ENGN2226 Portfolio
Frequency Transfer System

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Abstract

Systems engineering analysis was applied to the production of a Frequency Transfer System (FTS) as part of a large scale project. An FTS is responsible for ensuring that electronics that are separated by large distances have their clocks synchronised, which is vital for successful data collection. The report finds that fibre optic cables should be used for the frequency transfer transmission medium, as the performance cost of using a free space link outweighs the monetary cost of using fibre optic cable. It finds that the embodied energy and power usage of the system can be reduced by using dedicated electronics for the FTS, as opposed to individual components. The environmental impact can be further reduced by only laying the fibre optic cables along already disturbed land, such as along roadways. For the laser signal used by the FTS, a frequency comb is recommended. In order to develop an FTS as part of a project, it is recommended to include periods of inactivity in the Gantt chart, to allow for feedback processes in the design process to take effect if need be.

The report recommends considering future research into free space FTS and different modulation schemes, as these may change the recommendations of this report.

Contents

In this section, I conduct a simple survey of the technology of FTS, and produce some recommendations of topics of analysis.

In this section, I act on one of the analysis topics from the previous sections, by deciding between fibre optic cable or free space using a cost benefit analysis.

In this section, having decided upon fibre optic cables, I consider the environmental impact of the system.

This section is rather small, as the total power usage of the system is quite small. I simply use a sankey diagram to confirm the recommendations from the materials analysis that dedicated electronics should be used.

In this section I consider the safety factors associated with humans using lasers. I also consider the safety concerns for the fibre optic cable, which are typically broken by humans.

In this section, I consider that a frequency transfer system works by using a feedback system. I identify a potential issue with the modulation scheme used for the feedback. I then perform a survey of existing and new modulation schemes and recommend which should be used.

In this section I use a Gantt chart to consider how the project development of an FTS should proceed.

Figures

Tables

1 Introduction

A Frequency Transfer System (FTS) is a method of transferring frequency references between remote locations in order to provide common clock signals for distinct electronic devices (Foreman et al., 2007). A frequency signal, usually in the form of modulated laser light, is produced from a transmitter in phase with its own internal clock, and sent to a receiver, which uses the received signal to run its clock. By compensating for the changing delay in the transmission medium, caused by noise and other effects, the FTS can ensure that the electronics of each distinct electrical system are running according to a common clock frequency.

Such a system is important for large scale projects where knowing precisely when information was received at individual locations is extremely important, such as servers. Of particular interest is the Square Kilometre Array (SKA), which is a large scale telescope project currently being constructed in Australia and South Africa. The SKA will use phased array telescopes, which cleverly utilises combined signals from multiple telescopes to improve image resolution (Tingay, 2014). For such a system, having a common clock reference across all of the telescopes is vital to achieve any meaningful research results.

This report applies systems engineering techniques to produce recommendations on how an FTS can be developed and implemented as part of a bigger project, at the physical and monetary scale of the SKA. It aims to provide recommendations that are independent of the specific technological requirements (e.g. stability level) of the project.

2 Technology Survey

In this section, a literature survey is conducted, addressing the questions of how FTS currently function, and what metrics are used to measure the performance of an FTS. Answering such questions aids in the analysis from other system topics, particularly by revealing areas of potential improvement of an FTS.

2.1 Operation Methods of FTS

Foreman et al. (2007) adequately explains the standard operation of FTS. The objective is for an outgoing frequency reference signal (typically a laser signal) to be received at a remote location at exactly the same frequency as was sent, at all points in time. Noise in the transmission medium is what prevents this, as a momentary squishing or expansion of the transmission medium will stretch or compress the sent signal, thereby momentarily changing the signal frequency on the receiving end.

In general frequency transfer systems, a feedback loop is used, with a laser sending out a signal, which is partially reflected at the receiving station back towards the transmitter. The transmitter then locks onto the phase of the returning signal and compensates for any noise in this phase. A diagram of this partial reflection setup is shown in Figure 1. In this diagram, a signal is sent through a fibre optic cable, and it is partially reflected back and then detected at the transmitting side. A fibre stretcher is used to change the phase of the outgoing signal to compensate for the noise in the detected returning phase.

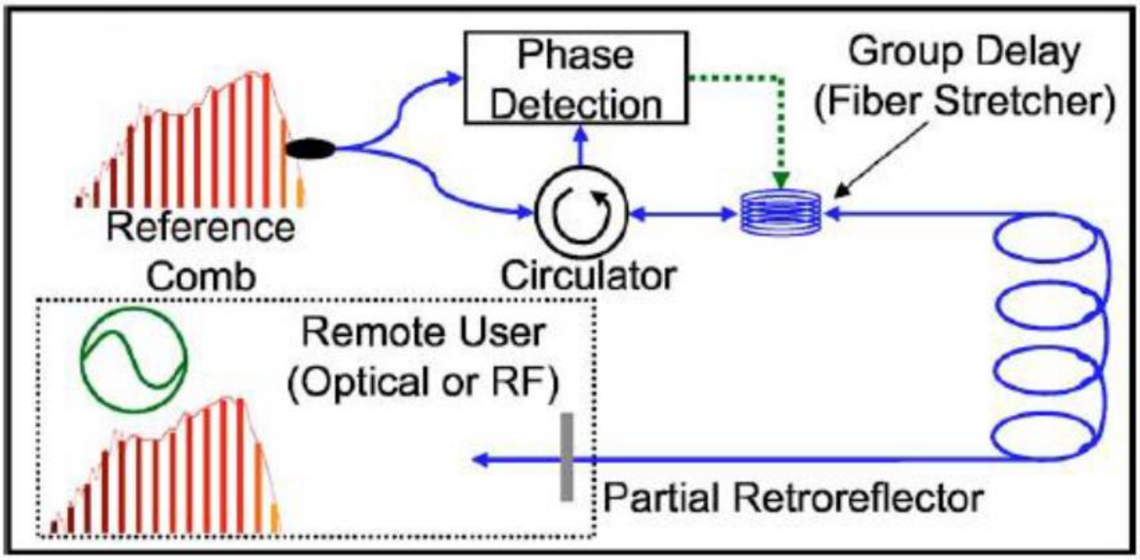

Figure 1: Typical setup for FTS over fibre optic cable (Adapted from Foreman et al., 2007)

The transmission medium is not only limited to fibre optic cable, with free space (through air) frequency transfers having been demonstrated (Giorgetta et al., 2013).

2.2 Performance Metrics

The most common stability measurement for FTS is the Allan Variance, which is a measure of the difference between frequency measurements as a function of the time delay between measurements. A low Allan variance indicates better performance. Such values are also quoted with reference to the distance that the frequency transfer was completed over. For example, an Allan variance of 10^{-19} at 30000s time delay has been demonstrated over a fibre length of 146km (Grosche et al., 2009). An Allan variance of 10^{-18} at 1000s delay has been demonstrated across a 2km free space link (Giorgetta et al., 2013).

As this report provides recommendations that are independent of the specific stability requirements of an end system, specific analysis of Allen Variance is not performed. However, it can be noted that varying delay times and stability numbers quoted in the research adds bias to the reported performance of FTS, as new technology can be made to look like they have similar or better performance than existing systems, simply by considering differing delays. This should be addressed in the FTS research field, with a standard averaging time to be quoted in all performance measurements. It may well turn out that systems are optimised for alternative averaging times. In this case, both numbers should be quoted, to allow for a reader to get a meaningful understanding of the performance of the system.

When choosing an FTS for an industry development, care should be taken not to be fooled by sneaky performance reporting.

2.3 Identification of Potential Analysis Areas based on Technology Survey

While free space and fibre optic FTS have been demonstrated, the distances over which these have been accomplished is vastly different. Fibre optic cable FTS have been demonstrated over distances on the order of 100km, while free space FTS have only been demonstrated over distances on the order of 1km. This presents an important analysis topic. If an FTS were to be completed over a very large distance, the demonstration of this technology over that distance should be considered.

Another potential area of improvement is in the modulation scheme used for the laser signal. Several different modulation schemes exist, including sinusoidal and frequency combs (Foreman et al., 2007). A systems analysis should evaluate which modulation scheme would be most appropriate for the target application.

3 Cost Factors

As an FTS only requires computers and minor electronics on either end of the link, a significant portion of the cost will come from the fibre optic cables, if they are used. The question of whether free space or fibre optic transfer should be used can be decided with a simple cost-benefit analysis, based on the existing technology.

3.1 Cost Estimates

Estimates of the price of laying fibre optic cable vary depending on location and application. The U.S. Department of Transportation (2015) lists several projects as having cost \$20000-\$50000 per mile of fibre. In AUD at the time of the publication of this report, this is approximately $17-$43 per metre. NBN Co Limited (2013) estimated costs of laying fibre for the Australian national broadband network at $31 per metre, which fits within the U.S. Department of Transportation range. As the NBN Co Limited estimation was for fibre rollout in Australia, it shall be assumed that this figure is more accurate for technological projects in Australia. However these estimates do not specify their methodology, so it is unclear exactly what elements are included. It is assumed, as these are government sources, that they are calculated appropriately to include both the cost of procurement of the fibre and the cost of laying it.

Ongoing maintenance costs of cabling tend to be difficult to quantify, as they are usually under contract and not released to the public. It is also particularly difficult to provide an accurate estimate of fibre optic maintenance costs in Australia, as the political divide between certain implementations of the National Broadband Network have resulted in a lot of misinformation on this topic. It can be concluded that the amount of maintenance on the fibre will be low, as fibre does not significantly degrade, having a lifespan of several decades (Ross, 2012). Most of the maintenance that will be required may come from human interference (See Section 6.4). It should therefore be assumed that most maintenance costs can be covered using insurance schemes, and thus excluded from this analysis.

3.2 Cost Benefit Analysis

The potential benefits of using a fibre optic link as opposed to a free space frequency transfer are:

- Minimal reduction in the required laser power (although laser power consumption is insignificant compared to total power consumption, see Section 5).
- No outage time due to laser obstruction. In a free space system, obstructions such as vehicles, animals or mist could make themselves present. This could be compensated for by transmitting from tall towers, but this would introduce an additional cost factor

These factors are summarised in Table 1.

Evaluating the true value for the outage probability for free space is difficult, as it depends on many factors such as weather patterns, specific location of transmitting and receiving stations and active directional control. It is however clear that this probability is above zero, particularly considering the fact that free space links have not been demonstrated over large distances.

Table 1: Costs and Benefits of Different Media

Cost/Benefit	Free Space	Fibre Optic Cable
Cost per metre	$0	$31
Transmission Power	>1W (Distance dependent)	<1W
Obstruction Probability	x	~0

For extremely large, research driven projects, such as the SKA, the cost of laying fibre optic cable is insignificant compared to the total cost. Outage problems in the FTS would however come at a large cost to the usefulness of the entire project, as outages would mean that the data collected at each telescope cannot be meaningfully combined with the data from other telescopes. This would in turn cripple the research capabilities of the entire Square Kilometre Array. As the SKA is not an economic venture, this would defeat the purpose of completing the project at all.

3.3 Key Recommendations

Therefore the potential benefit from laying fibre optic cable outweighs the larger cost of laying the fibre optic cable. Therefore a free space frequency transfer should not be used.

This result would not hold for a smaller project, where the budget of the FTS takes up a more substantial proportion of the total cost. In such a case, it may be more beneficial to accept outage and compensate for these times with other systems.

Based on this result, the material construction of an FTS can now be examined.

4 Material Factors

4.1 Embodied Energy

Based on the decision that the FTS should use fibre optic cables, an embodied audit of an FTS helps to allow for a more environmentally friendly design. In order to complete this embodied energy audit, a simplified model of an FTS was created, shown in Figure 2.

Figure 2: Simplified Model of FTS

Elmirghani (2013) estimates the embodied energy of the GYTY53 fibre optic cable at 18GJ/km. In order to provide an estimate for a more general type of cable, this is compared with a loose tube fibre optic cable. Unger and Gough (2008) provide a description of an example of this cable as consisting of an Optic Fibre core, gel, fibre cladding, an aramid sheath and an outer polyethylene sheath. It should be noted that they don't specify which aramid (a type of synthetic fibre) is used for the sheath. For the purpose of this analysis, it is assumed that it is Kevlar. The calculated embodied energy per metre for this type of cable is shown in Table 2.

Table 2: Embodied Energy of Fibre Optic Cable. Source for embodied energy of Fibre & Cladding: (Berge, 2009). Source for other embodied energies: (Institution of Mechanical Engineers, 2010)

Component	Primary Material	Weight (g/m)	Embodied Energy (MJ/g)	Embodied Energy (MJ/m)
Optic Fibre	SiO2	0.29	0.01	0.0029
Gel	Si	2.22	0.16	0.3552
Cladding	SiO2	4.25	0.01	0.0425
Aramid	Kevlar (Assumed)	3.1	0.28	0.868
Outer Sheath	Polyethylene	24.13	0.0809	1.952117
			Total	3.22

Therefore, the calculated value for the embodied energy of a loose tube fibre optic cable is approximately 1/6th of that of the GYTY53. Despite these estimates being quite different from one another, they do confirm that the embodied energy is on the order of 10GJ/km. This value shall be used for further analysis.

For the estimation of the embodied energy of the electrical components of the system, assumptions must be made about their composition. It is assumed that both the transmission and receiving ends contain analogue to digital converters, digital to analogue converters, frequency generators and microprocessors. Furthermore, it is assumed that these are purchased as separate elements. Based on this assumption, it is estimated that the total embodied energy of these components is approximately equal to having another computer on each end of the system. Duque Ciceri et al. (2010) estimate the total embodied energy of a computer at 3000MJ. This value is potentially dubious, as Decker (2009) suggests that the embodied energy of computers is changing over time, but it serves as an order of magnitude comparison to the embodied energy of the fibre optic cable. Based on an assumed frequency transfer distance of 100km, Figure 3 shows a summary of the embodied energy of this system.

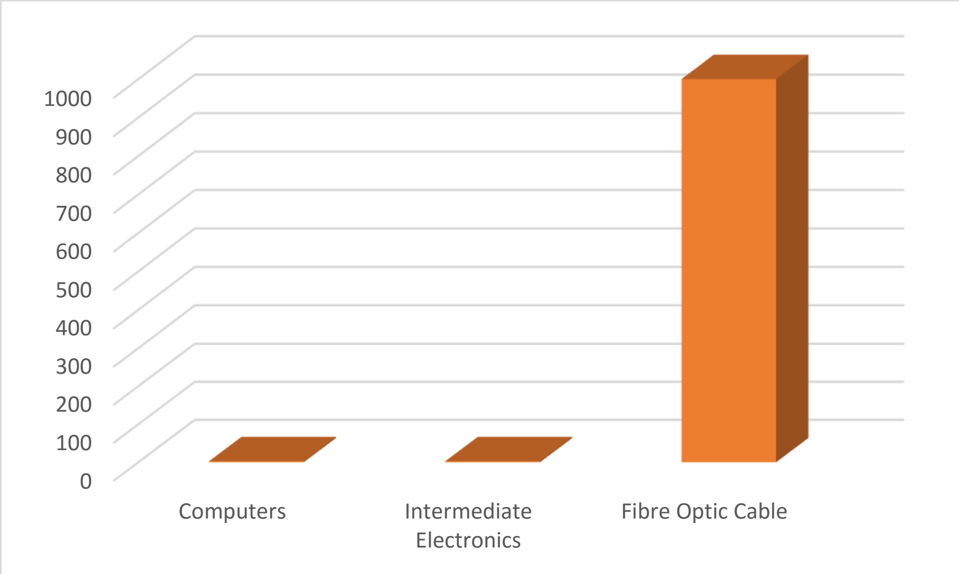

Figure 3: Embodied Energy of FTS

As can be seen, a significant proportion, far exceeding that expected by Pareto's Principle, of the embodied energy of the system comes from the fibre optic cables. This should increase interest in research into free space FTS; although any system implemented in the near future must opt for fibre optic cables, future systems could significantly save on embodied energy and monetary costs by using a free space link.

A potential method of reducing the embodied energy of the system could be to use specialised chips for the electronics on either end of the system. Instead of having separate boards that produce each of the functions, such as the analogue/digital conversions (which is what led to the assumption that the electronics would be approximately the same as additional computers in terms of embodied energy cost) all of these functions could be combined onto dedicated boards. This would reduce the total number of distinct components by a factor of four, therefore potentially decreasing the embodied energy of the intermediate electronics by 75%.

In addition to embodied energy cost, there are additional factors that determine the effect of the system on the environment. These are now discussed.

4.2 Direct Environmental Impact

A direct impact that the installation of a fibre optic cable based FTS on the environment is the effect of disturbing the land in order to install the fibre optic cable. Such an effect is difficult to model or quantify, however the effect can be minimised by only digging along already disturbed land, such as along roadways connecting the desired stations.

4.3 End of Life Considerations

For the end of life considerations, the recyclability of the components of the system is considered. Government schemes exist to assist in the recycling of computer electronics (Department of Environment, 2015), indicating that this will not be a significant concern for an FTS. However, according to Unger and Gough (2008), fibre optic cables are not easily recycled and are most likely disposed of using incineration. This, again should increase interest in the development of free space FTS, as this would also remove the end of life environmental impacts of using fibre optic cables.

4.4 Key Recommendations

The embodied energy cost of the system can be reduced by using specialised electronics to control the frequency transfer, and environmental impact can be reduced by burying the fibre optic cables under already disturbed land, such as along roadways. It is strongly recommended that more research be conducted to provide better free space FTS, such that all environmental impacts associated with fibre optic cables can be removed.

5 Energy Factors

5.1 Sankey Diagram Analysis

In an FTS, all of the energy used is "lost", as the system attempts to transfer timing information, rather than to achieve any useful work. Therefore, the objective for energy usage optimisation is simply to minimise the total power usage of the system. Again, using the simplified model in Figure 2 as a basis, a Sankey diagram was created showing the approximate power usage of an FTS, which is shown in Figure 4. This diagram is based on the average energy of a computer being approximately 200W (Griffith University, 2015).

This yields a surprising result; the laser, which could be considered the fundamental component of the system as it is the part that actually transmit the data, contributes almost none of the total power of the system. The majority of the power is consumed from the electronics controlling the frequency transfer. This adds merit to the recommendations from the materials analysis;

reducing the electrical components onto dedicated printed boards could reduce the total power usage by a similar factor, potentially to 50W

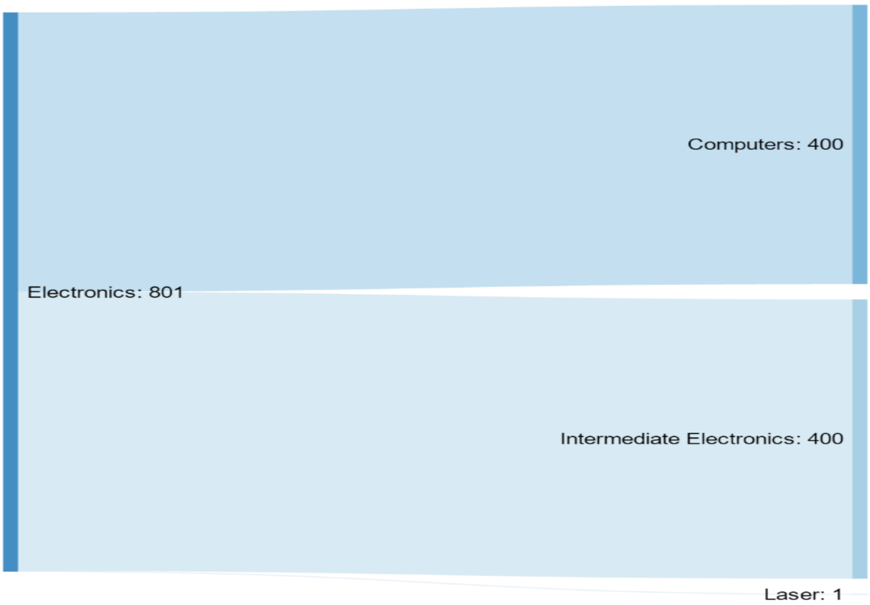

Figure 4: Sankey Diagram of System Power Usage

5.2 Key Recommendations

It is also recommended that the power usage be reduced by producing dedicated circuits to operate either end of the FTS. This agrees with the analysis of the material factors of the system.

6 Human Factors

6.1 Factors of Interest

The FTS of interest has the aim of aiding research and industrial interests of people. The use of an FTS allows for the collection and time stamping of data from multiple sources that would otherwise not be collated. For most purposes, any end user of the underlying research tool, such as a telescope array, will not have technical expertise in the aspect of frequency transfer. Therefore the FTS should largely be abstracted away from the end user, functioning essentially autonomously. Therefore consideration of human factors in this system are restricted to the few cases in which humans will interact with it, which is predominantly construction and maintenance.

6.2 Laser Safety Considerations

As FTS involve the use of lasers, legislation and industrial standards regarding safe practises around such devices must be considered. Lasers are categorised into several categories outlined in the IEC 825-1 standard. These are based on their power of operation, focusing optics and wavelength of light (ARPANSA, 2013). A summary of the risk associated with these categories is given in Table 3.

Table 3: Properties of Laser Categories

Class	Risk	Safety Requirements
1	None	None
1M	Minimal	Laser Safety Glasses Recommended
2	Minimal	None
2	Minimal	Laser Safety Glasses Recommended
3B	Eye or Skin damage. Viewing from diffuse reflection okay.	Laser Safety Glasses Required
4	Eye or Skin damage, fire hazard	Laser Safety Glasses Required

6.3 Laser Danger Mitigations

Regardless of the broad range of dangers produced by lasers, in general, risk to humans can be mitigated by (LightPointe, 2001):

- Limiting laser output power
- Minimising access to the laser
- Displaying proper eye safety labels
- Providing appropriate eye safety equipment
- Providing visible indication of laser on/off status
- Locating system controls away from laser devices
- Providing appropriate training for users for both setup and maintenance

From these standards and recommendations, the main safety concerns are minimising the exposure of the laser to humans.

Providing appropriate signage and eyewear is quite convenient for maintenance workers, with the only consideration being ensuring that the eyewear and signage are relevant to the laser being used. Alternatively, the laser being used can be restricted to a category from Table 3 that will not present a safety concern. However, this may have implications in the signal strength and therefore the quality of the frequency transfer.

An additional method of reducing exposure risk, in the case of a fibre optic FTS would be to use a fibre coupled laser. This means the laser pulses would be generated inside cables with protective coating, reducing (not removing) the risk of human exposure to the laser signals. As the risk would not entirely be removed, laser safety glasses should still be given to workers, in accordance with Table 3.

6.4 Safety of Equipment Considerations

Alcoa Fujikura LTD. (2001), quote that 80% of all direct breakages of fibre optic cables are a result of human excavation. This specific value is potentially error prone, as it is dated and is from a report targeted at business interests, however it does indicate that a significant human factor in any system involving fibre optic cables is digging.

While human excavation would pose little safety risk to the individual, it would render the FTS in-operational for the extent of the breakage period. Alcoa Fujikura LTD. (2001) indicate that it takes around 8 hours to fix a fibre optic cable. This value, again, may be dated, however for an FTS working over hundreds of kilometres, it seems reasonable that from the detection of a breakage to its repair would take many hours. Care should therefore be taken to avoid this problem by burying cables at standard depths, with appropriate signage, as specified by industrial standards.

The depths required in Australia vary based on the terrain under which the cable is being buried. Communications Alliance LTD. (2013) quote that for an under-road crossing, the burial depth should be 1-1.2m, alongside road reserves, a depth of 0.45m should be maintained, while on customer properties, 30cm of depth is permissible.

6.5 Key Recommendations

Safety of workers around the FTS should be maintained by using fibre coupled lasers, with appropriate eyewear and signage being applied in all working areas.

Safety of the fibre optic cable equipment should be maintained by conforming to depth and signage requirements to reduce the risk of excavation based breakages.

7 Dynamics and Control Factors

7.1 Problems with current Feedback System

As discussed in Section 2.3, FTS work by partially reflecting a laser signal, typically a sine wave from a target location, tracking the returning phase and compensating for the noise in the returning delay. A potential problem identified in this setup was the choice of transmitted signal. Using sine waves leaves the device susceptible to partial reflections inside the medium. If there is a break in one of the fibres, or some reflector in the way in free space, a part of the signal will be reflected prematurely and will be added to the actual reflected signal. As the sum of two sine waves is another sine wave with a different phase, this means that the phase detection will be incorrect and therefore the noise compensation will not be effective. Choosing a transmission signal that is not susceptible to these spurious reflections in the medium is therefore a method of improving this feedback system.

7.2 PRN Modulation

A potential signal type that should be considered is a pseudo-random noise code. Pseudo-random noise is not subject to the same problem as sine waves, as delaying by an arbitrary amount does not necessarily produce another pseudo-random noise code (although a delay by exactly an even number of time steps will, which is unlikely in a physical system)(Sarwate and Pursley, 1980). A pseudo-random noise code can also be conveniently generated by using a linear feedback shift register, making implementation simple. This type of signal therefore has the potential to improve the control of an FTS.

Research is currently being conducted at ANU about the application of PRN in frequency transfer systems, however complete analysis has not been published, meaning that analysis cannot be made on the efficacy of this scheme in FTS, however future analysis should be open to this option.

7.3 Comparison of Modulation Schemes

A summary of the properties of sinusoidal, frequency comb and PRN modulation schemes is provided in Table 4. The information is based on properties discussed in this section and additional information provided in Foreman et al. (2007).

Based on these properties, it is clear that for current systems, a frequency comb is the best modulation scheme to provide a good feedback control system for the frequency transfer that has been demonstrated in an existing FTS.

Table 4: Properties of Modulation Techniques

Modulation Scheme	Susceptible to Frequency Drifting	Susceptible to Spurious Reflections	Has been demonstrated in FTS
Sinusoidal	Yes	Yes	Yes
Frequency Comb	No	Yes	Yes
PRN	No	No	No

7.4 Key Recommendations

It is therefore recommended that this modulation scheme be used in upcoming applications. This recommendation may change in the future, with research currently being conducted into new modulation schemes. Anyone acting on the advice of this report should make themselves aware of this new research

8 Time Factors

An FTS is fundamentally about sending timing information between base stations, with the measure of performance being given by the Allen Variance, as discussed in Section 2.2. The specific requirements and tolerances on the Allen Variance for the FTS are however application dependent. As this report provides specific application independent advice, the timing tolerances shall not be discussed in this section, but rather the timing associated with the development of such a system will be discussed. An examination is conducted of the Gantt chart in the SKA project planning document (Schilizzi et al., 2011). This is used to inform recommendations about the project timing of an implementation of an FTS.

8.1 Gantt Chart Analysis

To develop a Gantt chart to describe the rollout timing, the system development and validation process must be thoroughly analysed. In order to ensure that the final system meets design requirements, it should undergo stages of modelling, simulation, physical development and physical testing. These steps should all feed back to each other, with the final design being informed by all of them. These steps would then allow for final performance analysis and final hardware deployment. The arrangement and information flows of such steps are shown in Figure 5.

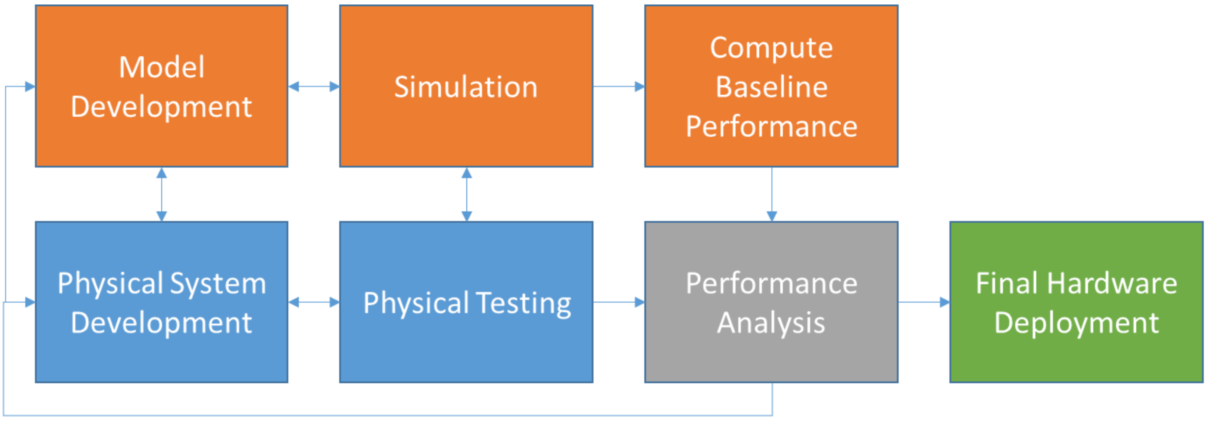

Figure 5: System Development and Validation Process

The problem with arranging a Gantt chart to describe such a development process is that it is difficult to determine a prior the number of iterations of the feedback loop that will be required. As such, these are often overlooked. Indeed, observing the proposed Gantt chart for the SKA (Schilizzi et al., 2011, p 55), no tolerance is given for feedback structures to take place. Also, in their system development flowcharts, feedback structure was limited to the Preliminary Design section of development, in which only the scope of work was expected to change.

Leaving the feedback structures of the design process unquantified, by using an 'As Soon As Possible' planning structure in the Gantt chart leaves the project susceptible to delays if the measured performance does not match expectations. For implementing an FTS, the author recommends a modified Gantt chart that incorporates a planned period of inactivity. Including such a period in the project planning has the effect of removing the vulnerabilities of delay, and allows for the feedback loops shown in Figure 5 to be implemented if necessary. The proposed Gantt chart is shown in in Figure 6. The timing units are estimates based on the timing proportions between stages in the Gantt chart for the SKA. It was assumed that the FTS would take a year to implement in its entirety, with the timing scheduled to fit this.

A feature of this Gantt chart is forward scheduling. This is preferred in order to allow even more time for the feedback structures to be acted upon as necessary.

8.2 Key Recommendations

Conventional Gantt chart project planning leaves projects vulnerable to delays if expected performance does not match actual performance. A schedule is proposed for the implementation of an FTS that incorporates planned period of inactivity, to allow for feedback processes to be acted upon if necessary.

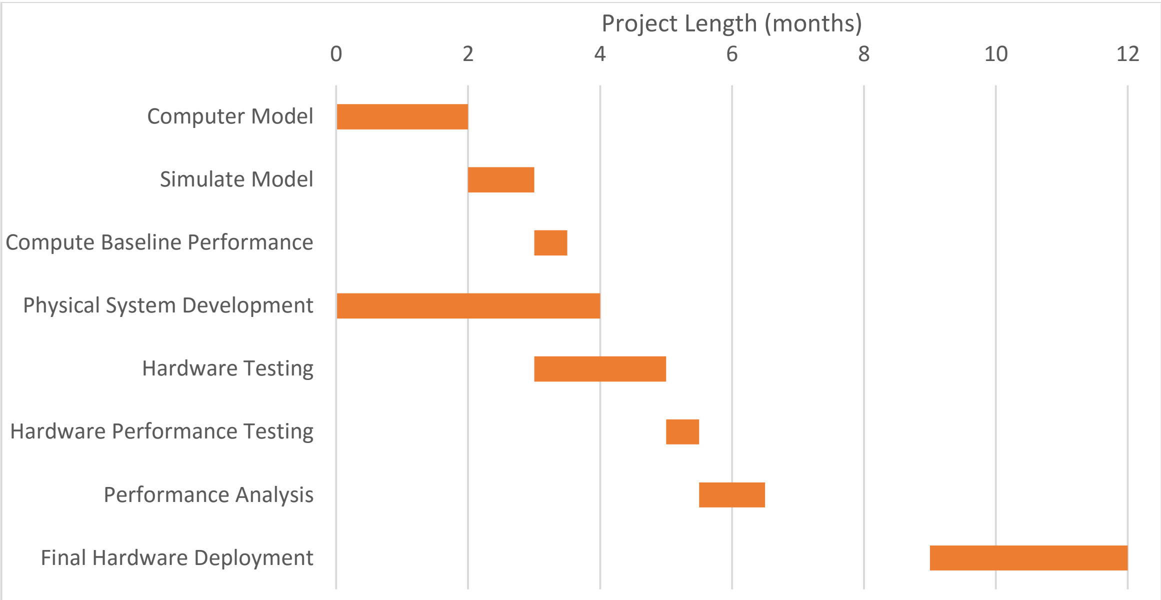

Figure 6: Gantt Chart of System Design Flow

9 Conclusions

A systems engineering approach was used to develop recommendations on the application of an FTS in a large scale project. The principal recommendations of this report are as follows.

A fibre optic cable FTS should be used over free space, as the cost to performance of free space transfer outweighs the monetary cost of using fibre optic cable. Research into this free space frequency transfer should be a priority, as achieving this to a suitable standard would reduce monetary and embodied energy cost, as well as overall environmental impact. In order to reduce embodied energy cost and power usage, dedicated circuitry should be used for the running of the frequency transfer. The total environmental impact of the FTS can be further reduced by only laying the fibre optic cables along already disturbed land, such as along roadways. Safety of humans and equipment should be maintained by providing appropriate eyewear and technology, and by burying fibre optic cables at standard depths. A frequency comb should be used as the laser modulation scheme, as at the moment, this has the best properties that have already been demonstrated in an FTS. Upcoming research may alter this recommendation. Finally, the scheduling of the FTS should contain a period of inactivity, instead of using an "As soon as possible" planning regime, to allow for feedback in the design process to take place if needed.

Following these recommendations would help for a successful industry development of an FTS.

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