Communications and Data in the Space Environment

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A key component of civilization is shared knowledge communicated in the form of data. Since the dawn of time, humans have communicated data that is necessary for life such as where to hunt, how to cook, build, dangerous areas to avoid and coming danger. Initially it was transmitted by voice and hand signals and later by writing. The speed by which data was disseminated was determined by the speed of personal travel.

Early attempts at transmitting data faster than available transport include signal fires, smoke signals, telegraph and early radio. All of these attempts suffered from (in today's parlance) low bandwidth and speed. Very limited amount of data could be sent over long periods of time. While the speed may have been a significant improvement over available transport it would be difficult to impossible to transmit the encyclopedia Britannica using these methods.

Eventually humans developed methods that can communicate large volumes of data at near light speeds. The internet is a good example. We can use our favorite search engine and find a plethora of information on almost any subject. We can also be entertained by endless video and audio content along with games that have people playing together from all over the world. The acquisition, storage, analysis and sharing of data has now become a cornerstone of human civilization.

Science and engineering, which have been major forces in the advancement of civilization, use the acquisition, storage, analysis and communication of data extensively. It has become so prevalent that we have created labels for it. The Internet of Things (IoT) is applied to systems that are more consumer oriented while Industrial Internet of Things (IIoT) tends to be applied to more professional systems. For the purpose of this essay both systems are considered identical and will be referred to as IoT.

Internet Of Things

The purpose of an IoT system is to control a process through the collection, storing and analysis of data. The result is used to make informed decisions on how to improve processes, insure smooth process flows and to illuminate new methods. The decisions and control can be done by Humans, A.I. or a combination of both. The unique part of IoT as compared to other data systems is that it is decentralized. Users and data do not, and in most cases are not, located in the same area. Systems located in remote areas can be monitored and controlled from anywhere in the world by authorized personnel. This allows experts to examine and control systems without having to travel to where the system is located.

IoT in its most base form collects data from a system, transfers it over the internet to a server system (cloud) where it is stored, analyzed and then accessed by any user device that is connected to the internet. An IoT system can also work in the reverse and affect a system by having a user or A.I. send commands through the internet to a device in the field. The data can take any number of forms including binary, text, audio or video. Consumer examples include smart refrigerators that will send you a notice or order an item when it gets low. A car that can be started and have the A/C or heater turned on by an app on your phone. Even streaming services such as Netflix are all examples of consumer IoT.

Commercial examples include automated factories that can be monitored and controlled remotely. An example would be monitoring fluid levels in storage tanks and controlling valves and/or pumps remotely by an A.I. and /or humans. Even smart TV's are IoT as they collect data on viewing habits and send it to the cloud.

The analysis of the data can show trends, issues, inefficiencies and preferences. The collection and analysis of data can be used to improve a system's efficiency, point the way to valuable resources, highlight population types and locations or even show that a piece of equipment is approaching failure. As humanity moves into space, our dependence on data will increase. So will the need to be able to share this data to persons across the solar system and with experts that are millions of miles away.

Proper IoT systems will allow experts to "be" in the field without leaving their office which will result in more efficient processes and the ability to design better vehicles, habitats and manufacturing processes. It will be used to find minerals, safe locations for landing sites and habitat sites. In short, IoT systems will let us conquer space and make it a home for humanity.

Problems

Multiple problems exist with developing a Solar System based IoT system. However the largest issue is distance.

In The Hitchhiker's Guide to the Galaxy Douglas Adams has one the characters try to describe the vastness of space as "Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space." The distances are so "mind-boggling" that normal units of measurement for distance become meaningless. To overcome this issue scientists and engineers have developed a unit of measurement called the light year which is equivalent to the distance that light travels in one year or 9.4607×10^{12} km (nearly 6 trillion miles). This can be broken down even further to a light second or 299,792,458 meters (186,282 miles).

These large distances affect communications in two ways, transit time and signal strength. The chart below illustrates the transit times for radio waves, which travel at the speed of light, to travel between points in the Solar System.

Point to Point	Distance	Transit time
Earth-Moon	384,000 km	1.3 s (1.3 light seconds)
Earth-Mars	55 - 378 million km	3 - 21 minutes (180 – 1,260 light seconds)
Earth-Jupiter	590 - 970 million km	33 - 53 minutes (1,980 – 3,180 light seconds)
Earth-Pluto	~5800 million km	5 hours (18,000 light seconds)

For data that is to be shared and accessed across the Solar System, transit times provide an issue in timing. In many instances, for data to be useful and understandable it must be in a time order sequence. For an event or process occurring in one location this does not pose an issue however, if data is collected from multiple sites across the Solar System and shared with other locations, time sequences become problematic. Each collection point must have a clock that is in sync with all other clocks in the solar system. This would allow the data to be tagged with a time stamp providing a way to do a meaningful comparison of data from separate collection sites.

A simple example of why synced time stamps could be useful is if two distantly separate systems under measurement fail in a relative close time period and/or experience similar failures. Having synced time stamps would provide method for determining if the failure was due to a solar system wide event such as a solar flare. The time of each failure could be compared to the travel time of the event. In the case of a solar flare, analysis would show that the system closest to the sun failed first followed by the more distant system as the shock wave passed. It would be far more difficult to find the relation between failures without a synced time stamp.

The time stamp is also critical for measurements of celestial, or other types of, events from distantly separate sites. Synced timestamps allow for easy alignment of timelines facilitating accurate comparison of the data.

NASA’s Deep Space Atomic Clock (DSAC) counts off the seconds with ticks that are about 50 times more uniform than the atomic clocks onboard GPS satellites. If these clock prove to be reliable and robust then they could be used for syncing time across the solar system. Each collection point would utilize this type of clock to insure data integrity at the final destination.

The other problem IoT encounters is signal strength. As electromagnetic wave propagates across space its intensity (signal strength) is reduced. The rate at which it is reduced is proportional to the inverse of the square of the distance. This effect applies to all electromagnetic waves and is independent of frequency. This causes a radio signal to be a quarter of its transmission strength at 2 meters.

Low strength intensity could easily be overcome if space was similar to a quiet room, a whisper could be heard from one side to the other however, space has more resemblance to a busy New York street. A whisper would be quickly lost in the noise and may not be heard by a listener in close proximity to the speaker. The noise generated by the “space street” is known as electromagnetic interference (EMI) and any person who has used an analog communication device (radio/TV) has experienced EMI in the form of “white noise”.

Modern technology and algorithms are able to resolve low signals buried in noise. This allows communication with probes at the edge of the Solar System. However, the further away the transmitter the slower the transmission must be for the signal to be differentiated from the noise. In modern terms, distance reduces bandwidth and increases errors.

Distance issues, EMI and signal strength, can be overcome using terrestrial system topology as a model. Solar System wide IoT systems will need to utilize mesh networks, cloud based computing/storage and multiple transmission modes.

A mesh IoT network allows the edge computers at the data collection point to transmit data through other edge computers that are within communication range. By providing multiple data paths to the final destination the network provides redundancy and reduces data loss and/or corruption. Mesh networking would be an excellent philosophy for consolidated operations or planetary bodies. Satellites, ground stations and mobile systems could be interconnected providing a robust system that is resistance to interference caused by EMI, individual unit loss or by a bad actor.

A terrestrial example would be of multiple edge computer data collection points interconnected by wifi and to a cellular tower. Normal operation would have each edge computer communicate to the cloud through a distant cellular tower. If an edge computer loses communication with the tower it can transmit the information through one of the other edge computers that still has connection. An extremely robust mesh network allows for multiple edge computers to pass on data until it reaches an edge computer that has communications with the cloud.

Another illustration of a mesh network can utilize communication satellites. Each satellite communicates directly to a ground station but if it loses contact with that station it could still send and receive information through other satellites that can still communicate to the target.

Expanding the network beyond consolidated operations or planetary bodies requires an expanded mesh network that utilizes relay stations, cloud computing hubs and multiple communication types / paths. In space, unlike in an atmosphere, all communication is by Line Of Sight (LOS). In an atmosphere certain frequencies can be bounced off an ionized layer and received half way around the globe. Shortwave radio works in this manner allowing people in different countries to communicate. The ability to reliably bounce signals in space does not exist, this requires each station in a communication to be able to "see each other". Determining LOS is done by drawing a straight line between the communicating stations without intersecting another object.

Not only must the communicating stations have LOS they must also be close enough to overcome EMI and other interference. The distance between the stations is determined by the output power of the transmitter and the sensitivity of the receiver compared against the background noise. The working distance will vary dramatically based on what is transmitting, a small mobile system traveling through the solar system will likely have less power available for transmission then a fixed system, and what is receiving, again a small mobile system will likely have less capability to have large antennas and power for amplifiers then a fixed system. This leads to a philosophy of having multiple fixed systems (more power and space) that can communicate with each other and with smaller systems, essentially becoming a relay network that is also a large mesh network.

The large relay stations will need to be strategically placed throughout the solar system so that they can service multiple clients in distance separated locations. To justify the expense of these stations they must be able to service many different clients in many different areas. The location of the stations have to be selected to provide LOS to as many locations as possible as well as be sensitive enough to receive transmissions from small mobile systems.

Another way to increase the return on investment is by having the relay stations provide cloud services. Client use of the relay station will be necessitated by the reach of the client. Distance and transmission power may preclude the client from accessing other resources. In space distance equates to time, so if a client is attempting to access remote resources through the relay station, a considerable delay could be encountered as the data/request is sent from relay to relay and then finally the target. However if the resources, such as cloud computing, are located on the relay station then the delay is only as great as the distance to the relay station.

Part of the cloud computing service would be to provide database services. These services would allow the client to store and access data generated by the client. It would also, if designed correctly, allow the client to access data generated in a separate part of the solar system. If the relay stations are connected in a mesh network and all provide cloud computing services then data can be shared among all of the stations. As data is generated in one part of the solar system it would be sent across the mesh network until all of the relays have a copy of the data. In this was a client on earth could monitor and make adjustments to systems on the Moon, Mars and beyond without changing systems.

Economic Benefits

The effect of IoT and cloud computing can be measured by examining the economic impact these system have on terrestrial economies. Currently enterprises typically save 4 to 5% of costs with minimal deployment which benefited global business in a productivity boost of $175 billion in 2018(1). In an article by Thierer and O'Sulivan they stated:

> "The cost savings and productivity gains generated through "smart" device monitoring and adaptation are projected to create $1.1 trillion to $2.5 trillion in value in the health care sector, $2.3 trillion to $11.6 trillion in global manufacturing, and $500 billion to $757 billion in municipal energy and service provision over the next decade. The total global impact of IoT technologies could generate anywhere from $2.7 trillion to $14.4 trillion in value by 2025."(2)

An integral part to any space based IoT system is the cloud computing component which has its own economic impact. In simple terms cloud computing allows users (business, explores, etc.) to rent hardware and software without the cost in resources for acquisition, installation and maintenance. All of the infrastructure is located at the vendor's location and users access the system through a network. A user would only pay for the capacity that is used. The benefits to users of such a system include:

- Reduction of startup costs
- Rapid software updates and easy modification of software
- Cost sharing among consumers
- Variable computational capacity and increased efficiency
- Lower energy requirements for users

In the U.S. alone, cloud computing added approximately $214 billion in value-added to GDP in 2017 and approximately 2.15 million jobs.(3) Since 2002 the cloud economy has nearly tripled in size.

Obsolesces

Technology is always progressing making what was once state of the art obsolete. An enormous amount of resources will have to be used for the build out and maintenance of a solar system wide IoT system. New communication technology utilizing quantum physics could turn relay stations into obsolete resource sinks. Two methods could be utilized to mitigate such a problem. 1) Wait until the new technology matures or 2) build the relay stations so that they can be used for multiple purposes. Waiting for the new communications technology has its own cost. The cost of missed opportunity could be greater than the cost to build and then abandon the system. As man progresses out into space the need for data will be great and immediate. The delay could not only squander precious resources but also result in the loss of life that could have been prevented.

Making the relay stations multiple purpose, and possibly reconfigurable for new customers, is the best path. It provides multiple routes for the return of investment and helps prevent the stations from becoming obsolete before their end of life. Multiple uses of the station equates to multiple revenue streams providing the best chance to profitability over the long term.

Solar System IoT Philosophy

The previously stated need and problems for a Solar System wide IoT system give rise to the following philosophical rules:

1. Data is paramount. The more data, especially quality data, increases accuracy of system models and improves decisions.
2. Quality data requires each location to be time synced. Each location has to have access to a clock that is in sync with all other clocks in the Solar System.
3. Data must be easily available to authorized users independent of location. Any authorized user should have access to data that is collected from anyplace in the solar system.
4. Systems for data storage and analysis must be readily available to users independent of location. To meet this requirement relay servers, which will already have large amounts of computing power, should have full cloud computing services available. This provides users throughout the Solar System quick access to required capabilities overcoming extended time delays.
5. Bandwidth determines data flow. Collection, dissemination and access of data will be limited by bandwidth. The greater the bandwidth the more data can be collected and analyzed. Number, size, transmission medium and location of relay stations will be determined by bandwidth. Locations with higher EMI or block to Line of Sight (LOS) will require a greater number of relay stations at a closer distance.
6. The IoT network must be have multiple data paths. All environments change over time, by natural and/or manmade events, stressing parts of the IoT system. Multiple data paths allow the flow of data around the affected area reducing loss of data and data corruption. This is equally important to both planetary locations and deep space locations.
7. Relay stations should be multi-use installations increasing short term profitability and act as a preventive to obsolescence.
8. He who controls the Data controls the fate of Mankind in space.

Conclusion

As humanity expands in to space, the need for the collection, transmission, storage, analysis and access of data becomes increasingly important requiring a unified Internet of Things. The space environment is imbued with many challenges to such a data system which must be overcome early in humanities expansion. A Solar System wide IoT system based on the basic philosophical rules stated in this paper provides the best path forward and insures that the decision makers and leaders of the expansion have the data required for success.

References

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