The Effect of RTS/CTS Control Signal on Throughput

The impact of the number of satellite nodes in a dense LEO constellation or cluster will have significant effect on the performance of IEEE 802.11 which needs to be investigated.

The results in Fig. 16 indicate the effect of nodes on the performance of IEEE 802.11 standards.

Showing decreasing throughput as the number of nodes increase mainly due to the medium contention algorithm.

Fig. 17 shows the effect of RTS/CTS control signals on the throughput of the IEEE 802.11 protocol.

The result indicates a drop in throughput if the option of control signal are enabled but with more data transfer reliability when used.

Testbed for IEEE 802.11/SpaceWire Internetworking On-Board a Small Satellite

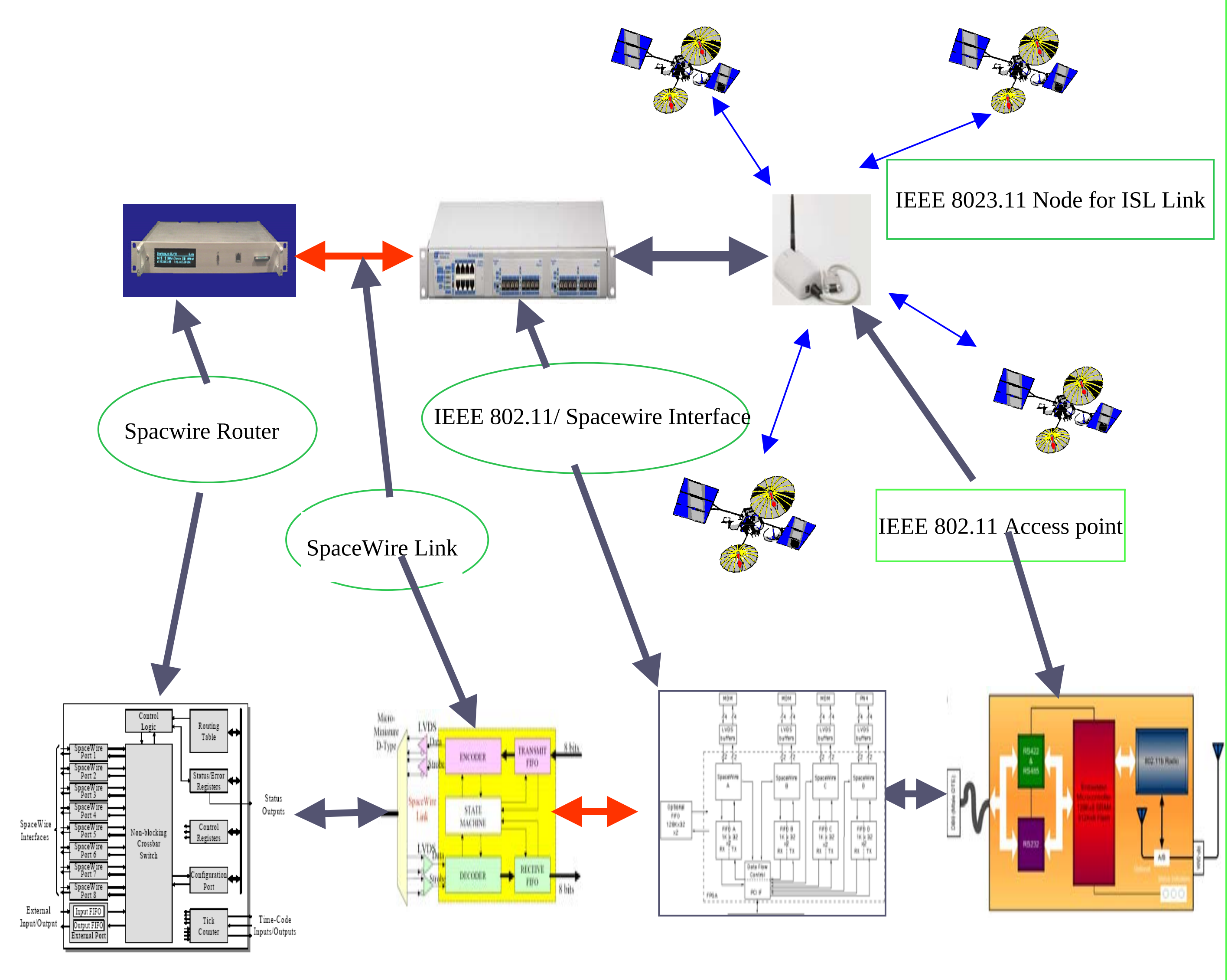

Fig. 18 IEEE 802.11/SpaceWire Network Architecture

This architectural concept is aimed at application of connection-less protocols to space communications.

The incorporation of IEEE 802.11 and SpaceWire could potentially allow the seamless interoperability and connectivity between all subsystems as well as other spacecraft in a constellation or cluster.

The IEEE 802.11 will be used as the inter-satellite communication protocol while the SpaceWire will perform the inter-module routing and spotbeam switching within the spacecraft.

The IEEE 802.11/SpaceWire interface will be used to connect the IEEE 802.11 Access Point (wireless) to the SpaceWire link (wired).

The interfacing problems and possible solutions are stated below:

Problems: the communication stacks are very different:

- **SpaceWire stops at layer 2**
- **WLAN is used with IP (layer 3)**

Possible solutions:

- **Tunnel SpaceWire over WLAN**
- **Create SpaceWire/WLAN bridge**
- **Simple ASIC/FPGA interface**

A Fault Tolerant High-Speed Network for ISL On-Board A Small Satellite

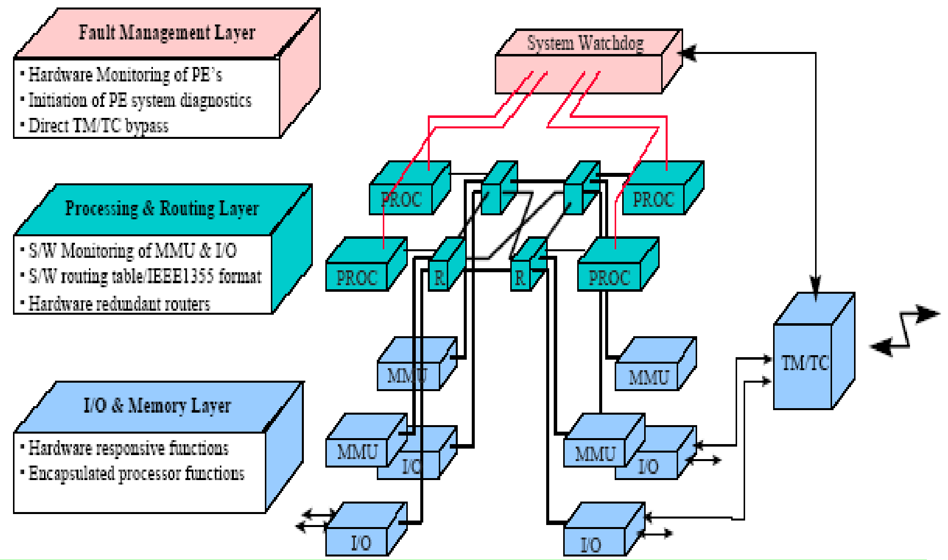

Fig.19 Open Scalable Fault Tolerant Architecture using SpaceWire[4]

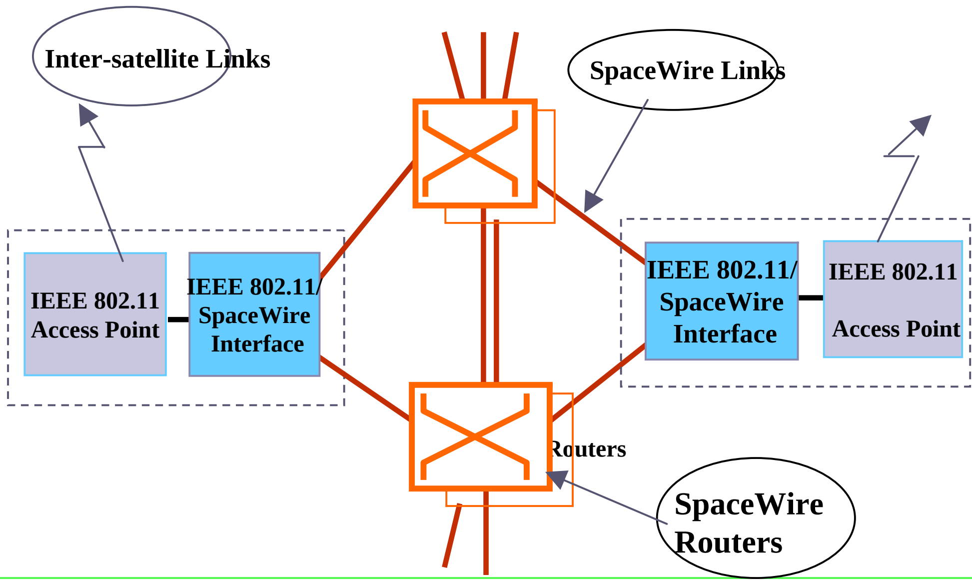

Fig. 20 IEEE 802.11/SpaceWire Architecture Fault-Tolerance Strategy for ISL

SpaceWire is an onboard communications standard designed specifically for spacecraft, consisting of links, nodes and routers defined at the physical and data link layers with the network layer partially covered. The key features of SpaceWire are:

- **High data rate (100 Mbps)**
- **Low gate count (5 – 10 kgates per interface)**
- **Low-power**
- **Topological freedom**
- **Bandwidth sharing**
- **Fault tolerance support**
- **Good EMC performance**
- **Low error rate**
- **Radiation tolerant components**

SpaceWire offers a low-complexity technology for the construction of scalable, fault tolerant networks but careful design is required to ensure that there are enough alternate routes for ISLs.

The fault-tolerant aspects of the On-Board High-Speed Network are:

- **Alternative routing provided by SpaceWire routers between access points for ISL**
- **Congestion avoidance based on the SpaceWire wormhole routing and built-in fault detection mechanism**
- **Network management to provide re-configuration aimed at establishing SpaceWire primary/secondary paths, which are not currently supported**
  - **Externally**
  - **Within the router**

Conclusions

- **The IEEE 802.11 LEO networks will integrate both the physical and MAC layers with the required antenna beam gains and the relative beam directions with changing LEO dynamic movements to reduce interference from neighbouring nodes while maximizing gains towards target nodes.**
- **The use of high-gain and agile antennas and the integration of MAC-layer protocol can enable the finding and tracking-over-time of every in range neighbour satellite with minimal interference.**
- **The IEEE 802.11 MAC will perform data transfer and routing based on the beacon signal strength received by using direction of arrival, time of arrival and antenna steering null methods.**
- **The high-speed IEEE 802.11/SpaceWire architecture will perform inter-module and spotbeam switching with minimum delay and buffering is expected to outperform ATM satellite networks (to be confirmed by experiment).**
- **The IEEE 802.11 physical layer can be optimised for ISL range by re-defining the inter-frame signals and using antenna null steering without any modification to the standard.**
- **Incorporation of IEEE 802.11 and SpaceWire could potentially allow the seamless interoperability and connectivity between all subsystems as well as other spacecraft in a constellation or cluster.**

References

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