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Sensor Network Communications Using Space-Division Optical Retro-Reflectors for In-Situ Science Applications[1]

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Abstract— In this paper we present a peer-to-peer sensor network architecture using space-division optical retro-reflector to provide energy efficient communication services for in-situ science applications. We describe how to operate the optical retro-reflector link in full-duplex (FDX) mode, and presents analytical results on the energy efficiency of the network and the trade-off between sensor traffic, network size, link budget and duplex mode, and the optical characteristics of the space-division retro-reflector link. Also our analysis shows FDX operation has the potential to double the energy efficiency achievable by traditional half-duplex (HDX) operation when in-situ peer-to-peer traffic becomes a dominant component in the network.

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1. INTRODUCTION

Optical communication based on retro-reflector technology brings many advantages to in-situ science applications. It reduces size and mass of the communication payload for each sensor because it does not need to carry its power sources and active laser. Furthermore the pointing requirement on both end of the link is more relaxed than conventional free space optical link, simplifying network self-organization and medium access control. In this paper we present a peer-to-peer network architecture designed to take advantage of the space-division, optical retro-reflector technology to provide energy efficient uni-cast, multi-cast, and broadcast services for in-situ science and signal processing. In section 2 provide some brief description of the optical retro-reflector technology. Then we describe what are some of the anticipated communication service needs and constraint for future in-situ science networks in section 3. Section 4 describes how one could operate the retro-reflector link in FDX mode and some of practice issue concerning modulation choices. In section 5, we present an system-level analysis comparing the energy efficiency between FDX and HDX mode and provide discussion on the trade-offs between link-budget, network size, traffic rate, optical characteristic of the receivers and retro-reflectors. Section 6 includes a summary of this paper and a few final remarks on possible future research efforts.

2. MODULATING RETRO-REFLECTOR

An optical modulating retro-reflector (MRR) allows a node to transmit data without supplying its own power and laser. In such system, the receiver of the signal actually supplies the optical power. Figure 1 illustrates such system.

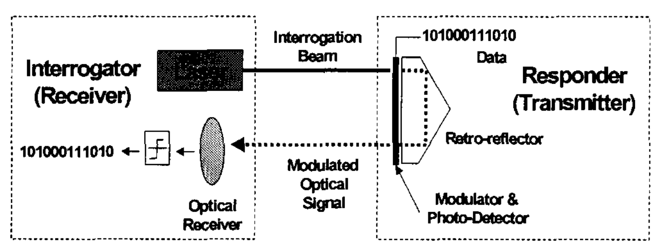

Figure 1: MRR-based Optical Link

When a node wishes to retrieve information from another node, it transmits an un-modulated laser beam, sometimes called an interrogation beam, toward that node. The purpose of the interrogation beam is two-fold: to cue the transmission of data and to supply the necessary optical power for the return signal. When a node has information to communicate and detects the interrogation beam, it will

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activate its MRR, which converts the un-modulated beam into a modulated optical signal and returns it to the receiver. An MRR-based optical link is a passive communication system because the "transmitter" of the data cannot initiate communication; it must operate passively, relying externally supplied optical power.

Characteristics and Link Budget of an MRR Link

An MRR link is highly asymmetric. The transmitters leverage heavily upon the resources and capabilities of the receivers to eliminate the need for an active laser, power supply and the associated pointing mechanism. Furthermore, MRR components can be very small and operates at extremely low power level, which significantly extends the operational lifetime of the sensor network. Two examples of such low power miniature systems are the MEM's mirror [2] and the MQW. [1] Another virtue of MRR is that the pointing requirement of the transmitters has been greatly reduced. The typical field of view (FOV) of an MRR device can be as large as several ten's degrees. Using an array of MRR, a very large field of regard (FOR) can be achieved. The relaxation of pointing requirements also remove the overhead associated with tracking and maintaining precise location information for each node and makes sensor mobility much more feasible.

Most free-space optical links attenuate as $e^{-\alpha R} \cdot R^{-2}$, but an MRR link attenuates as $e^{-2\alpha R} \cdot R^{-4}$ due to retro-reflection, which makes it suited for situations where the receiver node has significantly higher energy resources than the transmitter node. The link budget for an MRR is given by

$$P_r = P_t \frac{A_{ret} A_{rec} T_{atm}^{\ 2} \beta \gamma}{\Omega_t \Omega_{ret} R^4} \qquad \textbf{(1)}$$

where R is the link distance. P_t is the power expended by the receiver to transmit the un-modulated carrier beam. P_r is the power of the returned modulated signal at the receiver. A_{ret} is the aperture of the retro-modulator. A_{rec} is the receiver aperture. $T_{atm} = e^{-\alpha R}$ is the atmospheric attenuation where α is the coefficient of attenuation. β is the modulation index of the MRR and γ is the scintillation degradation. Ω_t and Ω_{ret} are the solid angles of the un-modulated beam and retro-reflected signals, respectively.

Space-Division Receiver

Using a space-division receiver, an MRR-based optical system can be channelized to receive multiple modulated signals simultaneously. Figure 2 illustrates how this works. Usually the receiver is equipped with a pixilated focal plane where each pixel is a photo-detector. When the interrogation beam covers more than one node that have data to send, two simultaneous streams of modulated signal can be returned from bearings. The receiver optics will focus these signals on different parts of the focal plane. If the angular separation is large enough, the two optical signals will strike two different pixels (photo-detectors), which allows both signal to be decoded independently without interference. A CCD camera or Cat's Eye receiver [cite: NRL reference] are both examples of space-division optical receivers.

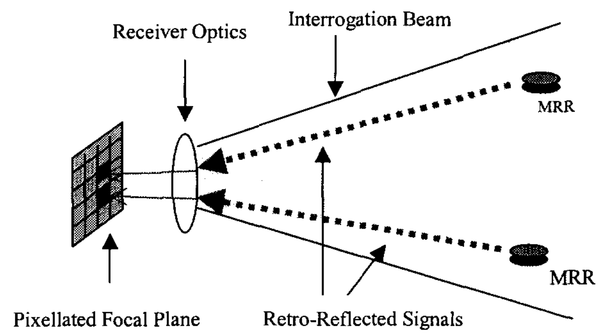

Figure 2: Space-division Receiver

The advantage of a space-division receiver is the obvious increase in bandwidth. As the angular resolution of the focal plane array increases, the number of simultaneous data streams that can be accommodated per "coverage area" – as defined by the width of the interrogation beam – will increase proportionally.

3. Sensor Networking For In-Situ Science

For space/planetary in-situ sensor networks, four factors are key to the design of a suitable architecture: payload mass and size, low power communications, in-situ signal processing and data fusion, and low-overhead self-organization.

Payload Mass and Size

The bulk of a space/planetary mission cost is determined by the mass and size of the payload. An MRR system has great potential in minimizing payload mass and size. They are extremely low power, which means they do not need to bring along dedicated power source; they have very compact form factor compare to a radio antenna that must occupy significant space on the sensor platform. Of course they require the support from sophisticated nodes that functions as a communications coordinator and supplies the necessary optical energy for communication. So if the sensor network consists only of a few nodes, then MRR don't necessarily make sense. However, if there is large number of sensor nodes, then the overall mass and size saving will be substantial.

Low-Power Communications

The operational lifetime of in-situ science mission is a fundamentally metric determined by the energy efficiency of the network. Since communication accounts for the bulk of energy usage, one must try to *minimize each sensor's energy cost for transmitting data.* An MRR-based optical system, such as the MEMS mirror or quantum-well modulators, can provide a low power solution by shifting the energy cost to a centrally located communications hub that is much more generously provisioned than the sensors and may even have capability to generate power on its own, i.e., solar or wind power.

In-Situ Signal Processing and Data Fusion

Another factor that has significant influence on the design of network architecture is the traffic characteristics required for in-situ science. Traditionally, for space/planetary science, signal processing and data fusion are strictly done on Earth; the spacecrafts and their onboard instruments are designed only for data collection and communication of the raw data back to Earth. There are no peer-to-peer communications between co-located spacecrafts or sensors.

In the future, however, data processing and data fusion will increasingly become in-situ generating significant peer-to-peer traffic in the network. There are several factors that contribute to this evolution. One is for functional enhancement of in-situ science. Many advanced science observational techniques require cooperative sensing and decision.[4]

Another reason for the need of peer-to-peer communication services is to facilitate efficient usage of the Deep Space Network (DSN). Since the increase in DSN capacity is not likely to keep up with the advancement in sensor instrument technology, more data will be collected then can ever be relayed back to Earth. An example of such situation is the Mar Global Survey (MGS), which has only been able to relay 1 to 2 percent of all its data back to Earth because the science instrument on the orbiter can collect much more data than can be transmitted back to Earth through the DSN within reasonable cost and time. Economic pragmatism shifts in favor of using in-situ cooperative data processing to determined the scientific "value" of each piece of sensor data and determine what data should be relayed back to Earth to maximize "science return."

Low-Overhead Self-Organization

To further maximize the operational simplicity for the sensors, communication overhead, especially those incurred during channel access, must be reduced as much as possible. The most favorable medium access architecture for this purpose is a *contention-free centralized scheme* that reduces the number of message exchange and negotiations required before a sensor can transmit and receive data. An MRR system naturally lends to a centralized access mechanism where the communications hub supplies the optical energy and performs all the necessarily coordination function. To minimize access contention, one can use space-division multiple access (SDMA) for the sensor-to-hub communication. Spatial diversity provides a natural "channelization" that separate data streams coming from different sensors.

The number of channels available depends on the coverage area – the size of optical footprint of the hub – and the degree of pixellation on the receiver focus plane. A high resolution CCD camera can provide hundreds or even thousands of space-division channels to sensors that are located within its field of view; with low probability of channel conflict, network organization becomes much simpler. A normally challenging area in optical communication is location determination, which is crucial for network "boot-up" and mobility management. MRR reduces the need for accurate pointing for both the hub and the sensor, which eliminates location/navigation overhead and simplifies the network organization process.

Episodic Network Connectivity

For any given sensor, we can model its connectivity with communications hub as having an "On-Off" behavior. This model is similar to space-based communications where orbital ephemerides and spacecraft/aircraft/rover mobility create episodic connectivities in the network. Similarly, an in-situ sensor network that relies on an orbiter, aircraft, or mobile rover for communications would experience alternating period of connectivity and dis-connectivity.

For the rest of this paper, we divide a sensor networks into clusters such that all nodes in the same cluster share the same "On-Off" link schedule, and schedules for different clusters do not overlap. Figure 3 illustrates an example of connectivity schedule for both FDX and HDX cluster.

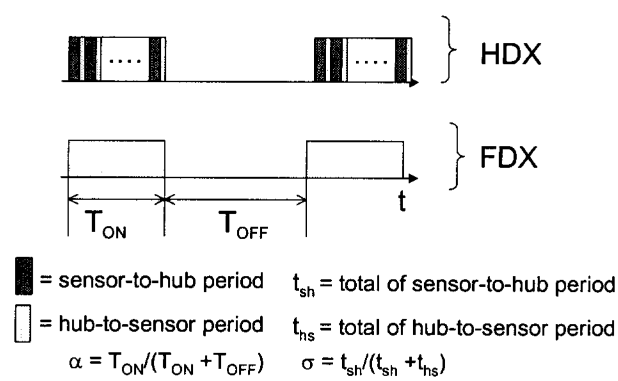

Figure 3: Connectivity Schedule of Each Sensor to the Hub

The parameter α depends on the relative geometry and planned resource allocation to the cluster. For a dedicated stationary hub, $\alpha = 1$; for a mobile hub or a hub that is time-shared by two or more clusters, $\alpha < 1$. In half-duplex mode, the "ON" period must be further divided into alternating sensor-to-hub and hub-to-sensor transmission periods whose ratio is σ, which depends on the data rate and data volume that is required on either direction. Full-duplex operation will be discussed in more detail in the next chapter when we analyze the energy efficiency of the system.

Traffic Model

We assume that within each cluster, a sensor can have one of n possible modalities, which includes imaging, seismic, acoustic, etc. We denote this set of modalities as $S = \{s_1, s_2, \ldots, s_n\}$ Each modality generates data at different rate. For modality j, we denote the data rate as $\lambda(s_j)$ bits per second. For each node, say node i, its associated modalities is a subset $N_i \subseteq S$. The required bandwidth for node i is

$$\lambda_i = \frac{1}{\alpha} \sum_{j \in N_i} \lambda(s_j) \tag{2}$$

The aggregate offered rate to sensor-to-hub channels during an "On" period is given by

$$\lambda = \sum_i \lambda_i = \frac{1}{\alpha} \sum_i \sum_{j \in N_i} \lambda(s_j) \tag{3}$$

Let λ_{in} be in-bound traffic rate from other clusters, and $0 \leq \delta_{out} \leq 1$ denotes the portion of λ that are either out-bound traffic destined for Earth or other clusters. Then the total offered rate to the hub-to-sensor channel is:

$$\mu = \lambda_{in} + (1-\delta)\lambda \tag{4}$$

Each node in the network has some hardware/software capability to process data associated with a particular set of sensor modalities. Let P_i be the set of modalities that node i can process, therefore, $P_i \subseteq S$ for all i. If $P_i = \phi$, that means node i cannot process any sensor data.

Using this simple model, a routing table $r_{i,j}$ can be created to map all possible peer-to-peer connections between the nodes:

$$r_{i,j} = \begin{cases} 1, \text{ if } N_i \cap P_j \neq \varnothing \text{ and } i \neq j \\ 0, \text{ otherwise} \end{cases} \tag{5}$$

If $r_{i,j} = 1$, then a connection between node i and node j is may be required. One must note that even though $r_{i,j} = 1$, it does not mean that every piece of data sent by node i is used by node j. It is up to the source node to properly address the frame header; if no uni-cast or multi-cast address is supplied, which is possible when a sensor node simply wish to forward the information to any or all processing nodes capable of handling the data, then all node j for which $r_{ij} = 1$ will receive the data.

In highly dynamic sensor systems, cueing is often used as a low power mechanism for long-term sensing. The idea is to activate only a small subset of sensors to look for environmental indicators for scientifically interesting phenomenon. When the appropriate sign appears, the subset of sensors will broadcast alert messages to awaken the rest of the network for high-resolution multi-point observation. The cueing mechanism requires a broadcast service that can be easily provided by an optical hub.

In-Situ Science Network Architecture

Figure 4 shows the architecture of an in-situ communications network using optical MRR. Each sensor node obtains peer-to-peer or telemetry communications services via an optical hub with space-division receiver. Each optical hub can be a stationary node, say a lander for a scout mission, or a dedicated telecommunication node in robotic outpost mission. [3] A mobile hub can service several clusters of sensor nodes in different view periods determined by flight/orbiter trajectories. This allows several science missions to time-share a single optical hub. Communications between sensors in different clusters can be achieved by uploading data to a mobile hub that will later move into communication range with other clusters. Alternatively, when there are multiple hubs nodes, they can form a "backbone" network linking distant clusters together.

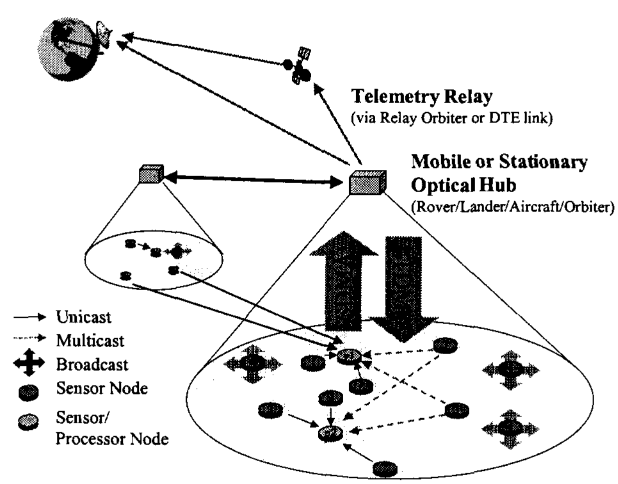

Figure 4: An In-Situ Science Network Architecture

An optical hub can provide low-delay peer-to-peer unicast, multicast, and broadcast services to sensor nodes within its coverage area. For the hub-to-sensor traffic, Time Division Multiplexing (TDM) is used; for the sensor-to-hub links we use SDMA. Both half-duplex and full-duplex modes are possible.

4. FULL-DUPLEX OPERATION

The proto-typical MRR link operates in HDX mode, where the receiver sends an un-modulated beam to the transmitter in order to receive information. Because the link budget is governed by 4th power propagation loss as a function of distance, it is highly desirable to operate in full-duplex mode if one can modulate information on the normally un-modulated beam in such way that it does not interfere with MRR operation.

There are other advantages to using full duplex mode, particularly when higher-layer automatic repeat request (ARQ) mechanism is used. Because performance of HDX ARQ is highly sensitive to the length of transmission period in each direction, it will be difficult to optimize operation across multiple peer-to-peer ARQ processes that have different data rate and frame/packet size under a common turn-around schedule.

Modulation Considerations

The selection of modulation type is important for FDX operation. The nature of the MRR dictates that the retro-reflected signals must use essentially an On-Off Keying (OOK) type of modulation because MRR modulates data by toggling its retro-reflecting mechanism between on/off states. Furthermore, it is important that the externally supplied optical beam should have a kind of "consistency" to be used as a power source for data transmission. For this reason, most MRR system operates with an un-modulated beam at with fixed power as its energy source. If one wishes to operate in FDX mode, the question to investigate is what happens if the externally supplied optical beam is already modulated with information.

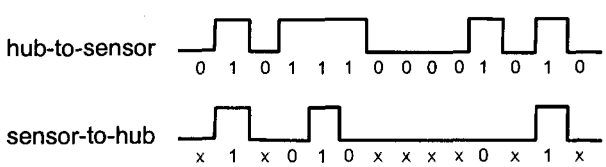

Figure 5: Balanced FDX using On-Off Keying

Figure 5 shows two data streams over an MRR-based FDX optical link between a hub and a sensor. Both directions use the OOK modulation at the same data rate. The hub, equipped with its own active laser, can transmit bit streams continuously to the sensor. However, the sensor can only modulate data when the in-coming bit is "1" (on). When the in-coming beam carries a "0", the sensor cannot modulate data because there is no optical energy; so null symbol is returned, which is denoted by "x" in the figure. There are two challenges that one must overcome: (1) the MRR must adapt, in real time, to the pattern of the in-coming bit stream by modulating data only when "1" (on) symbol is received; (2) the hub needs to differentiate whether a received symbol is "0" or null because in OOK both looked the same. This means the receiver need to correlate the incoming signal with the outgoing signal by adjusting for two-way propagation delay, and selectively decode only symbols that corresponds in time to the "1"s in on the out-going bit stream. This will raise the complexity of the optical transceiver considerably.

If the FDX link is asymmetric, the hub-to-sensor will typically operate at a much higher data rate because the link-budget strongly favors the hub-to-sensor link for a given bit error performance. Figure 6 shows an example where the data rate of the hub-to-sensor link is three times faster than the opposite direction. In this case, the problem we described with balanced FDX with OOK is somewhat alleviated because each retro-reflected bit would be mapped to multiple bits (3 bits) on the hub-to-sensor stream. But the probability of receiving a "null" symbol is not completely eliminated. Furthermore, the hub now must use adaptive threshold in the receiver because the average returned energy per bit is highly variable, depending on the stochastic characteristics of "1"s in the hub-to-sensor data stream. In the example in Figure 6, on the sensor-to-hub data stream the first "1" contains twice as much reflected optical energy than the second "1" received. Receiver performance cannot be optimized if one uses a static received-signal threshold.

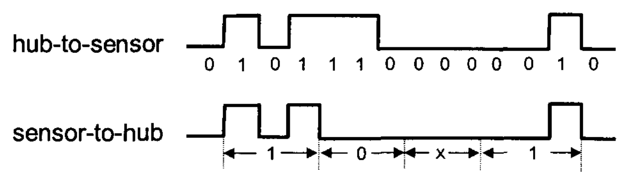

Figure 6: Asymmetric FDX with OOK

Therefore, to make FDX a feasible solution over existing MRR system, the hub-to-sensor link should choose only modulations that have constant energy output for all bits or symbol. An example would be the Manchester Coded OOK, where a "1" is encode as a transition from "on" to "off" at the center of the bit and a "0" is encoded as a transition from "off" to "on" at the center of the bit. The total photonic energy expended for "0" and "1", however, are the same. In other words, the modulation index is one for the hub-to-sensor link. This allows the retro-reflector to modulate data regardless whether each in-coming bit is "1" or "0" as long as synchronization at the bit or symbol level is maintained, which is easy given such level of synchronization is already part of the optical receiver functionality. Asymmetric data rate is also easily accommodated. Other possible modulations include 2-PPM, M-PPM, and coherent modulations such as FSK and PSK.

5. Analysis of Energy Efficiency

In this section we will derive analytical result showing system level trade-offs between parameters such as receiver and modulator aperture, optical beam solid angle, cluster size (number of sensors), aggregate data rate, communication range, link budget, and duplex mode with respect to the "energy-per-bit" metric. We do not model the detail characteristics of traffic arrival process and other

MAC layer overhead in detail. We assume the space-division receiver can provide each sensor an independent channel to the optical hub. We also ignore inter-cluster traffic at this time so that $\lambda_{in} = 0$.

Let E_b (joules/bit) be the minimum received-energy-per-bit to achieve a required link error performance on both the sensor-to-hub and the hub-to-sensor link. Let P_t, P_{r_MRR}, and P_r denote the transmission power of the hub, the received power at the sensor, and the received power at the hub, respectively. Ignoring the scintillation effect by setting $\gamma = 1$, equation (1) tells us that

$$\frac{P_r}{P_{r\_MRR}} = \frac{A_{rec} \cdot T_{atm} \cdot \beta}{\Omega_{ret} \cdot R^2} \qquad \textbf{(6)}$$

Let μ^* and λ^* be such that

$$E_b = \frac{P_{r\_MRR}}{\mu^*} = \frac{P_r}{\lambda^*} \qquad \textbf{(7)}$$

The parameters μ^* and λ^* represent the maximum data rates on the hub-to-sensor and sensor-to-hub directions that can still guarantee a received-energy-per-bit of E_b using transmission power of P_t watts.

Full-duplex Operation

With SDMA, we know that the hub can receive simultaneous data streams from multiple sensors. Suppose there are m sensors in a cluster. Let the average data rate be λ, and that the peak rate be less than λ^*. Stability condition requires that

$$\begin{aligned}\underbrace{(1-\delta_{out})m\lambda}_{\text{aggregate intracluster traffic rate}} &= (1-\delta_{out})m\lambda^* \underbrace{\frac{\lambda}{\lambda^*}}_{\rho} \\ &= (1-\delta_{out})m\lambda^* \rho \\ &\le \underbrace{\mu^*}_{\text{TDM channel service rate}}\end{aligned} \qquad \textbf{(8)}$$

where ρ is the normalized average traffic load of the cluster measured in Erlang with respect to λ^*. To operate efficiently, we set P_t such that λ^* equals the maximum data rate in the cluster; i.e., we use the lowest possible power to achieve the error performance while satisfying the highest data rate needed on the m SDMA channels.

We define the energy efficiency metric, η_e, as the average energy spent to service one "bit" of data generated within each cluster. For FDX operation, we have

$$\eta_{e\_FDX} = \frac{P_t}{m\lambda^* \rho} \qquad \textbf{(9)}$$

Combined with equation (6) and (7), we have

$$\begin{aligned}\eta_{e\_FDX} &= \frac{E_b}{m\rho}\frac{P_t}{P_r} \\ &= \frac{E_b}{m\rho}\frac{\Omega_t R^2}{A_{ret}T_{atm}}\frac{\Omega_{ret}R^2}{A_{rec}T_{atm}\beta} \\ &= \frac{E_b}{m\rho}\frac{\Omega_t R^2}{A_{ret}T_{atm}}\frac{\mu^*}{\lambda^*}\end{aligned} \qquad \textbf{(10)}$$

Let m^* be the maximum number of sensors that can be accommodated by the space-division receiver, then equation (8) tell us that the optimal energy efficiency, η^*_e, is given by,

$$\eta^*_{e\_FDX} = \begin{cases} \dfrac{E_b \Omega_t R^2}{A_{ret}T_{atm}}(1-\delta_{out}), & \text{if } m^*\rho \ge \dfrac{\mu^*}{\lambda^*(1-\delta_{out})} \\ \dfrac{E_b}{m^*\rho}\dfrac{\Omega_t R^2}{A_{ret}T_{atm}}\dfrac{\mu^*}{\lambda^*}, & \text{otherwise} \end{cases} \qquad (11)$$

Of particular importance in energy efficiency of the network are the solid angle of active laser and the aperture of the retro-reflector. The communication range and the coverage area will basically dictate the solid angle needed for the laser; the retro-reflector aperture will be determined by the size of the sensor platform and optical design. Typically, there is a trade-off between aperture size and the peak modulation rate of the retro-reflector, so proper selection of aperture size is very important. There are optical designs, such as the Fish Eye lens, which can maintain large aperture while focusing the optical energy on a small and therefore high-speed modulator. The focal plane structure will be more complex but perhaps worth the price for certain applications.

Another factor that affects the energy efficiency is the traffic pattern. In general, the larger the aggregate traffic load is, the better the efficiency (lower η^*_e.) Because of link budget, the maximum data rate for the SDMA channels is much smaller than TDM channel by a factor of $\frac{A_{rec} \cdot T_{atm} \cdot \beta}{\Omega_{ret} \cdot R^2}$, as given by equation (6). Here, the receiver aperture and the solid angle of the retro-reflector control the degree of data rate asymmetry. Having multiple simultaneous data streams on the SDMA channels counterbalances the asymmetry and therefore improves the utilization of the FDX link.

For telemetry destined for Earth, it does not need to be serviced by the TDM channel. Therefore we can leverage the capacity on the SDMA channels fully without the limitation of trying to stay below the TDM channel capacity.

So as δ_{out} increases, energy efficiency of the system also improves.

Half-duplex Operation

The only difference in the HDX case is that the SDMA and TDM channels will time-share the "contact" period between the hub and the sensor cluster. To achieve the same aggregate service rate, the data rate on the channel must be increased. In our analysis, we will ignore acquisition delay and other overheads associated with link turn around, although they could be significant in large time-bandwidth product situations.

Let σ be the fraction of time the sensors are transmitting to the hub. Then the aggregate data rates on the SDMA channel must be adjusted by a factor of $1/\sigma$; we have $m\lambda^*\rho/\sigma$ (bits/sec). On the TDM channel, the data rate will be $(1-\delta_{out})m\lambda^*\rho/(1-\sigma)$. In order to maintain the same E_b, the transmission power on the hub must be scaled up by $1/\sigma$ for SDMA, so we have $P_{t\_SDMA} = P_t/\sigma$. However, for the TDM channel, the transmission power can be substantially lowered because it is now just a one-way propagation. Let P_{t_TDM} and P_{r_TDM} be the transmission and received power, for the TDM channel respectively. Then we have

$$\begin{aligned} P_{r\_TDM} &= E_b \frac{1-\delta_{out}}{1-\sigma} m\lambda^*\rho \\ &= P_{t\_TDM} \frac{A_{ret}\cdot T_{atm}}{\Omega_t \cdot R^2} \end{aligned} \qquad \textbf{(12)}$$

Using equation (12), we can compute the energy efficiency for HDX for arbitrary choice of $0 < \sigma < 1$,

$$\begin{aligned} \eta_{e\_HDX} &= \frac{P_{t\_SDMA}}{m\lambda^*\rho/\sigma} + \frac{P_{t\_TDM}}{(1-\delta_{out})m\lambda^*\rho/(1-\sigma)} \\ &= \underbrace{\frac{P_t}{m\lambda^*\rho}}_{\text{same as FDX result}} + \frac{E_b\cdot\Omega_t\cdot R^2}{A_{ret}\cdot T_{atm}} \\ &= \eta_{e\_FDX} + \frac{E_b\cdot\Omega_t\cdot R^2}{A_{ret}\cdot T_{atm}} \end{aligned} \qquad \textbf{(13)}$$

Note that $\eta_{e\text{-}HDX}$ is independent of σ because the transmission power levels are adjusted to fully compensate for any choice of σ.

Comparison between FDX and HDX

Comparing the optimal energy efficiency achieved by FDX and HDX case, we have

$$\frac{\eta^*_{e\_HDX}}{\eta^*_{e\_FDX}} = \begin{cases} 2-\delta_{out}, \text{ if } m^*\rho \geq \dfrac{\mu^*}{\lambda^*(1-\delta_{out})} \\ 1+\dfrac{\mu^*}{m^*\rho\lambda^*}, \text{ otherwise} \end{cases} \qquad (14)$$

We see that if all the dominant traffic flow is in-situ (i.e., δ_{out} is small) and the aggregate traffic is sufficiently large, then FDX has a 3dB advantage in terms energy efficiency over the HDX case. When most data are telemetry rather than peer-to-peer, the energy efficiency for both duplex modes will converge. But as we have stated in earlier section, we fully expect that peer-to-peer communications will become the dominant traffic source as the sensor bandwidth continue to out-pace the capacity of the DSN. In-situ signal and data processing techniques will inevitably become the gatekeeper for accessing the DSN's precious bandwidth.

How many sensors will make FDX worthwhile?

One will notice that m^*, which is the maximum number of channels available on the space-division receiver, plays a significant role in the energy efficiency of both FDX and HDX operation. To make FDX worthwhile, there should be sufficient number of SDMA channels and sensor nodes for each cluster so that the asymmetry in link budget can be counterbalanced. The natural question to ask is: how many sensors do I need in a cluster to make FDX worthwhile?

The answer will depend on the link budget, the peak and average data rate from each sensor and the kind of laser, retro-reflector, and space-division receiver one uses. When the peer-to-peer traffic is dominant, we can take as guideline that the advantage of FDX can be leveraged when the number of sensors in the cluster that will generate data is close to m^*, which should be at least

$$\begin{aligned} m^* &\geq \mu^*/(\lambda^*\rho) \\ &= \frac{1}{\rho}\cdot\frac{\Omega_{ret}R^2}{A_{rec}T_{atm}\beta} \end{aligned} \qquad \textbf{(16)}$$

where $1/\rho$ represents the peak-to-average-rate ratio of sensor-to-hub traffic. Equation (16) tells us that the closer the peak data rate is to the average rate, the less number sensor is needed to make FDX worthwhile. This will usually be the case when the network uses a single sensing modality, i.e., the sensors are all of one kind at the same sampling rate. Also of particular importance are the range, the retro-reflector solid angle and optical hub aperture. The active laser solid angle and retro-reflector aperture do not play a role here because they do not determined the degree of asymmetry between the sensor-to-hub and hub-to-sensor links.

6. CONCLUSION

In this paper, we described the anticipated needs and constraints of future planetary in-situ science missions. These include low power communications, in-situ signal and data processing, low-overhead self-organization, and reduction of communications payload on compact sensor platforms. We proposed enabling network architecture that features point-to-multipoint optical communications using SDMA/TDM medium access methodology. The communications hub, which can be lander, rover, aircraft, or orbiting spacecraft, is equipped with high resolution space-division receiver while the sensor and processor nodes on the surface uses low mass, low power modulating retro-reflectors (MRR).

We analyzed the system level performance of this optical network as measured by the energy-spend-per-bit metric and compared the performance of full and half duplex schemes. In general we find that the full-duplex operation has a potential 3dB advantage over half-duplex. Our analysis demonstrates the trade-off between various system parameters such as communication range, peak and average traffic rate, network size, optical characteristics of the MRR and the space-division receiver, and provides the analytical tools for preliminary network design and planning.

Future issues to be addressed include: (1) development of location/navigation algorithm for the sensors and how the knowledge of location information impact network performance and operation; (2) development of suitable medium access control mechanism for a passive communication system such as MRR; (3) procedures for optimizing link acquisition, synchronization, and mobility; (4) inter-cluster networking.

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