INTRODUCTION

The following are the instructions for using the spreadsheet which numerically evaluates the model of a downlink for a low-mass interstellar probe.

TRANSPORT AND PHYSICAL LAYERS

The spreadsheet calculates performance metrics for the transport layer based on a specific model of the physical layer.

In Fig.25, the physical layer consists of all system elements with a physical realization, such as apertures, optical source and detectors, propagation, etc. The transport layer is everything else that builds on the physical layer, and includes the modulation coding and error-correction layers. The transport layer is logical and algorithmic, and thus processing (often software) based. Here is a definition of the two layers:

Physical layer: Everything that has a physical realization, such as apertures, light generators and detectors, optical filters, propagation, etc. Generally the study of these elements is based on an understanding of physics.

Transport layer: Everything needed to convey data reliably and efficiently from a probe to earth (and possibly earth to probe) that is based on services and capabilities provided by the physical layer and adds logical elements such as modulation (representation of scientific data in terms of a light intensity waveform), interpretation of individual photon detection events in the receiver, coding of scientific data to counter impairments, multiplexing of data from multiple probes, etc. Generally the study of these elements is based on an understanding of probability and statistics, communication theory, information theory, and signal processing, and thus has no foundation in the natural sciences.

For purposes of the transport layer, the physical layer is represented by a model, with a set of configuration parameters and performance metrics (like transmit power) and a set of assumed statistics for stochastic entities (such as quantum effects and noise and interference). The spreadsheet assumes a specific physical-layer model, accepts numerical values for configuration parameters and generates numerical values for performance metrics. The opportunities for improving the performance metrics through a knowledgeable design of the transport layer are substantial (measured in multiple orders of magnitude). The theory underlying the transport layer is relatively mature and well-known. One of the major results is a set of theoretical limits on the scientific data rate that can be achieved consistent with reliable recovery of that scientific data at the receiver. The models used in the paper are based on these theoretical limits, and therefore are somewhat idealized. Actual performance for concrete realizations and error-correction codes will fall somewhat short of these ideals, although the current state of the art can come pretty close if sufficient processing power is available. Therefore there is little or no opportunity to improve on the transport layer modeled in this spreadsheet as long as the model of the physical layer remains valid.

It is important to note that the physical layer model used here is idealized, and is missing a number of practical impairments such as pointing errors, atmospheric turbulence, etc. Thus the actual performance metrics will be less favorable than calculated here. With this limitation, the model is quite general, as its structure is based on fundamental physical principles.

Changes to the physical layer that are reflected in the structure of the model (not merely its parameterization) will require reformulation of the transport layer results here. The paper authors would be pleased to assist in this, should it prove advantageous.

RECEIVER APERTURE MODEL

A key part of the physical layer model is the specific architecture for the receive aperture, which assumes a decomposition of the receive aperture as a whole into apertures as shown in Fig.2 and Fig.3. This architecture is dictated by the laws of antennas in the context of a requirement that the receive aperture as a whole maintains a sufficiently large coverage solid angle `OmegaA` to accommodate the trajectories of a swarm of probes. The model makes the assumption that a single receive aperture is shared by all concurrently transmitting probes, and that the receive aperture is equally sensitive in the direction of all probe trajectories.

The parameters of the aperture determine the coverage solid angle `OmegaA`, and that coverage is maintained following the scale-out of `NS` aperture's with incoherent accumulation of signal photons. This incoherent accumulation has no impact on the receive aperture coverage, nor does it affect the signal-to-background ratio `SBR`. Thus `OmegaA` and `SBR` are determined by the sub-arrays, while the scale-out simply boosts the signal level sufficiently to support the target scientific data rate `Bitrate`.

The model is also valid for a receive aperture designed for a single probe as a special case. In this case, the model remains valid with `OmegaA` determined not by the probe swarm and its set of trajectories, but rather practical considerations that limit aperture pointing accuracy, including atmospheric refraction and the possibility of adaptive optics. `OmegaA` has to be chosen sufficiently large so that the coverage solid angle is guaranteed to include the probe trajectory in the worst case.

BURST-PULSE-POSITION MODULATION (BPPM)

The transport layer is built on an assumption of a specific modulation coding called burst pulse-position modulation (BPPM) (see §6.2). This is a generalization of PPM, which is widely used as the basis of optical communications in circumstances where transmit power is an expensive resource (see Fig.4). PPM is characterized by parameters `BitsPerFrame` and slot time duration `Ts`. In conventional PPM `Ts` is not a free parameter, but rather is determined by constraints that PPM frames are transmitted continuously. BPPM allows `Ts` to be chosen much smaller, resulting in PPM frames with intervening blank intervals and a resulting duty cycle `delta`. This decouples the frame duration `TF` from the inter-frame interval `TI`. The benefits are an increase in signal bandwidth (loosening the requirement in receive optical bandpass filtering) without an attendant increase in background radiation and a significant suppression of the dark count rate in the receive optical detectors. Conventional PPM is a special case when `Ts` is chosen so that `TF=TI`.

LIST OF CONFIGURATION PARAMETERS

The interpretation of parameters and metrics is given in the spreadsheet. The following are references relevant background information in the paper. We also describe briefly the rationale behind the choice of a nominal value, and a short description of the effect of that parameter on the overall design. See also Tbls.1, 2, 3, and 4 for a list of parameter definitions. The nominal values of the parameters in the spreadsheet are the same as in those tables for the swarm case.

- `Bitrate`: See (1). The nominal value is a rather arbitrary choice. In BPPM `PpT` is independent of this value, but `PaT` is proportional to `Bitrate`.
- `BitsPerFrame`: §6.2, Fig.4, §14, Fig.27. The nominal value is chosen to be the smallest such that theoretical bounds indicate that reliable recovery of scientific data is feasible at a `BPP>10`. If you would like to explore the tradeoff between smaller `PaT` and `PpT` against a larger total receive aperture effective area `AeS*NS`, you can decrease the chosen value of `BitsPerFrame` (see §10.5.2).
- `KsR`: XX, §10.2, §10.6, §14, Fig.27. As illlustrated in Fig.27, this is nearly the optimum (`BPP` maximizing) value over a range of `BitsPerFrame`. There is probably no reason to ever change this value.
- `SBR`: See §4.6, §10.6. This value results in a theoretical bound indicating that `BPP > 10` is feasible with reliable recovery of scientific data for the chosen value of `BitsPerFrame`. This could be reduced to as small as `SBR=3`, although such a low value would result in very little margin. If you would like to explore the tradeoff between larger `PaT` and `PpT` against a smaller total receive aperture effective area `AeS*NS`, you can increase the chosen value of `SBR` (see §10.5).
- `BPPQ`: See §14.3.4, Fig.27, §D, (D14). This is a calculated value, and depends on the choice of `Slots` and `KsR`. It indicates the ultimate quantum limit on reliable scientific data recovery.
- `BPPPC`: See §14.3.4, §E, (E15). This is a calculated value, and depends on the choice of `BitsPerFrame` and `SBR`. It indicates the theoretical limit for photon-counting detectors achieving reliable scientific data recovery.
- `BPPPPM`: See §14.3.4, §F, (18). Fig.27. This is a calculated value, and depends on the choice of `BitsPerFrame` and `KsR`. It indicates the theoretical limit for a PPM modulating code achieving reliable scientific data recovery at high `SBR`.
- `lambda`: See §8. Two values, 400 and 1000 nm, are supported in the spreadsheet. The choice 400 nm is advantageous in terms of reducing target star interference, whereas 1000 nm illustrates the effect of larger interference.
- `DayOfNight`: See §11. Two values, "day" and "night" are supported by the spreadsheet. Generally "day" will result in too large a component of noise from scattering sunlight. The "night" value replaces scattered sunlight by scattering moonlight for the full moon phase.
- `Pdaylight`: See §11. This is the probability of daylight outage, assuming that daylight is treated as an outage condition by the receiver.

- `Pweather`: See §11. This is the probability of outages for weather conditions treated as an outage by the receiver.
- `Ts`: See §6.2, Fig.4, §10.8, Fig.20, Fig.21. Generally choosing a smaller value results in a smaller duty cycle `delta` and hence reduces the effect of dark counts without harming other sources of background. However, this also increases `PpT`, so values in the range of 0.1 to 1 microseconds are advantageous. These values are several orders of magnitude smaller than for conventional PPM, and reduce the effect of dark counts accordingly.
- `Distance`: See §10.3. This is chosen to be the distance of Proxima Centauri, with an assumption that downlink operation begins immediately after star encounter.
- `AeT`: See §10.1. The for a given transmitter power-area metric, there is a tradeoff between the transmit aperture effective area `AeT` and the transmit peak and average powers `PpT` and `PaT`. The nominal value chosen seems reasonable for a low-mass probe.
- `effic`: See §6.1, Fig.24. Reducing this value will increase the required transmit powers `PpT` and `PaT`, although less than expected since `effic` has no impact on dark counts.
- `OmegaA`: See §4.1, Fig.1, §9, Fig.8, (7), Fig.11, Fig.12, §B. The larger `OmegaA` the lower the sensitivity of the aperture and the larger the transmit average power `PaT` required to achieve the specified `SBR`. The nominal value chosen is justified in §9, but the reasoning explained there can be extended to other scenarios, such as the inter-probe launch interval and the downlink transmission time for each probe. The case of a single-probe receiver can also be explored by choosing `OmegaA` based on the expected aperture pointing accuracy.
- `LambdaNS`: See §10.6, Tbl.9, Tbl.10, §11.1. The nominal numerical values are taken from Tbl.10, and these are dependent on the choice of `lambda` and the switch variable `DayOrNight`.
- `LambdaIS`: The nominal value is taken from Tbl.10 based on the choice of wavelength `lambda`.
- `We`: See (2), §6.1, §10.8, Fig.23, §13.2. The nominal value assumes an ideal bandpass filter with `We = 1/Ts`. Note also that when `Ts` is changed, it is appropriate to coordinate a change to `We`, and it should never occur that `We*Ts<1`.
- `Fc`: See Fig.19, §12.7. The numerical value is chosen to achieve balance between SIR and the other signal-to-noise ratios. For parameters which minimize the effect of dark counts (small `LambdaDS` or small `Ts`) SIR becomes small and reducing star interference (with a smaller `Fc`) is particularly advantageous.
- `Fx`: See §10.7, (12), §13.1. The numerical value must satisfy `Fc*M*SBR<1` (see §10.7). The value is large enough to render extinction a small effect, but it should be reduced for larger `BitsPerFrame` or `SBR`.
- `LambdaDS`: See Fig.17, Fig.18, Fig.20, Fig.21, Fig.23, §13.3. There is not a solid basis for the nominal value chosen, and it is based on achieving approximately equal `SNR` and `SDR` in the swarm probe case. Larger values will have a deleterious effect on performance parameters. There are possibilities such as sharing an optical detector across multiple apertures while avoiding optical interference (see §13.3).
- `Ractual`: See §14.4. The value is calculated from `Bitrate` reduced by the probability of non-outage, which depends on `Pdaylight` and `Pweather`.
- `TF`: See §6.2, Fig.4. This value is calculated from the transmitter configuration choice of `BitsPerFrame` and `Ts`.
- `TI`: See §6.2, Fig.4. This value is calculated from by the choice of `BPP`, `Bitrate` and `KsR`. A more aggressive (larger) choice of `BPP` will decrease the PPM frame rate, as will a lower `Bitrate`, because for fixed `Ks` the received signal photon rate is lower.
- `delta`: See §6.2, Fig.4. This duty cycle is calculated from `TF` and `TI`, and is the factor by which dark counts are reduced due to ignoring all background radiation during blank intervals.
- `AeS`: See §5.1, Fig.2, Fig.3, Fig.11, Fig.16, §B. The effective area of a diffraction-limited aperture is the ratio of power in the optical detector (assuming idea quantum efficiency) to the flux of an incident plane wave. The larger `AeS` the greater the sensitivity (or gain or directivity) of a aperture to probe signal, but the smaller the coverage solid angle `OmegaA`. In this spreadsheet, `OmegaA` is an input, and `AeS` is calculated from `OmegaA` and the wavelength `lambda`.

- `NS`: See §5.1, Fig.2, §5.2.1, Fig.3, §10.2, Fig.15, Fig.16, Fig.24. The number of apertures that are replicated and incoherently combined in the receive aperture. This is calculated from the specified `KsR`, or in other words `NS` must be large enough to insure data reliability in the face of signal shot noise.

- `PaT`: See §3.2, §??, Fig.12, Fig.20, Fig.23. The average transmit power determines the minimum electrical power requirement as well as the transmit laser. The value calculated here is the minimum `PaT` consistent with the chosen values of `SBR` and `BitsPerFrame`. You can explore the tradeoffs between `PaT` and `PpT` and the total receive aperture equivalent area `AeS*NS` by manipulating the values of `SBR` and `BitsPerFrame`.

- `PpT`: See §3.2, Fig.21, §13.1. The peak transmit power is consistent with `PaT`. If pulse compression technology is employed, the transmit laser does not necessarily have to generate this level of peak power (see §13.1.2).

- `SXR`: See §4.4, §10.6. These four signal-to-noise ratios SxR indicate the relative importance of the four types of background that are considered. Together these sources accumulate to achieve exactly the overall specified `SBR`. The smallest of the SxR's, especially one that is not too much larger than `SBR`, is the dominant source of background. This tells us which background radiation to focus on reducing by changes in the input parameters. `SXR` characterizes the background due to incomplete extinguishing of the light source in the transmitter, and can be increased by choosing a smaller `Fx`.

- `SNR`: See §4.4, §10.6, Fig.13, Fig.14. This is background noise originating with unresolved cosmic sources of background like the atmosphere, Zodiacal radiation, and the deep star field. There is no way of increasing `SNR` because it is not affected by coverage solid angle `OmegaA`, and it is proportional to `We Ts` which will generally stay fixed as `We` and `Ts` are changed in coordinated fashion. Fortunately it is often the least significant source of background radiation.

- `SIR`: §4.4, §10.6, Fig.13, Fig.14. This is background interference originates with the target star falling in the coverage angle `OmegaA` and reduced by the coronagraph attenuation factor `Fc`. It is unaffected by the choice of `OmegaA`, which affects signal and interference equally. `SIR` can be increased by choosing a smaller `Fc` and by choosing the smaller value of wavelength `lambda`.

- `SDR`: §4.4, §10.6, Fig.13, Fig.14. This background originates with dark counts in the optical detectors, which are oblivious to `OmegaA` and `We`. `SDR` can be increased by choosing a smaller `Ts`, which will reduce `delta` and require an increase in `We`. The deleterious effect will be an increase in peak power `PpT`.